

CRANFIELD UNIVERSITY

CRANFIELD POSTGRADUATE MEDICAL SCHOOL.
DEPARTMENT OF MATERIALS AND MEDICAL SCIENCES.

APPENDICES

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Non-Invasively Assessed Skeletal Bone Status and its Relationship to the
Biomechanical Properties and Condition of Cancellous Bone

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Introduction

This second volume encloses the appendices of the thesis. The initial appendices contain the questionnaires, information pamphlets and consent forms that were used in the clinical aspect of the study at the Great Western Hospital Swindon and the similar information pamphlet and consent form which were used at Gloucestershire Royal hospital and Standish hospital for the consensual collection of human femoral heads.

This second volume is dominated by the extensive full regression analyses which were performed for the in-vitro studies of the compressive and fracture mechanics of cancellous bone with respect to the independent variables and the QUS investigation results that were obtained using the CUBA Clinical and the Sunlight Omnisense clinical ultrasound scanners.

The later appendices contain both the documents which were written as deliverables for the BOSCOS project, outlining the work that was performed for that project which in many cases was not included in the main thesis. Finally there are reproductions of all the abstracts and articles which have been published in the scientific literature as a result of this study so far.

Appendix 1: Swindon Patient Information Pamphlet

BOSCOS TRIAL: The Abilities of Quantitative Ultrasound for the Assessment of Skeletal Condition

1. Study title

BOSCOS stands for Bone scanning for Occupant Safety and involves Bone scanning and material testing of bone to establish the correlation between material and non-invasive testing of bone strength.

2. What is the purpose of this study?

The purpose of this study is to come up with a simple technique for assessing the strength of bone in patients using a portable scanner that will scan your hand and feet. In the future it may be used in GP surgeries.

3. Why have I been chosen?

You have been chosen because you are undergoing DXA scan and we would like to use the information from this scan as a reference measure for the maximisation of the abilities of QUS.

4. Who is organising the study?

The study is being organised by the Cranfield University in association with the Department of Transport. This study will take 3 years to complete.

5. What will happen to me if I take part?

Taking part in the study in no way changes your medical and surgical care. As far as your investigations will be concerned you will have a standard procedure performed. However, after your DXA scan, a research assistant will ask you some questions about your health and lifestyle as this may be an important factor in predicting the condition of your bones. They will also scan your feet, legs and arms. This is a completely non-invasive procedure and is painless. This will also take place during your hospital visit so there will be no extra Clinic visits as a result of the study.

6. What is osteoporosis?

Osteoporosis is a medical term for thinning and weakening of the bones. Osteoporosis is a condition, which affects large numbers of older people, particularly women. Unfortunately this means that more people suffer from fractures (bone breaks) as the bone weakens. We are now discovering better ways of both preventing and treating this condition, however we need better and easier means of detecting osteoporosis.

We propose to undertake a study using the bone of people, like yourself, who are having DXA investigations and to further investigate your skeletal condition using ultrasound

by the use of two additional scanners so as to measure how solid your bone is (bone density).

By comparing the results of these bone investigations we shall be able to work out if there is any link between them. We may then be able to more accurately predict who is at risk of developing a fracture from the scan results.

7. Are there any disadvantages in taking part in this study?

There are no disadvantages in taking part in this study and it doesn't interfere with your treatment in any way. If you change your mind you can withdraw at any time without saying why. This will not affect your care in any way.

8. What are the possible risks of taking part in this study?

There are no risks at all involved in taking part in this study.

9. What are the possible benefits of taking part in this study?

If the scan gives any cause for concern you will be informed. We would like to share this information with the clinical team responsible for your care in hospital and with your general practitioner who will be able to give you the most appropriate advice.

10. Confidentiality – Who will know that I am taking part in the study?

Only certain members of the rheumatology department will be able to identify you from your scan results. All data will be anonymised so that the researchers who are outside the clinical team will not be able to identify you.

11. Who has reviewed the study

The ethical research committee of Swindon and Marlborough NHS Trust.

12. What will happen to the results of this study?

If you would like to be sent a short summary of the results of this study, we would be only too delighted to send one to you. If there is any further information that you require please call the hospital switch board on 01793 60 50 57 and ask for Dr. D Collins' Research Team.

Appendix 2: Clinical Studies Consent Form

Centre Number:

Study Number:

Patient Identification Number for this trial:

CONSENT FORM

Title Project: BOSCOS Trial

Name of Researcher:

Please initial box

1. I confirm that I have read and understand the information sheet dated _____ (version _____) for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time giving any reason, without my medical care or legal rights being affected.
3. I understand that I will have a scan of my spine, hip, leg, ankle, wrist and hand and will be asked questions from a questionnaire.
4. I agree to take part in the above study.

Name of Patient

Date

Signature

Name of person taking consent
(if different from researcher)

Date

Signature

Researcher

Date

Signature

1 for patient; 1 for researcher: 1 to be kept with hospital notes

Appendix 3: Questionnaire

Patient’s Details

Name: _____ Patient’s No.

Address: _____

Date of Birth: _____

GP’s Details

Name: _____

Address: _____

LIFESTYLE/QUESTIONNAIRE INTERVIEW

Patient Number

Weight.....

Date of Birth.....

Height.....

Age.....

Q1 Which of the following best describes your daily work or other daytime activity that you usually do?

- ☐₁ I am usually sitting and do not walk about much
- ☐₂ I stand or walk about quite a lot, but do not have to carry or lift things very often
- ☐₃ I usually lift or carry light loads or have to climb stairs or hills often
- ☐₄ I do heavy manual work or carry heavy loads often

Q2 On average, how often do you engage in vigorous physical activity in leisure time?

(activity that makes you breathless and sweat e.g. jogging, aerobics, football, tennis, squash, competitive sports etc)

- ☐₁ Rarely / infrequently
- ☐₂ Once / twice a month
- ☐₃ Once / twice a week
- ☐₄ Daily

Q3 How do you rate your present physical fitness for your age?

- ☐₁ Below average
- ☐₂ Average
- ☐₃ Good
- ☐₄ Very good

Q4 In the following age groups did you take exercise for 20 mins or more a day?

(tick as appropriate)

- ☐₁ under 20yr
- ☐₂ between 20 and 35yr
- ☐₃ between 35-55yr
- ☐₄ over 55 yrs

Q5 How often and how much do you smoke?

- ☐₁ I smoke every day *(number of cgrts/day)* _____
- ☐₂ I smoke occasionally, but not every day
- ☐₃ I used to smoke, but do not smoke at all now *(fill in next question as well)*
- ☐₄ I have never smoked

Q6 In the following age groups how much did you smoke?

(number of cgrts/day)

- ☐₁ under 20yr
- ☐₂ between 20 and 35yr
- ☐₃ between 35-55yr
- ☐₄ over 55 yrs

Q7 How often and how much alcohol do you consume?

(Estimate of the number of units per week e.g. a unit is ½ pint of beer, 1 glass of wine or 1 measure of a spirit)

(estimate of units/week)

- ☐₁ I drink alcohol every day of the week _____
- ☐₂ I drink alcohol about 3 or more days a week _____
- ☐₃ I drink alcohol about once or twice a week _____
- ☐₄ I do not drink alcohol _____

Q8 In the following age groups how much alcohol did you consume?

(Estimate of the number of units per week e.g. a unit is ½ pint of beer, 1 glass of wine or 1 measure of a spirit)

	(estimate of units/week)
☐ ₁ under 20yr	_____
☐ ₂ between 20 and 35yr	_____
☐ ₃ between 35-55yr	_____
☐ ₄ over 55 yrs	_____

Q9 Have you had any previous broken bones?

Yes/No _____

If yes, which bone did you break? (Please state whether left or right if extremity)

Q10 When and how did the break occur?

Q11 Have any members of your family suffered from broken bones as a result of osteoporosis?

Yes/No _____

Fracture site.....

Q12 Have any members of your family suffered from osteoporosis?

Yes/No _____

Relationship to interviewee.....

Q13 Have you ever been confined to your bed for more than two months?

Yes/No _____

If so, why and for how long?.....

Q14 Have you ever had any other health problems?

Yes/No _____

Details.....

Q15 Have you ever taken Steroids?

Yes/No At what age.....

For how long?.....

FOOD STUDY

Q16 Have you ever seriously controlled your weight?

Yes/No At what age.....

For how long?.....

Q17 Do you take calcium supplements?

Yes/No _____

For how long?.....

Q18 Do you have any specific dietary restrictions/requirements?

Yes/No _____

Details.....

Q19 Do you eat the following foods – milk, cheese, yoghurt, fish, eggs and nuts?
(Please tick as appropriate.)

☐₁ never

☐₂ once a week

☐₃ 2-4 times a week

☐₄ daily

Q20 Do you eat the following foods daily? *(tick as appropriate)*

Vegetables	_____
Fruit	_____
Bread, cereals, rice and pasta	_____
Milk, yoghurt and cheese	_____
Meat, poultry and nuts	_____

Q21 Have you ever had any problems with your diet during your life?
If so, at what age? *(details)*

☐ ₁	under 20yr	_____
☐ ₂	between 20 and 35yr	_____
☐ ₃	between 35-55yr	_____
☐ ₄	over 55 yrs	_____

Q22 How do you rate your diet compared with your peers?

☐ ₁	Below average
☐ ₂	Average
☐ ₃	Good
☐ ₄	Very good

FOR FEMALE PATIENTS ONLY

Q23 Do you have any children?

Yes/No

How many?.....

Q24 Did you breast-feed your children?

Yes/No

For how long?.....

Q25 At what age did your periods start?

.....years old

Q26 At what age did your periods stop?

..... years old

Q27 Have you had a hysterectomy?

Yes/No

How long ago?.....

at an Age of

Q28 Have you had your ovaries removed?

Yes/No

How long ago?.....

at an Age of

Q29 Have you ever taken the oral contraceptive pill?

Yes/No

How long ago?

For how long?

at an Age of

Q30 Have you ever used/Are you still using HRT?

Yes/No

How long ago?

For how long?

at an Age of

Appendix 4: Gloucester Patient Information Pamphlet

BOSCOS TRIAL: Bone scanning and material testing of bone to establish the correlation between material and non-invasive testing of bone strength.

1. Study title

BOSCOS stands for Bone scanning for Occupant Safety and involves Bone scanning and material testing of bone to establish the correlation between material and non-invasive testing of bone strength.

2. What is the purpose of this study?

The purpose of this study is to come up with a simple technique for assessing the strength of bone in patients using a portable scanner that will scan your hand and feet. In the future it may be used in GP surgeries.

3. Why have I been chosen?

You have been chosen because you are undergoing an operation on your hip which entails removing the ball part of your hip joint (femoral head). We would like to use the bone that has been removed to do some research on the structure of the bone.

4. Who is organising the study?

The study is being organised by the Cranfield University in association with the Department of Transport. This study will take 3 years to complete.

5. What will happen to me if I take part?

Taking part in the study in no way changes your medical and surgical care. As far as your operation will be concerned you will have a standard procedure performed. However, after your operation and when you are feeling up to it, a research assistant will ask you some questions about your health and lifestyle as this may be an important factor in predicting the strength of your bones. They will also scan your feet, legs and arms. This is a completely non-invasive procedure and is painless. This will also take place during your hospital stay so there will be no extra Clinic visits as a result of the study.

6. What is osteoporosis?

Osteoporosis is a medical term for thinning and weakening of the bones. Osteoporosis is a condition, which affects large numbers of older people, particularly women. Unfortunately this means that more people suffer from fractures (bone breaks) as the bone weakens. We are now discovering better ways of both preventing and treating this condition, however we need better and easier means of detecting osteoporosis.

We propose to undertake a study using the bone of people, like yourself, who have had either a hip fracture or who are having a new hip joint. We would like to use the bone that is taken from the hip and replaced during the operation. We would also like to use a scanner to measure how solid your bone is (bone density).

By comparing the results of these bone investigations with the results of the scans we shall be able to work out if there is any link between them. We may then be able to more accurately predict who is at risk of developing a fracture from the scan results. We will also compare the results from patients who are undergoing a hip replacement for arthritis with those who have suffered a broken hip.

9. Are there any disadvantages in taking part in this study?

There are no disadvantages in taking part in this study and it doesn't interfere with your treatment in any way. If you change your mind you can withdraw at any time without saying why. This will not affect your care in any way.

10. What are the possible risks of taking part in this study?

There are no risks at all involved in taking part in this study.

9. What are the possible benefits of taking part in this study?

If the scan gives any cause for concern you will be informed. We would like to share this information with the clinical team responsible for your care in hospital and with your general practitioner who will be able to give you the most appropriate advice.

11. Confidentiality – Who will know that I am taking part in the study?

Only the orthopaedic team, responsible for your care, will be able to identify you from your scan results. All data will be anonymised so that the researchers who are outside the clinical team will not be able to identify you.

13. Who has reviewed the study

The Gloucestershire Local Research Ethics Committee has approved this study.

14. What will happen to the results of this study?

If you would like to be sent a short summary of the results of this study, we would be only too delighted to send one to you. If there is any further information that you require please call, Mr. Curwen's Research Team. They can be contacted by telephoning Gloucester (01452) 395160

Appendix 5: Gloucester Consent Form

Centre Number:

Study Number:

Patient Identification Number for this trial:

CONSENT FORM

Title Project: BOSCOS Trial

Name of Researcher:

Please initial box

1. I confirm that I have read and understand the information sheet dated..... (version.....) for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time giving any reason, without my medical care or legal rights being affected.
3. I understand that my femoral head, which has to be removed as part of my operation for my joint replacement, will be used for analysis. I also understand that I will have a scan of my ankle, wrist and hand and will be asked questions from a questionnaire.
4. I agree to take part in the above study.

Name of Patient

Date

Signature

Name of person taking consent
(if different from researcher)

Date

Signature

Researcher

Date

Signature

1 for patient; 1 for researcher: 1 to be kept with hospital notes

Appendix 6: Osteoporotic Compression Regressions

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
Apparent Density	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-0.54 (87.6)	696 (220.7)	22.1	0.47	0.003	2.87	1.215	28.7	0.001
E- Contact (MPa)	-178.6 (187.4)	1573.9 (470.4)	24.8	0.498	0.002	3.091	1.479	22	0.004
ε _{Yield} Platens (%)	0.585 (0.295)	1.67 (0.732)	14	0.374	0.029	0.296	0.58	12.3	0.042
ε _{Ult.} Strain Platens (%)	0.934 (0.427)	2.83 (1.06)	18.3	0.428	0.012	0.515	0.57	13.7	0.031
ε _{Yield} Contact (%)	1.1 (0.476)	-0.06 (1.195)	0	-0.009	0.96	-0.005	0.114	0.3	0.747
ε _{Ult.} Contact (%)	3.01 (1.24)	-0.41 (3.11)	0.1	-0.023	0.896	0.303	-0.113	0.3	0.772
σ _{Yield} (MPa)	-1.71 (0.864)	12.1 (2.18)	45.6	0.675	<0.001	1.11	1.73	46.3	<0.001
σ _{Ult.} (MPa)	-2.1 (1.02)	14.9 (2.56)	47.7	0.69	<0.001	1.196	1.72	46.3	<0.001
Work to Failure Platens (Nmm ⁻¹)	-66.1 (28.87)	372.7 (72.73)	42.9	0.655	<0.001	2.56	1.89	35.3	<0.001
Work to Failure Contact (Nmm ⁻¹)	-16.7 (11.93)	118 (30.04)	30.4	0.552	<0.001	2.02	1.70	25.2	0.002

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	1123 (294.6)	-10.9 (3.74)	19.6	-0.443	0.006	9.22	-3.64	22.6	0.003
E- Contact (MPa)	2240 (647.1)	-23.2 (8.21)	19.0	-0.436	0.008	10.83	-4.43	16.7	0.013
ε _{Yield} Platens (%)	2.83 (1.01)	-0.021 (0.013)	7.3	-0.271	0.122	2.59	-1.35	5.7	0.175
ε _{Ult.} Strain Platens (%)	4.79 (1.48)	-0.035 (0.019)	9.9	-0.314	0.070	2.72	-1.29	6	0.162
ε _{Yield} Contact (%)	1.07 (1.58)	0.0001 (0.02)	0	0.001	0.995	0.19	-0.13	0	0.916
ε _{Ult.} Contact (%)	1.42 (4.12)	0.018 (0.052)	0.4	0.060	0.729	-1.12	0.78	1	0.562
σ _{Yield} (MPa)	16.3 (3.16)	-0.171 (0.04)	32.9	-0.574	<0.001	9.21	-4.68	29.8	<0.001
σ _{Ult.} (MPa)	20.1 (3.73)	-0.21 (0.047)	34.7	-0.589	<0.001	9.24	-4.65	29.7	<0.001
Work to Failure Platens (Nmm ⁻¹)	489 (105.3)	-5.26 (1.34)	30.7	-0.554	<0.001	10.95	-4.87	20.5	0.005
Work to Failure Contact (Nmm ⁻¹)	168 (41.42)	-1.78 (0.525)	24.7	-0.497	0.002	10.33	-4.78	17	0.011

Appendix 6: Continued

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
Material Density	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	435 (372.5)	-95 (207.4)	0.6	-0.076	0.649	2.42	-0.334	0.1	0.823
E- Contact (MPa)	32 (875.5)	217 (487.2)	0.6	0.076	0.658	2.19	1.012	0.6	0.662
ε _{Yield} Platens (%)	-1.93 (1.36)	1.77 (0.761)	14.5	0.381	0.026	-0.83	3.48	20.1	0.008
ε _{Ult.} Strain Platens (%)	-3.19 (1.98)	2.93 (1.11)	17.9	0.424	0.013	-0.61	3.495	23.3	0.004
ε _{Yield} Contact (%)	0.97 (1.93)	0.06 (1.08)	0	0.01	0.956	-0.17	0.469	0.3	0.754
ε _{Ult.} Contact (%)	-3.65 (4.92)	3.63 (2.74)	4.9	0.222	0.193	-0.14	1.971	4.2	0.231
σ _{Yield} (MPa)	-1.44 (4.64)	2.43 (2.49)	2.5	0.158	0.335	-0.17	2.095	4.3	0.207
σ _{Ult.} (MPa)	-1.42 (5.36)	2.78 (2.99)	2.3	0.151	0.358	-0.086	2.1	4.3	0.203
Work to Failure Platens (Nmm ⁻¹)	-93 (140.9)	94.3 (78.46)	4	0.199	0.238	0.62	4.42	12.8	0.030
Work to Failure Contact (Nmm ⁻¹)	-1.5 (58.01)	16.4 (32.25)	0.7	0.086	0.614	0.70	2.229	2.4	0.359

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
m/m OHPyr	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	312.3 (99.23)	-118.7 (274.3)	0.5	-0.071	0.668	2.364	0.0354	0	0.915
E- Contact (MPa)	737.8 (212.4)	-861.8 (573.5)	5.9	-0.243	0.142	2.13	-0.675	5.7	0.149
ε _{Yield} Platens (%)	1.602 (0.309)	-0.978 (0.849)	3.8	-0.194	0.258	-0.0783	-0.281	3.7	0.263
ε _{Ult.} Strain Platens (%)	2.212 (0.472)	-0.402 (1.298)	0.3	-0.053	0.759	0.211	-0.14	1	0.553
ε _{Yield} Contact (%)	0.876 (0.35)	0.346 (0.951)	0.4	0.061	0.719	0.0191	0.193	1.3	0.501
ε _{Ult.} Contact (%)	1.23 (1.178)	4.624 (3.18)	5.5	0.236	0.155	0.552	0.414	4.3	0.212
σ _{Yield} (MPa)	4.5 (1.20)	-4.141 (3.27)	3.9	-0.199	0.213	0.138	-0.489	4.5	0.181
σ _{Ult.} (MPa)	5.06 (1.43)	-3.87 (3.88)	2.5	-0.158	0.325	0.272	-0.393	3.0	0.278
Work to Failure Platens (Nmm ⁻¹)	24.29 (13.96)	13.10 (37.81)	0.3	0.057	0.731	1.206	-0.171	0.3	0.73
Work to Failure Contact (Nmm ⁻¹)	92.84 (36.75)	-39.4 (101.6)	0.4	-0.064	0.701	1.576	-0.36	1.7	0.434

Appendix 6: Continued

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
m/m LysPyr	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	302.5 (87.38)	-184.2 (486.1)	0.4	-0.062	0.707	2.354	0.0086	0	0.976
E- Contact (MPa)	601.7 (195)	-985 (1073)	2.3	-0.151	0.365	2.239	-0.266	1.1	0.527
ε _{Yield} Platens (%)	1.522 (0.27)	-1.532 (1.499)	3.0	-0.173	0.314	-0.0777	-0.168	1.8	0.436
ε _{Ult.} Strain Platens (%)	2.188 (0.411)	-0.681 (2.282)	0.3	-0.051	0.767	0.227	-0.0642	0.3	0.751
ε _{Yield} Contact (%)	1.047 (0.318)	-0.286 (1.74)	0.1	-0.028	0.870	0.0183	0.1158	0.6	0.648
ε _{Ult.} Contact (%)	2.181 (1.085)	4.01 (5.973)	1.2	0.111	0.507	0.57	0.2693	2.3	0.363
σ _{Yield} (MPa)	3.612 (1.079)	-3.375 (6.029)	0.8	-0.089	0.579	0.174	-0.245	1.5	0.449
σ _{Ult.} (MPa)	4.028 (1.275)	-1.96 (7.122)	0.2	-0.044	0.785	0.345	-0.143	0.5	0.657
Work to Failure Platens (Nmm ⁻¹)	18.77 (12.42)	59.28 (68.69)	2.0	0.140	0.394	1.24	-0.0589	0	0.893
Work to Failure Contact (Nmm ⁻¹)	79.52 (32.41)	-2 (180.3)	0	-0.002	0.991	1.628	-0.152	0.4	0.702

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HHL	Mechanical Parameter = a + b(m/m HHL)					log(Mechanical Parameter) = a + b log(m/m HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	299.94 (43)	-838 (956.5)	2.0	-0.153	0.366	2.121	-0.141	3.0	0.302
E- Contact (MPa)	454.44 (99.05)	-636 (2174)	0.2	-0.078	0.653	2.32	-0.0828	0.4	0.712
ε _{Yield} Platens (%)	1.296 (0.134)	-1.0 (2.90)	0.4	-0.081	0.649	0.03	-0.017	0.1	0.867
ε _{Ult.} Strain Platens (%)	2.158 (0.201)	-2.45 (4.35)	0.9	-0.119	0.502	0.232	-0.0295	0.3	0.756
ε _{Yield} Contact (%)	1.093 (0.158)	-2.695 (3.436)	1.7	-0.145	0.405	-0.351	-0.178	5.4	0.180
ε _{Ult.} Contact (%)	3.196 (0.544)	-9.20 (11.95)	1.6	-0.134	0.436	0.273	-0.050	0.3	0.750
σ _{Yield} (MPa)	3.343 (0.525)	-9.04 (11.91)	1.5	-0.137	0.406	0.231	-0.0858	0.8	0.577
σ _{Ult.} (MPa)	4.13 (0.617)	-12.88 (13.97)	2.1	-0.164	0.318	0.2993	-0.0989	1.1	0.516
Work to Failure Platens (Nmm ⁻¹)	34.4 (6.21)	-155.5 (137.2)	3.4	-0.193	0.252	0.866	-0.266	3.8	0.250
Work to Failure Contact (Nmm ⁻¹)	91.74 (15.85)	-365.3 (352.7)	2.8	-0.203	0.228	1.411	-0.215	3.6	0.259

Appendix 6: Continued

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HLKNL	Mechanical Parameter = a + b(m/m HLKNL)					log(Mechanical Parameter) = a + b log(m/m HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	379.23 (74.32)	-631 (399.9)	6.5	-0.254	0.123	1.985	-0.449	8.1	0.083
E- Contact (MPa)	594.3 (178.8)	-893.1 (940.1)	2.5	-0.159	0.349	2.215	-0.298	1.5	0.469
ε _{Yield} Platens (%)	1.467 (0.227)	-1.185 (1.237)	2.7	-0.165	0.345	-0.0855	-0.176	2.4	0.374
ε _{Ult.} Strain Platens (%)	2.298 (0.336)	-1.496 (1.827)	2.0	-0.141	0.419	0.138	-0.166	2.5	0.361
ε _{Yield} Contact (%)	1.086 (0.288)	-0.472 (1.519)	0.3	-0.053	0.758	-0.16	-0.111	0.6	0.655
ε _{Ult.} Contact (%)	2.983 (0.985)	-0.996 (5.178)	0.1	-0.033	0.849	0.265	-0.104	0.4	0.716
σ _{Yield} (MPa)	4.125 (0.911)	-6.364 (4.937)	4.2	-0.205	0.205	0.142	-0.28	2.5	0.333
σ _{Ult.} (MPa)	4.778 (1.074)	-6.537 (5.819)	3.2	-0.179	0.268	0.263	-0.236	1.8	0.408
Work to Failure Platens (Nmm ⁻¹)	40.03 (10.03)	-72.01 (53.35)	4.8	-0.219	0.186	0.902	-0.465	3.8	0.238
Work to Failure Contact (Nmm ⁻¹)	95.67 (28.03)	-103.5 (150.8)	1.3	-0.114	0.497	1.382	-0.447	4.2	0.216

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HLNL	Mechanical Parameter = a + b(m/m HLNL)					log(Mechanical Parameter) = a + b log(m/m HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	274.6 (73.27)	-32.4 (533.1)	0	-0.010	0.952	2.482	0.147	0.9	0.562
E- Contact (MPa)	303.9 (158.9)	1065 (1180)	2.3	0.151	0.373	2.833	0.404	3.3	0.279
ε _{Yield} Platens (%)	1.242 (0.24)	0.191 (1.78)	0	0.019	0.915	0.0195	-0.04	0.1	0.841
ε _{Ult.} Strain Platens (%)	1.883 (0.352)	1.298 (2.61)	0.7	0.086	0.622	0.293	0.0215	0	0.907
ε _{Yield} Contact (%)	1.121 (0.256)	-0.957 (1.896)	0.7	-0.086	0.617	-0.134	-0.064	0.2	0.778
ε _{Ult.} Contact (%)	2.825 (0.875)	-0.154 (6.495)	0	-0.004	0.981	0.235	-0.117	0.6	0.653
σ _{Yield} (MPa)	2.505 (0.887)	4.271 (6.54)	1.1	0.105	0.518	0.577	0.222	1.6	0.435
σ _{Ult.} (MPa)	2.787 (1.034)	6.996 (7.628)	2.2	0.147	0.365	0.744	0.308	3.2	0.269
Work to Failure Platens (Nmm ⁻¹)	28.88 (9.44)	-11.56 (68.98)	0.1	-0.028	0.868	1.22	-0.0519	0.1	0.890
Work to Failure Contact (Nmm ⁻¹)	53.53 (26.53)	192.2 (193.1)	2.7	0.164	0.326	1.926	0.199	0.9	0.571

Appendix 6: Continued

Osteoporotic Compression	Linear Relationships					Power (log) Function Relationship			
fmoles Pentosidine / pmole collagen	Mech. Parameter = a + b(fmoles Pentosidine / pmole collagen)					log(Mech. Parameter) = a + b log(fmoles Pentosidine / pmole collagen)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	290.7 (73.1)	-1.28 (3.67)	0.3	-0.059	0.730	2.406	-0.0566	0.1	0.832
E- Contact (MPa)	415.8 (146.3)	0.018 (7.21)	0	0	0.998	2.441	-0.0078	0	0.983
ε _{Yield} Platens (%)	1.19 (0.221)	0.0036 (0.011)	0.3	0.057	0.751	-0.055	0.0877	0.6	0.662
ε _{Ult.} Strain Platens (%)	1.991 (0.331)	0.0048 (0.017)	0.3	0.051	0.775	0.191	0.0713	0.5	0.704
ε _{Yield} Contact (%)	1.072 (0.251)	-0.004 (0.013)	0.2	-0.050	0.776	-0.085	0.015	0	0.947
ε _{Ult.} Contact (%)	2.643 (0.829)	0.0168 (0.041)	0.5	0.070	0.683	0.285	0.074	0.3	0.763
σ _{Yield} (MPa)	2.69 (0.843)	0.0158 (0.041)	0.4	0.063	0.703	0.11	0.202	1.4	0.472
σ _{Ult.} (MPa)	3.325 (0.996)	0.0174 (0.049)	0.3	0.059	0.723	0.194	0.208	1.5	0.455
Work to Failure Platens (Nmm ⁻¹)	33.134 (9.59)	-0.198 (0.465)	0.5	-0.072	0.673	0.992	0.248	1.2	0.510
Work to Failure Contact (Nmm ⁻¹)	67.42 (27.0)	0.633 (1.36)	0.6	0.079	0.643	1.48	0.214	1.0	0.565

Appendix 7: Osteoarthritic Compression Regressions

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
Apparent Density (g cm ⁻³)	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	187 (160.9)	392 (246.9)	29.6	0.544	0.164	2.752	0.663	37.6	0.106
E- Contact (MPa)	225 (305.5)	502 (468.8)	16.1	0.401	0.325	2.849	0.82	32.2	0.143
ε _{Yield} Platens (%)	1.08 (0.316)	0.755 (0.485)	28.8	0.536	0.17	0.255	0.313	28.7	0.171
ε _{Ult.} Strain Platens (%)	0.004 (0.559)	4.84 (0.857)	84.1	0.917	0.01	0.634	0.828	67.8	0.012
ε _{Yield} Contact (%)	1.03 (0.313)	0.602 (0.471)	24.7	0.497	0.257	0.211	0.315	25.9	0.244
ε _{Ult.} Contact (%)	1.91 (1.35)	4.41 (2.022)	48.8	0.699	0.081	0.765	0.553	31.6	0.189
σ _{Yield} (MPa)	-0.02 (1.01)	9.42 (1.55)	86.0	0.927	0.001	0.979	1.067	86.2	0.001
σ _{Ult.} (MPa)	-2.05 (1.07)	15.3 (1.65)	93.5	0.967	<0.001	1.108	1.27	88.7	<0.001
Work to Failure Platens (Nmm ⁻¹)	-306 (67.88)	922 (104.2)	92.9	0.964	<0.001	2.7	2.086	89	<0.001
Work to Failure Contact (Nmm ⁻¹)	-88.8 (45.18)	332 (67.87)	82.7	0.909	0.005	2.278	1.649	65.1	0.028

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	798.2 (259.3)	-5.8 (3.79)	28	-0.53	0.177	3.956	-0.774	30.3	0.157
E- Contact (MPa)	995 (492.1)	-7.21 (7.2)	14.3	-0.379	0.355	4.209	-0.885	22.1	0.239
ε _{Yield} Platens (%)	2.28 (0.506)	-0.011 (0.007)	28.3	-0.532	0.174	0.846	-0.378	24.8	0.209
ε _{Ult.} Strain Platens (%)	7.73 (0.838)	-0.074 (0.012)	86	-0.927	0.001	2.506	-1.171	80.5	0.003
ε _{Yield} Contact (%)	1.98 (0.488)	-0.0092 (0.007)	24.7	-0.497	0.257	0.808	-0.383	22.3	0.284
ε _{Ult.} Contact (%)	9 (2.06)	-0.069 (0.03)	50.7	-0.712	0.073	2.06	-0.81	39.6	0.13
σ _{Yield} (MPa)	14.86 (1.696)	-0.142 (0.025)	84.5	-0.919	0.001	2.93	-1.253	70.3	0.009
σ _{Ult.} (MPa)	22.21 (1.69)	-0.232 (0.025)	93.6	-0.968	<0.001	3.58	-1.576	80.7	0.002
Work to Failure Platens (Nmm ⁻¹)	1166.3 (93.13)	-14.1 (1.36)	94.7	-0.973	<0.001	7.07	-2.756	92.0	<0.001
Work to Failure Contact (Nmm ⁻¹)	441.8 (66.1)	-5.12 (0.97)	84.8	-0.921	0.003	5.92	-2.297	73.7	0.013

Appendix 7: Continued

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
Material Density (g cm ⁻³)	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	2053 (1374)	-927 (777.4)	19.2	-0.438	0.278	3.669	-4.476	24.9	0.208
E- Contact (MPa)	2111 (2578)	-901 (1458)	6.0	-0.244	0.56	3.65	-4.18	12.1	0.398
ε _{Yield} Platens (%)	4.9 (2.65)	-1.91 (1.499)	21.3	-0.461	0.25	0.693	-2.13	19.3	0.276
ε _{Ult.} Strain Platens (%)	26.8 (5.42)	-13.6 (3.07)	76.5	-0.875	0.004	2.169	-7.17	74.1	0.006
ε _{Yield} Contact (%)	4.70 (2.42)	-1.89 (1.37)	27.4	-0.523	0.228	0.813	-2.82	29.4	0.209
ε _{Ult.} Contact (%)	29.9 (9.5)	-14.4 (5.39)	58.8	-0.767	0.044	2.00	-5.7	47.4	0.087
σ _{Yield} (MPa)	48.7 (12.35)	-24.5 (6.99)	67.2	-0.82	0.013	2.488	-7.34	59.2	0.026
σ _{Ult.} (MPa)	78.9 (16.03)	-40.8 (9.07)	77.1	-0.878	0.004	3.05	-9.34	69.6	0.010
Work to Failure Platens (Nmm ⁻¹)	4700.4 (884.7)	-2530 (500.5)	81.0	-0.900	0.002	6.165	-16.43	80.3	0.003
Work to Failure Contact (Nmm ⁻¹)	1749.3 (437)	-933 (248)	73.9	-0.860	0.013	5.329	-14.36	69.7	0.019

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
m/m OHPyr	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	10.4 (203.9)	902.9 (430.8)	42.3	0.65	0.081	2.497	-0.0565	0.1	0.955
E- Contact (MPa)	-432 (225)	2116.8 (475.5)	76.8	0.876	0.004	3.345	1.96	51.9	0.068
ε _{Yield} Platens (%)	1.571 (0.524)	-0.1 (1.107)	0.1	-0.037	0.931	0.6541	1.144	87.6	0.002
ε _{Ult.} Strain Platens (%)	3.075 (1.961)	-0.51 (4.144)	0.3	-0.050	0.906	1.005	1.409	39.5	0.13
ε _{Yield} Contact (%)	1.844 (0.863)	-1.148 (2.113)	5.6	-0.236	0.610	-0.0431	-0.4097	7.3	0.558
ε _{Ult.} Contact (%)	5.963 (4.583)	-3.57 (11.22)	2.0	-0.141	0.763	0.355	-0.631	6.9	0.57
σ _{Yield} (MPa)	2.189 (3.504)	7.404 (7.404)	14.3	0.378	0.356	1.182	1.294	22.8	0.279
σ _{Ult.} (MPa)	3.388 (5.685)	7.86 (12.01)	6.7	0.258	0.537	1.314	1.429	19.3	0.323
Work to Failure Platens (Nmm ⁻¹)	-64.6 (255.5)	430.5 (625.7)	8.6	0.294	0.522	2.104	0.711	2.0	0.761
Work to Failure Contact (Nmm ⁻¹)	184.4 (355.5)	113.7 (751.1)	0.4	0.062	0.885	3.211	2.681	24.5	0.259

Appendix 7: Continued

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
m/m LysPyr	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	227.9 (205.6)	974.4 (983.8)	14.0	0.375	0.360	2.863	0.394	11.3	0.415
E- Contact (MPa)	-1.1 (309.9)	2692 (1483)	35.4	0.595	0.119	3.525	1.203	59.0	0.026
ε _{Yield} Platens (%)	1.173 (0.405)	1.825 (1.936)	12.9	0.359	0.382	0.339	0.227	12.9	0.382
ε _{Ult.} Strain Platens (%)	0.630 (1.297)	11.43 (6.21)	36.1	0.601	0.115	0.853	0.598	30.2	0.158
ε _{Yield} Contact (%)	1.604 (0.393)	-1.174 (1.912)	7.0	-0.265	0.566	-0.0625	-0.242	12.3	0.441
ε _{Ult.} Contact (%)	3.60 (2.08)	4.94 (10.10)	4.6	0.214	0.645	0.690	0.104	0.9	0.839
σ _{Yield} (MPa)	1.216 (2.49)	22.22 (11.91)	36.7	0.606	0.111	1.198	0.687	30.4	0.156
σ _{Ult.} (MPa)	0.154 (3.842)	34.94 (18.39)	37.6	0.613	0.106	1.363	0.811	30.7	0.154
Work to Failure Platens (Nmm ⁻¹)	-29.5 (102.8)	730.5 (499.7)	29.9	0.547	0.204	2.537	0.940	17.1	0.357
Work to Failure Contact (Nmm ⁻¹)	-184.3 (229)	2167 (1096)	39.5	0.628	0.095	3.22	1.462	37.3	0.108

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HHL	Mechanical Parameter = a + b(m/m HHL)					log(Mechanical Parameter) = a + b log(m/m HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	403.3 (136.1)	398 (3196)	0.3	0.051	0.905	2.359	-0.147	5.0	0.631
E- Contact (MPa)	343 (232.8)	2563 (5468)	3.5	0.188	0.656	2.815	0.0878	1.4	0.803
ε _{Yield} Platens (%)	1.10 (0.149)	12.68 (3.51)	68.5	0.828	0.011	0.587	0.258	72.2	0.015
ε _{Ult.} Strain Platens (%)	1.157 (0.488)	50.01 (11.46)	76.0	0.872	0.005	1.184	0.4941	69.8	0.019
ε _{Yield} Contact (%)	1.426 (0.284)	-1.147 (6.253)	0.7	-0.082	0.862	-0.022	-0.0943	4.2	0.696
ε _{Ult.} Contact (%)	3.851 (1.436)	18.31 (31.66)	6.3	0.250	0.588	0.699	0.0694	0.9	0.858
σ _{Yield} (MPa)	3.173 (1.493)	69.56 (35.08)	39.6	0.629	0.095	0.9758	0.164	7.0	0.566
σ _{Ult.} (MPa)	2.957 (2.18)	117.5 (51.2)	46.7	0.684	0.062	1.191	0.256	11.5	0.457
Work to Failure Platens (Nmm ⁻¹)	6.94 (65.42)	2727 (1442)	41.7	0.646	0.117	2.609	0.523	12.1	0.5
Work to Failure Contact (Nmm ⁻¹)	-40.3 (111.9)	8174 (2627)	61.7	0.786	0.021	3.284	0.718	32.2	0.184

Appendix 7: Continued

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HLKNL	Mechanical Parameter = $a + b(\text{m/m HLKNL})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{m/m HLKNL})$			
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	p - value
E- Platens (MPa)	509.7 (219.5)	-255.7 (560)	3.4	-0.183	0.664	2.452	-0.237	6.0	0.557
E- Contact (MPa)	646.6 (384.4)	-346.5 (980.9)	2.0	-0.143	0.736	2.54	-0.166	1.7	0.761
ϵ_{Yield} Platens (%)	0.8447 (0.317)	1.874 (0.809)	47.2	0.687	0.060	0.301	0.271	27.1	0.186
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	0.382 (1.223)	6.772 (3.12)	44.0	0.663	0.073	0.622	0.449	25.0	0.207
ϵ_{Yield} Contact (%)	0.978 (0.436)	1.047 (1.059)	16.4	0.404	0.368	0.208	0.186	9.8	0.493
$\epsilon_{\text{Ult.}}$ Contact (%)	4.156 (2.48)	0.969 (6.018)	0.5	0.072	0.878	0.559	-0.113	1.4	0.798
σ_{Yield} (MPa)	3.053 (2.956)	6.783 (7.542)	11.9	0.345	0.403	0.731	0.101	1.0	0.817
$\sigma_{\text{Ult.}}$ (MPa)	2.182 (4.429)	13.03 (11.30)	18.1	0.426	0.293	0.842	0.179	2.2	0.726
Work to Failure Platens (Nmm ⁻¹)	-9.4 (132.2)	303.9 (320.9)	15.2	0.390	0.387	1.852	0.0775	0.2	0.933
Work to Failure Contact (Nmm ⁻¹)	-163.1 (238.9)	1095.9 (609.5)	35.0	0.592	0.122	2.42	0.614	9.7	0.453

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
m/m HLNL	Mechanical Parameter = $a + b(\text{m/m HLNL})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{m/m HLNL})$			
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	p - value
E- Platens (MPa)	435.0 (209.7)	-74.5 (785.9)	0.1	-0.039	0.928	2.482	-0.128	2.0	0.741
E- Contact (MPa)	577.9 (364.1)	-234 (1365)	0.5	-0.070	0.869	2.538	-0.125	1	0.81
ϵ_{Yield} Platens (%)	0.985 (0.332)	2.21 (1.244)	34.5	0.587	0.126	0.318	0.226	20.8	0.256
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	0.204 (0.989)	10.78 (3.71)	58.5	0.765	0.027	0.711	0.463	29.6	0.163
ϵ_{Yield} Contact (%)	0.938 (0.392)	1.70 (1.393)	22.9	0.479	0.277	0.255	0.209	13.8	0.412
$\epsilon_{\text{Ult.}}$ Contact (%)	3.032 (2.21)	5.734 (7.867)	9.6	0.310	0.499	0.630	0.0316	0.1	0.940
σ_{Yield} (MPa)	2.323 (2.595)	13.05 (9.728)	23.1	0.480	0.228	0.789	0.16	2.7	0.697
$\sigma_{\text{Ult.}}$ (MPa)	1.05 (3.787)	23.99 (14.19)	32.3	0.568	0.142	0.925	0.256	5.0	0.594
Work to Failure Platens (Nmm ⁻¹)	-47.3 (111.5)	595.1 (397.0)	31	0.557	0.194	2.01	0.308	2.8	0.722
Work to Failure Contact (Nmm ⁻¹)	-219.5 (191.4)	1857.5 (717.2)	52.8	0.727	0.041	2.599	0.718	14.7	0.348

Appendix 7: Continued

Osteoarthritic Compression	Linear Relationships					Power (log) Function Relationship			
fmoles Pentosidine / pmole collagen	Mech. Parameter = a + b(fmoles Pentosidine / pmole collagen)					log(Mech Parameter) = a + b log(fmoles Pentosidine / pmole collagen)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	471.8 (131.5)	-3.4 (6.38)	4.5	-0.213	0.613	2.641	-0.067	0.9	0.827
E- Contact (MPa)	702.6 (214.1)	-11.23 (10.39)	16.3	-0.404	0.321	2.945	-0.294	9.3	0.464
ε _{Yield} Platens (%)	1.716 (0.244)	-0.012 (0.012)	14	-0.374	0.361	0.243	-0.068	0.3	0.68
ε _{Ult.} Strain Platens (%)	3.173 (0.97)	-0.02 (0.047)	3.0	-0.173	0.683	0.362	0.0376	0.3	0.895
ε _{Yield} Contact (%)	1.388 (0.273)	0.0003 (0.0125)	0	-0.010	0.984	0.127	-0.0034	0	0.987
ε _{Ult.} Contact (%)	3.91 (1.377)	0.036 (0.063)	6.1	0.246	0.595	0.343	0.235	11.6	0.455
σ _{Yield} (MPa)	6.625 (1.809)	-0.0681 (0.088)	9.1	-0.302	0.467	0.835	0.139	3.3	0.669
σ _{Ult.} (MPa)	8.32 (2.86)	-0.086 (0.139)	6.0	-0.246	0.558	0.865	-0.1	1.2	0.793
Work to Failure Platens (Nmm ⁻¹)	127.7 (81.36)	-1.113 (3.721)	1.8	-0.133	0.777	1.595	0.195	1.8	0.771
Work to Failure Contact (Nmm ⁻¹)	302.4 (175.2)	-4.125 (8.5)	3.8	-0.194	0.645	2.209	-0.0793	0.3	0.899

Appendix 8: Fracture Toughness Regression Equine Material

Appendix 8.1: Equine Beams AC

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Apparent Density (g cm ⁻³)	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.25 (0.087)	1.181 (0.177)	42.5	0.652	<0.001	0.0425	1.852	39.6	<0.001
Kc Pop Ins	-0.378 (0.126)	1.724 (0.259)	42.5	0.652	<0.001	0.182	1.81	39.3	<0.001
J-Integral PQ	173.1 (22.16)	-136.1 (45.43)	13.0	-0.361	0.004	1.825	-0.575	13.6	0.003
J-Integral Pop Ins	368.4 (55.93)	-151.9 (114.7)	2.8	-0.169	0.190	2.346	-0.321	3.9	0.124
GQ	-370.2 (151.5)	1367.5 (310.6)	24.4	0.494	<0.001	3.10	2.528	23.4	<0.001
Gc Pop Ins	-824.2 (317.7)	2929.2 (651.4)	25.2	0.502	<0.001	3.383	2.448	22.8	<0.001

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.566 (0.257)	-0.0169 (0.0035)	28.4	-0.533	<0.001	9.149	-5.19	41.6	<0.001
Kc Pop Ins	2.287 (0.374)	-0.025 (0.005)	28.8	-0.537	<0.001	9.149	-5.11	41.5	<0.001
J-Integral PQ	-51.71 (59.72)	2.156 (0.805)	10.7	0.327	0.01	-1.182	1.707	14.8	0.002
J-Integral Pop Ins	137 (149.5)	2.143 (2.015)	1.8	0.136	0.292	0.786	0.889	3.7	0.138
GQ	1657.7 (428)	-18.54 (5.769)	14.7	-0.383	0.002	15.56	-7.092	25.9	<0.001
Gc Pop Ins	3569 (897.3)	-40.39 (12.09)	15.7	-0.396	0.001	15.55	-6.93	25.4	<0.001

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Material Density (g cm ⁻³)	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.011 (0.495)	0.717 (0.267)	10.7	0.327	0.009	-1.569	3.782	4.5	0.101
Kc Pop Ins	-1.40 (0.726)	1.00 (0.392)	9.8	0.313	0.013	-1.466	3.964	5.1	0.081
J-Integral PQ	135.2 (108.9)	-14.75 (58.85)	0.1	-0.032	0.803	1.643	1.368	1.9	0.285
J-Integral Pop Ins	443.0 (259.6)	-79.7 (140.3)	0.5	-0.073	0.572	2.163	1.065	1.1	0.427
GQ	-1841.7 (750.6)	1150 (405.5)	11.8	0.344	0.006	0.211	7.775	6.3	0.051
Gc Pop Ins	-3606 (1596)	2263.3 (862.4)	10.3	0.321	0.011	0.417	8.14	7.1	0.038

Appendix 8.1: Continued

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Relative Density	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.123 (0.092)	1.689 (0.346)	28.4	0.533	<0.001	0.313	1.48	27.5	<0.001
Kc Pop Ins	-0.197 (0.133)	2.484 (0.504)	28.8	0.537	<0.001	0.446	1.44	27.2	<0.001
J-Integral PQ	163.9 (21.32)	-215.6 (80.49)	10.7	-0.327	0.010	1.70	-0.52	12.2	0.005
J-Integral Pop Ins	351.2 (53.39)	-214.2 (201.5)	1.8	-0.136	0.292	2.283	-0.283	3.3	0.157
GQ	-196.5 (152.8)	1854.0 (576.9)	14.7	0.383	0.002	3.377	1.852	13.7	0.003
Gc Pop Ins	-469.5 (320.4)	4038 (1209)	15.7	0.396	0.001	3.643	1.786	13.3	0.004

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Water Content (%)	Mechanical Parameter = a + b(Water Content)					log(Mechanical Parameter) = a + b log(Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.355 (0.148)	-0.0018 (0.007)	0.1	-0.034	0.792	-0.669	0.0804	0	0.879
Kc Pop Ins	0.488 (0.216)	-0.002 (0.01)	0.1	-0.024	0.855	-0.453	0.0318	0	0.951
J-Integral PQ	120.5 (30.74)	-0.61 (1.454)	0.3	-0.054	0.679	2.077	-0.0487	0.1	0.862
J-Integral Pop Ins	279.9 (73.5)	0.75 (3.48)	0.1	0.028	0.830	2.449	0.0021	0	0.994
GQ	439.3 (224.9)	-7.36 (10.64)	0.8	-0.089	0.492	2.29742	-0.0157	0	0.987
Gc Pop Ins	798.3 (475.1)	-10.44 (22.48)	0.4	-0.060	0.644	2.731	-0.113	0	0.902

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Hydrated Mineral Content (%)	Mechanical Parameter = a + b(Hydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Hydrated Mineral Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.024 (0.417)	0.0058 (0.0083)	0.8	0.09	0.487	-2.01	0.8496	0.4	0.618
Kc Pop Ins	0.08 (0.61)	0.007 (0.012)	0.6	0.078	0.547	-1.205	0.4683	0.1	0.779
J-Integral PQ	98.05 (87.26)	0.195 (1.736)	0	0.015	0.911	2.785	-0.453	0.4	0.616
J-Integral Pop Ins	414.7 (207.9)	-2.37 (4.14)	0.5	-0.074	0.568	5.616	-1.856	7.8	0.03
GQ	-437.4 (633.1)	14.39 (12.59)	2.1	0.146	0.258	-1.68	2.327	1.0	0.441
Gc Pop Ins	-660 (1340)	24.68 (26.65)	1.4	0.119	0.358	-0.0736	1.564	0.5	0.595

Appendix 8.1: Continued

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Hydrated Organic Content %	Mechanical Parameter = a + b(Hydrated Organic Content)					log(Mechanical Parameter) = a + b log(Hydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.74 (0.515)	-0.015 (0.018)	1.1	-0.106	0.413	2.677	-2.219	2.6	0.213
Kc Pop Ins	1.072 (0.751)	-0.022 (0.026)	1.1	-0.107	0.409	2.494	-1.99	2.1	0.256
J-Integral PQ	19.3 (107.1)	3.07 (3.71)	1.1	0.106	0.411	1.582	0.2952	0.2	0.756
J-Integral Pop Ins	121 (256.4)	6.05 (8.88)	0.8	0.088	0.498	1.695	0.518	0.5	0.601
GQ	810.2 (787.3)	-18.19 (27.26)	0.7	-0.086	0.507	9.148	-4.71	3.7	0.136
Gc Pop Ins	1893 (1658)	-45.51 (57.38)	1.0	-0.102	0.431	8.784	-4.248	3.1	0.170

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Dehydrated Mineral Content %	Mechanical Parameter = a + b(Dehydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Dehydrated Mineral Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.828 (0.964)	0.018 (0.0152)	2.3	0.151	0.240	-8.848	4.596	3.1	0.168
Kc Pop Ins	-1.143 (1.41)	0.025 (0.022)	2.1	0.144	0.263	-8.733	4.617	3.3	0.158
J-Integral PQ	199 (202.7)	-1.44 (3.19)	0.3	-0.058	0.655	2.961	-0.526	0.1	0.768
J-Integral Pop Ins	703.2 (482.2)	-6.42 (7.595)	1.2	-0.109	0.401	3.349	-0.498	0.1	0.788
GQ	-1863 (1463)	33.85 (23.05)	3.5	0.186	0.147	-17.17	10.79	5.5	0.067
Gc Pop Ins	-3695 (3091)	67.35 (48.69)	3.1	0.176	0.172	-16.939	10.83	5.8	0.06

Equine Beams Ac	Linear Relationships					Power (log) Function Relationship			
Dehydrated Organic Content %	Mechanical Parameter = a + b(Dehydrated Organic Content)					log(Mechanical Parameter) = a + b log(Dehydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.974 (0.555)	-0.018 (0.0152)	2.3	-0.151	0.240	3.629	-2.684	3.1	0.171
Kc Pop Ins	1.364 (0.811)	-0.025 (0.022)	2.1	-0.144	0.263	3.748	-2.662	3.2	0.166
J-Integral PQ	55.4 (116.7)	1.44 (3.19)	0.3	0.058	0.665	1.514	0.3194	0.2	0.760
J-Integral Pop Ins	61.0 (277.6)	6.422 (7.595)	1.2	0.109	0.401	1.793	0.421	0.3	0.699
GQ	1521.5 (842.3)	-33.85 (23.05)	3.5	-0.186	0.147	12.09	-6.28	5.4	0.069
Gc Pop Ins	3040 (1779)	-67.35 (48.69)	3.1	-0.176	0.172	12.33	-6.24	5.5	0.066

Appendix 8.2: Equine Beams AL

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Apparent Density (g cm ⁻³)	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.264 (0.0835)	0.872 (0.145)	44.0	0.663	<0.001	-0.105	2.326	41.4	<0.001
Kc Pop Ins	-0.352 (0.121)	1.202 (0.21)	41.6	0.645	<0.001	0.0486	2.322	40.9	<0.001
J-Integral PQ	63.186 (9.176)	-54.79 (15.94)	20.4	-0.452	0.001	1.222	-1.051	20.5	0.001
J-Integral Pop Ins	127.24 (17.43)	-73.21 (30.29)	11.3	-0.336	0.020	1.807	-0.462	7.7	0.056
GQ	-228.23 (86.37)	618.4 (150.1)	27.0	0.519	<0.001	2.81	3.477	28.3	<0.001
Gc Pop Ins	-418.2 (178.8)	1179.2 (310.5)	23.9	0.488	<0.001	3.116	3.468	27.8	<0.001

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.01 (0.158)	-0.0112 (0.0023)	34.4	-0.587	<0.001	4.814	-2.99	26.9	<0.001
Kc Pop Ins	1.388 (0.229)	-0.0152 (0.0033)	31.6	-0.562	<0.001	4.831	-2.914	25.3	<0.001
J-Integral PQ	-14.99 (16.65)	0.6782 (0.24)	14.8	0.385	0.007	-0.8015	1.243	11.3	0.02
J-Integral Pop Ins	10.86 (30.53)	1.078 (0.44)	11.6	0.340	0.018	0.5132	0.766	8.3	0.047
GQ	665 (158.2)	-7.81 (2.278)	20.4	-0.451	0.001	9.71	-4.221	16.4	0.004
Gc Pop Ins	1265.5 (326.7)	-14.62 (4.704)	17.3	-0.416	0.003	9.740	-4.071	15.1	0.006

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Material Density (g cm ⁻³)	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.801 (0.359)	-0.305 (0.193)	5.2	-0.227	0.120	-0.258	-1.575	1.9	0.345
Kc Pop Ins	1.03 (0.513)	-0.374 (0.275)	3.9	-0.197	0.181	-0.178	-1.297	1.3	0.44
J-Integral PQ	0.32 (33.71)	16.98 (18.1)	1.9	0.137	0.352	1.262	0.822	1.3	0.444
J-Integral Pop Ins	-30.87 (58.77)	62.47 (31.51)	7.9	0.281	0.053	1.526	1.466	8.0	0.052
GQ	506 (329.6)	-204.9 (176.7)	2.8	-0.169	0.252	2.216	-1.0	0.2	0.741
Gc Pop Ins	871.1 (671.6)	-331.4 (360.1)	1.8	-0.134	0.362	2.375	-0.446	0	0.884

Appendix 8.2: Continued

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Relative Density	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.112 (0.071)	1.12 (0.228)	34.4	0.587	<0.001	0.191	1.686	32.1	<0.001
Kc Pop Ins	-0.136 (0.103)	1.524 (0.33)	31.6	0.563	<0.001	0.334	1.663	31.0	<0.001
J-Integral PQ	52.83 (7.5)	-67.82 (23.98)	14.8	-0.385	0.007	1.085	-0.769	16.2	0.005
J-Integral Pop Ins	118.7 (13.74)	-107.83 (43.95)	11.6	-0.340	0.018	1.707	-0.414	9.2	0.036
GQ	-116.2 (71.23)	781.2 (227.8)	20.4	0.451	0.001	3.203	2.43	20.3	0.001
Gc Pop Ins	-196.0 (147.1)	1461.6 (470.4)	17.3	0.417	0.003	3.489	2.381	19.4	0.002

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
(% Water Content	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.29 (0.104)	-0.003 (0.0054)	0.7	-0.081	0.585	-0.316	-0.288	0.7	0.566
Kc Pop Ins	0.401 (0.148)	-0.0036 (0.0076)	0.5	-0.068	0.644	-0.1256	-0.316	0.9	0.531
J-Integral PQ	50.41 (9.23)	-0.966 (0.478)	8.2	-0.286	0.049	2.23	-0.581	7.1	0.066
J-Integral Pop Ins	124.5 (16.32)	-2.043 (0.845)	11.3	-0.336	0.020	2.618	-0.546	12.3	0.015
GQ	174.2 (94.33)	-2.615 (4.882)	0.6	-0.079	0.595	2.855	-0.712	1.4	0.431
Gc Pop Ins	321.1 (191.5)	-3.53 (9.913)	0.3	-0.052	0.724	3.235	-0.768	1.6	0.398

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Hydrated Mineral Content	Mechanical Parameter = a + b(Hydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Hydrated Mineral Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.4472 (0.3382)	-0.0042 (0.0066)	0.9	-0.093	0.529	0.341	-0.599	0.3	0.704
Kc Pop Ins	0.6179 (0.48)	-0.0056 (0.0093)	0.8	-0.087	0.555	0.167	-0.407	0.1	0.798
J-Integral PQ	-52.38 (28.74)	1.641 (0.559)	15.8	0.397	0.005	-2.834	2.524	13.6	0.01
J-Integral Pop Ins	-93.63 (49.76)	3.486 (0.967)	22.0	0.469	0.001	-2.065	2.331	22.7	0.001
GQ	293.6 (306.7)	-3.296 (5.962)	0.7	-0.081	0.583	2.15	-0.12	0	0.967
Gc Pop Ins	590.1 (621.8)	-6.55 (12.09)	0.6	-0.080	0.591	1.802	0.265	0	0.927

Appendix 8.2: Continued

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Hydrated Organic Content (%)	Mechanical Parameter = a + b(Hydrated Organic Content)					log(Mechanical Parameter) = a + b log(Hydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.557 (0.324)	0.0268 (0.011)	11.5	0.339	0.019	-5.792	3.477	10.1	0.028
Kc Pop Ins	-0.667 (0.465)	0.034 (0.0158)	9.1	0.302	0.037	-5.494	3.379	9.4	0.034
J-Integral PQ	50.4 (31.64)	-0.625 (1.071)	0.7	-0.086	0.563	2.391	-0.618	0.8	0.553
J-Integral Pop Ins	125.9 (56.82)	-1.368 (1.923)	1.1	-0.104	0.480	2.27	-0.237	0.2	0.751
GQ	-537.9 (296.3)	22.43 (10.03)	9.8	0.313	0.03	-6.93	6.04	9.3	0.035
Gc Pop Ins	-832.2 (611.7)	36.80 (20.71)	6.4	0.253	0.082	-6.33	5.843	8.6	0.043

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Dehydrated Mineral Content (%)	Mechanical Parameter = a + b(Dehydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Dehydrated Mineral Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.82 (0.685)	-0.025 (0.011)	10.5	-0.324	0.025	11.34	-6.668	8.3	0.047
Kc Pop Ins	2.36 (0.982)	-0.032 (0.0155)	8.5	-0.291	0.045	10.58	-6.164	7.0	0.069
J-Integral PQ	-135.7 (62.01)	2.64 (0.976)	13.7	0.370	0.01	-8.075	5.302	12.7	0.013
J-Integral Pop Ins	-274.8 (107.7)	5.674 (1.695)	19.6	0.443	0.002	-5.985	4.386	16.9	0.004
GQ	1434.2 (626.7)	-20.63 (9.87)	8.7	-0.295	0.042	19.94	-9.984	5.7	0.103
Gc Pop Ins	2488 (1288)	-35.18 (20.27)	6.1	-0.248	0.089	18.43	-8.975	4.5	0.146

Equine Beams AL	Linear Relationships					Power (log) Function Relationship			
Dehydrated Organic Content	Mechanical Parameter = a + b(Dehydrated Organic Content)					log(Mechanical Parameter) = a + b log(Dehydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.68 (0.394)	0.025 (0.011)	10.5	0.324	0.025	-6.465	3.702	8.1	0.05
Kc Pop Ins	-0.832 (0.566)	0.0319 (0.0155)	8.5	0.291	0.045	-5.895	3.436	6.9	0.072
J-Integral PQ	128.3 (35.65)	-2.64 (0.976)	13.7	-0.370	0.010	6.135	-2.979	12.7	0.013
J-Integral Pop Ins	292.6 (61.91)	-5.674 (1.695)	19.6	-0.443	0.002	5.732	-2.44	16.6	0.004
GQ	-628.5 (360.3)	20.63 (9.87)	8.7	0.295	0.042	-6.733	5.557	5.6	0.107
Gc Pop Ins	-1030.2 (740.4)	35.18 (20.27)	6.1	0.248	0.089	-5.592	5.024	4.5	0.148

Appendix 8.3: Equine Disks Ac

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Apparent Density (g cm ⁻³)	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.072 (0.137)	0.606 (0.197)	33.3	0.577	0.006	-0.165	0.95	39.1	0.002
Kc Pop Ins	0.095 (0.201)	0.833 (0.288)	30.6	0.553	0.009	-0.0263	0.978	37.3	0.003
J-Integral PQ	630.3 (156.4)	-439.5 (223.8)	16.9	-0.411	0.064	2.358	-0.767	14.2	0.092
J-Integral Pop Ins	1219 (316.8)	-500.7 (543.4)	6.0	-0.246	0.283	2.868	-0.33	3.8	0.399
GQ	195.2 (231.4)	303.4 (331.1)	4.2	0.206	0.371	2.689	7.24	8.5	0.199
Gc Pop Ins	363.2 (468.8)	575.3 (670.9)	3.7	0.193	0.402	2.966	0.779	8.6	0.196

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.799 (0.155)	-0.0053 (0.0026)	17.9	-0.423	0.056	0.84	-0.661	19.4	0.046
Kc Pop Ins	1.085 (0.225)	-0.0071 (0.0038)	15.6	-0.395	0.076	0.981	-0.665	17.7	0.058
J-Integral PQ	75.3 (163.7)	4.3 (2.75)	11.4	0.338	0.135	1.453	0.587	8.5	0.2
J-Integral Pop Ins	493 (319.3)	6.49 (5.36)	7.2	0.268	0.241	2.283	0.364	4.7	0.347
GQ	438.2 (239.6)	-0.579 (4.02)	0.1	-0.033	0.887	2.92	-0.2	0.7	0.724
Gc Pop Ins	796.1 (484.3)	-0.623 (8.13)	0	-0.018	0.940	3.203	-0.2086	0.6	0.732

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Material Density (g cm ⁻³)	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.6087 (0.3632)	-0.0703 (0.2132)	0.6	-0.075	0.745	-0.24	-0.373	1.3	0.629
Kc Pop Ins	0.7674 (0.522)	-0.0581 (0.3065)	0.2	-0.043	0.852	-0.116	-0.326	0.9	0.688
J-Integral PQ	105.7 (367.9)	130.6 (215.9)	1.9	0.137	0.552	2.392	0.416	0.9	0.687
J-Integral Pop Ins	-72.1 (673.4)	557 (395.2)	9.5	0.308	0.175	2.729	0.851	5.2	0.320
GQ	-258.2 (390)	488.7 (286.9)	8.9	0.298	0.19	2.259	1.346	6.1	0.279
Gc Pop Ins	-678 (980.3)	846.3 (575.4)	10.2	0.320	0.158	2.51	1.439	6.1	0.279

Appendix 8.3: Continued

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Relative Density	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.272 (0.11)	0.527 (0.26)	17.9	0.423	0.056	-0.116	0.527	23.5	0.026
Kc Pop Ins	0.377 (0.16)	0.708 (0.378)	15.6	0.395	0.076	0.022	0.537	21.9	0.032
J-Integral PQ	504.8 (116.6)	-429.5 (274.8)	11.4	-0.338	0.135	2.313	-0.438	9.0	0.186
J-Integral Pop Ins	1141.8 (227.4)	-648.9 (536.0)	7.2	0.268	0.241	2.82	-0.26	4.6	0.353
GQ	380.4 (170.6)	57.8 (402.2)	0.1	0.033	0.887	2.658	0.228	1.6	0.579
Gc Pop Ins	733.9 (344.9)	62.1 (813.1)	0	0.018	0.940	2.933	0.246	1.7	0.576

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
% Water Content	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.961 (0.22)	-0.027 (0.0123)	19.7	-0.444	0.044	1.014	-1.074	21.8	0.033
Kc Pop Ins	1.35 (0.315)	-0.038 (0.0176)	20.0	-0.447	0.042	1.224	-1.136	21.9	0.032
J-Integral PQ	505.4 (246.7)	-10.03 (13.81)	2.7	-0.164	0.477	2.918	-0.346	1.3	0.628
J-Integral Pop Ins	1538.9 (451.2)	-37.47 (25.26)	10.4	-0.322	0.154	3.772	-0.681	7.0	0.248
GQ	1277.3 (279.7)	-49.21 (15.66)	34.2	-0.585	0.005	5.346	-2.23	35.3	0.005
Gc Pop Ins	2505.8 (568.2)	-98.43 (31.81)	33.5	-0.579	0.006	5.767	-2.352	34.3	0.005

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Hydrated Mineral Content (%)	Mechanical Parameter = a + b(Hydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Hydrated Mineral Content)			
Parameter	a	b	r ² (%)	R	p - value	a	b	r ² (%)	p - value
Kq	-0.531 (0.928)	0.0192 (0.0174)	6.0	0.245	0.285	-3.994	2.126	5.8	0.291
Kc Pop Ins	-0.931 (1.324)	0.03 (0.025)	7.1	0.267	0.241	-4.326	2.396	6.7	0.258
J-Integral PQ	-606 (952.1)	17.55 (17.89)	4.8	0.220	0.339	-1.242	2.161	3.4	0.426
J-Integral Pop Ins	-1744 (1760)	49.21 (33.06)	10.4	0.323	0.153	-1.652	2.652	7.2	0.239
GQ	-2291 (1195)	50.66 (22.44)	21.1	0.460	0.036	-7.88	6.056	17.8	0.057
Gc Pop Ins	-4895 (2389)	106.27 (44.88)	22.8	0.477	0.029	-8.547	6.596	18.4	0.052

Appendix 8.3: Continued

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Hydrated Organic Content (%)	Mechanical Parameter = a + b(Hydrated Organic Content)					log(Mechanical Parameter) = a + b log(Hydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.92 (0.744)	0.083 (0.0256)	35.6	0.596	0.004	-8.266	5.428	40.4	0.002
Kc Pop Ins	-2.6 (1.099)	0.112 (0.038)	31.8	0.564	0.008	-8.162	5.449	36.6	0.004
J-Integral PQ	360.3 (945.3)	-1.13 (32.52)	0	-0.008	0.973	2.583	-0.0655	0	0.98
J-Integral Pop Ins	-498 (1774)	47.23 (61.02)	3.1	0.175	0.448	0.793	1.457	2.3	0.510
GQ	-2675 (1095)	105.99 (37.66)	29.4	0.542	0.011	-9.487	8.24	35.0	0.005
Gc Pop Ins	-4947 (2284)	196.4 (78.6)	24.7	0.497	0.022	-9.278	8.28	30.8	0.009

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Dehydrated Mineral Content (%)	Mechanical Parameter = a + b(Dehydrated Mineral Content)					log(Mechanical Parameter) = a + b log(Dehydrated Mineral Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	3.82 (2.211)	-0.052 (0.0342)	10.7	-0.327	0.148	13.651	-7.718	12.7	0.112
Kc Pop Ins	4.75 (3.22)	-0.0631 (0.0498)	7.8	-0.279	0.221	12.82	-7.186	9.9	0.164
J-Integral PQ	-1715 (2338)	31.58 (36.15)	3.9	0.196	0.393	-5.721	4.533	2.4	0.499
J-Integral Pop Ins	-1485 (4512)	36.47 (69.76)	1.4	0.119	0.607	-1.147	2.248	0.9	0.689
GQ	1723 (3274)	-20.38 (50.61)	0.8	-0.092	0.692	12.91	-5.71	2.6	0.484
Gc Pop Ins	1856 (6639)	-17.0 (102.6)	0.1	-0.038	0.871	11.25	-4.645	1.5	0.595

Equine Disks Ac	Linear Relationships					Power (log) Function Relationship			
Dehydrated Organic Content (%)	Mechanical Parameter = a + b(Dehydrated Organic Content)					log(Mechanical Parameter) = a + b log(Dehydrated Organic Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.33 (1.21)	0.052 (0.0342)	10.7	0.327	0.148	-6.903	4.249	12.9	0.109
Kc Pop Ins	-1.56 (1.761)	0.0631 (0.0498)	7.8	0.279	0.221	-6.32	3.96	10.1	0.16
J-Integral PQ	1443 (1277)	-31.58 (36.15)	3.9	-0.196	0.393	6.63	-2.674	2.8	0.464
J-Integral Pop Ins	2162 (2465)	-36.47 (69.76)	1.4	-0.119	0.607	4.983	-1.33	1.0	0.665
GQ	-316 (1788)	20.38 (50.61)	0.8	0.092	0.692	-2.282	3.133	2.6	0.482
Gc Pop Ins	161 (3626)	17.0 (102.6)	0.1	0.038	0.871	-1.16	2.553	1.5	0.593

Appendix 8.4: Disks AL

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.131 (0.1396)	0.708 (0.211)	34.9	0.591	0.003	-0.266	1.233	34.0	0.003
Kc Pop Ins	-0.165 (0.204)	0.916 (0.308)	29.7	0.545	0.007	-0.164	1.169	28.0	0.009
J-Integral PQ	274.3 (53.91)	-201.7 (82.24)	23.1	-0.481	0.023	1.98	-0.849	22.4	0.026
J-Integral Pop Ins	354.2 (35.83)	-118.6 (53.91)	20.3	-0.450	0.04	2.388	-0.276	20.0	0.042
GQ	-143.8 (143.1)	507.4 (216.3)	21.6	0.465	0.029	2.459	1.244	14.1	0.085
Gc Pop Ins	-254.4 (276.5)	878.5 (418.0)	18.1	0.425	0.048	2.658	1.112	10.1	0.15

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.708 (0.197)	-0.006 (0.0032)	14.8	-0.385	0.070	1.539	-1.141	15.7	0.061
Kc Pop Ins	0.901 (0.281)	-0.008 (0.0046)	11.7	-0.342	0.111	1.47	-1.039	11.9	0.106
J-Integral PQ	-83.24 (56.19)	3.673 (0.906)	45.1	0.672	0.001	-0.796	1.644	45.3	0.001
J-Integral Pop Ins	144.79 (38.78)	2.141 (0.628)	37.9	0.616	0.003	1.514	0.518	38.2	0.003
GQ	438.4 (191.7)	-4.083 (3.116)	7.9	-0.281	0.205	3.982	-0.985	4.7	0.331
Gc Pop Ins	750.2 (365.2)	-7.01 (5.936)	6.5	-0.255	0.251	3.888	-0.807	2.8	0.454

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	B	r ² (%)	p - value
Kq	0.119 (0.358)	0.126 (0.209)	1.7	0.130	0.554	-0.6512	0.666	2.0	0.523
Kc Pop Ins	0.058 (0.5)	0.221 (0.292)	2.7	0.163	0.458	-0.607	0.964	3.8	0.374
J-Integral PQ	-315.8 (68.41)	268.4 (39.92)	69.3	0.833	<0.001	1.36	3.372	75.8	<0.001
J-Integral Pop Ins	-26.53 (55.9)	175.96 (32.43)	60.8	0.780	<0.001	2.17	1.15	60.6	<0.001
GQ	-83.8 (343.1)	160.1 (201.1)	3.1	0.175	0.435	1.723	2.179	8.0	0.202
Gc Pop Ins	-201.3 (648.4)	307.1 (380.1)	3.2	0.178	0.429	1.828	2.698	11.0	0.132

Appendix 8.4: Continued

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.097 (0.126)	0.611 (0.32)	14.8	0.385	0.070	-0.233	0.631	15.5	0.063
Kc Pop Ins	0.141 (0.18)	0.761 (0.457)	11.7	0.342	0.111	-0.149	0.560	11.2	0.118
J-Integral PQ	284.1 (35.26)	-367.4 (90.62)	45.1	-0.672	0.001	1.77	-0.878	42.9	0.001
J-Integral Pop Ins	358.8 (24.65)	-214 (62.79)	37.9	-0.616	0.003	2.324	-0.273	34.2	0.005
GQ	30.1 (122.9)	408.3 (311.6)	7.9	0.281	0.205	2.43	0.484	3.7	0.391
Gc Pop Ins	49.0 (234.1)	701.2 (593.6)	6.5	0.255	0.251	2.596	0.352	1.8	0.556

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.328 (0.157)	0.0003 (0.0084)	0	0.008	0.972	-0.5498	0.0419	0	0.927
Kc Pop Ins	0.413 (0.22)	0.0012 (0.118)	0.1	0.023	0.918	-0.446	0.0493	0.1	0.918
J-Integral PQ	151.3 (54.35)	-0.444 (2.941)	0.1	-0.034	0.881	2.31	-0.131	0.6	0.738
J-Integral Pop Ins	288.03 (36.12)	-0.644 (1.93)	0.6	-0.076	0.743	2.506	-0.0532	0.8	0.704
GQ	151.8 (147)	2.002 (7.874)	0.3	0.057	0.802	2.2	0.0199	0	0.978
Gc Pop Ins	210.8 (277.3)	5.99 (14.85)	0.8	0.090	0.691	2.387	0.0493	0.0	0.950

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.669 (0.684)	-0.025 (0.1298)	15.9	-0.399	0.066	5.924	-3.73	15.3	0.072
Kc Pop Ins	2.546 (0.934)	-0.04 (0.0177)	20.3	-0.450	0.035	7.247	-4.43	19.9	0.038
J-Integral PQ	330.5 (288.4)	-3.539 (5.453)	2.2	-0.147	0.524	4.34	-1.275	2.0	0.538
J-Integral Pop Ins	262.5 (182.7)	0.253 (3.476)	0	0.017	0.943	2.447	-0.0049	0	0.994
GQ	1611.4 (615.1)	-26.92 (11.66)	21.9	-0.468	0.032	13.05	-6.28	17.9	0.056
Gc Pop Ins	3388 (1113)	-58.04 (21.12)	28.4	-0.533	0.013	15.69	-7.682	24.2	0.024

Appendix 8.4: Continued

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.416 (0.504)	0.0257 (0.0173)	9.5	0.309	0.151	-3.787	2.246	10.5	0.131
Kc Pop Ins	-0.697 (0.702)	0.039 (0.024)	11.1	0.332	0.121	-4.242	2.634	13.2	0.088
J-Integral PQ	-23.7 (176.9)	5.72 (6.059)	4.3	0.207	0.356	-0.0784	1.516	7.2	0.228
J-Integral Pop Ins	156.0 (127.3)	4.098 (4.338)	4.5	0.212	0.357	1.802	0.435	4.1	0.379
GQ	-426.4 (480.5)	21.10 (16.47)	7.6	0.275	0.215	-3.1	3.637	11.0	0.132
Gc Pop Ins	-900.3 (904.8)	41.92 (31.01)	8.4	0.289	0.192	-3.894	4.33	13.9	0.087

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	2.529 (1.098)	-0.034 (0.017)	16.0	-0.40	0.059	10.72	-6.21	15.6	0.062
Kc Pop Ins	3.85 (1.51)	-0.0532 (0.0235)	19.6	-0.443	0.034	12.89	-7.35	20.0	0.032
J-Integral PQ	595.2 (416.5)	-7.03 (6.476)	5.6	-0.236	0.291	9.338	-3.98	8.8	0.18
J-Integral Pop Ins	562.6 (307.7)	-4.473 (4.805)	4.4	-0.209	0.364	4.43	-1.102	4.5	0.358
GQ	2217 (1029)	-31.58 (16.02)	16.3	-0.403	0.063	19.951	-9.81	15.8	0.067
Gc Pop Ins	4623 (1897)	-66.96 (29.52)	20.5	-0.452	0.035	24.083	-11.967	21.0	0.032

Equine Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.8896 (0.612)	0.0342 (0.017)	16.0	0.40	0.059	-5.936	3.501	15.9	0.059
Kc Pop Ins	-1.467 (0.84)	0.0532 (0.0235)	19.6	0.443	0.034	-6.84	4.157	20.6	0.030
J-Integral PQ	-107.8 (231.3)	7.03 (6.476)	5.6	0.236	0.291	-1.408	2.287	9.3	0.167
J-Integral Pop Ins	115.3 (172.9)	4.473 (4.805)	4.4	0.209	0.364	1.458	0.631	4.6	0.35
GQ	-940.3 (573.1)	31.58 (16.02)	16.3	0.403	0.063	-6.398	5.552	16.2	0.064
Gc Pop Ins	-2073 (1056)	66.96 (29.52)	20.5	0.452	0.035	-8.1	6.794	21.7	0.029

Appendix 9: Fracture Toughness Regression Osteoporotic Material

Appendix 9.1: Beams Ac

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
Apperant Density (g cm ⁻³)	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.194 (0.043)	0.959 (0.0981)	62.6	0.791	<0.001	0.0492	2.076	65.2	<0.001
Kc Pop Ins	-0.241 (0.06)	1.297 (0.139)	60.5	0.778	<0.001	0.158	1.92	61.0	<0.001
J-Integral PQ	64.72 (8.95)	-33.24 (20.48)	4.6	-0.214	0.110	1.588	-0.248	4.1	0.133
J-Integral Pop Ins	228.51 (28.90)	-139.15 (66.15)	7.3	-0.271	0.040	2.08	-0.327	5.3	0.081
GQ	-207.46 (60.71)	839.6 (139.5)	38.9	0.623	<0.001	3.118	2.977	49.1	<0.001
Gc Pop Ins	-366.9 (121.4)	1594.4 (278.9)	36.4	0.604	<0.001	3.335	2.661	42.9	<0.001

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
Porosity (%)	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.591 (0.15)	-0.0177 (0.0019)	60.3	-0.777	<0.001	12.389	-6.955	61.2	<0.001
Kc Pop Ins	2.19 (0.211)	-0.024 (0.0027)	58.9	-0.767	<0.001	11.67	-6.484	57.9	<0.001
J-Integral PQ	13.92 (30.80)	0.4752 (0.3952)	2.6	0.161	0.234	0.453	0.653	2.3	0.263
J-Integral Pop Ins	-9.94 (98.71)	2.32 (1.267)	5.7	0.240	0.072	0.255	1.034	4.5	0.115
GQ	1395.3 (208.6)	-16.04 (2.67)	39.1	-0.625	<0.001	21.11	-10.13	46.9	<0.001
Gc Pop Ins	2703.5 (415.2)	-30.78 (5.32)	37.4	-0.612	<0.001	19.66	-9.185	42.0	<0.001

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.931 (0.831)	-0.383 (0.436)	1.4	-0.119	0.384	0.2817	-0.3804	1.4	0.385
Kc Pop Ins	1.472 (1.159)	-0.618 (0.608)	1.9	-0.137	0.314	0.634	-4.454	2.0	0.299
J-Integral PQ	119.8 (122.9)	-35.40 (64.46)	0.6	-0.076	0.585	1.899	-0.728	0.2	0.749
J-Integral Pop Ins	42.9 (359.7)	68.3 (188.6)	0.2	0.050	0.719	1.988	0.809	0.2	0.735
GQ	669.9 (944.8)	-277.9 (495.4)	0.6	-0.076	0.577	3.226	-4.699	0.7	0.539
Gc Pop Ins	1495 (1867)	-629.4 (979.2)	0.8	-0.087	0.523	3.931	-5.998	1.2	0.427

Appendix 9.1: Combined

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.224 (0.0478)	1.98 (0.215)	62.0	0.787	<0.001	0.697	2.171	64.1	<0.001
Kc Pop Ins	-0.299 (0.066)	2.765 (0.297)	62.5	0.790	<0.001	0.780	2.04	61.0	<0.001
J-Integral PQ	66.66 (10.27)	-72.59 (46.00)	4.7	-0.218	0.121	1.50	-0.272	4.2	0.144
J-Integral Pop Ins	224.34 (33.33)	-237.4 (149.3)	4.7	-0.217	0.118	2.022	-0.284	3.5	0.181
GQ	-258.44 (67.30)	1858.6 (302.6)	42.0	0.648	<0.001	4.10	3.2	49.5	<0.001
Gc Pop Ins	-494.8 (132.2)	3687.8 (594.4)	42.5	0.652	<0.001	4.272	2.93	45.0	<0.001

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.15 (0.097)	0.003 (0.006)	0.6	0.077	0.556	-0.94	0.14	0.1	0.784
Kc Pop Ins	0.215 (0.135)	0.005 (0.0077)	0.7	0.083	0.523	-0.875	0.224	0.3	0.653
J-Integral PQ	46.09 (14.23)	0.339 (0.811)	0.3	0.055	0.678	1.575	0.096	0.2	0.721
J-Integral Pop Ins	181.8 (40.98)	-0.683 (2.35)	0.1	-0.038	0.772	2.395	-0.153	0.5	0.577
GQ	72.3 (107.5)	4.124 (6.158)	0.8	0.087	0.506	1.837	0.0783	0	0.929
Gc Pop Ins	164.9 (211.4)	7.74 (12.11)	0.7	0.083	0.525	1.967	0.245	0.1	0.777

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	R	p - value	a	b	r ² (%)	p - value
Kq	-0.136 (0.359)	0.007 (0.0069)	1.5	0.124	0.342	-4.029	1.903	1.8	0.303
Kc Pop Ins	-0.095 (0.4974)	0.0076 (0.0096)	1.1	0.103	0.429	-2.875	1.328	0.9	0.461
J-Integral PQ	93.48 (51.5)	-0.802 (0.994)	1.1	-0.106	0.423	3.163	-0.858	1.5	0.362
J-Integral Pop Ins	218.7 (151.5)	-0.938 (2.92)	0.2	-0.042	0.749	2.603	-0.231	0.1	0.816
GQ	-203.1 (396.5)	6.683 (7.642)	1.3	0.113	0.385	-3.299	3.053	1.6	0.337
Gc Pop Ins	-310.6 (780.6)	11.75 (15.05)	1.0	0.101	0.438	-0.991	1.902	0.6	0.543

Appendix 9.1: Combined

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.245 (0.384)	-0.034 (0.0124)	11.3	-0.336	0.009	5.785	-4.399	7.3	0.036
Kc Pop Ins	1.65 (0.537)	-0.044 (0.0173)	9.9	-0.315	0.014	5.175	-3.876	6.0	0.059
J-Integral PQ	37.19 (60.01)	0.484 (1.935)	0.1	0.033	0.803	1.01	0.459	0.32	0.678
J-Integral Pop Ins	12.1 (174.3)	5.123 (5.617)	1.4	0.12	0.366	0.277	1.296	2.2	0.261
GQ	1213.1 (417.9)	-34.67 (13.46)	10.3	-0.32	0.013	9.849	-5.316	3.6	0.145
Gc Pop Ins	2235 (835.6)	-62.77 (26.91)	8.6	-0.293	0.023	8.628	-4.272	2.4	0.236

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-2.299 (0.781)	0.04 (0.0125)	15.1	0.389	0.002	-19.86	10.63	10.2	0.013
Kc Pop Ins	-2.869 (1.097)	0.051 (0.0175)	12.6	0.355	0.005	-16.65	8.934	7.5	0.034
J-Integral PQ	124.2 (117.6)	-1.16 (1.88)	0.7	-0.082	0.539	4.8	-1.731	1.1	0.429
J-Integral Pop Ins	361.3 (344.4)	-3.08 (5.495)	0.5	-0.074	0.577	5.31	-1.731	1.0	0.457
GQ	-2651.6 (863.8)	44.64 (13.79)	15.3	0.391	0.002	-24.93	14.961	6.8	0.045
Gc Pop Ins	-4725 (1725)	80.24 (27.53)	12.8	0.357	0.005	-18.5	11.565	4.1	0.119

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.705 (0.466)	-0.04 (0.125)	15.1	-0.389	0.002	9.24	-6.36	10.4	0.012
Kc Pop Ins	2.195 (0.654)	-0.051 (0.0175)	12.6	-0.355	0.005	7.817	-5.351	7.7	0.032
J-Integral PQ	8.14 (70.17)	1.161 (1.877)	0.7	0.082	0.539	-0.0526	1.11	1.3	0.392
J-Integral Pop Ins	52.9 (205.3)	3.08 (5.495)	0.5	0.074	0.577	0.464	1.11	1.1	0.423
GQ	1812.9 (515.2)	-44.64 (13.79)	15.3	-0.391	0.002	16.05	-8.972	6.9	0.042
Gc Pop Ins	3299 (1029)	-80.24 (27.53)	12.8	-0.357	0.005	13.2	-6.952	4.3	0.114

Appendix 9.1: Combined

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.2398 (0.0468)	-0.089 (0.12)	0.9	-0.096	0.463	-0.838	-0.149	1.0	0.439
Kc Pop Ins	0.332 (0.0649)	-0.085 (0.166)	0.4	-0.066	0.612	-0.643	-0.0918	0.4	0.624
J-Integral PQ	54.15 (6.63)	-5.97 (16.94)	0.2	-0.047	0.726	1.699	0.0128	0	0.894
J-Integral Pop Ins	162.07 (19.72)	21.85 (50.87)	0.3	0.056	0.669	2.244	0.077	1.0	0.454
GQ	161.87 (51.80)	-50.8 (132.9)	0.2	-0.050	0.704	1.9	-0.07	0.1	0.833
Gc Pop Ins	315.6 (102)	-47.6 (261.5)	0.1	-0.024	0.856	2.29	0.044	0	0.892

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.2772 (0.0431)	-0.449 (0.232)	6.3	-0.25	0.058	-1.118	-0.419	8.0	0.032
Kc Pop Ins	0.402 (0.0602)	-0.638 (0.324)	6.5	-0.254	0.054	-0.948	-0.418	8.3	0.028
J-Integral PQ	47.97 (6.484)	23.74 (34.82)	0.9	0.092	0.498	1.807	0.142	3.6	0.159
J-Integral Pop Ins	164.77 (19.17)	42.9 (103.2)	0.3	0.056	0.679	2.277	0.0807	1.0	0.455
GQ	225.57 (48.80)	-503.2 (263.0)	6.1	-0.248	0.061	1.393	-0.65	6.3	0.057
Gc Pop Ins	467.9 (96.43)	-1017.2 (519.7)	6.4	-0.253	0.055	1.733	-0.65	6.5	0.054

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.19 (0.0257)	0.746 (0.62)	3.0	0.173	0.235	-0.548	0.118	4.1	0.164
Kc Pop Ins	0.281 (0.0361)	0.985 (0.87)	2.7	0.163	0.263	-0.4183	0.0968	2.8	0.252
J-Integral PQ	50.52 (3.769)	4.26 (89.94)	0	0.007	0.962	1.74	0.0364	1.5	0.404
J-Integral Pop Ins	171.8 (11.23)	-110.8 (268.0)	0.4	-0.061	0.681	2.203	0.0006	0	0.990
GQ	134.99 (29.75)	514.6 (717.0)	1.1	0.104	0.476	2.172	0.128	1.5	0.396
Gc Pop Ins	287.9 (58.89)	938 (1419)	0.9	0.096	0.512	2.43	0.0852	0.7	0.573

Appendix 9.1: Combined

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.21 (0.0359)	-0.07 (0.216)	0.2	-0.043	0.747	-0.785	-0.00195	0	0.991
Kc Pop Ins	0.299 (0.05)	-0.051 (0.303)	0.1	-0.023	0.866	-0.593	0.0234	0	0.886
J-Integral PQ	43.64 (5.181)	56.68 (31.06)	5.8	0.241	0.073	1.854	0.182	8.1	0.033
J-Integral Pop Ins	137.1 (14.82)	235.1 (88.71)	11.3	0.337	0.01	2.403	0.216	10.1	0.016
GQ	162.3 (40.49)	-160.2 (244.2)	0.8	-0.087	0.514	1.93	0.0233	0	0.936
Gc Pop Ins	327.6 (80.25)	-240.1 (484.0)	0.4	-0.066	0.622	2.318	0.074	0.1	0.797

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.225 (0.045)	-0.153 (0.277)	0.6	-0.075	0.583	-0.757	0.0232	0	0.912
Kc Pop Ins	0.322 (0.0623)	-0.171 (0.387)	0.4	-0.060	0.661	-0.588	0.0216	0	0.916
J-Integral PQ	45.42 (6.46)	47.77 (39.88)	2.7	0.164	0.236	1.833	0.157	4.2	0.137
J-Integral Pop Ins	152.5 (19.11)	142 (118)	2.7	0.163	0.234	2.289	0.084	1.0	0.461
GQ	197.2 (50.02)	-370.6 (310.6)	2.6	-0.160	0.238	1.863	-0.0678	0.1	0.853
Gc Pop Ins	400 (99.05)	-676.3 (615.0)	2.2	-0.148	0.276	2.201	-0.071	0.1	0.844

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole collagen))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.876 (0.0288)	0.001 (0.001)	1.7	0.13	0.326	-0.9671	0.165	2.9	0.195
Kc Pop Ins	0.276 (0.04)	0.0013 (0.0015)	1.3	0.115	0.384	-0.7854	0.153	2.7	0.217
J-Integral PQ	54.43 (4.181)	-0.1 (0.158)	0.7	-0.085	0.529	1.68	0.015	0.1	0.863
J-Integral Pop Ins	173.21 (12.39)	-0.112 (0.46)	0.1	-0.033	0.809	2.209	-0.000096	0	0.999
GQ	126.4 (30.1)	0.876 (1.198)	0.9	0.096	0.468	1.564	0.2998	3.2	0.173
Gc Pop Ins	272.13 (63.17)	1.392 (2.361)	0.6	0.078	0.558	1.927	0.276	2.8	0.202

Appendix 9.2: Osteoporotic Beams AL

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.216 (0.0531)	0.98 (0.13)	51.3	0.716	<0.001	0.127	2.398	53.7	<0.001
Kc Pop Ins	-0.278 (0.0688)	1.282 (0.169)	51.7	0.719	<0.001	0.141	2.092	49.7	<0.001
J-Integral PQ	168.75 (18.31)	-196 (44.81)	26.2	-0.511	<0.001	1.526	-0.977	26.6	<0.001
J-Integral Pop Ins	666.7 (86.83)	-757.5 (212.5)	19.0	-0.436	0.001	2.137	-0.938	17.6	0.001
GQ	-234.2 (75.36)	878.2 (184.4)	29.6	0.544	<0.001	3.274	3.622	39.8	<0.001
Gc Pop Ins	-499.1 (122.7)	1633.2 (300.3)	35.4	0.595	<0.001	3.302	3.01	33.8	<0.001

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.387 (0.184)	-0.015 (0.0023)	44.7	-0.668	<0.001	11.96	-6.762	44.3	<0.001
Kc Pop Ins	1.793 (0.242)	-0.0198 (0.003)	43.5	-0.659	<0.001	10.33	-5.828	40.1	<0.001
J-Integral PQ	-160.55 (60.27)	3.192 (0.765)	24.4	0.494	<0.001	-3.543	2.886	24.1	<0.001
J-Integral Pop Ins	-671.5 (280.4)	13.17 (3.56)	20.2	0.450	0.001	-3.132	2.983	18.5	0.001
GQ	1166.8 (254.6)	-13.36 (3.23)	24.0	-0.490	<0.001	20.83	-10.05	31.8	<0.001
Gc Pop Ins	2135.8 (420.9)	-24.58 (5.34)	28.2	-0.531	<0.001	17.57	-8.177	26.0	<0.001

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.696 (0.435)	-0.276 (0.23)	2.6	-0.162	0.236	-0.0146	-3.041	2.8	0.223
Kc Pop Ins	0.731 (0.568)	-0.262 (0.301)	1.4	-0.119	0.387	-0.198	-1.858	1.3	0.411
J-Integral PQ	-46.6 (122.0)	72.79 (64.68)	2.3	0.153	0.265	1.453	1.716	2.7	0.235
J-Integral Pop Ins	-783.5 (536)	609.4 (284.2)	8.0	0.283	0.037	1.662	3.121	6.3	0.065
GQ	360.9 (518.4)	-129.0 (274.8)	0.4	-0.064	0.641	2.953	-4.2	1.7	0.338
Gc Pop Ins	475.2 (880.8)	-142.7 (466.9)	0.2	-0.042	0.761	2.586	-1.834	0.4	0.641

Appendix 9.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.167 (0.051)	1.61 (0.233)	47.5	0.689	<0.001	0.661	2.21	51.7	<0.001
Kc Pop Ins	-0.209 (0.066)	2.09 (0.302)	47.5	0.689	<0.001	0.602	1.917	47.7	<0.001
J-Integral PQ	159.5 (17.1)	-324.2 (78.3)	24.4	-0.494	<0.001	1.302	-0.91	26.2	<0.001
J-Integral Pop Ins	647.8 (79.63)	-1329.5 (364.6)	20.1	-0.448	0.001	1.894	-0.915	18.9	0.001
GQ	-182.04 (71.15)	1411.2 (325.7)	26.2	0.511	<0.001	4.077	3.332	38.2	<0.001
Gc Pop Ins	-348.3 (116.7)	2609.3 (534.2)	31.0	0.557	<0.001	3.96	2.745	32.4	<0.001

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.166 (0.084)	0.0005 (0.0042)	0	0.016	0.909	-1.179	0.256	0.5	0.607
Kc Pop Ins	0.316 (0.108)	-0.004 (0.0055)	1.1	-0.103	0.455	-0.387	-0.252	0.6	0.575
J-Integral PQ	120 (23.08)	-1.516 (1.17)	3.1	-0.175	0.201	2.338	-0.323	2.4	0.260
J-Integral Pop Ins	627.5 (99.56)	-13.56 (5.047)	12.0	-0.346	0.01	3.456	-0.732	8.8	0.028
GQ	139.6 (98.6)	-1.125 (4.999)	0.1	-0.031	0.823	1.258	0.423	0.4	0.628
Gc Pop Ins	384.1 (165.5)	-9.194 (8.392)	2.2	-0.149	0.278	2.842	-0.594	1.1	0.446

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	R	p - value	a	b	r ² (%)	p - value
Kq	0.503 (0.248)	-0.006 (0.005)	3.2	-0.178	0.19	1.116	-1.151	1.1	0.434
Kc Pop Ins	0.781 (0.32)	-0.011 (0.006)	5.2	-0.227	0.092	1.892	-1.524	2.4	0.252
J-Integral PQ	8.77 (69.70)	1.593 (1.357)	2.5	0.158	0.245	-0.33	1.319	4.5	0.118
J-Integral Pop Ins	23.8 (316.3)	6.639 (6.156)	2.1	0.145	0.286	0.153	1.385	3.5	0.166
GQ	510.3 (292.5)	-7.68 (5.694)	3.3	-0.181	0.183	5.018	-1.886	1.0	0.465
Gc Pop Ins	1028.8 (492.9)	-16.1 (9.594)	5.0	-0.223	0.099	6.571	-2.631	2.4	0.256

Appendix 9.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.1723 (0.118)	0.0002 (0.0039)	0	0.006	0.966	-0.0925	-0.511	1.3	0.403
Kc Pop Ins	0.111 (0.152)	0.0042 (0.005)	1.4	0.117	0.398	-0.691	-0.0068	0	0.990
J-Integral PQ	98.38 (33.17)	-0.239 (1.088)	0.1	-0.30	0.827	2.021	-0.064	0.1	0.860
J-Integral Pop Ins	274.2 (148.9)	3.139 (4.881)	0.8	0.089	0.523	1.975	0.373	1.5	0.376
GQ	56.8 (139.8)	2.06 (4.58)	0.4	0.062	0.655	3.058	-0.852	1.2	0.431
Gc Pop Ins	-94.2 (233.3)	10.04 (7.65)	3.2	0.179	0.195	1.861	0.155	0.1	0.872

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.226 (0.586)	0.0064 (0.0094)	0.9	0.093	0.497	-6.324	3.047	1.5	0.368
Kc Pop Ins	-0.841 (0.753)	0.017 (0.012)	3.6	0.191	0.159	-10.7	5.56	6.1	0.067
J-Integral PQ	375.8 (160.3)	-4.56 (2.56)	5.5	-0.235	0.081	8.255	-3.524	6.0	0.069
J-Integral Pop Ins	702.4 (745.7)	-5.41 (11.92)	0.4	-0.062	0.652	5.77	-1.81	1.1	0.435
GQ	-324.4 (692.6)	7.05 (11.07)	0.7	0.086	0.527	-8.016	5.463	1.6	0.357
Gc Pop Ins	-1254 (1165)	23.29 (18.62)	2.8	0.168	0.216	-16.77	10.49	7.1	0.047

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.415 (0.351)	-0.0064 (0.0094)	0.9	-0.093	0.497	2.121	-1.889	1.5	0.364
Kc Pop Ins	0.878 (0.451)	-0.017 (0.012)	3.6	-0.191	0.159	4.629	-3.396	6.0	0.069
J-Integral PQ	-80.40 (96.05)	4.562 (2.562)	5.5	0.235	0.081	-1.527	2.194	6.2	0.065
J-Integral Pop Ins	161.6 (446.8)	5.41 (11.92)	0.4	0.062	0.652	0.532	1.264	1.5	0.375
GQ	380.5 (414.9)	-7.05 (11.07)	0.7	-0.086	0.527	7.126	-3.389	1.6	0.353
Gc Pop Ins	1075.7 (698)	-23.29 (18.62)	2.8	-0.168	0.216	12.14	-6.4	7.0	0.048

Appendix 9.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.25 (0.042)	-0.22 (0.112)	6.8	-0.261	0.052	-1.059	-0.405	6.9	0.051
Kc Pop Ins	3.41 (0.054)	-0.316 (0.145)	8.1	-0.285	0.033	-0.917	-0.3998	8.2	0.033
J-Integral PQ	68.03 (11.56)	65.55 (31.10)	7.6	0.276	0.040	2.065	0.2776	9.6	0.020
J-Integral Pop Ins	292.17 (53.38)	205.1 (143.6)	3.6	0.191	0.159	2.618	0.199	3.6	0.163
GQ	191 (49.67)	-218.7 (133.6)	4.7	-0.217	0.108	1.47	-0.629	5.3	0.089
Gc Pop Ins	359.3 (83.37)	-458.1 (224.3)	7.2	-0.268	0.046	1.753	-0.618	6.3	0.062

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.21 (0.041)	-0.224 (0.232)	1.7	-0.130	0.339	-1.145	-0.352	4.0	0.140
Kc Pop Ins	0.284 (0.053)	-0.317 (0.302)	2.0	-0.142	0.297	-1.01	-0.354	4.9	0.101
J-Integral PQ	59.79 (10.65)	188.8 (60.06)	15.5	0.393	0.003	2.256	0.402	15.6	0.003
J-Integral Pop Ins	307.5 (51.70)	338.9 (291.7)	2.4	0.156	0.25	2.704	0.227	3.6	0.162
GQ	147.5 (48.77)	-195.6 (275.1)	0.9	-0.096	0.480	1.356	-0.523	2.8	0.218
Gc Pop Ins	267.9 (82.7)	-407.8 (466.7)	1.4	-0.118	0.386	1.632	-0.526	3.5	0.167

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.175 (0.025)	0.091 (0.435)	0.1	0.029	0.835	-0.721	0.0757	1.0	0.465
Kc Pop Ins	0.25 (0.032)	-0.256 (0.567)	0.4	-0.063	0.653	-0.720	-0.013	0	0.892
J-Integral PQ	83.53 (6.765)	149.3 (120.1)	2.9	0.170	0.220	2.077	0.101	5.3	0.095
J-Integral Pop Ins	364.8 (29.94)	-233.5 (531.6)	0.4	-0.061	0.662	2.568	0.0379	0.6	0.593
GQ	119.3 (29.21)	19.8 (518.5)	0	0.005	0.970	1.995	0.117	0.8	0.524
Gc Pop Ins	236.76 (49.42)	-659.3 (877.3)	1.1	-0.104	0.456	1.998	-0.0604	0.3	0.716

Appendix 9.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.15 (0.0297)	0.144 (0.153)	1.6	0.126	0.35	-0.728	0.149	1.4	0.381
Kc Pop Ins	0.216 (0.038)	0.098 (0.2)	0.4	0.066	0.627	-0.704	0.0118	0	0.939
J-Integral PQ	79.13 (8.17)	68.86 (41.98)	4.7	0.216	0.11	1.999	0.0862	1.4	0.380
J-Integral Pop Ins	371.8 (37.88)	-45.7 (194.6)	0.1	-0.032	0.815	2.488	-0.0378	0.2	0.745
GQ	79.28 (34.97)	214.5 (179.7)	2.5	0.159	0.238	2.045	0.306	1.9	0.308
Gc Pop Ins	160.75 (59.87)	239.5 (307.6)	1.1	0.104	0.440	2.092	0.0316	0.0	0.907

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.171 (0.032)	0.023 (0.206)	0	0.015	0.913	-0.867	-0.0134	0	0.936
Kc Pop Ins	0.214 (0.042)	0.14 (0.267)	0.5	0.070	0.603	-0.691	0.0253	0.1	0.867
J-Integral PQ	71.32 (8.43)	141.98 (54.23)	11.1	0.333	0.011	2.107	0.195	7.4	0.040
J-Integral Pop Ins	318.36 (39.85)	339.2 (256.4)	3.1	0.176	0.191	2.621	0.108	1.6	0.341
GQ	101.7 (37.78)	96.7 (243.1)	0.3	0.054	0.692	1.859	0.0789	0.1	0.790
Gc Pop Ins	151.7 (63.85)	360.0 (410.8)	1.4	0.117	0.385	2.211	0.156	0.6	0.556

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole coll)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.275 (0.032)	-0.005 (0.001)	18.9	-0.434	0.001	-0.239	-0.494	17.6	0.001
Kc Pop Ins	0.353 (0.043)	-0.006 (0.002)	16.0	-0.400	0.002	-0.212	-0.404	14.4	0.004
J-Integral PQ	92.7 (9.84)	-0.07 (0.419)	0.1	-0.023	0.868	1.847	0.066	1.0	0.470
J-Integral Pop Ins	306.5 (43.81)	2.956 (1.866)	4.5	0.213	0.119	2.313	0.17	4.6	0.116
GQ	230.9 (38.66)	-5.542 (1.646)	17.6	-0.420	0.001	2.841	-0.848	16.6	0.002
Gc Pop Ins	390.44 (66.12)	-9.127 (2.816)	16.5	-0.407	0.002	2.895	-0.669	12.8	0.007

Appendix 9.3 Osteoporotic Disks Ac

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.0188 (0.051)	0.538 (0.10)	55.6	0.746	<0.001	-0.191	1.477	54.1	<0.001
Kc Pop Ins	0.0145 (0.071)	0.663 (0.139)	49.9	0.706	<0.001	-0.109	1.257	50.7	<0.001
J-Integral PQ	280.5 (85.08)	-3.7 (167.3)	0.0	-0.005	0.983	2.405	0.0166	0	0.956
J-Integral Pop Ins	903.7 (209)	-372.4 (411)	3.4	-0.186	0.374	2.728	-0.27	4.3	0.323
GQ	21.52 (51.02)	258.3 (100.2)	23.2	0.482	0.017	2.603	1.743	30.8	0.005
Gc Pop Ins	94.98 (98.03)	382.3 (192.5)	15.2	0.390	0.060	2.766	1.3	23.4	0.017

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.701 (0.101)	-0.007 (0.0014)	48.2	-0.695	<0.001	3.037	-2.025	35.9	0.002
Kc Pop Ins	0.901 (0.138)	-0.008 (0.0019)	43.1	-0.657	<0.001	2.657	-1.734	34.0	0.002
J-Integral PQ	305.1 (155.8)	-0.375 (2.178)	0.1	-0.036	0.865	2.054	0.188	0.6	0.709
J-Integral Pop Ins	505.7 (386.9)	3.093 (5.41)	1.4	0.118	0.573	1.974	0.4596	4.3	0.317
GQ	356.2 (96.34)	-2.98 (1.35)	18.2	-0.427	0.038	6.228	-2.292	18.8	0.034
Gc Pop Ins	588.4 (182.9)	-4.386 (2.56)	11.8	-0.343	0.101	5.465	-1.707	14.2	0.069

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.855 (0.248)	-0.363 (0.147)	21.1	-0.459	0.021	0.0692	-3.367	20.1	0.025
Kc Pop Ins	1.095 (0.328)	-0.451 (0.193)	19.1	-0.437	0.029	0.117	-2.886	19.1	0.029
J-Integral PQ	703.1 (298.1)	-251.4 (176.0)	8.2	-0.285	0.167	2.627	-1.008	3.6	0.364
J-Integral Pop Ins	1441.7 (763.1)	-425.3 (450.4)	3.7	-0.193	0.355	2.961	-0.624	1.6	0.544
GQ	386 (207.6)	-142.3 (122.8)	5.8	-0.240	0.259	2.907	-3.986	11.3	0.108
Gc Pop Ins	642.1 (383.3)	-215.2 (226.7)	3.9	-0.198	0.353	2.999	-3.005	8.8	0.16

Appendix 9.3: Continued

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.067 (0.046)	0.607 (0.141)	45.9	0.678	<0.001	-0.093	1.022	48.6	<0.001
Kc Pop Ins	0.123 (0.062)	0.743 (0.192)	40.5	0.636	0.001	-0.023	0.876	44.3	<0.001
J-Integral PQ	267.6 (69.49)	37.5 (217.8)	0.1	0.036	0.865	2.433	0.06	0.3	0.807
J-Integral Pop Ins	815.0 (172.6)	-309.3 (541.0)	1.4	-0.118	0.573	2.733	-0.154	2.0	0.497
GQ	58.09 (43.22)	298.1 (134.7)	18.2	0.427	0.038	2.79	1.38	28.3	0.007
Gc Pop Ins	149.9 (82.1)	438.6 (255.8)	11.8	0.343	0.101	2.91	1.031	21.6	0.022

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.225 (0.108)	0.0008 (0.0053)	0.1	0.032	0.878	-1.268	0.447	2.2	0.481
Kc Pop Ins	0.3305 (0.141)	0.0002 (0.0069)	0	0.007	0.974	-1.005	0.365	1.9	0.513
J-Integral PQ	44.5 (109.6)	11.71 (5.35)	17.3	0.415	0.039	1.477	0.715	11.1	0.103
J-Integral Pop Ins	281.5 (286)	22.11 (13.95)	9.8	0.314	0.127	2.288	0.412	4.4	0.316
GQ	136.4 (84.95)	0.49 (4.11)	0.1	0.025	0.906	0.487	1.176	5.9	0.253
Gc Pop Ins	267.7 (155.4)	0.589 (7.51)	0	0.017	0.938	1.028	1.001	5.8	0.257

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.071 (0.374)	0.0033 (0.0072)	0.9	0.095	0.653	-1.334	0.375	0.1	0.863
Kc Pop Ins	0.212 (0.488)	0.0024 (0.0094)	0.3	0.053	0.803	-0.875	0.199	0.0	0.917
J-Integral PQ	-137.5 (408.7)	8.02 (7.86)	4.3	0.208	0.318	0.6435	1.024	2.0	0.503
J-Integral Pop Ins	-153 (1028)	16.9 (19.77)	3.1	0.175	0.402	1.536	0.749	1.2	0.596
GQ	135.1 (286.1)	0.215 (5.51)	0	0.008	0.969	3.186	-0.686	0.2	0.844
Gc Pop Ins	430.2 (522.1)	-2.9 (10.05)	0.4	-0.062	0.775	4.104	-1.039	0.6	0.727

Appendix 9.3: Continued

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.278 (0.108)	-0.0013 (0.0038)	0.5	-0.072	0.731	-0.272	-0.292	1.6	0.549
Kc Pop Ins	0.356 (0.141)	-0.008 (0.005)	0.1	-0.032	0.878	-0.224	-0.216	1.1	0.614
J-Integral PQ	507.9 (110.5)	-8.158 (3.837)	16.4	-0.405	0.044	3.21	-0.566	11.9	0.092
J-Integral Pop Ins	1169.9 (286.6)	-15.88 (9.96)	10	-0.316	0.124	3.339	-0.362	5.7	0.249
GQ	154.7 (82.72)	-0.301 (2.89)	0	-0.022	0.918	2.796	-0.549	2.3	0.482
Gc Pop Ins	265.5 (151.2)	0.507 (5.275)	0	-0.020	0.924	2.889	-0.395	1.6	0.556

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.77 (1.661)	0.16 (0.027)	1.7	0.130	0.553	-10.9	5.671	1.6	0.563
Kc Pop Ins	-0.861 (2.204)	0.0189 (0.035)	1.4	0.117	0.596	-8.03	4.163	1.1	0.632
J-Integral PQ	4662 (1602)	-70.05 (25.59)	26.3	-0.513	0.012	2.594	-13.11	17.6	0.046
J-Integral Pop Ins	12736 (3839)	-191.8 (61.30)	31.8	-0.564	0.005	30.24	-15.26	29.5	0.007
GQ	-539 (1306)	10.88 (20.86)	1.3	0.116	0.608	-12.8	8.23	1.4	0.606
Gc Pop Ins	-670 (2412)	15.12 (38.52)	0.8	0.087	0.699	-7.073	5.223	0.7	0.705

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.829 (0.992)	-0.0156 (0.0265)	1.7	-0.130	0.553	4.935	-3.59	1.8	0.546
Kc Pop Ins	1.032 (1.32)	-0.019 (0.035)	1.4	-0.117	0.596	3.577	-2.625	1.2	0.618
J-Integral PQ	-2342.3 (956.8)	70.05 (25.59)	26.3	0.513	0.012	-9.883	7.81	17.0	0.051
J-Integral Pop Ins	-6448 (2293)	191.8 (61.3)	31.8	0.564	0.005	-11.68	9.22	29.2	0.008
GQ	549.1 (780.4)	-10.88 (20.86)	1.3	-0.116	0.608	10.36	-5.323	1.5	0.583
Gc Pop Ins	842 (1441)	-15.12 (38.52)	0.8	-0.087	0.699	7.651	-3.396	0.8	0.685

Appendix 9.3: Continued

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.255 (0.094)	-0.037 (0.253)	0.1	-0.031	0.884	-0.754	-0.137	0.3	0.802
Kc Pop Ins	0.353 (0.122)	-0.051 (0.33)	0.1	-0.032	0.878	-0.575	-0.0889	0.2	0.853
J-Integral PQ	225.1 (103.7)	149.8 (280.4)	1.2	0.111	0.598	2.472	0.157	0.7	0.685
J-Integral Pop Ins	633.1 (260.1)	253.2 (703.2)	0.6	0.075	0.722	2.917	0.212	1.6	0.551
GQ	32.71 (72.15)	312.1 (192.4)	10.7	0.327	0.119	2.338	0.725	2.7	0.444
Gc Pop Ins	68.2 (131.6)	581 (351)	11.1	0.333	0.112	2.70	0.837	4.9	0.3

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.264 (0.071)	-0.163 (0.431)	0.6	-0.081	0.708	-0.942	-0.29	2.4	0.466
Kc Pop Ins	0.354 (0.0925)	-0.141 (0.564)	0.3	-0.053	0.806	-0.72	-0.215	1.7	0.541
J-Integral PQ	263.9 (73.65)	33.3 (449.4)	0	0.016	0.942	2.366	-0.0239	0.0	0.930
J-Integral Pop Ins	631 (193.9)	523 (1183)	0.9	0.094	0.663	2.955	0.17	2.0	0.506
GQ	116.41 (53.23)	163.9 (321.5)	1.2	0.111	0.616	1.835	-0.19	0.4	0.766
Gc Pop Ins	206.7 (98.42)	435 (594.5)	2.5	0.158	0.472	2.278	-0.04	0	0.942

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	620.1 (11.43)	3223 (2282)	9.1	0.287	0.173	-0.383	0.193	11.5	0.123
Kc Pop Ins	87.52 (29.32)	1333.6 (572)	22.2	0.243	0.031	-0.257	0.172	11.8	0.118
J-Integral PQ	187.8 (56.2)	2146 (1096)	16.8	0.516	0.065	2.684	0.173	17.5	0.053
J-Integral Pop Ins	0.23 (0.0617)	0.052 (0.357)	9.1	0.301	0.173	3.015	0.113	9.0	0.174
GQ	87.52 (29.32)	1333.6 (572)	22.2	0.472	0.031	2.635	0.405	19.7	0.044
Gc Pop Ins	187.8 (56.2)	2146 (1096)	16.8	0.410	0.065	2.883	0.3589	20.9	0.037

Appendix 9.3: Continued

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.23 (0.062)	0.052 (0.357)	0.1	0.031	0.885	-0.595	0.1222	0.8	0.676
Kc Pop Ins	0.324 (0.081)	0.054 (0.467)	0.1	0.025	0.909	-0.457	0.0979	0.7	0.704
J-Integral PQ	131.2 (55.66)	869.6 (321.9)	24.9	0.499	0.013	2.665	0.329	12.8	0.086
J-Integral Pop Ins	343.1 (146.7)	2322.8 (848.5)	25.4	0.504	0.012	3.01	0.230	7.0	0.213
GQ	104.2 (46.43)	233.7 (264.8)	3.6	0.189	0.387	2.316	0.3834	3.2	0.410
Gc Pop Ins	196.7 (86.05)	480.9 (490.7)	4.4	0.209	0.338	2.591	0.332	3.3	0.407

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.2196 (0.0711)	0.178 (0.55)	0.5	0.067	0.749	-0.638	0.0556	0.1	0.873
Kc Pop Ins	0.297 (0.092)	0.311 (0.715)	0.8	0.090	0.668	-0.457	0.0818	0.3	0.789
J-Integral PQ	308.4 (79.01)	-243.5 (611.5)	0.7	-0.083	0.694	2.346	-0.056	0.2	0.820
J-Integral Pop Ins	830.6 (196.8)	-878 (1523)	1.4	-0.119	0.570	2.74	-0.0841	0.6	0.711
GQ	76.67 (51.85)	573.1 (401.4)	8.5	0.291	0.167	2.443	0.456	3.1	0.410
Gc Pop Ins	137.5 (93.72)	1170.1 (725.6)	10.6	0.325	0.121	2.81	0.509	5.3	0.280

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole collagen)					log(Mechanical Parameter) = a + b log(Fmoles Pentosidine / pmole collagen)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.239 (0.045)	0.0001 (0.0017)	0	0.014	0.945	-0.998	0.239	4.1	0.330
Kc Pop Ins	0.323 (0.059)	0.0005 (0.0022)	0.3	0.050	0.812	-0.809	0.214	4.3	0.321
J-Integral PQ	330.2 (48.51)	-2.27 (1.82)	6.4	-0.252	0.224	2.581	-0.142	2.9	0.416
J-Integral Pop Ins	861.3 (120.7)	-6.06 (4.52)	7.3	-0.269	0.193	3.12	-0.232	9.1	0.142
GQ	152.5 (34.23)	-0.277 (1.29)	0.2	-0.046	0.831	1.497	0.402	4.7	0.309
Gc Pop Ins	277.8 (62.66)	0.081 (2.35)	0	0.007	0.973	1.874	0.352	4.9	0.298

Appendix 9.3: Osteoporotic Disks AL

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.082 (0.04)	0.583 (0.0818)	67.1	0.819	<0.001	-0.196	1.6997	65.8	<0.001
Kc Pop Ins	-0.064 (0.0545)	0.691 (0.111)	61.0	0.781	<0.001	-0.126	1.487	60.1	<0.001
J-Integral PQ	204.2 (29.69)	-71.83 (61.08)	5.0	-0.225	0.250	2.168	-0.139	1.9	0.480
J-Integral Pop Ins	372.95 (31.38)	-68.0 (62.75)	4.9	-0.220	0.290	2.497	-0.094	3.9	0.346
GQ	-52.3 (10.49)	326.8 (82.24)	38.7	0.622	0.001	2.628	2.223	45.2	<0.001
Gc Pop Ins	-40.89 (72.09)	480.3 (146.4)	30.1	0.549	0.003	2.766	1.798	35.5	0.001

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.974 (0.112)	-0.011 (0.0015)	68.3	-0.826	<0.001	6.723	-4.024	54.0	<0.001
Kc Pop Ins	1.247 (0.144)	-0.013 (0.0019)	67.4	-0.821	<0.001	6.187	-3.658	52.1	<0.001
J-Integral PQ	148.2 (86.55)	0.352 (1.158)	0.4	0.062	0.764	2.02	0.111	0.2	0.834
J-Integral Pop Ins	322.69 (81.59)	0.296 (1.101)	0.3	0.059	0.791	2.46	0.04	0.1	0.865
GQ	607.7 (107.8)	-6.823 (1.447)	49.1	-0.701	<0.001	12.03	-5.448	38.2	0.001
Gc Pop Ins	1011.6 (185.0)	-11.1 (2.483)	46.5	-0.682	<0.001	10.96	-4.718	33.9	0.002

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.565 (0.217)	-0.215 (0.126)	10.1	-0.319	0.099	-0.344	-1.823	7.3	0.165
Kc Pop Ins	0.687 (0.273)	-0.245 (0.157)	8.5	-0.292	0.131	-0.263	-1.565	6.4	0.195
J-Integral PQ	23.89 (99.39)	83.74 (57.53)	7.3	0.270	0.157	1.976	0.992	8.8	0.118
J-Integral Pop Ins	292.7 (98.66)	28.78 (56.92)	1.1	0.103	0.618	2.492	0.166	1.3	0.575
GQ	178.6 (170.3)	-45.27 (98.34)	0.8	-0.090	0.649	2.03	-0.718	0.4	0.735
Gc Pop Ins	230 (285.1)	-27.1 (164.6)	0.1	-0.032	0.870	2.193	-0.202	0	0.917

Appendix 9.3: Continued

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.001 (0.038)	0.7 (0.129)	54.0	0.735	<0.001	-0.025	1.29	54.9	<0.001
Kc Pop Ins	0.035 (0.05)	0.819 (0.171)	47.7	0.691	<0.001	0.020	1.129	49.8	<0.001
J-Integral PQ	200.35 (23.88)	-107.9 (81.47)	6.3	-0.251	0.197	2.139	-0.133	2.6	0.417
J-Integral Pop Ins	369.5 (24.62)	-103.5 (81.71)	6.5	-0.255	0.218	2.479	-0.087	5.0	0.283
GQ	-0.10 (35.5)	368.1 (119.9)	27.4	0.523	0.005	2.81	1.62	34.6	0.001
Gc Pop Ins	41.64 (62.25)	520.2 (210.2)	19.7	0.444	0.020	2.902	1.292	26.4	0.006

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.3191 (0.1186)	-0.007 (0.006)	4.2	-0.205	0.296	0.229	-0.786	4.6	0.274
Kc Pop Ins	0.3997 (0.148)	-0.007 (0.008)	3.2	-0.180	0.360	0.139	-0.604	3.2	0.360
J-Integral PQ	203.8 (57.97)	-1.867 (2.994)	1.4	-0.119	0.538	2.485	-0.216	1.3	0.562
J-Integral Pop Ins	333.4 (66.39)	0.483 (0.547)	0.1	0.028	0.893	2.535	-0.0031	0	0.988
GQ	220.84 (87.13)	-6.322 (4.52)	7.0	-0.264	0.174	3.877	-1.582	7.4	0.161
Gc Pop Ins	361.0 (146.5)	-9.339 (7.61)	5.5	-0.234	0.230	3.697	-1.218	5.3	0.240

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.154 (0.389)	0.0068 (0.0075)	3.0	0.173	0.378	-5.78	2.926	5.7	0.220
Kc Pop Ins	-0.232 (0.481)	0.0096 (0.0093)	3.9	0.198	0.312	-5.84	3.045	7.4	0.162
J-Integral PQ	254.2 (182.3)	-1.678 (3.549)	0.8	-0.091	0.640	2.778	-0.333	0.3	0.782
J-Integral Pop Ins	219.2 (187.3)	2.408 (3.656)	1.8	0.133	0.516	1.839	0.405	1.9	0.497
GQ	-20.0 (293.4)	2.341 (5.696)	0.6	0.080	0.684	-4.771	3.877	4.0	0.307
Gc Pop Ins	-107.6 (487.7)	5.651 (9.469)	1.4	0.116	0.556	-4.896	4.116	5.4	0.234

Appendix 9.3: Continued

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.1562 (0.1497)	0.0013 (0.005)	0.3	0.050	0.80	-1.023	0.1696	0.2	0.835
Kc Pop Ins	0.25 (0.186)	0.0004 (0.0063)	0	0.014	0.944	-0.553	-0.0538	0	0.942
J-Integral PQ	112.46 (69.43)	1.883 (2.334)	2.4	0.153	0.427	1.733	0.324	2.4	0.424
J-Integral Pop Ins	416 (100.9)	-2.43 (3.324)	2.2	-0.148	0.471	2.817	-0.194	1.9	0.498
GQ	10.5 (110.3)	3.048 (3.71)	2.5	0.159	0.419	0.823	0.708	1.2	0.581
Gc Pop Ins	78.3 (185.3)	3.55 (6.23)	1.2	0.111	0.573	1.762	0.262	0.2	0.824

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.247 (1.221)	0.023 (0.0196)	5.5	0.233	0.251	-16.04	8.496	5.1	0.267
Kc Pop Ins	-1.12 (1.564)	0.0221 (0.0251)	3.1	0.177	0.338	-10.37	5.417	2.4	0.447
J-Integral PQ	187.3 (551.9)	-0.244 (8.849)	0	-0.006	0.978	1.928	0.163	0	0.964
J-Integral Pop Ins	296.5 (650.9)	0.70 (10.40)	0	0.014	0.947	2.44	0.05	0	0.980
GQ	-934.1 (931.1)	16.59 (41.92)	4.9	0.221	0.277	-19.17	11.71	3.8	0.341
Gc Pop Ins	-923 (1586)	17.77 (25.40)	2.0	0.141	0.491	-7.825	5.555	1.0	0.626

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.054 (0.736)	-0.023 (0.0196)	5.5	-0.233	0.251	7.259	-5.11	5.1	0.266
Kc Pop Ins	1.087 (0.943)	-0.022 (0.0251)	3.1	-0.177	0.388	4.533	-3.286	2.5	0.442
J-Integral PQ	162.8 (333.1)	0.244 (8.849)	0	0.006	0.978	2.44	-0.138	0	0.949
J-Integral Pop Ins	366.6 (389.5)	-0.70 (10.40)	0	-0.014	0.947	2.622	-0.0596	0	0.961
GQ	724.4 (561.0)	-16.59 (14.92)	4.9	-0.221	0.277	13.01	-7.084	3.8	0.338
Gc Pop Ins	854.3 (955.4)	-17.77 (25.40)	2.0	-0.141	0.491	7.564	-3.44	1.1	0.616

Appendix 9.3: Continued

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.247 (0.041)	-0.16 (0.112)	7.3	-0.271	0.163	-0.933	-0.297	8.1	0.143
Kc Pop Ins	0.321 (0.052)	-0.174 (0.14)	5.6	-0.236	0.227	-0.773	-0.262	7.5	0.159
J-Integral PQ	127.4 (18.07)	114 (49.1)	17.7	0.421	0.029	2.31	0.201	15.1	0.045
J-Integral Pop Ins	347.2 (19.28)	-3.17 (51.53)	0	-0.013	0.952	2.531	-0.011	0.3	0.815
GQ	120.2 (31.57)	-59.42 (85.77)	1.8	-0.135	0.495	1.704	-0.292	3.1	0.369
Gc Pop Ins	195.99 (53.08)	-38.7 (144.2)	0.3	-0.053	0.790	2.026	-0.223	2.2	0.454

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.22 (0.0396)	-0.174 (0.204)	2.8	-0.168	0.401	-0.914	-0.157	2.6	0.426
Kc Pop Ins	0.288 (0.0491)	-0.177 (0.253)	1.9	-0.139	0.489	-0.752	-0.133	2.2	0.461
J-Integral PQ	140.44 (18.59)	138.48 (94.84)	8.2	0.286	0.157	2.33	0.155	9.9	0.118
J-Integral Pop Ins	353.7 (18.62)	-45.7 (100.6)	0.9	-0.096	0.654	2.51	-0.0336	2.6	0.451
GQ	110.51 (28.75)	-85.5 (147.8)	1.3	-0.115	0.568	1.693	-0.181	1.4	0.561
Gc Pop Ins	185.6 (47.34)	-65.1 (243.5)	0.3	-0.053	0.791	2.02	-0.132	0.9	0.640

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.185 (0.0329)	0.142 (0.867)	0.1	0.035	0.872	-0.728	0.0395	0.3	0.804
Kc Pop Ins	0.245 (0.04)	0.334 (1.065)	0.4	0.067	0.757	-0.055	0.061	0.8	0.674
J-Integral PQ	156.3 (13.91)	129.4 (366.1)	0.6	0.075	0.727	2.24	0.0294	0.7	0.695
J-Integral Pop Ins	338.7 (13.43)	383.3 (372)	5.6	0.236	0.316	2.599	0.0348	5.9	0.302
GQ	90.44 (24.06)	148.8 (633.1)	0.3	0.050	0.816	1.922	0.0621	0.3	0.801
Gc Pop Ins	157.1 (38.82)	445 (1021)	0.9	0.092	0.668	2.277	0.105	1.0	0.638

Appendix 9.3: Continued

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.244 (0.0456)	-0.324 (0.29)	4.7	-0.218	0.275	-0.939	-0.197	2.2	0.463
Kc Pop Ins	0.312 (0.0576)	-0.313 (0.367)	2.8	-0.168	0.401	-0.745	-0.134	1.2	0.589
J-Integral PQ	132.6 (21.56)	244.7 (142.9)	10.9	0.330	0.1	2.347	0.16	5.2	0.264
J-Integral Pop Ins	340.4 (20.21)	41.8 (134.2)	0.4	0.066	0.758	2.57	0.0376	1.7	0.538
GQ	130.7 (34.37)	193.0 (219.0)	3.0	-0.174	0.386	1.641	-0.264	1.5	0.537
Gc Pop Ins	210.1 (58.34)	-163.5 (371.7)	0.8	-0.088	0.664	2.03	-0.138	0.5	0.726

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.244 (0.0396)	-0.41 (0.289)	7.1	-0.266	0.172	-1.105	-0.338	12.6	0.064
Kc Pop Ins	0.316 (0.0497)	-0.429 (0.363)	5.1	-0.226	0.248	-0.905	-0.279	10.2	0.098
J-Integral PQ	128.9 (18.45)	308.6 (141.6)	16.0	0.399	0.039	2.35	0.15	9.3	0.122
J-Integral Pop Ins	349.8 (17.72)	-30.2 (130.1)	0.2	-0.049	0.818	2.52	-0.0159	0.7	0.701
GQ	134.2 (29.69)	-275.4 (216.7)	5.8	-0.242	0.215	1.388	-0.483	10.2	0.097
Gc Pop Ins	224.5 (50.24)	-338.1 (366.7)	3.2	-0.178	0.365	1.788	-0.364	7.0	0.174

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole coll)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.177 (0.039)	0.0008 (0.0027)	0.3	0.058	0.778	-0.999	0.198	2.9	0.407
Kc Pop Ins	0.244 (0.048)	0.0008 (0.0033)	0.2	0.047	0.819	-0.797	0.143	1.8	0.515
J-Integral PQ	170.7 (18.76)	-0.099 (1.29)	0	-0.015	0.939	2.186	0.024	0.2	0.839
J-Integral Pop Ins	339.02 (20.29)	0.095 (1.325)	0	0.015	0.944	2.571	-0.039	1.7	0.544
GQ	87.29 (29.43)	0.669 (2.021)	0.5	0.067	0.743	1.46	0.358	3.7	0.348
Gc Pop Ins	160 (48.71)	1.217 (3.346)	0.5	0.074	0.719	1.864	0.247	2.1	0.480

Appendix 10: Fracture Toughness Regression Osteoarthritic Material

Appendix 10.1: Osteoarthritic Beams Ac

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.136 (0.0768)	0.834 (0.128)	54.1	0.735	<0.001	-0.103	1.68	59.2	<0.001
Kc Pop Ins	-0.163 (0.1036)	1.181 (0.1726)	56.5	0.752	<0.001	0.04	1.496	58.4	<0.001
J-Integral PQ	255.2 (29.88)	-148.2 (50.49)	20.2	-0.450	0.006	2.08	-0.511	19.7	0.007
J-Integral Pop Ins	1107.2 (141)	-661.7 (235.7)	18.4	-0.429	0.008	2.687	-0.578	18.7	0.007
GQ	-122.6 (109.3)	668.8 (182.1)	27.3	0.522	0.001	2.813	2.184	38.0	<0.001
Gc Pop Ins	-200.1 (216.5)	1358.6 (360.8)	28.3	0.532	0.001	3.1	1.815	34.0	<0.001

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.21 (0.158)	-0.013 (0.002)	45.7	-0.676	<0.001	4.29	-2.63	40.8	<0.001
Kc Pop Ins	1.763 (0.212)	-0.0181 (0.0031)	49.3	-0.702	<0.001	4.12	-2.43	43.4	<0.001
J-Integral PQ	15.95 (59.48)	2.236 (0.853)	16.8	0.410	0.013	0.513	0.925	17.3	0.012
J-Integral Pop Ins	17.3 (277.2)	10.27 (3.99)	15.9	0.399	0.014	0.964	1.02	16.0	0.014
GQ	925.3 (215.5)	-9.62 (3.112)	21.0	-0.458	0.004	8.05	-3.161	22.4	0.003
Gc Pop Ins	1950.2 (426)	-19.86 (6.15)	22.4	-0.474	0.003	7.71	-2.77	22.3	0.003

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.852 (0.7)	-0.8 (0.373)	11.6	-0.341	0.039	0.772	-4.73	10.3	0.053
Kc Pop Ins	2.876 (0.96)	-1.253 (0.512)	14.6	-0.382	0.02	0.947	-4.69	12.3	0.034
J-Integral PQ	64.2 (235.1)	56.4 (125.2)	0.6	0.078	0.656	2.02	0.705	0.7	0.629
J-Integral Pop Ins	98 (1026)	334.4 (547.3)	1.1	0.103	0.545	2.54	1.088	1.4	0.486
GQ	997 (833.9)	-387.1 (444.8)	2.1	-0.146	0.390	3.684	-5.14	4.9	0.190
Gc Pop Ins	2479 (1653)	-1002.8 (881.4)	3.6	-0.189	0.263	4.03	-5.05	5.8	0.150

Appendix 10.1: Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.0782 (0.068)	1.387 (0.209)	55.8	0.747	<0.001	0.312	1.57	63.7	<0.001
Kc Pop Ins	-0.084 (0.092)	1.974 (0.284)	58.1	0.762	<0.001	0.406	1.399	61.0	<0.001
J-Integral PQ	243.97 (27.89)	-242.3 (87.5)	18.9	-0.434	0.009	1.96	-0.468	19.0	0.009
J-Integral Pop Ins	1044 (129.3)	-1026.7 (398.6)	15.9	-0.399	0.014	2.565	-0.511	17.2	0.011
GQ	-66.36 (98.61)	1087.6 (303.9)	26.8	0.518	0.001	3.37	2.07	44.1	<0.001
Gc Pop Ins	-94.6 (194.7)	2236 (600.1)	28.4	0.533	0.001	3.563	1.721	37.8	<0.001

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.182 (0.139)	0.009 (0.0074)	4.0	0.200	0.229	-0.769	0.196	0.4	0.702
Kc Pop Ins	0.196 (0.19)	0.018 (0.01)	7.9	0.281	0.088	-0.899	0.448	2.6	0.333
J-Integral PQ	186.6 (42.39)	-0.857 (2.234)	0.4	-0.066	0.704	2.351	-0.11	0.4	0.698
J-Integral Pop Ins	636.9 (194.1)	4.72 (10.27)	0.6	0.076	0.648	2.713	0.096	0.3	0.761
GQ	211.3 (161.7)	2.931 (8.558)	0.3	0.057	0.734	2.388	-0.0969	0	0.908
Gc Pop Ins	312.7 (321)	14.83 (16.99)	2.1	0.144	0.388	2.127	0.407	0.8	0.588

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.091 (0.481)	-0.015 (0.0095)	6.4	-0.254	0.130	2.11	-1.55	2.6	0.340
Kc Pop Ins	1.90 (0.652)	-0.0274 (0.0129)	11.4	-0.338	0.041	3.484	-2.25	6.6	0.124
J-Integral PQ	3.4 (1.442)	3.289 (2.853)	3.9	0.197	0.257	0.616	0.935	3.4	0.291
J-Integral Pop Ins	579.5 (677.3)	2.78 (13.39)	0.1	0.035	0.837	2.12	0.417	0.5	0.679
GQ	625.9 (564.5)	-7.15 (11.16)	1.2	-0.108	0.526	4.0	-1.02	0.4	0.701
Gc Pop Ins	1896 (1115)	-25.97 (22.04)	3.8	-0.195	0.247	6.75	-2.42	2.9	0.311

Appendix 10.1: Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.262 (0.919)	0.0195 (0.0294)	1.2	0.110	0.510	-5.52	3.346	3.2	0.282
Kc Pop Ins	0.050 (1.287)	0.0151 (0.041)	0.4	0.061	0.715	-3.5	2.12	1.6	0.456
J-Integral PQ	229.6 (269.9)	-1.886 (8.625)	0.1	-0.037	0.828	2.59	-0.253	0.1	0.881
J-Integral Pop Ins	2260 (1240)	-49.1 (39.63)	4.1	-0.202	0.224	5.57	-1.83	2.5	0.343
GQ	-618 (1043)	28.24 (33.34)	2.0	0.140	0.403	-5.598	5.26	3.0	0.3
Gc Pop Ins	-470 (2103)	33.79 (67.20)	0.7	0.084	0.618	-1.55	2.803	1.0	0.542

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	2.613 (1.04)	-0.0368 (0.017)	11.6	-0.340	0.037	10.97	-6.42	8.3	0.080
Kc Pop Ins	4.19 (1.423)	-0.0596 (0.023)	15.6	-0.395	0.014	12.35	-7.09	12.2	0.031
J-Integral PQ	30.7 (325.2)	3.27 (5.28)	1.1	0.106	0.54	0.422	1.0	0.7	0.622
J-Integral Pop Ins	68 (1517)	10.67 (24.64)	0.5	0.072	0.668	1.025	1.01	0.5	0.662
GQ	1731 (1242)	-23.81 (20.17)	3.7	-0.193	0.246	14.52	-6.85	3.6	0.257
Gc Pop Ins	4377 (2455)	-61.57 (39.86)	6.2	-0.249	0.131	17.28	-8.18	6.2	0.130

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.065 (0.653)	0.0368 (0.017)	11.6	0.340	0.037	-6.80	3.963	7.7	0.091
Kc Pop Ins	-1.767 (0.889)	0.0596 (0.0231)	15.6	0.395	0.014	-7.367	4.44	11.7	0.035
J-Integral PQ	296.6 (203.4)	-3.27 (5.283)	1.1	-0.106	0.54	3.20	-0.625	0.7	0.630
J-Integral Pop Ins	1134.5 (947.9)	-10.67 (24.64)	0.5	-0.072	0.668	3.766	-0.588	0.4	0.691
GQ	-649.6 (776)	23.81 (20.17)	3.7	0.193	0.246	-4.292	4.14	3.2	0.285
Gc Pop Ins	-1780 (1534)	61.57 (39.86)	6.2	0.249	0.131	-5.42	5.089	5.9	0.142

Appendix 10.1: Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.341 (0.098)	0.031 (0.237)	0	0.022	0.896	-0.544	-0.069	0.1	0.823
Kc Pop Ins	0.477 (0.135)	0.139 (0.326)	0.5	0.072	0.673	-0.339	-0.032	0	0.907
J-Integral PQ	173.9 (29.5)	-4.78 (70.23)	0	-0.012	0.946	2.21	-0.009	0	0.957
J-Integral Pop Ins	752.4 (135.8)	-94.9 (327.4)	0.2	-0.049	0.774	2.813	-0.036	0.1	0.852
GQ	385.8 (139.6)	-227.1 (339.2)	1.2	-0.111	0.507	2.20	-0.212	0.5	0.686
Gc Pop Ins	725.9 (271.1)	-200.5 (658.9)	0.3	-0.051	0.763	2.169	-0.12	0.2	0.795

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.355 (0.0599)	-0.064 (0.292)	0.1	-0.036	0.829	-0.711	-0.225	3.6	0.248
Kc Pop Ins	0.509 (0.83)	0.045 (0.405)	0	0.018	0.911	-0.47	-0.161	2.3	0.358
J-Integral PQ	182.4 (17.88)	-52.53 (85.74)	1.0	-0.102	0.544	2.188	-0.038	0.3	0.732
J-Integral Pop Ins	711.5 (82.39)	45.7 (399.6)	0	0.019	0.91	2.84	0.007	0	0.952
GQ	334.3 (85.41)	-275.2 (418.9)	1.1	-0.106	0.515	2.03	-0.3	2.1	0.372
Gc Pop Ins	669.7 (166.5)	-264.7 (816.6)	0.3	-0.053	0.748	2.51	-0.169	0.9	0.571

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.3398 (0.0452)	-1.832 (1.44)	6.6	-0.256	0.216	-0.93	-0.19	9.3	0.158
Kc Pop Ins	0.498 (0.061)	-2.01 (1.94)	4.5	-0.211	0.311	-0.635	-0.136	6.4	0.245
J-Integral PQ	170.4 (13.44)	313.3 (428.3)	2.3	0.151	0.472	2.27	0.016	0.3	0.808
J-Integral Pop Ins	684.4 (74.8)	3190 (2351)	7.7	0.278	0.189	3.01	0.083	4.9	0.321
GQ	256.9 (56.17)	-1492 (1790)	2.9	-0.171	0.413	1.72	-0.247	5.1	0.301
Gc Pop Ins	533.1 (111.1)	-1879 (3540)	1.2	-0.110	0.601	2.31	-0.139	2.2	0.502

Appendix 10.1: Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.275 (0.055)	0.219 (0.149)	6.0	0.245	0.151	-0.487	0.075	0.6	0.664
Kc Pop Ins	0.3899 (0.0741)	0.41 (0.2)	10.9	0.330	0.05	-0.255	0.147	2.7	0.338
J-Integral PQ	179.95 (15.31)	-29.87 (41.54)	1.5	-0.124	0.477	2.22	0.011	0	0.906
J-Integral Pop Ins	749.8 (77.43)	-77.9 (211.8)	0.4	-0.063	0.715	2.87	0.054	0.8	0.609
GQ	270.5 (81.87)	42.9 (223.0)	0.1	0.032	0.849	2.25	-0.03	0	0.927
Gc Pop Ins	538.3 (156.4)	251.2 (426.0)	1.0	0.099	0.559	2.712	0.118	0.6	0.649

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.302 (0.0645)	0.132 (0.331)	0.5	0.068	0.693	-0.574	-0.025	0.1	0.857
Kc Pop Ins	0.439 (0.0877)	0.283 (0.45)	1.1	0.107	0.534	0.351	0.015	0	0.901
J-Integral PQ	164.2 (18.99)	75.0 (99.46)	1.7	0.130	0.456	2.29	0.067	2.8	0.337
J-Integral Pop Ins	671.99 (89.85)	367.3 (460.6)	1.8	0.135	0.431	2.92	0.092	3.8	0.256
GQ	235.3 (99.57)	230.7 (507.8)	0.6	0.077	0.652	2.25	0.003	0	0.990
Gc Pop Ins	498.8 (192.4)	558.5 (981.2)	0.9	0.096	0.573	2.686	0.077	0.4	0.720

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole coll)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.133 (0.091)	0.0213 (0.094)	15.9	0.399	0.032	-0.994	0.467	11.8	0.068
Kc Pop Ins	0.206 (0.123)	0.033 (0.0128)	19.2	0.439	0.017	-0.75	0.422	12.0	0.066
J-Integral PQ	208.3 (26.52)	-3.26 (2.768)	4.7	-0.217	0.248	2.37	-0.146	4.9	0.238
J-Integral Pop Ins	822.1 (140.5)	-9.79 (14.44)	1.7	-0.129	0.504	2.96	-0.127	2.5	0.415
GQ	139.7 (142.9)	15.18 (14.92)	3.6	0.189	0.318	1.372	0.929	15.1	0.034
Gc Pop Ins	283.4 (275.4)	37.25 (28.75)	5.7	0.238	0.206	1.86	0.837	16.0	0.029

Appendix 10.2: Osteoarthritic Beams AL

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.243 (0.074)	0.85 (0.119)	82.2	0.861	<0.001	-0.258	1.785	69.0	<0.001
Kc Pop Ins	-0.331 (0.095)	1.21 (0.155)	84.7	0.849	<0.001	-0.091	1.71	72.2	<0.001
J-Integral PQ	501.6 (76.87)	-235.6 (124.9)	24.5	-0.401	0.086	2.454	-0.349	22.0	0.106
J-Integral Pop Ins	2387.6 (579.9)	-1367.5 (942)	16.1	-0.495	0.175	3.04	0.459	14.9	0.192
GQ	-224.3 (72.83)	630 (118.3)	72.1	0.920	<0.001	2.50	2.395	50.0	0.007
Gc Pop Ins	-439 (139.9)	1278.5 (227.3)	74.2	0.906	<0.001	2.837	2.25	52.8	0.005

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1216 (0.123)	-0.014 (0.0018)	85.4	-0.888	<0.001	4.90	-3.09	71.8	<0.001
Kc Pop Ins	1.747 (0.155)	-0.02 (0.002)	88.2	-0.874	<0.001	4.86	-2.963	75.0	<0.001
J-Integral PQ	110.9 (143.3)	3.731 (2.07)	22.9	0.368	0.098	1.37	0.645	25.9	0.076
J-Integral Pop Ins	197 (1086)	20.53 (15.66)	13.5	0.478	0.217	1.951	0.664	10.8	0.272
GQ	864.1 (123.6)	-10.62 (1.782)	76.4	-0.939	<0.001	9.75	-4.321	56.6	0.003
Gc Pop Ins	1772.4 (233.3)	-21.59 (3.37)	78.9	-0.924	<0.001	9.659	-4.067	59.9	0.002

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	4.07 (0.884)	-2.08 (0.48)	63.0	-0.806	0.001	3.03	-14.22	56.6	0.003
Kc Pop Ins	5.892 (1.17)	-3 (0.635)	67.0	-0.776	0.001	3.13	-13.9	61.4	0.002
J-Integral PQ	-18.8 (728.9)	208.6 (395.7)	2.5	-0.036	0.609	2.222	1.227	3.5	0.541
J-Integral Pop Ins	2229 (5280)	-344 (2866)	0.1	0.157	0.907	3.36	-0.74	0.5	0.818
GQ	3095.7 (725.7)	-1605.6 (393.9)	60.2	-0.818	0.002	7.51	-21.33	51.3	0.006
Gc Pop Ins	6444 (1360)	-3337.5 (738.2)	65.0	-0.794	0.001	7.712	-20.68	57.7	0.003

Appendix 10.2: Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.203 (0.061)	1.42 (0.177)	85.4	0.924	<0.001	0.160	1.684	71.8	<0.001
Kc Pop Ins	-0.274 (0.077)	2.02 (0.223)	88.2	0.939	<0.001	0.312	1.619	75.3	<0.001
J-Integral PQ	484 (70.95)	-373.1 (206.6)	22.9	-0.478	0.098	2.381	-0.313	20.5	0.120
J-Integral Pop Ins	2250.1 (537.8)	-2053 (1566)	13.5	-0.368	0.217	2.958	-0.384	12.2	0.241
GQ	-198.1 (61.19)	1062.2 (178.2)	76.4	0.874	<0.001	3.08	2.284	53.2	0.005
Gc Pop Ins	-386.9 (115.6)	2159.3 (336.5)	78.9	0.888	<0.001	3.381	2.153	56.5	0.003

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.4575 (0.2845)	0.033 (0.013)	38.7	0.634	0.031	-4.123	2.55	35.2	0.042
Kc Pop Ins	-0.694 (0.379)	0.0498 (0.0175)	44.8	0.576	0.017	-4.12	2.697	44.3	0.018
J-Integral PQ	572.4 (145.3)	-10.36 (6.695)	19.3	0.066	0.153	3.31	-0.585	18.7	0.161
J-Integral Pop Ins	1280 (1277)	12.34 (58.88)	0.4	-0.440	0.838	2.575	0.432	3.5	0.559
GQ	-377.6 (234.8)	24.11 (10.82)	33.2	0.669	0.050	-3.285	3.872	33.4	0.049
Gc Pop Ins	-837.6 (445)	53.18 (20.51)	40.2	0.622	0.027	-3.28	4.16	45.4	0.016

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	2.722 (0.825)	-0.052 (0.0174)	47.4	-0.696	0.013	15.34	-9.6	45.8	0.016
Kc Pop Ins	4.01 (1.106)	-0.077 (0.023)	52.0	-0.659	0.008	15.66	-9.68	52.4	0.008
J-Integral PQ	-124.5 (483.4)	10.02 (10.17)	8.9	-0.041	0.348	0.156	1.418	10.1	0.315
J-Integral Pop Ins	2062 (4005)	-10.92 (84.23)	0.2	0.298	0.899	4.394	-0.744	1.0	0.762
GQ	2008.5 (676.5)	-39.42 (14.23)	43.4	-0.721	0.020	26.61	-14.19	41.2	0.024
Gc Pop Ins	4255 (1295)	-83.35 (27.23)	48.4	-0.689	0.012	26.25	-14.34	49.6	0.011

Appendix 10.2: Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.405 (0.623)	-0.039 (0.02)	29.5	-0.666	0.084	7.278	-5.416	23.0	0.136
Kc Pop Ins	2.24 (0.834)	-0.062 (0.0267)	37.6	-0.558	0.045	8.11	-5.844	30.1	0.081
J-Integral PQ	-427.8 (430.3)	25.23 (13.79)	27.1	-0.071	0.101	-0.903	2.31	31.1	0.074
J-Integral Pop Ins	2444 (4059)	-27.9 (130.1)	0.5	0.521	0.835	3.558	-0.271	0.1	0.913
GQ	910.2 (405)	-26.15 (12.98)	31.1	-0.613	0.075	14.75	-8.71	23.5	0.131
Gc Pop Ins	2225.8 (751.5)	-64.53 (24.08)	44.4	-0.543	0.025	16.41	-9.566	33.3	0.063

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	3.224 (2.491)	-0.049 (0.041)	12.5	-0.351	0.259	15.77	-9.277	7.9	0.375
Kc Pop Ins	4.335 (3.519)	-0.066 (0.058)	11.3	-0.382	0.286	14.271	-8.328	7.2	0.399
J-Integral PQ	1071 (1163)	-11.92 (19.26)	3.7	0.037	0.550	6.402	-2.174	4.4	0.513
J-Integral Pop Ins	451 (9373)	18.1 (155.3)	0.1	-0.192	0.909	4.377	-0.691	0.2	0.904
GQ	2680 (1945)	-42.14 (32.22)	14.6	-0.336	0.220	23.36	-12.09	5.6	0.461
Gc Pop Ins	4972 (3949)	-77.46 (65.41)	12.3	0.354	0.264	20.36	-10.19	4.6	0.501

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.71 (1.638)	0.049 (0.041)	12.5	0.351	0.259	-10	5.79	7.1	0.401
Kc Pop Ins	-2.24 (2.31)	0.066 (0.058)	11.3	0.382	0.286	-8.875	5.21	6.5	0.424
J-Integral PQ	-121.5 (764.2)	11.92 (19.26)	3.7	-0.037	0.550	0.155	1.487	4.8	0.496
J-Integral Pop Ins	2262 (6160)	-18.1 (155.3)	0.1	0.192	0.909	2.192	0.598	0.3	0.874
GQ	-1534 (1278)	42.14 (32.22)	14.6	0.336	0.220	-10.08	7.454	4.9	0.490
Gc Pop Ins	-2773 (2595)	77.46 (65.41)	12.3	0.354	0.264	-7.83	6.284	4.1	0.529

Appendix 10.2: Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.111 (0.173)	0.223 (0.396)	3.1	0.102	0.586	-0.66	0.323	1.4	0.710
Kc Pop Ins	0.181 (0.245)	0.302 (0.561)	2.8	0.092	0.601	-0.52	0.194	0.6	0.811
J-Integral PQ	503.3 (127.4)	-308.3 (291.6)	10.1	-0.278	0.315	2.41	-0.375	12.5	0.260
J-Integral Pop Ins	2466.9 (942.1)	-1973 (2156)	7.7	-0.317	0.382	2.955	-0.556	10.3	0.309
GQ	69.4 (117.5)	78.3 (269)	0.8	0.168	0.777	1.93	0.362	0.7	0.797
Gc Pop Ins	151.2 (238.6)	176.5 (546.2)	1.0	0.175	0.753	2.21	0.105	0.1	0.935

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.123 (0.101)	0.46 (0.517)	7.3	0.358	0.395	-0.572	0.271	2.6	0.615
Kc Pop Ins	0.180 (0.142)	0.717 (0.725)	8.9	0.285	0.346	-0.386	0.267	2.9	0.596
J-Integral PQ	457 (74.98)	-470.3 (383)	13.1	0.109	0.248	2.359	-0.251	14.3	0.225
J-Integral Pop Ins	1444.5 (583.7)	1030 (2982)	1.2	-0.362	0.737	3.184	0.0184	0	0.958
GQ	44.04 (67.71)	325.8 (345.9)	8.1	0.298	0.368	2.251	0.588	4.7	0.497
Gc Pop Ins	76.7 (134.1)	831 (684.9)	12.8	0.270	0.253	2.623	0.579	5.5	0.462

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.121 (0.069)	2.19 (1.48)	18.0	0.409	0.169	-0.628	0.097	2.6	0.616
Kc Pop Ins	0.186 (0.096)	3.17 (2.07)	19.0	0.364	0.157	-0.473	0.0763	1.8	0.675
J-Integral PQ	441.1 (51.67)	-1771 (1113)	20.2	-0.21	0.143	2.364	-0.119	24.7	0.10
J-Integral Pop Ins	1864.1 (412.8)	-6049 (8893)	4.4	-0.449	0.512	2.979	-0.119	9.2	0.337
GQ	53.85 (47.33)	1258 (1020)	13.2	0.436	0.245	2.022	0.144	2.2	0.647
Gc Pop Ins	114.6 (94.24)	2877 (2030)	16.7	0.424	0.187	2.333	0.102	1.3	0.723

Appendix 10.2: Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.016 (0.089)	0.486 (0.213)	34.3	0.530	0.045	-0.486	0.644	27.2	0.082
Kc Pop Ins	0.042 (0.127)	0.686 (0.301)	34.1	0.519	0.046	-0.327	0.58	25.2	0.097
J-Integral PQ	369.9 (84.41)	6.8 (200.7)	0	-0.091	0.974	2.587	0.0699	2.0	0.658
J-Integral Pop Ins	1794.5 (613.7)	-423 (1459)	0.8	0.011	0.778	3.21	0.086	1.2	0.739
GQ	-10.08 (63.38)	289.3 (150.7)	26.9	0.584	0.084	2.23	0.954	22.8	0.116
Gc Pop Ins	-7.8 (127.8)	600.6 (304)	28.1	0.586	0.076	2.551	0.824	20.6	0.139

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.021 (0.082)	0.668 (0.271)	37.8	0.549	0.034	-0.388	0.639	30.5	0.063
Kc Pop Ins	0.049 (0.116)	0.941 (0.385)	37.5	0.542	0.034	-0.238	0.575	28.3	0.075
J-Integral PQ	374.2 (79.25)	-6.1 (263.0)	0	-0.141	0.982	2.592	0.0599	1.7	0.685
J-Integral Pop Ins	1866.4 (572.7)	-858 (1901)	2.0	-0.007	0.661	3.202	0.053	0.5	0.827
GQ	-6.63 (58.50)	395.9 (194.1)	29.4	0.612	0.069	2.367	0.928	24.6	0.101
Gc Pop Ins	1.2 (118.3)	815.2 (392.5)	30.1	0.614	0.065	2.666	0.801	22.1	0.123

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole coll)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.248 (0.087)	-0.002 (0.0031)	3.0	-0.203	0.588	-0.724	-0.046	0.1	0.905
Kc Pop Ins	0.375 (0.123)	-0.0027 (0.0044)	3.6	-0.147	0.552	-0.538	-0.043	0.1	0.905
J-Integral PQ	277.4 (58.23)	3.84 (2.07)	25.5	0.115	0.094	2.31	0.188	16.0	0.198
J-Integral Pop Ins	1471.5 (489.4)	6.38 (17.42)	1.3	0.505	0.722	3.142	0.02	0.1	0.935
GQ	126.86 (58.63)	-0.979 (2.087)	2.2	-0.191	0.649	2.04	-0.192	1.0	0.758
Gc Pop Ins	294.1 (118)	-2.747 (4.2)	4.1	-0.174	0.528	2.415	-0.186	1.1	0.743

Appendix 10.3: Osteoarthritic Disks Ac

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.523 (0.0637)	0.375 (0.0899)	71.3	0.844	0.004	-0.561	1.134	42.3	0.058
Kc Pop Ins	-0.006 (0.1754)	0.76 (0.248)	57.3	0.757	0.018	-0.188	0.993	28.6	0.138
J-Integral PQ	183.04 (30.55)	-76.90 (43.11)	31.3	-0.559	0.118	2.018	-0.405	36.6	0.084
J-Integral Pop Ins	361.67 (29.47)	-99.57 (41.58)	45.0	-0.671	0.048	2.415	-0.238	44.3	0.050
GQ	-8.58 (38.38)	121.8 (54.15)	42.0	0.648	0.059	1.898	1.09	14.5	0.312
Gc Pop Ins	231.3 (281)	380.5 (396.5)	11.6	0.341	0.369	2.643	0.81	6.2	0.517

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.520 (0.08)	-0.0055 (0.0013)	72.1	-0.849	0.004	1.467	-1.3	51.0	0.031
Kc Pop Ins	1.144 (0.226)	-0.011 (0.0036)	56.6	-0.753	0.019	1.589	-1.142	34.6	0.096
J-Integral PQ	66.65 (39.22)	1.11 (0.63)	30.7	0.554	0.121	1.468	0.365	27.2	0.150
J-Integral Pop Ins	213.4 (38.77)	1.398 (0.623)	41.8	0.647	0.060	2.063	0.232	38.2	0.076
GQ	178.5 (48.46)	-1.805 (0.779)	43.4	-0.659	0.054	4.191	-1.45	23.3	0.188
Gc Pop Ins	808.1 (359.6)	-5.51 (5.78)	11.5	-0.339	0.372	4.433	-1.127	11.1	0.382

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.275 (0.643)	-0.657 (0.39)	28.8	-0.537	0.136	0.177	-4.562	14.2	0.317
Kc Pop Ins	2.354 (1.571)	-1.13 (0.952)	16.8	-0.409	0.274	0.229	-2.93	5.2	0.555
J-Integral PQ	-249.3 (186.9)	231.7 (113.2)	37.4	0.612	0.08	1.561	2.525	29.6	0.130
J-Integral Pop Ins	32.4 (234.5)	160.2 (142.1)	15.4	0.392	0.297	2.264	0.94	14.3	0.315
GQ	437.9 (291.7)	-222.5 (176.7)	18.5	-0.430	0.248	2.401	-3.433	3.0	0.657
Gc Pop Ins	1081 (1904)	-364 (1153)	1.4	-0.118	0.762	2.503	-0.174	0	0.984

Appendix 10.3: Continued

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.029 (0.058)	0.549 (0.129)	72.1	0.849	0.004	-0.371	1.01	40.6	0.065
Kc Pop Ins	0.046 (0.162)	1.099 (0.363)	56.6	0.753	0.019	-0.03	0.862	26.4	0.157
J-Integral PQ	177.67 (28.10)	-111.02 (63.02)	30.7	-0.554	0.121	1.944	-0.374	38.3	0.076
J-Integral Pop Ins	353.1 (27.78)	-139.75 (62.29)	41.8	-0.647	0.060	2.376	-0.211	42.4	0.057
GQ	-1.93 (34.72)	180.45 (77.86)	43.4	0.659	0.054	2.073	0.952	13.5	0.331
Gc Pop Ins	257.2 (257.7)	550.9 (577.8)	11.5	0.339	0.372	2.755	0.665	5.2	0.557

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.003 (0.171)	0.0085 (0.0074)	15.9	0.399	0.288	-2.261	1.086	10.2	0.402
Kc Pop Ins	0.0832 (0.389)	0.0183 (0.017)	14.3	0.379	0.315	-1.677	0.951	6.9	0.494
J-Integral PQ	150.3 (57.25)	-0.791 (2.492)	1.4	-0.119	0.760	2.262	-0.116	0.8	0.819
J-Integral Pop Ins	299.8 (62.19)	-0.151 (2.71)	0	-0.021	0.957	2.468	-0.00022	0	0.999
GQ	32.38 (77.36)	1.746 (3.367)	3.7	0.192	0.620	0.401	0.941	2.8	0.665
Gc Pop Ins	386.1 (466.3)	4.25 (20.30)	0.6	0.079	0.840	1.57	0.67	1.1	0.786

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.885 (0.4098)	-0.0147 (0.0087)	29.1	-0.539	0.134	3.941	-2.84	17.2	0.267
Kc Pop Ins	1.81 (0.979)	-0.028 (0.021)	20.6	-0.454	0.219	3.464	-2.316	10.1	0.405
J-Integral PQ	33.0 (146.0)	2.12 (3.09)	6.3	0.251	0.515	1.217	0.532	4.1	0.602
J-Integral Pop Ins	213.8 (159.6)	1.754 (3.377)	3.7	0.193	0.619	2.1	0.218	2.4	0.690
GQ	255.7 (193.9)	-3.918 (4.102)	11.5	-0.340	0.371	6.064	-2.637	5.5	0.545
Gc Pop Ins	793 (1218)	-6.63 (25.76)	0.9	-0.097	0.804	5.11	-1.58	1.5	0.750

Appendix 10.3: Continued

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.064 (0.688)	0.004 (0.0224)	0.5	0.071	0.856	1.148	-1.317	1.5	0.751
Kc Pop Ins	0.732 (1.56)	-0.0079 (0.0506)	0.3	-0.059	0.881	2.663	-2.066	3.3	0.639
J-Integral PQ	254.8 (208.6)	-3.99 (6.793)	4.7	-0.217	0.576	3.591	-0.999	6.0	0.526
J-Integral Pop Ins	516.6 (214.9)	-7.186 (6.998)	13.1	-0.362	0.339	3.648	-0.795	13.2	0.336
GQ	-88.9 (285.8)	5.227 (9.306)	4.3	0.208	0.592	4.569	-1.96	1.3	0.775
Gc Pop Ins	514 (1734)	-1.09 (56.45)	0	-0.007	0.985	7.597	-3.455	3.1	0.653

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	2.396 (0.982)	-0.036 (0.016)	41.8	-0.647	0.060	13.33	-7.938	16.2	0.282
Kc Pop Ins	4.071 (2.574)	-0.059 (0.043)	21.7	-0.466	0.207	8.817	-5.177	6.1	0.521
J-Integral PQ	-309.1 (362.4)	7.304 (5.988)	17.5	0.419	0.262	-3.585	3.195	17.9	0.257
J-Integral Pop Ins	-222.7 (383.2)	8.582 (6.331)	20.8	0.456	0.217	-0.868	1.873	21.4	0.209
GQ	828.9 (464.3)	-12.53 (7.67)	27.6	-0.525	0.147	13.35	-6.56	4.1	0.601
Gc Pop Ins	1456 (3216)	-16.13 (53.15)	1.3	-0.114	0.770	4.314	-1.037	0.1	0.942

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.245 (0.642)	0.0364 (0.0162)	41.8	0.647	0.060	-8.795	5.003	14.2	0.318
Kc Pop Ins	-1.847 (1.683)	0.0592 (0.043)	21.7	0.466	0.207	-5.383	3.118	4.9	0.568
J-Integral PQ	421.2 (237)	-7.3 (5.988)	17.5	-0.419	0.262	5.453	-2.097	16.9	0.272
J-Integral Pop Ins	635.5 (250.5)	-8.582 (6.331)	20.8	-0.456	0.217	4.388	-1.203	19.5	0.235
GQ	-423.7 (303.6)	12.53 (7.672)	27.6	0.525	0.147	-4.5	3.859	3.1	0.649
Gc Pop Ins	-157 (2103)	16.13 (53.15)	1.3	0.114	0.770	2.325	0.0879	0	0.993

Appendix 10.3: Continued

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.0072 (0.13)	0.451 (0.2999)	24.4	0.494	0.176	-0.512	0.727	12.5	0.350
Kc Pop Ins	0.204 (0.318)	0.695 (0.7334)	11.4	0.337	0.375	-0.181	0.549	6.3	0.514
J-Integral PQ	177.6 (42.75)	-108.95 (98.65)	14.8	-0.385	0.306	1.979	-0.312	15.7	0.291
J-Integral Pop Ins	357.9 (43.62)	-148.9 (100.7)	23.8	-0.488	0.183	2.391	-0.188	19.9	0.229
GQ	6.34 (57.86)	157.2 (133.5)	16.5	0.407	0.277	2.077	1.026	9.3	0.426
Gc Pop Ins	449 (375.6)	76.9 (866.7)	0.1	0.034	0.932	2.739	0.67	3.1	0.651

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.124 (0.075)	0.378 (0.341)	15.0	0.387	0.304	-0.495	0.38	11.5	0.371
Kc Pop Ins	0.383 (0.177)	0.593 (0.803)	7.2	0.269	0.484	-0.1099	0.357	9.0	0.433
J-Integral PQ	138.34 (25.1)	-31.2 (113.8)	1.1	-0.103	0.792	2.061	-0.0553	1.7	0.741
J-Integral Pop Ins	318.9 (25.17)	-123 (114.4)	14.2	-0.377	0.318	2.4	-0.08	12.3	0.356
GQ	37.55 (30.83)	184.4 (140.1)	19.8	0.445	0.230	2.293	0.767	17.4	0.264
GcPop Ins	401.6 (201.1)	432.4 (913.9)	3.1	0.176	0.651	3.063	0.721	12.1	0.359

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.125 (0.053)	1.656 (0.908)	32.2	0.567	0.111	-0.21	0.418	19.3	0.277
Kc Pop Ins	0.383 (0.133)	2.617 (2.286)	15.8	0.397	0.290	0.112	0.367	13.4	0.373
J-Integral PQ	145.3 (18.74)	-305.9 (321.6)	11.4	-0.338	0.373	1.995	-0.0665	3.7	0.650
J-Integral Pop Ins	320.03 (17.43)	-570.3 (299.2)	34.2	-0.585	0.098	2.351	-0.0745	16.0	0.327
GQ	42.11 (22.38)	704.1 (384.1)	32.4	0.569	0.109	2.768	0.786	26.6	0.191
Gc Pop Ins	426.5 (159)	1310 (2728)	3.2	0.179	0.646	3.412	0.685	16.2	0.322

Appendix 10.3: Continued

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.091 (0.0813)	0.273 (0.189)	23.0	0.480	0.191	-0.812	-0.0055	0	0.989
Kc Pop Ins	0.368 (0.203)	0.327 (0.47)	6.5	0.255	0.509	-0.487	-0.163	2.2	0.705
J-Integral PQ	160.2 (26.12)	-73.34 (60.60)	17.3	-0.416	0.265	2.049	-0.113	8.0	0.460
J-Integral Pop Ins	329.2 (27.55)	-87.04 (63.92)	20.9	-0.458	0.215	2.442	-0.0512	5.8	0.533
GQ	28.31 (34.59)	114.17 (80.24)	22.4	0.474	0.198	1.602	-0.111	0.4	0.868
Gc Pop Ins	461.1 (232.9)	52.2 (540.2)	0.1	0.037	0.926	2.25	-0.425	4.9	0.568

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.0733 (0.068)	0.534 (0.258)	38.0	0.616	0.077	-0.676	0.181	3.1	0.653
Kc Pop Ins	0.2996 (0.1758)	0.8526 (0.6659)	19.0	0.436	0.241	-0.352	0.0719	0.4	0.868
J-Integral PQ	151.91 (25.40)	-85.68 (96.20)	10.2	-0.319	0.403	2.04	-0.09	5.1	0.557
J-Integral Pop Ins	328.6 (25.15)	-142.9 (95.26)	24.3	-0.493	0.177	2.421	-0.063	8.8	0.439
GQ	15.52 (27.05)	247.7 (102.4)	45.5	0.675	0.046	1.865	0.281	2.7	0.672
Gc Pop Ins	335 (207.6)	647.6 (786.3)	8.8	0.297	0.437	2.512	0.063	0.1	0.934

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole collagen)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole collagen))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.167 (0.061)	0.001 (0.0018)	5.3	0.231	0.550	-1.3	0.444	50.3	0.032
Kc Pop Ins	0.386 (0.129)	0.0046 (0.0039)	16.9	0.411	0.272	-1	0.534	64.2	0.009
J-Integral PQ	119.38 (17.96)	0.577 (0.54)	14.0	0.374	0.321	2.03	0.0674	7.9	0.465
J-Integral Pop Ins	284.6 (19.87)	0.513 (0.598)	9.5	0.308	0.419	2.462	0.0053	0.2	0.917
GQ	51.76 (24.22)	0.85 (0.729)	16.3	0.403	0.282	0.753	0.812	62.2	0.012
Gc Pop Ins	271.3 (107.5)	9.121 (3.23)	53.2	0.729	0.026	1.361	0.991	72.6	0.004

Appendix 10.4: Osteoarthritic Disks AL

Osteoarthritic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Apparent Density)					log(Mechanical Parameter) = a + b log(Apparent Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.161 (0.051)	0.491 (0.093)	87.5	0.935	0.006	-0.328	2.51	78.4	0.019
Kc Pop Ins	-0.552 (0.148)	1.55 (0.271)	89.1	0.944	0.005	0.153	2.69	82.0	0.013
J-Integral PQ	948.3 (368.6)	-877.8 (675.9)	39.7	-0.545	0.264	2.373	-1.07	30.5	0.256
J-Integral Pop Ins	2891 (1044)	-2780 (1915)	34.5	-0.588	0.220	2.792	-1.25	42.1	0.163
GQ	-77.07 (28.58)	191.5 (52.4)	77.0	0.877	0.022	2.457	4.123	66.9	0.047
Gc Pop Ins	-749.7 (149)	1751.5 (273.2)	91.1	0.955	0.003	3.42	4.479	76.2	0.023

Osteoarthritic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Porosity)					log(Mechanical Parameter) = a + b log(Porosity)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.619 (0.085)	-0.0075 (0.001)	90.2	-0.950	0.004	7.355	-4.56	83.7	0.011
Kc Pop Ins	1.904 (0.25)	-0.024 (0.0036)	91.3	-0.956	0.003	8.414	-4.897	88.1	0.005
J-Integral PQ	-48.1 (789.9)	7.60 (11.48)	9.9	0.314	0.544	0.618	1.114	10.7	0.527
J-Integral Pop Ins	-412 (2271)	26.2 (33.0)	13.6	0.369	0.472	0.0428	1.682	24.7	0.316
GQ	218.4 (58.7)	-2.796 (0.853)	72.9	-0.854	0.031	14.9	-7.386	69.5	0.039
Gc Pop Ins	1985.7 (306.4)	-26.05 (4.45)	89.5	-0.946	0.004	17.01	-8.069	80.0	0.016

Osteoarthritic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Material Density)					log(Mechanical Parameter) = a + b log(Material Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.428 (0.342)	-0.1867 (0.1975)	18.3	-0.427	0.398	-0.184	-3.46	23.4	0.331
Kc Pop Ins	1.23 (1.085)	-0.545 (0.626)	15.9	-0.399	0.433	0.202	-3.264	19.0	0.387
J-Integral PQ	1662.6 (997.2)	-686.7 (575.2)	26.3	-0.513	0.298	3.26	-2.51	26.4	0.298
J-Integral Pop Ins	4661 (2990)	-1891 (1725)	23.1	-0.481	0.334	3.57	-1.852	14.5	0.456
GQ	122.2 (149.8)	-55.29 (86.41)	9.3	-0.305	0.557	2.716	-5.78	20.6	0.365
Gc Pop Ins	1116 (1239)	-530.6 (714.9)	12.1	-0.348	0.499	3.488	-5.386	17.3	0.412

Appendix 10.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Relative Density)					log(Mechanical Parameter) = a + b log(Relative Density)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.171 (0.015)	0.883 (0.039)	99.1	0.995	<0.001	-0.023	1.94	95.9	<0.001
Kc Pop Ins	0.288 (0.049)	1.821 (0.125)	97.7	0.988	<0.001	0.297	1.73	92.4	0.001
J-Integral PQ	567.7 (126.3)	-291.9 (318.9)	14.4	-0.379	0.402	2.52	-0.286	15.0	0.390
J-Integral Pop Ins	1671.5 (368.5)	-876.8 (930.3)	15.1	-0.388	0.389	2.972	-0.319	18.9	0.329
GQ	-105.68 (12.29)	424.11 (31.01)	97.4	0.987	<0.001	2.794	2.876	89.0	0.001
Gc Pop Ins	-402.55 (62.22)	1901.2 (157.1)	96.7	0.983	<0.001	3.435	2.45	83.5	0.004

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(% Water Content)					log(Mechanical Parameter) = a + b log(% Water Content)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.0758 (0.117)	0.0015 (0.006)	1.5	0.124	0.814	-1.766	0.593	6.8	0.617
Kc Pop Ins	0.228 (0.369)	0.003 (0.019)	0.6	0.080	0.881	-1.195	0.0485	4.2	0.698
J-Integral PQ	51.8 (293.4)	21.83 (15.0)	34.6	0.588	0.219	1.504	0.905	34.0	0.224
J-Integral Pop Ins	59.9 (827.1)	68.70 (42.29)	39.7	0.630	0.180	2.05	0.846	30.1	0.260
GQ	21.28 (49.07)	0.27 (2.51)	0.3	0.054	0.920	-0.138	1.156	8.2	0.582
Gc Pop Ins	166.6 (412.8)	1.6 (21.11)	0.1	0.038	0.943	1	0.94	5.2	0.663

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Mineral %)					log(Mechanical Parameter) = a + b log(Wet Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.256 (0.325)	-0.003 (0.0065)	5.1	-0.227	0.666	2.281	-1.935	9.5	0.553
Kc Pop Ins	0.667 (1.03)	-0.0076 (0.02)	3.3	-0.182	0.730	2.254	-1.664	6.4	0.629
J-Integral PQ	1575.3 (862.9)	-21.98 (17.19)	29.0	-0.539	0.270	6.708	-2.381	30.7	0.254
J-Integral Pop Ins	4817 (2468)	-68.44 (49.17)	32.6	-0.571	0.236	6.875	-2.20	26.6	0.295
GQ	67.9 (137.1)	-0.827 (2.732)	2.2	-0.150	0.777	7.598	-3.68	10.8	0.524
Gc Pop Ins	528 (1154)	-6.6 (22.99)	2.0	-0.142	0.788	7.543	-3.14	7.6	0.597

Appendix 10.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Wet Organic %)					log(Mechanical Parameter) = a + b log(Wet Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.513 (1.086)	0.053 (0.036)	35.7	0.598	0.210	-19.87	12.7	24.4	0.319
Kc Pop Ins	-5.06 (3.284)	0.1748 (0.1074)	39.8	0.631	0.179	-22.49	14.76	30.0	0.260
J-Integral PQ	6458 (2880)	-195.8 (94.2)	51.9	-0.721	0.106	21.61	-12.75	52.6	0.103
J-Integral Pop Ins	21194 (7113)	-648 (232.7)	66.0	-0.812	0.05	24.62	-14.47	68.5	0.042
GQ	-651.6 (448.7)	22.19 (14.68)	36.4	0.603	0.205	-27.81	19.63	18.4	0.396
Gc Pop Ins	-6119 (3517)	206.7 (115.1)	44.6	0.668	0.147	-33.05	23.74	26.0	0.301

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Mineral %)					log(Mechanical Parameter) = a + b log(Dry Mineral %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.931 (0.921)	-0.013 (0.015)	16.8	-0.410	0.420	15.81	-9.382	23.9	0.325
Kc Pop Ins	2.611 (2.933)	-0.0374 (0.0473)	13.6	-0.368	0.472	15.32	-8.86	19.5	0.381
J-Integral PQ	3127 (2796)	-42.75 (45.04)	18.4	-0.429	0.396	13.01	-5.77	19.3	0.383
J-Integral Pop Ins	9452 (8145)	-129.9 (131.2)	19.7	-0.444	0.378	11.73	-4.798	13.5	0.473
GQ	296.8 (396.8)	-4.35 (6.391)	10.4	-0.322	0.533	31.66	-16.91	24.5	0.318
Gc Pop Ins	2534 (3324)	-37.63 (53.54)	11.0	-0.332	0.521	30.67	-15.87	20.9	0.362

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Dry Organic %)					log(Mechanical Parameter) = a + b log(Dry Organic %)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.4 (0.563)	0.013 (0.015)	16.8	0.410	0.420	-10.23	5.842	25.0	0.313
Kc Pop Ins	-1.13 (1.793)	0.037 (0.047)	13.6	0.368	0.472	-9.292	5.522	20.3	0.369
J-Integral PQ	-1148 (1709)	42.75 (45.04)	18.4	0.429	0.396	-2.804	3.463	18.7	0.391
J-Integral Pop Ins	-3541 (4977)	129.9 (131.2)	19.7	0.444	0.378	-1.384	2.859	12.9	0.484
GQ	-138.6 (242.5)	4.35 (6.391)	10.4	0.322	0.533	-15.28	10.53	25.6	0.306
Gc Pop Ins	-1230 (2031)	37.63 (53.54)	11.0	0.332	0.521	-13.40	9.888	21.8	0.350

Appendix 10.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m OHPyr)					log(Mechanical Parameter) = a + b log(m/m OHPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.058 (0.0825)	0.125 (0.187)	8.2	0.286	0.535	-0.858	0.322	3.7	0.678
Kc Pop Ins	0.0106 (0.277)	0.724 (0.628)	21.0	0.458	0.302	-0.287	0.648	11.2	0.463
J-Integral PQ	430.9 (313.6)	187.8 (712.1)	1.4	0.117	0.803	2.684	-0.0235	0	0.969
J-Integral Pop Ins	959 (1114)	1377 (2530)	5.6	0.237	0.610	3.21	0.101	0.5	0.882
GQ	32.9 (32.03)	-16.77 (72.75)	1.1	-0.103	0.827	1.197	-0.3779	2.0	0.762
Gc Pop Ins	103.7 (267.5)	236.1 (607.5)	2.9	0.171	0.714	2.338	0.274	1.0	0.835

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(m/m LysPyr)					log(Mechanical Parameter) = a + b log(m/m LysPyr)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.0275 (0.0404)	0.501 (0.228)	49.1	0.700	0.08	-0.339	0.807	42.0	0.115
Kc Pop Ins	0.059 (0.163)	1.564 (0.921)	36.6	0.605	0.150	0.163	0.875	36.4	0.151
J-Integral PQ	772.5 (167.7)	-1545.9 (947.6)	34.7	-0.589	0.164	2.215	-0.602	39.3	0.132
J-Integral Pop Ins	2409.4 (637.7)	-5076 (3604)	28.4	-0.533	0.218	2.657	-0.646	35.6	0.157
GQ	-10.57 (12.60)	215 (71.22)	64.6	0.804	0.029	2.44	1.392	48.6	0.081
GcPop Ins	-126.7 (86.8)	1971 (490.5)	76.4	0.874	0.010	3.446	1.528	52.8	0.064

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HHL)					log(Mechanical Parameter) = a + b log(HHL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.081 (0.0146)	1.21 (0.398)	64.7	0.804	0.029	-0.569	0.23	27.1	0.368
Kc Pop Ins	0.199 (0.042)	4.763 (1.156)	77.3	0.879	0.009	0.101	0.375	46.0	0.208
J-Integral PQ	495.8 (89.28)	619 (2443)	1.3	0.113	0.810	2.592	-0.0779	4.7	0.728
J-Integral Pop Ins	1520.7 (325.6)	1268 (8909)	0.4	0.064	0.892	2.976	-0.136	9.5	0.614
GQ	18.67 (8.04)	269.2 (220)	23.0	0.480	0.276	1.647	0.157	4.5	0.732
Gc Pop Ins	107.2 (46.34)	3783 (1268)	64.0	0.800	0.031	2.988	0.446	29.9	0.340

Appendix 10.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLKNL)					log(Mechanical Parameter) = a + b log(HLKNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.0662 (0.0209)	0.151 (0.0581)	57.5	0.758	0.048	-0.73	0.429	45.0	0.145
Kc Pop Ins	0.144 (0.066)	0.591 (0.184)	67.3	0.820	0.024	-0.195	0.607	59.3	0.073
J-Integral PQ	405.7 (103)	350.8 (286.8)	23.0	0.480	0.276	2.772	0.112	5.1	0.668
J-Integral Pop Ins	1203.6 (383.9)	1156 (1069)	19.0	0.435	0.329	3.249	0.126	4.3	0.694
GQ	17.38 (11.14)	27.38 (31.02)	13.5	0.367	0.418	1.583	0.389	14.1	0.463
Gc Pop Ins	79.55 (75.73)	415.9 (210.8)	43.8	0.662	0.106	2.654	0.745	42.8	0.159

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(HLNL)					log(Mechanical Parameter) = a + b log(HLNL)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.068 (0.029)	0.191 (0.111)	37.2	0.610	0.146	-0.7997	0.251	19.1	0.327
Kc Pop Ins	0.115 (0.081)	0.896 (0.309)	62.8	0.792	0.034	-0.242	0.405	36.7	0.149
J-Integral PQ	415.3 (125.2)	417.4 (477.8)	13.2	0.364	0.422	2.8	0.155	12.3	0.441
J-Integral Pop Ins	1219.7 (458)	1443 (1747)	12.0	0.346	0.446	3.247	0.109	4.7	0.639
GQ	22.49 (13.62)	13.74 (51.96)	1.4	0.117	0.802	1.43	0.128	1.9	0.766
Gc Pop Ins	75.22 (94.94)	563 (362.2)	32.6	0.571	0.181	2.546	0.436	20.2	0.312

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Fmoles Pentosidine / pmole coll)					log(Mechanical Parameter) = a + b log((Fmoles Pentosidine / pmole coll)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.114 (0.027)	-0.0001 (0.001)	0.3	-0.050	0.915	-1.003	0.023	0.2	0.922
Kc Pop Ins	0.313 (0.0974)	0.0006 (0.0048)	0.3	0.056	0.905	-0.648	0.109	3.6	0.686
J-Integral PQ	458.3 (93.91)	3.425 (4.61)	9.9	0.315	0.491	2.484	0.194	25.3	0.249
J-Integral Pop Ins	1408.6 (349.3)	9.25 (17.16)	5.5	0.234	0.613	3.01	0.147	11.5	0.457
GQ	29.45 (9.85)	-0.241 (0.484)	4.7	-0.218	0.639	1.457	-0.11	1.9	0.768
Gc Pop Ins	214.8 (84.92)	-0.589 (4.17)	0.4	-0.063	0.893	2.168	0.063	0.6	0.874

Appendix 11: Compression Testing Results vs. Clinical QUS Regressions

Appendix 11.1: Osteoporotic Samples

Age Osteoporotic	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	R ² (%)	r	p - value	a	b	R ² (%)	p - value
E- Platens (MPa)	436.8 (247.2)	-1.84 (3.09)	2.3	-0.152	0.561	3.194	-0.396	1.3	0.665
E- Contact (MPa)	299 (1016)	2.58 (12.72)	0.3	0.052	0.842	1.594	0.513	0.3	0.842
ε _{Yield} Platens (%)	2.846 (1.217)	-0.0177 (0.015)	7.8	-0.279	0.262	1.984	-0.972	8.7	0.236
ε _{Ult.} Strain Platens (%)	3.582 (1.661)	-0.0145 (0.021)	3.0	-0.172	0.494	1.372	-0.526	4.2	0.417
ε _{Yield} Contact (%)	2.003 (0.936)	-0.014 (0.0117)	9.0	-0.300	0.242	1.659	-0.92	5.1	0.384
ε _{Ult.} Contact (%)	2.083 (3.491)	0.0028 (0.0435)	0	0.017	0.950	0.646	-0.174	0.1	0.898
σ _{Yield} (MPa)	10.18 (5.969)	-0.0774 (0.074)	5.7	-0.238	0.312	2.979	-1.286	3.6	0.421
σ _{Ult.} (MPa)	10.82 (6.98)	-0.074 (0.087)	3.8	-0.196	0.408	2.371	-0.912	2.3	0.522
Work to Failure Platens (Nmm ⁻¹)	158.6 (81.0)	-1.527 (1.007)	11.3	-0.336	0.147	3.976	-1.351	1.5	0.602
Work to Failure Contact (Nmm ⁻¹)	328.1 (196.6)	-2.793 (2.448)	6.7	-0.260	0.269	4.71	-1.46	4.1	0.392

Appendix 11.1: Continued

Osteoporotic	Linear: Distal Radius SOS (m s ⁻¹)					Log: Distal Radius SOS (m s ⁻¹)			
Distal Radius SOS (m s ⁻¹)	Mechanical Parameter = a + b(Distal Radius SOS (m s ⁻¹))					log(Mechanical Parameter) = a + b log(Distal Radius SOS (m s ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-831.2 (776.3)	0.2774 (0.1926)	12.2	0.349	0.170	-9.5	3.32	14.6	0.144
E- Contact (MPa)	-1862 (2808)	0.5896 (0.7)	4.5	0.212	0.413	-21.26	6.62	5.4	0.387
ε _{Yield} Platens (%)	-4.77 (3.54)	0.00154 (0.0009)	16	0.400	0.100	-15.68	4.39	22.0	0.057
ε _{Ult.} Strain Platens (%)	-7.16 (4.72)	0.0024 (0.0012)	20.4	0.451	0.060	-14.37	4.09	34.2	0.014
ε _{Yield} Contact (%)	0.795 (2.782)	0.00002 (0.0007)	0	0.007	0.980	1.06	-0.319	0.1	0.924
ε _{Ult.} Contact (%)	6.56 (9.78)	-0.0011 (0.0024)	1.3	-0.12	0.672	9.04	-2.42	2.5	0.562
σ _{Yield} (MPa)	-26.3 (16.27)	0.00753 (0.004)	16.1	0.402	0.079	-22.84	6.49	12.7	0.135
σ _{Ult.} (MPa)	-32.9 (18.62)	0.0094 (0.0046)	18.6	0.432	0.057	-22.56	6.44	17.5	0.075
Work to Failure Contact (Nmm ⁻¹)	-249 (0.0714)	0.0714 (0.058)	8.2	0.286	0.236	-16.74	5.04	2.5	0.515
Work to Failure Platens (Nmm ⁻¹)	-1009 (497.7)	0.278 (0.124)	22.9	0.479	0.038	-27.61	8.21	18.9	0.063

	Linear: Distal Radius T-score					Linear: Distal Radius Z-score				
	Mechanical Parameter = a + b(Distal Radius T-score)					Mechanical Parameter = a + b(Distal Radius Z-score)				
	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	318 (32.68)	24.8 (18.65)	10.5	0.325	0.203	262.5 (31.76)	25.6 (22.4)	8.5	0.292	0.272
E- Contact (MPa)	599 (131.1)	64.49 (67.26)	5.8	0.240	0.353	473 (109.2)	53.62 (80.76)	3.1	0.175	0.518
ε _{Yield} Platens (%)	1.59 (0.159)	0.133 (0.085)	13.1	0.362	0.140	1.27 (0.136)	0.19 (0.097)	20.4	0.452	0.069
ε _{Ult.} Strain Platens (%)	2.68 (0.211)	0.214 (0.114)	18.2	0.427	0.077	2.13 (0.184)	0.26 (0.131)	20.8	0.456	0.066
ε _{Yield} Contact (%)	0.843 (0.13)	-0.017 (0.067)	0.4	-0.07	0.806	0.86 (0.114)	0.011 (0.079)	0.1	0.038	0.893
ε _{Ult.} Contact (%)	2.14 (0.454)	-0.137 (0.236)	2.4	-0.15	0.569	2.24 (0.299)	-0.117 (0.206)	2.4	-0.16	0.582
σ _{Yield} (MPa)	4.82 (0.727)	0.622 (0.394)	12.1	0.349	0.132	3.21 (0.615)	0.919 (0.451)	19.6	0.443	0.058
σ _{Ult.} (MPa)	5.96 (0.836)	0.775 (0.454)	14.0	0.374	0.105	3.88 (0.71)	1.15 (0.52)	22.5	0.474	0.040
Work to Failure Contact (Nmm ⁻¹)	46.3 (10.8)	5.8 (5.71)	5.7	0.239	0.324	30.3 (8.51)	5.497 (6.11)	4.8	0.219	0.382
Work to Failure Platens (Nmm ⁻¹)	140.4 (22.6)	22.85 (12.24)	17.0	0.412	0.079	79.2 (19.2)	33.02 (13.82)	26.3	0.513	0.030

Appendix 11.1: Continued

Osteoporotic	Linear: Proximal Phalanx SOS (m s ⁻¹)					Log: Proximal Phalanx SOS (m s ⁻¹)			
Proximal Phalanx SOS (m s ⁻¹)	Mechanical Parameter = a + b(Proximal Phalanx SOS (m s ⁻¹))					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS (m s ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-41.34 (498.9)	0.182 (0.131)	11.5	0.339	0.184	-4.99	2.077	9.9	0.236
E- Contact (MPa)	710 (1933)	-0.061 (0.511)	0.1	-0.030	0.907	0.177	0.669	0.1	0.900
ε _{Yield} Platens (%)	-1.45 (2.38)	0.00075 (0.00062)	8.2	0.286	0.249	-4.53	1.30	4.1	0.434
ε _{Ult.} Strain Platens (%)	-2.13 (3.21)	0.0012 (0.00084)	10.7	0.327	0.185	-3.68	1.13	5.2	0.377
ε _{Yield} Contact (%)	0.36 (1.66)	0.00013 (0.0004)	0.6	0.078	0.766	-0.152	0.0172	0	0.993
ε _{Ult.} Contact (%)	2.9 (5.93)	-0.0002 (0.00156)	0.1	-0.026	0.921	2.122	-0.505	0.3	0.842
σ _{Yield} (MPa)	-12.7 (10.7)	0.0044 (0.0028)	11.8	0.344	0.138	-9.37	2.77	4.7	0.373
σ _{Ult.} (MPa)	-15.7 (12.44)	0.0054 (0.0033)	13.1	0.362	0.116	-9.055	2.709	5.7	0.326
Work to Failure Contact (Nmm ⁻¹)	-115 (144.2)	0.0397 (0.0379)	5.7	0.240	0.309	-3.27	1.31	0.4	0.790
Work to Failure Platens (Nmm ⁻¹)	-527.3 (331.6)	0.1664 (0.087)	17.7	0.421	0.073	-11.61	3.784	7.5	0.256

	Linear: Proximal Phalanx T-score					Linear: Proximal Phalanx Z-score				
Osteoporotic	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	321.3 (37.21)	27.78 (19.6)	11.8	0.344	0.177	260.2 (33.68)	22.22 (23.5)	6.0	0.245	0.360
E- Contact (MPa)	471.7 (155.7)	-5.66 (76.16)	0	-0.019	0.942	528 (106.5)	-61 (103.1)	2.3	-0.151	0.563
ε _{Yield} Platens (%)	1.57 (0.185)	0.116 (0.093)	8.9	0.298	0.230	1.31 (0.149)	0.128 (0.11)	8.4	0.289	0.260
ε _{Ult.} Strain Platens (%)	2.59 (0.25)	0.178 (0.126)	11.1	0.333	0.177	2.09 (0.192)	0.237 (0.14)	16.0	0.401	0.111
ε _{Yield} Contact (%)	0.887 (0.133)	0.012 (0.065)	0.2	0.046	0.862	0.838 (0.103)	0.044 (0.08)	2.1	0.146	0.589
ε _{Ult.} Contact (%)	2.245 (0.474)	-0.038 (0.233)	0.2	-0.042	0.872	2.07 (0.277)	0.066 (0.215)	0.7	0.081	0.765
σ _{Yield} (MPa)	4.885 (0.821)	0.64 (0.421)	11.4	0.337	0.146	3.32 (0.654)	0.742 (0.491)	11.8	0.344	0.149
σ _{Ult.} (MPa)	6.01 (0.956)	0.782 (0.49)	12.4	0.352	0.128	3.97 (0.756)	0.97 (0.568)	14.7	0.383	0.106
Work to Failure Contact (Nmm ⁻¹)	44.92 (11.08)	5.572 (5.681)	5.1	0.225	0.340	28.6 (8.15)	6.06 (6.11)	5.5	0.234	0.335
Work to Failure Platens (Nmm ⁻¹)	143.7 (25.6)	24.3 (13.1)	16.9	0.411	0.080	79.37 (20.44)	20.44 (15)	20.4	0.452	0.060

Appendix 11.1: Continued

Osteoporotic	Linear: Mid-Shaft Tibia SOS (m s^{-1})					Log: Mid-Shaft Tibia SOS (m s^{-1})			
	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia SOS (m s}^{-1}\text{)})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Mid-Shaft Tibia SOS (m s}^{-1}\text{)})$			
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	p - value
E- Platens (MPa)	-1146.1 (512.2)	0.367 (0.132)	34.1	0.584	0.014	-10.53	3.61	17.1	0.112
E- Contact (MPa)	-2963 (1778)	0.88 (0.459)	19.7	0.444	0.074	-40.96	12.12	27.4	0.037
ϵ_{Yield} Platens (%)	-0.014 (3.47)	0.00036 (0.0009)	1.1	0.105	0.688	-4.61	1.33	2.8	0.562
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	0.29 (4.68)	0.00053 (0.0012)	1.3	0.113	0.666	-2.02	0.668	1.1	0.695
ϵ_{Yield} Contact (%)	3.14 (2.22)	-0.0006 (0.0006)	6.9	-0.26	0.327	10.81	-3.03	9.2	0.253
$\epsilon_{\text{Ult.}}$ Contact (%)	8.065 (8.187)	-0.0015 (0.0021)	3.4	-0.18	0.496	8.80	-2.36	3.3	0.499
σ_{Yield} (MPa)	-22.2 (12.21)	0.0067 (0.0032)	21.1	0.459	0.048	-26.34	7.49	24.1	0.038
$\sigma_{\text{Ult.}}$ (MPa)	-26.18 (14.31)	0.00796 (0.0037)	21.5	0.464	0.045	-21.06	6.04	19.8	0.064
Work to Failure Contact (Nmm^{-1})	2.6 (181.5)	0.0088 (0.0468)	0.2	0.045	0.854	-9.49	3.03	1.6	0.610
Work to Failure Platens (Nmm^{-1})	-429.4 (442.2)	0.138 (0.114)	8.4	0.290	0.243	-15.78	4.934	8.7	0.234

	Linear: Mid-Shaft Tibia T-score					Linear: Mid-Shaft Tibia Z-score				
Osteoporotic	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia T-score})$					Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia Z-score})$				
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	r	p - value
E- Platens (MPa)	307.8 (20.24)	60.9 (17.1)	45.9	0.678	0.003	204.2 (34.73)	58.5 (20.87)	36.0	0.600	0.014
E- Contact (MPa)	512.7 (82.1)	117.9 (66.4)	17.4	0.417	0.096	345.4 (122.9)	96.31 (80.42)	9.3	0.305	0.251
ϵ_{Yield} Platens (%)	1.41 (0.133)	-0.001 (0.14)	0	-0.002	0.995	1.371 (0.253)	0.039 (0.149)	0.5	0.070	0.798
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	2.368 (0.179)	0.061 (0.188)	0.7	0.083	0.751	2.18 (0.335)	0.086 (0.198)	1.3	0.116	0.668
ϵ_{Yield} Contact (%)	0.878 (0.0866)	-0.04 (0.093)	1.3	-0.12	0.671	0.813 (0.168)	0.053 (0.098)	2.2	0.150	0.594
$\epsilon_{\text{Ult.}}$ Contact (%)	2.34 (0.316)	-0.071 (0.339)	0.3	-0.06	0.838	2.179 (0.462)	-0.016 (0.268)	0	-0.02	0.954
σ_{Yield} (MPa)	4.34 (0.523)	1.02 (0.43)	24.8	0.498	0.030	2.34 (0.754)	1.21 (0.469)	29.5	0.543	0.020
$\sigma_{\text{Ult.}}$ (MPa)	5.34 (0.61)	1.23 (0.501)	26	0.510	0.026	2.91 (0.889)	1.421 (0.552)	29.3	0.541	0.020
Work to Failure Contact (Nmm^{-1})	37.25 (7.96)	1.32 (6.55)	0.2	0.049	0.843	34.31 (10.94)	-0.404 (6.797)	0	-0.02	0.953
Work to Failure Platens (Nmm^{-1})	115.4 (18.75)	20.96 (16.16)	9.5	0.308	0.213	70.21 (29.38)	26.21 (17.73)	12.7	0.357	0.160

Appendix 11.1: Continued

	Linear: Calcaneal BUA (dB MHz ⁻¹)					Log: Calcaneal BUA (dB MHz ⁻¹)			
Osteoporotic	Mechanical Parameter = a + b(Calcaneal BUA (dB MHz ⁻¹))					log(Mechanical Parameter) = a + b log(Calcaneal BUA (dB MHz ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	P-value
E- Platens (MPa)	165 (70)	2.29 (1.36)	15.2	0.390	0.110	2.013	0.26	15.2	0.121
E- Contact (MPa)	86 (231.4)	8.35 (4.61)	17	0.412	0.089	1.12	0.886	22.6	0.054
ε _{Yield} Platens (%)	0.845 (0.319)	0.0113 (0.0063)	15.9	0.399	0.090	-0.323	0.28	19.3	0.068
ε _{Ult.} Strain Platens (%)	1.83 (0.464)	0.0109 (0.0092)	7.6	0.276	0.252	0.151	0.135	7.3	0.278
ε _{Yield} Contact (%)	1.142 (0.238)	-0.0056 (0.0046)	9	-0.30	0.243	0.344	-0.264	11.6	0.180
ε _{Ult.} Contact (%)	2.86 (0.876)	-0.011 (0.017)	2.9	-0.17	0.514	0.693	-0.229	5.5	0.365
σ _{Yield} (MPa)	1.08 (1.416)	0.0579 (0.0285)	17.9	0.423	0.056	-0.257	0.48	0.095	0.445
σ _{Ult.} (MPa)	1.554 (1.659)	0.0669 (0.033)	17.5	0.418	0.059	-0.095	0.445	14.8	0.093
Work to Failure Contact (Nmm ⁻¹)	27.74 (21.59)	0.177 (0.427)	0.9	0.097	0.684	0.936	0.284	1.8	0.568
Work to Failure Platens (Nmm ⁻¹)	33.78 (48.23)	1.479 (0.956)	11.7	0.343	0.139	1.04	0.546	15.4	0.087

	Linear: Calcaneal BUA T-score					Linear: Calcaneal Z-score				
Osteoporotic	Mechanical Parameter = a + b(Calcaneal BUA T-score)					Mechanical Parameter = a + b(Calcaneal BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	371.1 (59.5)	38.24 (22.4)	15.4	0.392	0.108	298.3 (27.9)	29.6 (22.1)	10.1	0.318	0.199
E- Contact (MPa)	857.4 (206.5)	148.1 (75.7)	19.3	0.439	0.068	582.1 (100.4)	133.34 (84.04)	13.6	0.369	0.132
ε _{Yield} Platens (%)	1.86 (0.285)	0.188 (0.105)	15.8	0.397	0.092	1.52 (0.131)	0.175 (0.103)	14.6	0.382	0.107
ε _{Ult.} Strain Platens (%)	2.787 (0.415)	0.176 (0.153)	7.2	0.267	0.268	2.46 (0.191)	0.15 (0.15)	5.6	0.236	0.330
ε _{Yield} Contact (%)	0.627 (0.204)	-0.098 (0.077)	9.8	-0.313	0.220	0.816 (0.097)	-0.077 (0.084)	5.3	-0.231	0.373
ε _{Ult.} Contact (%)	1.81 (0.752)	-0.201 (0.283)	3.3	-0.181	0.488	2.22 (0.354)	-0.121 (0.304)	1.0	-0.102	0.696
σ _{Yield} (MPa)	6.35 (1.284)	0.995 (0.47)	19.1	0.437	0.048	4.55 (0.579)	0.948 (0.458)	18.4	0.429	0.052
σ _{Ult.} (MPa)	7.64 (1.51)	1.146 (0.551)	18.5	0.431	0.051	5.58 (0.676)	1.112 (0.535)	18.5	0.431	0.051
Work to Failure Contact (Nmm ⁻¹)	43.48 (19.04)	2.90 (7.113)	0.9	0.096	0.688	38.0 (8.51)	2.59 (7.49)	0.7	0.081	0.734
Work to Failure Platens (Nmm ⁻¹)	167.2 (42.78)	24.95 (15.9)	12	0.347	0.134	122.7 (19.1)	24.5 (15.32)	12.4	0.352	0.128

Appendix 11.1: Continued

Osteoporotic	Linear : Calcaneal VOS (m s ⁻¹)					Log: Calcaneal VOS (m s ⁻¹)			
	Mechanical Parameter = a + b(Calcaneal VOS (m s ⁻¹))					log(Mechanical Parameter) = a + b log(Calcaneal VOS (m s ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-2320 (1187)	1.674 (0.765)	23.1	0.480	0.044	-28.27	9.63	30.3	0.022
E- Contact (MPa)	-3039 (4430)	2.28 (2.87)	3.8	0.195	0.438	-52.92	17.4	13.9	0.141
ε _{Yield} Platens (%)	-12.27 (4.92)	0.0088 (0.0032)	31.2	0.559	0.013	-25.5	8.038	25.2	0.034
ε _{Ult.} Strain Platens (%)	-13.37 (7.29)	0.0102 (0.0047)	21.5	0.463	0.046	-14.72	4.73	14.3	0.122
ε _{Yield} Contact (%)	0.23 (4.19)	0.0004 (0.0027)	0.2	0.039	0.881	-4.65	1.43	0.6	0.775
ε _{Ult.} Contact (%)	1.61 (14.93)	0.00045 (0.0096)	0	0.012	0.964	-2.06	0.743	0.1	0.906
σ _{Yield} (MPa)	-55.98 (23.18)	0.0387 (0.015)	25.9	0.509	0.018	-43.06	13.67	18.8	0.056
σ _{Ult.} (MPa)	-64.7 (27.15)	0.0449 (0.0176)	25.6	0.506	0.019	-38.94	12.41	19.6	0.050
Work to Failure Contact (Nmm ⁻¹)	-272.1 (361.4)	0.1992 (0.234)	3.9	0.197	0.405	-42.6	13.8	7.4	0.246
Work to Failure Platens (Nmm ⁻¹)	-1795.1 (752.9)	1.228 (0.486)	26.1	0.511	0.021	-51.24	16.67	24.5	0.027

Osteoporotic	Linear: Calcaneal VOS T-score					Linear: Calcaneal VOS Z-score				
	Mechanical Parameter = a + b(Calcaneal VOS T-score)					Mechanical Parameter = a + b(Calcaneal VOS Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	529.6 (117.2)	71.96 (32.86)	23.1	0.480	0.044	337.1 (42.06)	56.13 (33.38)	15.0	0.388	0.112
E- Contact (MPa)	838.2 (456.9)	97.8 (123.1)	3.8	0.195	0.439	613 (167.5)	107.4 (119.2)	4.8	0.220	0.381
ε _{Yield} Platens (%)	2.751 (0.499)	0.38 (0.136)	31.4	0.560	0.013	1.71 (0.197)	0.281 (0.147)	17.7	0.421	0.073
ε _{Ult.} Strain Platens (%)	3.916 (0.74)	0.437 (0.202)	21.6	0.464	0.045	2.753 (0.279)	0.356 (0.207)	14.8	0.385	0.104
ε _{Yield} Contact (%)	0.933 (0.422)	0.018 (0.116)	0.2	0.041	0.877	0.808 (0.152)	-0.053 (0.114)	1.4	-0.12	0.648
ε _{Ult.} Contact (%)	2.38 (1.5)	0.0195 (0.414)	0	0.012	0.963	2.292 (0.544)	-0.013 (0.408)	0	-0.01	0.976
σ _{Yield} (MPa)	9.85 (2.375)	1.664 (0.644)	26.0	0.510	0.018	5.33 (0.912)	1.277 (0.663)	16.3	0.404	0.069
σ _{Ult.} (MPa)	11.71 (2.78)	1.931 (0.754)	25.6	0.506	0.019	6.54 (1.059)	1.541 (0.77)	17.4	0.417	0.060
Work to Failure Contact (Nmm ⁻¹)	67.02 (36.62)	8.58 (10.03)	3.9	0.198	0.404	38.39 (13.25)	1.88 (9.854)	0.2	0.045	0.851
Work to Failure Platens (Nmm ⁻¹)	294.5 (76.4)	52.83 (20.89)	26.2	0.512	0.021	147.9 (29.63)	37.81 (22.18)	13.9	0.373	0.105

Appendix 11.2: Osteoarthritic Samples

Age Osteoarthritic	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	R ² (%)	r	p - value	a	b	R ² (%)	p - value
E- Platens (MPa)	1381 (1020)	-14.37 (15.16)	13.0	-0.361	0.380	6.236	-2.01	9.3	0.463
E- Contact (MPa)	2431 (1735)	-28.46 (25.77)	16.9	-0.411	0.312	8.783	-3.375	14.6	0.350
ϵ_{Yield} Platens (%)	3.762 (1.932)	-0.033 (0.0287)	18.3	-0.428	0.290	2.624	-1.345	14.3	0.357
$\epsilon_{Ult.}$ Strain Platens (%)	13.02 (6.84)	-0.152 (0.102)	27.1	-0.520	0.186	5.766	-2.94	23.0	0.230
ϵ_{Yield} Contact (%)	3.786 (1.782)	-0.0356 (0.0263)	26.8	-0.517	0.234	3.785	-2.003	26.7	0.235
$\epsilon_{Ult.}$ Contact (%)	9.06 (10.66)	-0.067 (0.157)	3.5	-0.187	0.688	1.904	-0.707	1.3	0.806
σ_{Yield} (MPa)	27.42 (12.56)	-0.326 (0.187)	33.8	-0.581	0.131	7.83	-3.915	31.2	0.150
$\sigma_{Ult.}$ (MPa)	40.36 (19.70)	-0.498 (0.293)	32.6	-0.571	0.140	9.1	-4.57	30.8	0.153
Work to Failure Platens (Nmm ⁻¹)	741.7 (559)	-9.375 (8.247)	20.5	-0.453	0.307	9.06	-3.962	9.6	0.499
Work to Failure Contact (Nmm ⁻¹)	2239 (1198)	-29.85 (17.80)	31.9	-0.565	0.144	15.97	-7.588	31.6	0.147

Appendix 11.2: Continued

Osteoarthritic	Linear: Distal Radius SOS (m s^{-1})					Log: Distal Radius SOS (m s^{-1})			
	Mechanical Parameter = $a + b(\text{Distal Radius SOS (m s}^{-1}\text{)})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Distal Radius SOS (m s}^{-1}\text{)})$			
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	p - value
E- Platens (MPa)	-581 (2736)	0.246 (0.673)	2.2	0.147	0.728	-8.961	3.195	3.7	0.648
E- Contact (MPa)	-421 (4796)	0.232 (1.18)	0.6	0.08	0.851	-13.07	4.35	3.8	0.642
ϵ_{Yield} Platens (%)	-7.30 (4.03)	0.0022 (0.001)	44.5	0.667	0.071	-20.22	5.65	39.7	0.094
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	-41.57 (8.98)	0.011 (0.002)	80.3	0.896	0.003	-48.96	13.68	78.6	0.003
ϵ_{Yield} Contact (%)	-3.71 (4.96)	0.00125 (0.0012)	17.4	0.417	0.351	-16.07	4.485	19.4	0.322
$\epsilon_{\text{Ult.}}$ Contact (%)	-30.35 (23.78)	0.0086 (0.0058)	30.1	0.549	0.202	-26.11	7.401	21.0	0.302
σ_{Yield} (MPa)	59.9 (28.42)	0.0161 (0.007)	46.9	0.685	0.061	-37.22	10.5	35.4	0.120
$\sigma_{\text{Ult.}}$ (MPa)	-104.7 (40)	0.0275 (0.0098)	56.5	0.752	0.032	-48.53	13.66	43.3	0.076
Work to Failure Contact (Nmm^{-1})	-2584 (1117)	0.66 (0.274)	53.8	0.733	0.061	-76.82	21.781	42.1	0.115
Work to Failure Platens (Nmm^{-1})	-7378 (1951)	1.874 (0.48)	71.8	0.847	0.008	-94.35	26.73	61.9	0.020

Osteoarthritic	Linear: Distal Radius T-score					Linear: Distal Radius Z-score				
	Mechanical Parameter = $a + b(\text{Distal Radius T-score})$					Mechanical Parameter = $a + b(\text{Distal Radius Z-score})$				
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	r	p - value
E- Platens (MPa)	415.5 (92.7)	-2 (66.67)	0	-0.012	0.977	402.1 (85.8)	51.83 (98.46)	4.4	0.21	0.617
E- Contact (MPa)	512.8 (161.2)	-12.6 (115.9)	0.2	-0.044	0.917	509.4 (152)	39.6 (174.4)	0.8	0.092	0.828
ϵ_{Yield} Platens (%)	1.665 (0.129)	0.224 (0.093)	49.1	0.701	0.053	1.44 (0.136)	0.295 (0.156)	37.5	0.613	0.106
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	3.479 (0.35)	1.02 (0.251)	73.5	0.857	0.007	2.4 (0.3)	1.6 (0.344)	78.2	0.884	0.004
ϵ_{Yield} Contact (%)	1.413 (0.167)	0.076 (0.136)	5.9	0.243	0.6	1.29 (0.147)	0.249 (0.16)	32.6	0.571	0.18
$\epsilon_{\text{Ult.}}$ Contact (%)	4.85 (0.779)	0.81 (0.632)	24.7	0.497	0.256	4.03 (0.762)	1.32 (0.829)	33.5	0.579	0.173
σ_{Yield} (MPa)	6.32 (1.08)	1.29 (0.78)	31.3	0.559	0.149	4.818 (0.861)	2.5 (0.988)	51.6	0.719	0.045
$\sigma_{\text{Ult.}}$ (MPa)	8.35 (1.56)	2.3 (1.12)	41.3	0.643	0.086	5.74 (1.21)	4.21 (1.39)	60.5	0.778	0.023
Work to Failure Contact (Nmm^{-1})	133.6 (37.74)	64.6 (30.62)	47.1	0.686	0.089	71.38 (36.2)	97.37 (39.38)	55.0	0.742	0.056
Work to Failure Platens (Nmm^{-1})	338.5 (78.85)	166.4 (56.7)	59	0.768	0.026	156.3 (59.2)	282 (67.91)	74.2	0.861	0.006

Appendix 11.2: Continued

Osteoarthritic	Linear: Proximal Phalanx SOS (m s^{-1})					Log: Proximal Phalanx SOS (m s^{-1})			
	Mechanical Parameter = $a + b(\text{Proximal Phalanx SOS (m s}^{-1}\text{)})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Proximal Phalanx SOS (m s}^{-1}\text{)})$			
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	p - value
E- Platens (MPa)	-1000 (3040)	0.366 (0.786)	3.5	0.187	0.658	-7.59	2.832	2.4	0.715
E- Contact (MPa)	-3414 (5138)	1.02 (1.328)	8.9	0.299	0.473	-41.17	12.21	24.7	0.210
ϵ_{Yield} Platens (%)	-9.73 (3.932)	0.0029 (0.001)	57.7	0.760	0.029	-26.30	7.38	55.4	0.034
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	-30.97 (17.95)	0.0087 (0.0046)	37.2	0.610	0.108	-40.35	11.36	44.3	0.071
ϵ_{Yield} Contact (%)	1.868 (5.704)	-0.00013 (0.0015)	0.1	-0.038	0.936	0.192	-0.0195	0	0.997
$\epsilon_{\text{Ult.}}$ Contact (%)	-7.69 (29.25)	0.0032 (0.0076)	3.4	0.184	0.693	-2.876	0.972	0.3	0.902
σ_{Yield} (MPa)	-55.46 (35.84)	0.0158 (0.0093)	32.6	0.571	0.140	-41.595	11.79	36.4	0.113
$\sigma_{\text{Ult.}}$ (MPa)	-85.28 (56.45)	0.028 (0.0146)	30.8	0.555	0.153	-47.898	13.56	35.0	0.123
Work to Failure Contact (Nmm^{-1})	-1654 (1527)	0.455 (0.394)	21.0	0.459	0.301	-45.25	13.12	14.2	0.404
Work to Failure Platens (Nmm^{-1})	-5053 (3494)	1.367 (0.903)	27.6	0.526	0.181	-82.28	23.53	39.3	0.096

Osteoarthritic	Linear: Proximal Phalanx T-score					Linear: Proximal Phalanx Z-score				
	Mechanical Parameter = $a + b(\text{Proximal Phalanx T-score})$					Mechanical Parameter = $a + b(\text{Proximal Phalanx Z-score})$				
Parameter	a	b	r^2 (%)	r	p - value	a	b	r^2 (%)	r	p - value
E- Platens (MPa)	4222.3 (131.8)	6.2 (113.7)	0	0.022	0.958	424 (70.99)	232.8 (155.3)	27.3	0.522	0.184
E- Contact (MPa)	582.5 (227.0)	68.8 (195.8)	2.0	0.142	0.737	535.2 (115.5)	468 (252.6)	36.4	0.603	0.113
ϵ_{Yield} Platens (%)	1.89 (0.17)	0.409 (0.147)	56.3	0.751	0.032	1.533 (0.158)	0.211 (0.345)	5.8	0.242	0.564
$\epsilon_{\text{Ult.}}$ Strain Platens (%)	3.97 (0.761)	1.252 (0.657)	37.7	0.614	0.105	2.85 (0.61)	0.27 (1.33)	0.7	0.083	0.846
ϵ_{Yield} Contact (%)	1.32 (0.24)	-0.079 (0.212)	2.7	-0.164	0.725	1.388 (0.17)	0.044 (0.392)	0.3	0.050	0.915
$\epsilon_{\text{Ult.}}$ Contact (%)	4.9 (1.246)	0.443 (1.104)	3.1	0.177	0.705	4.55 (0.886)	0.181 (2.05)	0.2	0.040	0.933
σ_{Yield} (MPa)	7.13 (1.66)	1.79 (1.43)	20.8	0.456	0.257	5.61 (1.06)	2.76 (2.31)	19.3	0.439	0.276
$\sigma_{\text{Ult.}}$ (MPa)	9.53 (2.55)	2.892 (2.197)	22.4	0.473	0.236	7.02 (1.73)	3.15 (3.78)	10.4	0.322	0.437
Work to Failure Contact (Nmm^{-1})	159.4 (66.3)	61.2 (58.7)	17.9	0.423	0.345	116.1 (49.68)	64.5 (114.7)	5.9	0.244	0.598
Work to Failure Platens (Nmm^{-1})	401.4 (151.7)	184.2 (130.9)	24.8	0.498	0.209	237.9 (109.6)	73.5 (239.7)	1.5	0.124	0.769

Appendix 11.2: Continued

Osteoarthritic	Mid-Shaft Tibia SOS (m s ⁻¹) Linear					Mid-Shaft Tibia SOS (m s ⁻¹) Power			
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS (m s ⁻¹))					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS (m s ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	681 (3058)	-0.067 (0.775)	0.1	-0.035	0.934	10.84	-2.3	1.6	0.764
E- Contact (MPa)	-2367 (5191)	0.732 (1.32)	4.9	0.222	0.598	-26.47	8.09	11.2	0.419
ε _{Yield} Platens (%)	-7.73 (4.635)	0.0023 (0.0012)	39.9	0.632	0.093	-20.38	5.71	34.2	0.128
ε _{Ult.} Strain Platens (%)	-29.1 (18.21)	0.0081 (0.0046)	33.8	0.582	0.130	-34.63	9.74	33.6	0.132
ε _{Yield} Contact (%)	3.2 (5.61)	-0.00046 (0.0014)	2.1	-0.143	0.759	6.828	-1.86	3.2	0.701
ε _{Ult.} Contact (%)	7.44 (29.49)	-0.00074 (0.0075)	0.2	-0.044	0.925	11.18	-2.938	3.2	0.703
σ _{Yield} (MPa)	-32.75 (40.22)	0.0097 (0.0102)	13.1	0.362	0.378	-16.84	4.872	6.4	0.545
σ _{Ult.} (MPa)	-60.46 (61.19)	0.0171 (0.0155)	16.8	0.410	0.313	-22.58	6.49	8.2	0.490
Work to Failure Contact (Nmm ⁻¹)	-1158 (1608)	0.321 (0.407)	11	0.332	0.467	-11	3.564	1.1	0.825
Work to Failure Platens (Nmm ⁻¹)	-4913 (3474)	1.31 (0.88)	26.8	0.518	0.189	-55.63	16.06	18.8	0.283

Osteoarthritic	Linear: Mid-Shaft Tibia T-score					Linear: Mid-Shaft Tibia Z-score				
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	424.8 (90.5)	22.2 (101.3)	0.8	0.089	0.834	403.3 (78.72)	86.13 (90.73)	13.1	0.361	0.379
E- Contact (MPa)	577.3 (147.4)	156.5 (165)	13.0	0.361	0.379	483.1 (119.9)	239.5 (138.2)	33.4	0.578	0.134
ε _{Yield} Platens (%)	1.625 (0.147)	0.271 (0.165)	31.1	0.557	0.151	1.515 (0.163)	0.075 (0.188)	2.6	0.16	0.704
ε _{Ult.} Strain Platens (%)	3.196 (0.564)	0.968 (0.631)	28.2	0.531	0.176	2.80 (0.61)	0.282 (0.703)	2.6	0.161	0.703
ε _{Yield} Contact (%)	1.37 (0.178)	-0.035 (0.187)	0.7	-0.084	0.858	1.384 (0.16)	0.093 (0.207)	3.9	0.197	0.672
ε _{Ult.} Contact (%)	4.48 (0.929)	-0.14 (0.976)	0.4	-0.064	0.892	4.52 (0.835)	-0.484 (1.078)	3.9	-0.197	0.672
σ _{Yield} (MPa)	6.04 (1.172)	1.423 (1.31)	16.4	0.405	0.320	5.34 (1.121)	1.132 (1.292)	11.3	0.337	0.415
σ _{Ult.} (MPa)	7.776 (1.798)	2.35 (2.012)	18.6	0.431	0.287	6.686 (1.771)	1.519 (2.041)	8.5	0.291	0.485
Work to Failure Contact (Nmm ⁻¹)	124.4 (50.73)	41.93 (53.29)	11	0.332	0.467	108.6 (48.26)	27.37 (62.3)	3.7	0.193	0.679
Work to Failure Platens (Nmm ⁻¹)	296 (104.1)	166.9 (116.5)	25.5	0.505	0.202	223.2 (108.5)	79.4 (125)	6.3	0.251	0.549

Appendix 11.2: Continued

Osteoarthritic	Linear: Calcaneal BUA (dB MHz ⁻¹)					Log: Calcaneal BUA (dB MHz ⁻¹)			
	Mechanical Parameter = a + b(Calcaneal BUA (dB MHz ⁻¹))					log(Mechanical Parameter) = a + b log(Calcaneal BUA (dB MHz ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - values
E- Platens (MPa)	911.6 (738.6)	-6.427 (9.536)	7.0	-0.265	0.525	4.501	-1.026	5.1	0.592
E- Contact (MPa)	1867 (1213)	-17.48 (15.65)	17.2	-0.415	0.307	8.158	-2.94	23.2	0.227
ε _{Yield} Platens (%)	2.268 (1.466)	-0.0096 (0.019)	4.1	-0.203	0.629	1.189	-0.542	4.8	0.601
ε _{Ult.} Strain Platens (%)	10.54 (4.63)	-0.0999 (0.0598)	31.8	-0.564	0.146	4.585	-2.219	27.4	0.183
ε _{Yield} Contact (%)	1.095 (1.412)	0.0037 (0.0182)	0.8	0.091	0.845	-0.846	0.514	3.9	0.673
ε _{Ult.} Contact (%)	8.486 (7.171)	-0.051 (0.0923)	5.8	-0.241	0.603	1.987	-0.731	3.1	0.706
σ _{Yield} (MPa)	18.33 (9.44)	-0.166 (0.122)	23.7	-0.487	0.221	4.05	-1.788	13.6	0.369
σ _{Ult.} (MPa)	28.64 (14.23)	-0.282 (0.184)	28.2	-0.531	0.176	5.17	-2.34	16.9	0.311
Work to Failure Contact (Nmm ⁻¹)	570 (372.7)	-5.98 (4.795)	23.7	-0.487	0.268	7.822	-3.186	13.6	0.415
Work to Failure Platens (Nmm ⁻¹)	1742.5 (806.7)	-19.57 (10.41)	37.0	-0.609	0.109	11.28	-4.86	27.2	0.185

Osteoarthritic	Calcaneal BUA T-score					Calcaneal BUA Z-score				
	Mechanical Parameter = a + b(Calcaneal BUA T-score)					Mechanical Parameter = a + b(Calcaneal BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	337.6 (143.3)	-104.1 (156.4)	6.9	-0.262	0.530	416.7 (83.26)	0.1 (113.8)	0	0	0.999
E- Contact (MPa)	305.5 (235.7)	-282.9 (257.2)	16.8	-0.41	0.313	524.2 (143.4)	-68.8 (196.0)	2.0	-0.142	0.737
ε _{Yield} Platens (%)	1.41 (0.284)	-0.157 (0.31)	4.1	-0.202	0.632	1.541 (0.141)	-0.272 (0.193)	24.9	-0.499	0.208
ε _{Ult.} Strain Platens (%)	1.60 (0.898)	-1.637 (0.98)	31.7	-0.563	0.146	2.923 (0.423)	-1.467 (0.579)	51.7	-0.719	0.044
ε _{Yield} Contact (%)	1.427 (0.276)	0.0592 (0.298)	0.8	0.089	0.850	1.385 (0.161)	0.0895 (0.215)	3.3	0.183	0.695
ε _{Ult.} Contact (%)	3.902 (1.4)	-0.841 (1.511)	5.8	-0.242	0.602	4.514 (0.821)	-0.679 (1.01)	7.1	-0.266	0.564
σ _{Yield} (MPa)	3.458 (1.832)	-2.714 (1.999)	23.5	-0.485	0.223	5.612 (1.054)	-1.731 (1.442)	19.4	-0.440	0.275
σ _{Ult.} (MPa)	3.419 (2.763)	-4.61 (3.01)	28.1	-0.530	0.177	7.093 (1.56)	-3.2 (2.13)	27.5	-0.524	0.183
Work to Failure Contact (Nmm ⁻¹)	35.12 (72.8)	-97.77 (78.59)	23.6	-0.486	0.269	106.2 (42.0)	-76.7 (56.2)	27.1	-0.521	0.231
Work to Failure Platens (Nmm ⁻¹)	-8 (156.5)	-320.5 (170.7)	37.0	-0.608	0.110	248.6 (82.6)	-245.7 (113.0)	44.1	-0.664	0.073

Appendix 11.2: Continued

Osteoarthritic	Linear: Calcaneal VOS (m s ⁻¹)					Log: Calcaneal VOS (m s ⁻¹)			
	Mechanical Parameter = a + b(Calcaneal VOS (m s ⁻¹))					log(Mechanical Parameter) = a + b log(Calcaneal VOS (m s ⁻¹))			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-1903 (4879)	1.461 (3.072)	3.6	0.191	0.651	-8.365	3.416	1.3	0.784
E- Contact (MPa)	-5764 (8257)	3.96 (5.2)	8.8	0.297	0.475	-37.68	12.59	10.2	0.440
ε _{Yield} Platens (%)	-0.937 (9.662)	0.0016 (0.0061)	1.1	0.104	0.807	-6.908	2.211	1.9	0.743
ε _{Ult.} Strain Platens (%)	27.83 (34.91)	-0.0157 (0.022)	7.9	-0.28	0.501	21.51	-6.593	5.8	0.565
ε _{Yield} Contact (%)	3.264(9.948)	-0.0012 (0.0063)	0.7	-0.084	0.857	4.803	-1.463	0.6	0.866
ε _{Ult.} Contact (%)	45.51(48.7)	-0.0259 (0.0308)	12.4	-0.352	0.438	35.55	-10.92	13.9	0.410
σ _{Yield} (MPa)	3.91(70.1)	0.001 (0.044)	0	0.009	0.982	-16.37	5.327	2.9	0.687
σ _{Ult.} (MPa)	34.4 (108.4)	-0.0173 (0.0683)	1.1	-0.103	0.809	-6.715	2.334	0.4	0.881
Work to Failure Contact (Nmm ⁻¹)	1442 (2946)	-0.842 (1.86)	3.9	-0.198	0.670	40.73	-12.16	4.0	0.667
Work to Failure Platens (Nmm ⁻¹)	4554 (6357)	-2.72 (4.003)	7.1	-0.267	0.522	18.88	-5.236	0.8	0.838

Osteoarthritic	Calcaneal VOS T-score					Calcaneal VOS Z-score				
	Mechanical Parameter = a + b(Calcaneal VOS T-score)					Mechanical Parameter = a + b(Calcaneal VOS Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	283.3 (359.7)	62.7 (132.0)	3.6	0.19	0.651	417.2 (115.2)	1.0 (150.4)	0.995	0.003	0.995
E- Contact (MPa)	971.6 (608.8)	169.9 (223.3)	8.8	0.297	0.476	558.3 (199.1)	71.2 (260)	0.793	0.111	0.793
ε _{Yield} Platens (%)	1.702 (0.712)	0.066 (0.261)	1.1	0.103	0.808	1.578 (0.223)	0.0981 (0.291)	1.9	0.136	0.748
ε _{Ult.} Strain Platens (%)	1.047 (2.574)	-0.677 (0.944)	7.9	-0.281	0.5	2.40 (0.8)	-0.843 (1.045)	9.8	-0.313	0.451
ε _{Yield} Contact (%)	1.242 (0.76)	-0.051 (0.27)	0.7	-0.085	0.857	1.285 (0.221)	-0.172 (0.272)	7.4	-0.272	0.556
ε _{Ult.} Contact (%)	1.474 (3.718)	-1.112 (1.321)	12.4	-0.352	0.438	3.835 (1.114)	-1.217 (1.368)	13.7	-0.37	0.415
σ _{Yield} (MPa)	5.63 (5.168)	0.042 (1.896)	0	0.009	0.983	5.171 (1.611)	-0.659 (2.104)	1.6	-0.127	0.765
σ _{Ult.} (MPa)	4.942 (7.992)	-0.746 (2.932)	1.1	-0.103	0.808	5.989 (2.464)	-1.761 (3.218)	4.8	-0.218	0.604
Work to Failure Contact (Nmm ⁻¹)	8.6 (224.9)	-36.24 (79.88)	4	-0.199	0.669	79.42 (66.75)	-50.31 (82.01)	7.0	-0.25	0.566
Work to Failure Platens (Nmm ⁻¹)	-75.2 (468.6)	117.1 (171.9)	7.2	-0.268	0.521	144.9 (143.2)	-170.8 (187.0)	12.2	-0.349	0.396

Appendix 11.3: Osteoporotic and Osteoarthritic Samples Combined

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	861.7 (245.4)	-7.023 (3.225)	17.1	-0.413	0.040	4.72	-1.192	11.7	0.094
E- Contact (MPa)	720.4 (628.0)	-2.79 (8.254)	0.5	-0.070	0.738	3.64	-0.563	0.6	0.705
ε _{Yield} Platens (%)	2.561 (0.728)	-0.0145 (0.0095)	8.7	-0.296	0.142	1.578	-0.762	9.3	0.129
ε _{Ult.} Strain Platens (%)	5.44 (1.658)	-0.038 (0.0217)	11.3	-0.337	0.093	1.844	-0.778	8.0	0.161
ε _{Yield} Contact (%)	3.219 (0.6283)	-0.0288 (0.0082)	36.1	-0.601	0.002	3.608	-1.93	28.8	0.007
ε _{Ult.} Contact (%)	9.54 (3.031)	-0.0863 (0.0395)	17.8	-0.422	0.040	4.022	-1.93	15.6	0.056
σ _{Yield} (MPa)	13.83 (3.943)	-0.123 (0.0513)	18.1	-0.426	0.024	4.188	-1.922	14.0	0.050
σ _{Ult.} (MPa)	17.48 (5.338)	-0.157 (0.0695)	16.4	-0.405	0.033	3.784	-1.656	11.4	0.078
Work to Failure Contact (Nmm ⁻¹)	382.4 (111.5)	-4.259 (1.442)	25.9	-0.509	0.007	8.166	-3.534	14.6	0.049
Work to Failure Platens (Nmm ⁻¹)	840.1 (263.6)	-9.143 (3.431)	21.4	-0.463	0.013	7.02	-2.677	15.5	0.038

Appendix 11.3: Continued

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-890.3 (981.7)	0.304 (0.243)	6.7	0.258	0.223	-10.83	3.695	8.8	0.158
E- Contact (MPa)	-1272 (2264)	0.446 (0.562)	2.8	0.167	0.435	-18.40	5.83	5.0	0.295
ε _{Yield} Platens (%)	-5.75 (2.319)	0.00179 (0.00057)	29.8	0.546	0.005	-16.996	4.757	27.1	0.008
ε _{Ult.} Strain Platens (%)	-18.58 (4.78)	0.0053 (0.00119)	46.1	0.679	<0.001	-24.665	6.949	46.2	<0.001
ε _{Yield} Contact (%)	-2.125 (2.76)	0.0008 (0.00068)	5.8	0.242	0.267	-9.556	2.643	3.9	0.369
ε _{Ult.} Contact (%)	-10.98 (11.63)	0.00347 (0.00288)	6.4	0.254	0.242	-8.95	2.595	2.1	0.514
σ _{Yield} (MPa)	-38.19 (13.57)	0.0106 (0.0034)	28.4	0.533	0.004	-28.994	8.21	20.0	0.019
σ _{Ult.} (MPa)	-56.97 (17.59)	0.0155 (0.0044)	33.7	0.580	0.002	-31.50	8.93	26.7	0.006
Work to Failure Contact (Nmm ⁻¹)	-1118.3 (409.2)	0.2914 (0.1015)	25.6	0.506	0.008	-43.06	12.37	13.3	0.067
Work to Failure Platens (Nmm ⁻¹)	-3214.4 (901.9)	0.833 (0.224)	35.7	0.598	0.001	-49.83	14.38	33.6	0.002

OP + OA Compression	Linear Relationships					Linear Relationships				
	Mechanical Parameter = a + b(Distal Radius T-score)					Mechanical Parameter = a + b(Distal Radius Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	362.8 (38.44)	22.46 (23.37)	4.0	0.201	0.347	329.78 (37.46)	17.02 (29.55)	1.6	0.125	0.571
E- Contact (MPa)	565.6 (95.61)	33.51 (53.26)	1.8	0.133	0.536	501.6 (83.45)	56.86 (68.60)	3.2	0.178	0.416
ε _{Yield} Platens (%)	1.665 (0.0969)	0.157 (0.056)	25.8	0.508	0.010	1.36 (0.082)	0.224 (0.0661)	34.4	0.586	0.003
ε _{Ult.} Strain Platens (%)	3.12 (0.203)	0.465 (0.117)	40.9	0.640	0.001	2.257 (0.2027)	0.508 (0.163)	30.7	0.554	0.005
ε _{Yield} Contact (%)	1.102 (0.114)	0.0695 (0.0654)	5.1	0.226	0.300	1.024 (0.111)	0.0122 (0.085)	0.1	0.032	0.888
ε _{Ult.} Contact (%)	3.412 (0.475)	0.3661 (0.2723)	7.9	0.282	0.193	2.931 (0.452)	-0.045 (0.346)	0.1	-0.029	0.897
σ _{Yield} (MPa)	5.55 (0.5697)	0.867 (0.3301)	21.6	0.465	0.015	3.924 (0.533)	0.997 (0.425)	18.6	0.432	0.028
σ _{Ult.} (MPa)	7.129 (0.745)	1.283 (0.432)	26.1	0.511	0.006	4.686 (0.7123)	1.434 (0.569)	20.9	0.458	0.019
Work to Failure Contact (Nmm ⁻¹)	89.14 (16.72)	27.43 (9.616)	25.3	0.503	0.009	44.52 (17.54)	15.09 (13.73)	5.0	0.223	0.283
Work to Failure Platens (Nmm ⁻¹)	230.9 (37.38)	73.31 (21.66)	31.4	0.561	0.002	103.38 (38.42)	63.75 (30.67)	15.3	0.391	0.048

Appendix 11.3: Continued

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-639.2 (688.2)	0.254 (0.179)	8.4	0.289	0.170	-6.685	2.56	7.4	0.198
E- Contact (MPa)	-41 (1714)	0.1445 (0.45)	0.4	0.067	0.751	-6.741	2.605	1.7	0.539
ε _{Yield} Platens (%)	-1.763 (1.948)	0.00084 (0.00051)	10.7	0.328	0.110	-7.52	2.14	9.6	0.131
ε _{Ult.} Strain Platens (%)	-5.09 (4.51)	0.00199 (0.00118)	11.1	0.333	0.103	-8.65	2.52	11.0	0.106
ε _{Yield} Contact (%)	-0.379 (1.911)	0.00037 (0.0005)	2.4	0.154	0.472	-3.743	1.037	1.2	0.606
ε _{Ult.} Contact (%)	-2.478 (8.146)	0.00142 (0.0021)	2.0	0.141	0.511	-3.597	1.116	0.8	0.682
σ _{Yield} (MPa)	-19.1 (10.51)	0.0062 (0.0027)	16.8	0.410	0.034	-15.10	4.379	9.8	0.112
σ _{Ult.} (MPa)	-25.78 (14.17)	0.0082 (0.0037)	16.4	0.405	0.036	-15.11	4.408	10.8	0.094
Work to Failure Contact (Nmm ⁻¹)	-412.5 (309.5)	0.122 (0.081)	8.4	0.289	0.143	-14.414	4.446	3.3	0.364
Work to Failure Platens (Nmm ⁻¹)	-1265.8 (743.3)	0.3687 (0.1942)	12.6	0.355	0.069	-22.51	6.84	13.3	0.061

OP + OA Compression	Linear Relationships					Linear Relationships				
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	379.97 (45.20)	34.96 (26.48)	7.3	0.271	0.20	329.5 (36.81)	14.23 (30.80)	1.0	0.100	0.649
E- Contact (MPa)	527.5 (118.3)	12.22 (64.51)	0.2	0.039	0.851	510.45 (79.94)	21.63 (92.01)	0.3	0.050	0.816
ε _{Yield} Platens (%)	1.637 (0.128)	0.127 (0.074)	11.3	0.336	0.101	1.447 (0.102)	0.0757 (0.0862)	3.4	0.184	0.389
ε _{Ult.} Strain Platens (%)	2.945 (0.294)	0.309 (0.171)	12.5	0.354	0.083	2.481 (0.243)	0.076 (0.206)	0.6	0.078	0.717
ε _{Yield} Contact (%)	1.0996 (0.131)	0.0589 (0.0723)	2.9	0.171	0.424	1.05 (0.0982)	-0.053 (0.0892)	1.7	-0.128	0.559
ε _{Ult.} Contact (%)	3.343 (0.557)	0.2798 (0.3063)	3.7	0.191	0.371	3.021 (0.396)	-0.364 (0.36)	4.7	-0.216	0.323
σ _{Yield} (MPa)	5.684 (0.707)	0.8703 (0.402)	15.8	0.398	0.040	4.291 (0.57)	0.469 (0.491)	3.7	0.192	0.349
σ _{Ult.} (MPa)	7.165 (0.951)	1.167 (0.541)	15.7	0.396	0.041	5.27 (0.570)	0.57 (0.667)	3.0	0.172	0.401
Work to Failure Contact (Nmm ⁻¹)	81.92 (20.62)	19.68 (11.62)	10.3	0.321	0.103	56.97 (16.30)	-5.77 (14.04)	0.7	-0.084	0.685
Work to Failure Platens (Nmm ⁻¹)	221.4 (49.26)	56.72 (28.0)	14.1	0.375	0.054	142.2 (40.31)	4.90 (34.70)	0.1	0.029	0.889

Appendix 11.3: Continued

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-622.4 (887.2)	0.245 (0.226)	5.0	0.224	0.292	-7.724	2.843	5.8	0.259
E- Contact (MPa)	-2552 (1862)	0.7772 (0.4761)	10.8	0.329	0.117	-38.24	11.362	24.2	0.015
ε _{Yield} Platens (%)	-1.40 (2.59)	0.00074 (0.0007)	5.4	0.231	0.277	-8.15	2.311	7.1	0.209
ε _{Ult.} Strain Platens (%)	-6.00 (5.875)	0.0022 (0.0015)	8.8	0.297	0.158	-9.145	2.652	7.8	0.185
ε _{Yield} Contact (%)	2.3 (2.51)	-0.0003 (0.0006)	1.2	-0.109	0.621	6.854	-1.913	2.7	0.457
ε _{Ult.} Contact (%)	4.25 (10.91)	-0.00032 (0.0028)	0.1	-0.025	0.911	4.999	-1.277	0.6	0.721
σ _{Yield} (MPa)	-23.47 (12.66)	0.0072 (0.0032)	16.9	0.411	0.037	-26.72	7.60	21.7	0.017
σ _{Ult.} (MPa)	-31.54 (17.11)	0.0095 (0.0044)	16.4	0.405	0.040	-22.873	6.556	17.6	0.033
Work to Failure Contact (Nmm ⁻¹)	-351.1 (369.7)	0.104 (0.095)	4.8	0.219	0.282	-17.771	5.371	3.7	0.347
Work to Failure Platens (Nmm ⁻¹)	-1463.4 (902.4)	0.4121 (0.231)	11.7	0.342	0.087	-25.576	7.676	12.2	0.080

OP + OA Compression	Linear Relationships					Linear Relationships				
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)		p - value
E- Platens (MPa)	347.2 (32.41)	37.23 (34.25)	5.1	0.226	0.289	330.1 (44.43)	7.33 (30.24)	0.3	0.053	0.811
E- Contact (MPa)	533.24 (71.15)	119.7 (71.84)	11.2	0.335	0.110	423.12 (91.83)	80.02 (67.41)	6.3	0.251	0.248
ε _{Yield} Platens (%)	1.50 (0.097)	0.0597 (0.102)	1.5	0.124	0.565	1.474 (0.127)	0.0287 (0.087)	0.5	0.072	0.744
ε _{Ult.} Strain Platens (%)	2.662 (0.218)	0.283 (0.23)	6.4	0.254	0.232	2.56 (0.3)	-0.0035 (0.204)	0	-0.004	0.986
ε _{Yield} Contact (%)	1.022 (0.0913)	-0.058 (0.097)	1.7	-0.129	0.559	1.136 (0.119)	-0.089 (0.0798)	5.8	0.242	0.279
ε _{Ult.} Contact (%)	2.966 (0.396)	-0.175 (0.423)	0.8	-0.090	0.683	3.607 (0.455)	-0.699 (0.306)	20.8	-0.456	0.033
σ _{Yield} (MPa)	4.89 (0.504)	1.01 (0.465)	16.4	0.405	0.040	4.03 (0.673)	0.52 (0.463)	5.2	0.228	0.273
σ _{Ult.} (MPa)	6.112 (0.6816)	1.342 (0.628)	16.0	0.400	0.043	5.012 (0.92)	0.584 (0.634)	3.6	0.189	0.366
Work to Failure Contact (Nmm ⁻¹)	61.14 (15.59)	10.80 (13.55)	2.6	0.161	0.433	64.99 (18.64)	-11.65 (13.07)	3.3	-0.183	0.382
Work to Failure Platens (Nmm ⁻¹)	168.3 (36.29)	53.23 (33.44)	9.5	0.309	0.125	143.42 (48.07)	3.24 (33.11)	0	0.020	0.923

Appendix 11.3: Continued

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(BUA Calcaneus dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA Calcaneus dB MHz ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	169.65 (87.48)	2.784 (1.42)	14.1	0.376	0.064	1.939	0.315	13.5	0.071
E- Contact (MPa)	317.1 (205)	3.39 (3.40)	4.1	0.204	0.329	1.534	0.613	12.8	0.080
ε _{Yield} Platens (%)	1.145 (0.254)	0.0056 (0.0042)	6.8	0.261	0.197	-0.236	12.9	12.9	0.072
ε _{Ult.} Strain Platens (%)	2.276 (0.605)	0.00487 (0.01)	1.0	0.099	0.631	0.218	0.095	1.9	0.498
ε _{Yield} Contact (%)	0.727 (0.255)	0.0051 (0.004)	6.2	0.249	0.241	-0.137	0.063	0.5	0.736
ε _{Ult.} Contact (%)	1.552 (1.075)	0.0246 (0.0178)	8.0	0.283	0.181	0.126	0.160	1.8	0.528
σ _{Yield} (MPa)	2.19 (1.39)	0.0397 (0.0234)	10.0	0.316	0.101	-0.257	0.486	14.2	0.048
σ _{Ult.} (MPa)	3.01 (1.891)	0.0443 (0.032)	6.9	0.263	0.176	-0.04	0.415	11.4	0.079
Work to Failure Contact (Nmm ⁻¹)	8.10 (40.88)	0.8421 (0.6951)	5.5	0.235	0.237	0.445	0.624	7.5	0.166
Work to Failure Platens (Nmm ⁻¹)	44.13 (97.80)	1.742 (1.646)	4.1	0.203	0.300	1.08	0.53	9.7	0.107

OP + OA Compression	Linear Relationships					Linear Relationships				
	Mechanical Parameter = a + b(BUA Calcaneus T-score)					Mechanical Parameter = a + b(BUA Calcaneus Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
E- Platens (MPa)	419.2 (53.42)	46.15 (23.66)	14.2	0.377	0.063	352.14 (31.89)	44.47 (27.80)	10.0	0.316	0.123
E- Contact (MPa)	629.1 (131.0)	60.54 (56.44)	4.8	0.218	0.295	553.7 (77.44)	86.16 (70.85)	6.0	0.246	0.236
ε _{Yield} Platens (%)	1.642 (0.16)	0.092 (0.07)	6.7	0.258	0.203	1.506 (0.0934)	0.844 (0.082)	4.2	0.206	0.313
ε _{Ult.} Strain Platens (%)	2.70 (0.380)	0.0756 (0.167)	0.9	0.092	0.654	2.517 (0.22)	-0.075 (0.193)	0.6	-0.079	0.702
ε _{Yield} Contact (%)	1.18 (0.162)	0.083 (0.071)	5.8	0.242	0.255	1.037 (0.097)	0.0391 (0.0913)	0.8	0.091	0.673
ε _{Ult.} Contact (%)	3.744 (0.681)	0.423 (0.298)	7.7	0.277	0.190	3.016 (0.413)	0.125 (0.389)	0.5	0.068	0.751
σ _{Yield} (MPa)	5.78 (0.903)	0.673 (0.388)	10.4	0.322	0.095	4.726 (0.524)	0.583 (0.467)	5.7	0.238	0.223
σ _{Ult.} (MPa)	6.997 (1.231)	0.748 (0.529)	7.1	0.267	0.170	5.768 (0.713)	0.531 (0.635)	2.6	0.162	0.411
Work to Failure Contact (Nmm ⁻¹)	83.34 (27.22)	13.89 (11.57)	5.5	0.234	0.241	54.65 (15.81)	-0.49 (15.07)	0	-0.006	0.975
Work to Failure Platens (Nmm ⁻¹)	199.96 (63.71)	28.84 (27.39)	4.1	0.202	0.302	142.67 (36.81)	1.38 (32.78)	0	0.008	0.967

Appendix 11.3: Continued

OP + OA Compression	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
E- Platens (MPa)	-2901 (1294)	2.0674 (0.8276)	21.3	0.462	0.020	-26.59	9.103	21.7	0.019
E- Contact (MPa)	-2575 (3092)	1.979 (1.983)	4.2	0.204	0.329	-36.78	12.33	11.1	0.103
ε _{Yield} Platens (%)	-6.09 (3.704)	0.0048 (0.00237)	14.8	0.385	0.052	-17.45	5.512	16.2	0.041
ε _{Ult.} Strain Platens (%)	-3.65 (9.18)	0.00397 (0.0059)	1.9	0.137	0.506	-6.29	2.09	1.9	0.50
ε _{Yield} Contact (%)	-4.33 (3.924)	0.0034 (0.00252)	7.8	0.279	0.186	-17.96	5.62	8.2	0.176
ε _{Ult.} Contact (%)	-13.11 (17.05)	0.0103 (0.011)	3.9	0.197	0.356	-17.098	5.481	4.2	0.334
σ _{Yield} (MPa)	-41.63 (20.30)	0.0295 (0.013)	16.5	0.407	0.032	-38.11	12.12	19.5	0.019
σ _{Ult.} (MPa)	-44.96 (28.08)	0.0324 (0.018)	11.1	0.332	0.084	-31.62	10.11	14.9	0.042
Work to Failure Contact (Nmm ⁻¹)	-659.8 (653.7)	0.459 (0.4197)	4.6	0.214	0.285	-49.76	16.06	10.1	0.106
Work to Failure Platens (Nmm ⁻¹)	-1602 (1478)	1.12 (0.9475)	5.1	0.226	0.248	-39.18	12.89	12.6	0.064

OP + OA Compression	Linear Relationships					Linear Relationships				
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)		p - value
E- Platens (MPa)	617.6 (117.9)	88.81 (35.54)	21.4	0.462	0.020	389.94 (47.09)	66.38 (41.66)	9.9	0.315	0.125
E- Contact (MPa)	792.2 (292)	84.84 (85.15)	4.1	0.203	0.329	596.7 (117.4)	86.57 (94.10)	3.5	0.188	0.367
ε _{Yield} Platens (%)	2.145 (0.343)	0.208 (0.102)	14.8	0.385	0.052	1.634 (0.135)	0.184 (0.116)	9.5	0.308	0.126
ε _{Ult.} Strain Platens (%)	3.112 (0.849)	0.171 (0.253)	1.9	0.137	0.505	2.653 (0.327)	0.107 (0.281)	0.6	0.077	0.707
ε _{Yield} Contact (%)	1.51 (0.369)	0.148 (0.108)	7.9	0.280	0.185	1.061 (0.144)	0.045 (0.1196)	0.6	0.079	0.712
ε _{Ult.} Contact (%)	4.43 (1.601)	0.4436 (0.469)	3.9	0.198	0.355	3.2 (0.611)	0.254 (0.508)	1.1	0.106	0.623
σ _{Yield} (MPa)	8.649 (1.911)	1.27 (0.559)	16.5	0.407	0.032	5.37 (0.781)	0.973 (0.651)	7.9	0.281	0.147
σ _{Ult.} (MPa)	10.12 (2.643)	1.391 (0.773)	11.1	0.333	0.084	6.50 (1.063)	1.036 (0.886)	5.0	0.224	0.253
Work to Failure Contact (Nmm ⁻¹)	121.45 (62.25)	19.74 (18.02)	4.6	0.214	0.284	63.50 (23.75)	8.59 (19.33)	0.8	0.088	0.661
Work to Failure Platens (Nmm ⁻¹)	301.9 (139.1)	48.09 (40.69)	5.1	0.226	0.248	169.68 (55.16)	28.55 (45.94)	1.5	0.121	0.540

Appendix 12: Osteoporotic Group Fracture Toughness Testing Results vs. Clinical QUS Regressions

Appendix 12.1: Osteoporotic Beams Ac

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.753 (0.188)	-0.0069 (0.0024)	12.5	-0.354	0.005	3.657	-2.331	9.8	0.014
Kc Pop Ins	1.051 (0.26)	-0.0095 (0.0033)	12.4	-0.352	0.005	3.653	-2.24	9.6	0.015
J-Integral PQ	-29.25 (26.40)	1.025 (0.332)	14.3	0.378	0.003	-1.445	1.654	20.0	<0.001
J-Integral Pop Ins	-18.0 (80.87)	2.367 (1.015)	8.6	0.293	0.023	0.332	0.988	6.3	0.054
GQ	749 (207.4)	-7.631 (2.61)	12.7	-0.356	0.005	8.776	-3.61	7.9	0.028
Gc Pop Ins	1495.8 (407.6)	-15.09 (5.118)	12.8	-0.358	0.005	8.769	-3.424	7.4	0.034

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.221 (0.577)	0.0001 (0.0001)	1.0	0.098	0.458	-9.017	2.29	1.0	0.445
Kc Pop Ins	-0.137 (0.8)	0.0001 (0.0002)	0.5	0.072	0.584	-4.901	1.194	0.3	0.683
J-Integral PQ	71.97 (80.38)	-0.0051 (0.0199)	0.1	-0.034	0.799	4.194	-0.695	0.4	0.641
J-Integral Pop Ins	318.6 (241.4)	-0.0371 (0.0598)	0.7	-0.082	0.537	4.873	-0.7398	0.4	0.645
GQ	-55.0 (641.4)	0.0496 (0.159)	0.2	0.041	0.756	-1.21	0.874	0	0.866
Gc Pop Ins	113 (1262)	0.047 (0.313)	0	0.020	0.882	7.023	-1.316	0.1	0.796

	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.241 (0.022)	0.028 (0.013)	7.4	0.272	0.035	0.233 (0.021)	-0.0226 (0.0153)	3.8	-0.194	0.144
Kc Pop Ins	0.343 (0.03)	0.035 (0.018)	6.0	0.245	0.06	0.339 (0.029)	-0.033 (0.021)	4.3	-0.208	0.116
J-Integral PQ	49.64 (3.097)	-1.63 (1.88)	1.3	-0.115	0.39	49.88 (2.97)	2.21 (2.17)	1.9	0.137	0.314
J-Integral Pop Ins	159.98 (9.187)	-7.97 (5.61)	3.4	-0.185	0.160	164.72 (8.51)	7.82 (6.19)	2.8	0.168	0.211
GQ	171.73 (24.26)	23.47 (14.79)	4.2	0.204	0.118	174.6 (23.03)	-29.33 (16.85)	5.1	-0.227	0.087
Gc Pop Ins	348.1 (47.92)	40.78 (29.22)	3.2	0.180	0.168	363.1 (45.1)	-60.97 (32.95)	5.8	-0.240	0.07

Appendix 12.1: Continued

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.099 (0.331)	0.00008 (0.00008)	1.5	0.122	0.376	-7.996	2.011	2.5	0.252	
Kc Pop Ins	-0.122 (0.462)	0.00011 (0.00012)	1.5	0.121	0.378	-6.952	1.767	2.0	0.304	
J-Integral PQ	80.15 (49.71)	-0.0072 (0.013)	0.6	-0.077	0.582	4.02	-0.648	1.0	0.481	
J-Integral Pop Ins	255.4 (146.2)	-0.0216 (0.0382)	0.6	-0.078	0.575	3.415	-0.336	0.2	0.731	
GQ	-72.4 (375.1)	0.055 (0.098)	0.6	0.076	0.579	-6.77	2.421	1.2	0.430	
Gc Pop Ins	-162.6 (737.3)	0.118 (0.193)	0.7	0.084	0.544	-4.682	1.933	0.8	0.525	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.229 (0.0242)	0.0227 (0.0127)	5.7	0.238	0.080	0.211 (0.021)	-0.012 (0.015)	1.4	-0.116	0.407
Kc Pop Ins	0.332 (0.0337)	0.0314 (0.0178)	5.6	0.236	0.083	0.307 (0.029)	-0.016 (0.02)	1.2	-0.110	0.432
J-Integral PQ	50.03 (3.68)	-1.87 (1.942)	1.8	-0.134	0.340	52.23 (3.13)	0.972 (2.245)	0.4	0.062	0.667
J-Integral Pop Ins	164.54 (10.82)	-6.02 (5.695)	2.1	-0.145	0.296	172.41 (8.771)	4.398 (6.21)	1.0	0.100	0.482
GQ	165.6 (27.52)	20.71 (14.49)	3.7	0.193	0.159	155.67 (23.17)	-18.99 (16.53)	2.5	-0.159	0.256
Gc Pop Ins	346.2 (54.03)	42.21 (28.46)	4.0	0.200	0.144	323.5 (45.53)	-35.09 (32.48)	2.2	-0.15	0.285

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.305 (0.237)	0.00013 (0.00006)	7.7	0.277	0.034	-10.44	2.688	7.2	0.040	
Kc Pop Ins	-0.349 (0.329)	0.00016 (0.00008)	6.4	0.253	0.053	-8.865	2.295	5.5	0.073	
J-Integral PQ	83.59 (34.4)	-0.0079 (0.0086)	1.5	-0.123	0.36	3.772	-0.577	1.4	0.384	
J-Integral Pop Ins	322.1 (102.3)	-0.038 (0.026)	3.8	-0.196	0.14	5.01	-0.778	2.1	0.277	
GQ	-242.8 (267.2)	0.0967 (0.067)	3.6	0.188	0.153	-10.998	3.591	4.3	0.113	
Gc Pop Ins	-385.9 (526.6)	0.171 (0.131)	2.9	0.170	0.199	-7.84	2.806	2.7	0.21	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.203 (0.0162)	0.0155 (0.0075)	6.9	0.263	0.044	0.206 (0.0243)	0.0036 (0.0098)	0.2	0.050	0.714
Kc Pop Ins	0.295 (0.0225)	0.0195 (0.0105)	5.7	0.239	0.068	0.303 (0.0335)	0.0029 (0.014)	0.1	0.028	0.833
J-Integral PQ	52.22 (2.38)	-0.79 (1.092)	0.9	-0.097	0.473	51.8 (3.476)	0.238 (1.385)	0.1	0.024	0.864
J-Integral Pop Ins	170.86 (7.01)	-4.184 (3.258)	2.9	-0.169	0.204	172.3 (10.02)	-0.18 (4.01)	0	-0.006	0.964
GQ	139.89 (18.26)	11.16 (8.496)	2.9	0.171	0.194	153.1 (26.93)	-3.03 (10.87)	0.1	-0.038	0.781
Gc Pop Ins	291.07 (35.97)	19.42 (16.74)	2.3	0.152	0.251	321.9 (52.74)	-8.93 (21.29)	0.3	-0.056	0.677

Appendix 12.1: Continued

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.0085 (0.065)	0.0036 (0.0012)	14.4	0.379	0.005	-2.151	0.796	14.8	0.004	
Kc Pop Ins	0.022 (0.091)	0.005 (0.0017)	14.6	0.382	0.004	-1.87	0.731	13.1	0.007	
J-Integral PQ	68.55 (10.32)	-0.308 (0.19)	5.0	-0.224	0.111	2.016	-0.189	3.2	0.205	
J-Integral Pop Ins	198.37 (31.70)	-0.49 (0.583)	1.4	-0.117	0.405	2.44	-0.136	1.4	0.403	
GQ	-41.51 (75.53)	3.366 (1.397)	10.0	0.317	0.020	0.031	1.094	9.2	0.026	
Gc Pop Ins	-70.4 (148.3)	6.765 (2.74)	10.5	0.324	0.017	0.592	0.964	7.3	0.048	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.331 (0.048)	0.061 (0.020)	14.9	0.385	0.004	0.198 (0.021)	0.005 (0.022)	0.1	0.032	0.821
Kc Pop Ins	0.477 (0.066)	0.086 (0.028)	15.2	0.390	0.004	0.291 (0.029)	0.01 (0.031)	0.2	0.044	0.750
J-Integral PQ	40.62 (7.44)	-5.27 (3.17)	5.2	-0.229	0.103	51.72 (3.09)	-1.05 (3.28)	0.2	-0.045	0.751
J-Integral Pop Ins	154.4 (22.86)	-8.18 (9.759)	1.4	-0.117	0.406	177.13 (9.087)	8.89 (9.86)	1.6	0.125	0.372
GQ	263.6 (55.16)	57.50 (23.31)	10.5	0.324	0.017	133.2 (23.5)	-3.46 (25.04)	0	-0.019	0.891
Gc Pop Ins	543.9 (108.2)	116.1 (45.73)	11.0	0.332	0.014	282.8 (46.22)	-3.37 (49.29)	0	-0.009	0.946

Osteoporotic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-2.18 (0.09)	0.0015 (0.0006)	11.5	0.339	0.011	-41.54	12.77	12.1	0.009	
Kc Pop Ins	-3.112 (1.255)	0.0022 (0.001)	12.2	0.349	0.009	-40.02	12.34	11.8	0.01	
J-Integral PQ	291.3 (141.2)	-0.154 (0.091)	5.3	-0.230	0.097	14.52	-4.02	4.5	0.129	
J-Integral Pop Ins	425 (426.7)	-0.162 (0.275)	0.7	-0.082	0.557	7.34	-1.61	0.6	0.571	
GQ	-2327 (1028)	1.586 (0.662)	9.8	0.313	0.020	-58.37	18.89	8.7	0.029	
Gc Pop Ins	-4712 (2015)	3.219 (1.297)	10.4	0.323	0.016	-55.31	18.04	8.1	0.035	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.425 (0.088)	0.066 (0.025)	11.5	0.339	0.011	0.248 (0.0297)	0.05 (0.025)	7.4	0.272	0.045
Kc Pop Ins	0.614 (0.122)	0.094 (0.035)	12.2	0.349	0.009	0.361 (0.041)	0.072 (0.034)	7.7	0.278	0.040
J-Integral PQ	29.86 (13.70)	-6.605 (3.909)	5.3	-0.230	0.097	49.88 (4.58)	-2.753 (3.83)	1.0	-0.100	0.475
J-Integral Pop Ins	149 (41.42)	-6.93 (11.81)	0.7	-0.081	0.560	171.5 (13.6)	-1.43 (11.45)	0	-0.017	0.901
GQ	372.9 (100.3)	68.24 (28.48)	9.8	0.313	0.020	185.32 (33.80)	48.14 (27.98)	5.3	0.230	0.091
Gc Pop Ins	766.8 (196.5)	138.51 (55.82)	10.4	0.323	0.016	385.13 (66.39)	96.80 (54.95)	5.5	0.235	0.084

Appendix 12.2: Osteoporotic Beams AL

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.0013 (0.217)	0.0021 (0.0026)	1.2	0.109	0.424	-2.89	1.06	1.3	0.409
Kc Pop Ins	0.2778 (0.284)	-0.00055 (0.0034)	0	-0.022	0.872	0.092	-0.422	0.2	0.717
J-Integral PQ	152.2 (60.38)	-0.745 (0.727)	1.9	-0.138	0.310	3.62	-0.886	2.7	0.231
J-Integral Pop Ins	805.5 (268.7)	-5.31 (3.23)	4.8	-0.218	0.107	5.533	-1.57	6.0	0.069
GQ	-135.2 (255.8)	3.017 (3.078)	1.7	0.132	0.331	-2.99	2.488	2.2	0.271
Gc Pop Ins	178.3 (438.6)	0.266 (5.277)	0	0.007	0.960	2.967	-0.472	0.1	0.817

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.696 (0.502)	-0.00014 (0.00012)	4.7	-0.218	0.266	18.23	-5.329	4.9	0.255
Kc Pop Ins	0.966 (0.692)	-0.00019 (0.00017)	4.6	-0.215	0.273	15	-4.376	4.3	0.292
J-Integral PQ	-11.8 (201.7)	0.0289 (0.05)	1.3	0.113	0.567	-2.269	1.186	1.4	0.552
J-Integral Pop Ins	-56 (1011)	0.1259 (0.2503)	1.0	0.098	0.619	-3.55	1.715	2.1	0.467
GQ	272.2 (447.4)	-0.0516 (0.111)	0.8	-0.091	0.645	30.08	-7.908	3.3	0.357
Gc Pop Ins	593.9 (925.7)	-0.111 (0.229)	0.9	-0.095	0.631	23.61	-6	2.5	0.426
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.112 (0.018)	-0.013 (0.012)	4.1	-0.204	0.299	0.129 (0.017)	-0.0057 (0.0148)	0.6	-0.079 0.701
Kc Pop Ins	0.175 (0.025)	-0.0165 (0.0165)	3.7	-0.192	0.327	0.1995 (0.0231)	-0.01 (0.0199)	1.1	-0.105 0.608
J-Integral PQ	105.36 (7.24)	0.382 (4.82)	0	0.016	0.937	98.24 (6.674)	6.334 (5.765)	4.8	0.219 0.283
J-Integral Pop Ins	448.46 (36.21)	-3.64 (24.11)	0.1	-0.030	0.881	423.4 (34.65)	36.70 (29.93)	5.9	0.243 0.232
GQ	56.95 (15.90)	-6.65 (10.59)	1.5	-0.122	0.536	60.02 (15.29)	5.21 (13.20)	0.6	0.080 0.697
Gc Pop Ins	130.6 (32.92)	-13.64 (21.92)	1.5	-0.121	0.539	138.14 (31.23)	7.80 (26.98)	0.3	0.059 0.775

Appendix 12.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.717 (0.279)	-0.00015 (0.000073)	15.8	-0.397	0.045	13.81	-4.125	9.8	0.119	
Kc Pop Ins	1.01 (0.391)	-0.002 (0.0001)	15.4	-0.392	0.048	12.16	-3.611	9.1	0.134	
J-Integral PQ	179.7 (122.1)	-0.019 (0.032)	1.5	-0.123	0.548	3.965	-0.546	0.9	0.645	
J-Integral Pop Ins	287.1 (594.2)	0.042 (0.155)	0.3	0.056	0.787	0.42	0.617	0.9	0.652	
GQ	497.1 (253.7)	-0.113 (0.066)	10.8	-0.329	0.101	26.121	-6.848	8.3	0.154	
Gc Pop Ins	1054.9 (527.1)	-0.237 (0.137)	11.1	-0.333	0.097	22.83	-5.82	7.3	0.182	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.099 (0.0191)	-0.0219 (0.0114)	13.2	-0.364	0.068	0.138 (0.0163)	-0.0167 (0.012)	7.7	-0.277	0.19
Kc Pop Ins	0.156 (0.0266)	-0.0302 (0.016)	13.0	-0.360	0.071	0.211 (0.222)	-0.025 (0.0168)	9.0	-0.300	0.155
J-Integral PQ	98.7 (8.05)	-5.578 (4.824)	5.3	-0.230	0.259	104.23 (6.943)	-1.895 (5.26)	0.6	-0.077	0.722
J-Integral Pop Ins	438.6 (39.89)	-8.63 (23.91)	0.5	-0.074	0.721	429.1 (34.50)	22.90 (26.14)	3.4	0.184	0.390
GQ	42.91 (17.01)	-17.82 (10.20)	11.3	-0.336	0.093	71.40 (15.12)	-10.04 (11.45)	3.4	-0.184	0.390
Gc Pop Ins	99.88 (35.3)	-37.76 (21.16)	11.7	-0.342	0.087	160.7 (30.85)	-23.2 (23.37)	4.3	-0.207	0.332

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.297 (0.206)	-0.00004 (0.00005)	2.6	-0.163	0.408	5.383	-1.768	3.2	0.364	
Kc Pop Ins	0.388 (0.285)	-0.00005 (0.00007)	1.8	-0.134	0.495	2.992	-1.05	1.4	0.545	
J-Integral PQ	116.1 (82.35)	-0.0028 (0.021)	0.1	-0.026	0.894	2.32	-0.0871	0	0.916	
J-Integral Pop Ins	477.8 (412.2)	-0.006 (0.103)	0	-0.012	0.951	2.783	-0.0413	0	0.966	
GQ	169.2 (181.1)	-0.026 (0.045)	1.3	-0.114	0.564	13.43	-3.296	3.3	0.353	
Gc Pop Ins	342.9 (375.3)	-0.0497 (0.0938)	1.1	-0.103	0.601	8.652	-1.855	1.4	0.552	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.127 (0.013)	-0.0084 (0.007)	5.2	-0.228	0.243	0.138 (0.019)	-0.0082 (0.0089)	3.4	-0.186	0.364
Kc Pop Ins	0.194 (0.019)	-0.0097 (0.00978)	3.7	-0.191	0.330	0.207 (0.0257)	-0.0097 (0.012)	2.6	-0.162	0.429
J-Integral PQ	104.83 (5.43)	0.444 (0.285)	0.1	0.031	0.877	99.43 (7.63)	2.13 (3.58)	1.5	0.121	0.556
J-Integral Pop Ins	449.6 (27.03)	7.76 (14.20)	1.1	0.107	0.589	411.02 (38.63)	25.21 (18.09)	7.5	0.274	0.176
GQ	65.37 (11.87)	-5.196 (6.234)	2.6	-0.161	0.412	67.67 (17.2)	-2.71 (8.06)	0.5	-0.068	0.740
Gc Pop Ins	147.5 (24.63)	-9.56 (12.94)	2.1	-0.143	0.467	150.98 (35.11)	-4.98 (16.44)	0.4	-0.062	0.764

Appendix 12.2: Continued

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.108 (0.049)	0.0003 (0.00088)	0.4	0.067	0.736	-1.263	0.166	1.5	0.532	
Kc Pop Ins	0.181 (0.068)	0.00019 (0.0012)	0.1	0.030	0.879	-0.912	0.0784	0.4	0.738	
J-Integral PQ	107.67 (19.36)	-0.05 (0.346)	0.1	-0.028	0.886	2.09	-0.0496	0.8	0.657	
J-Integral Pop Ins	566.4 (94.1)	-2.125 (1.682)	5.8	-0.241	0.218	2.936	-0.178	7.0	0.173	
GQ	53.84 (42.82)	0.183 (0.766)	0.2	0.047	0.813	1.15	0.245	1.0	0.612	
Gc Pop Ins	133.8 (88.7)	0.198 (1.586)	0.1	0.024	0.902	1.852	0.0713	0.1	0.867	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.134 (0.0343)	0.0046 (0.0145)	0.4	0.063	0.752	0.132 (0.0162)	0.01 (0.013)	2.4	0.153	0.436
Kc Pop Ins	0.197 (0.0472)	0.0027 (0.02)	0.1	0.026	0.894	0.198 (0.022)	0.0095 (0.018)	1.0	0.102	0.605
J-Integral PQ	103.3 (13.54)	-0.775 (5.736)	0.1	-0.026	0.894	106.5 (6.44)	2.253 (5.175)	0.7	0.085	0.667
J-Integral Pop Ins	376.2 (65.78)	-35.03 (27.88)	5.7	-0.239	0.220	445.1 (32.24)	-10.10 (25.91)	0.6	-0.076	0.7
GQ	69.67 (29.94)	2.77 (12.69)	0.2	0.043	0.829	70.36 (14.11)	9.60 (11.34)	2.7	0.164	0.405
Gc Pop Ins	150.5 (62.01)	2.79 (26.28)	0	0.021	0.916	155.67 (29.33)	16.17 (23.58)	1.8	0.133	0.499

Osteoporotic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.311 (0.916)	0.00028 (0.00059)	0.9	0.093	0.638	-18.173	5.385	1.6	0.519	
Kc Pop Ins	0.01 (1.265)	0.00012 (0.0008)	0.1	0.028	0.887	-5	1.323	0.1	0.858	
J-Integral PQ	458.9 (355.9)	-0.227 (0.229)	3.7	-0.191	0.329	14.396	-3.88	4.7	0.266	
J-Integral Pop Ins	2708 (1760)	-1.45 (1.13)	5.9	-0.244	0.211	20.014	-5.44	6.6	0.186	
GQ	-118.1 (801.7)	0.117 (0.515)	0.2	0.044	0.822	-22.74	7.614	1.0	0.618	
Gc Pop Ins	207 (1661)	-0.041 (1.067)	0	-0.007	0.970	3.603	-0.511	0	0.97	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.165 (0.0867)	0.012 (0.025)	0.9	0.093	0.639	0.1413 (0.0258)	0.0196 (0.0256)	2.2	0.148	0.451
Kc Pop Ins	0.208 (0.12)	0.005 (0.035)	0.1	0.028	0.888	0.204 (0.036)	0.0148 (0.0355)	0.7	0.082	0.679
J-Integral PQ	71.91 (33.73)	-9.76 (9.831)	3.6	-0.191	0.330	97.83 (10.16)	-8.29 (10.07)	2.5	-0.159	0.418
J-Integral Pop Ins	240.9 (166.7)	-62.34 (48.60)	6.0	-0.244	0.211	399.7 (50.05)	-60.86 (49.63)	5.5	-0.234	0.231
GQ	80.66 (75.69)	5.01 (22.14)	0.2	0.044	0.823	74.21 (22.64)	12.23 (22.45)	1.1	0.106	0.59
Gc Pop Ins	138.5 (157.4)	-1.75 (45.87)	0	-0.007	0.970	155.41 (47.05)	12.79 (46.66)	0.3	0.054	0.786

Appendix 12.3: Osteoporotic Disks Ac

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.523 (0.434)	-0.0035 (0.0053)	1.9	-0.139	0.516	0.375	-0.563	0.2	0.825
Kc Pop Ins	0.679 (0.569)	-0.0043 (0.007)	1.7	-0.129	0.547	0.495	-0.543	0.3	0.809
J-Integral PQ	-236.8 (476.9)	6.31 (5.87)	5.0	0.223	0.294	-1.835	2.215	7.1	0.209
J-Integral Pop Ins	-984 (1179)	21.01 (14.51)	8.7	0.295	0.162	-0.914	1.954	6.4	0.235
GQ	-135.1 (347.6)	3.395 (4.261)	2.9	0.171	0.434	-4.136	3.209	2.6	0.461
Gc Pop Ins	-496.7 (635.8)	9.46 (7.792)	6.6	0.256	0.238	-3.847	3.22	3.6	0.389

Osteoporotic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.837 (0.962)	0.0005 (0.0002)	28.1	0.530	0.051	-38.8	10.58	27.2	0.056
Kc Pop Ins	-2.384 (1.289)	0.0068 (0.0003)	27.2	0.521	0.056	-35.58	9.726	28.9	0.047
J-Integral PQ	669.9 (584.6)	-0.114 (0.145)	4.6	-0.214	0.443	11.77	-2.63	5.6	0.395
J-Integral Pop Ins	1453 (1206)	-0.222 (0.299)	4.1	-0.202	0.471	10.26	-2.087	5.4	0.404
GQ	-753.7 (853.4)	0.221 (0.212)	8.3	0.288	0.317	-36.5	10.66	6.7	0.372
Gc Pop Ins	-1108 (1558)	0.34 (0.387)	6.1	0.246	0.396	-30.84	9.186	7.2	0.355
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.3 (0.04)	0.047 (0.023)	25.0	0.500	0.069	0.199 (0.037)	0.0468 (0.025)	22.1	0.470
Kc Pop Ins	0.416 (0.053)	0.062 (0.031)	24.8	0.498	0.070	0.286 (0.051)	0.058 (0.034)	19.3	0.440
J-Integral PQ	195.5 (23.34)	-10.33 (13.96)	4.0	-0.201	0.472	215.4 (22.01)	-7.64 (14.88)	2.0	-0.141
J-Integral Pop Ins	532.9 (48.04)	-20.88 (28.73)	3.9	-0.198	0.480	575.02 (45.18)	-17.28 (30.54)	2.4	-0.155
GQ	159.97 (35.10)	19.01 (20.37)	6.8	0.260	0.369	113.7 (31.03)	24.43 (21.35)	9.8	0.314
Gc Pop Ins	300.9 (63.80)	30.26 (37.03)	5.3	0.230	0.430	231.03 (57.09)	34.76 (39.28)	6.1	0.247

Appendix 12.3: Continued

Osteoporotic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.392 (0.727)	0.0002 (0.0002)	4.9	0.222	0.426	-18.61	4.979	8.6	0.288	
Kc Pop Ins	-0.427 (0.974)	0.00019 (0.0003)	4.0	0.200	0.474	-14.773	3.954	6.9	0.343	
J-Integral PQ	118.2 (372.1)	0.0241 (0.0974)	0.5	0.068	0.809	1.453	0.238	0.1	0.897	
J-Integral Pop Ins	1605 (709.2)	-0.273 (0.186)	14.3	-0.378	0.165	10.18	-2.0769	14.9	0.155	
GQ	-238.9 (568.3)	0.094 (0.149)	3.2	0.180	0.539	-24.484	7.358	7.2	0.354	
Gc Pop Ins	-297 (1037)	0.139 (0.272)	2.1	0.146	0.618	-16.86	5.321	5.2	0.435	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.234 (0.053)	0.0198 (0.0292)	3.4	0.185	0.51	0.185 (0.0393)	0.0234 (0.0284)	5.0	0.223	0.424
Kc Pop Ins	0.325 (0.07)	0.024 (0.039)	2.9	0.169	0.547	0.268 (0.529)	0.0252 (0.0383)	3.2	0.180	0.522
J-Integral PQ	217.2 (26.6)	4.92 (14.79)	0.8	0.092	0.745	211.9 (20.16)	-2.18 (14.59)	0.2	-0.041	0.884
J-Integral Pop Ins	507.9 (51.76)	-36.87 (28.73)	11.2	-0.335	0.222	610.5 (35.45)	-55.97 (26.65)	26.8	-0.518	0.048
GQ	136.98 (41.66)	11.26 (22.76)	2.0	0.141	0.630	101.8 (30.56)	21.50 (21.72)	7.5	0.275	0.342
Gc Pop Ins	258.8 (75.8)	17.2 (41.43)	1.4	0.119	0.685	206.7 (56.3)	31.1 (40.01)	4.8	0.219	0.452

Osteoporotic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.61 (0.51)	0.0002 (0.0001)	17.5	0.418	0.121	-16.2	4.301	11.7	0.212	
Kc Pop Ins	-0.765 (0.677)	0.0003 (0.0002)	16.6	0.407	0.132	-14.171	3.782	11.7	0.213	
J-Integral PQ	555.8 (266.2)	-0.089 (0.067)	12.0	-0.346	0.206	10.66	-2.328	18.0	0.115	
J-Integral Pop Ins	1564.9 (529.6)	-0.2576 (0.134)	22.2	-0.471	0.076	11.27	-2.377	26.9	0.047	
GQ	-247 (390.7)	0.097 (0.0984)	7.4	0.273	0.345	-17.68	5.454	7.6	0.340	
Gc Pop Ins	-359.5 (710.5)	0.157 (0.179)	6.0	0.246	0.398	-13.42	4.361	6.9	0.364	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.23 (0.031)	0.274 (0.0157)	18.9	0.435	0.106	0.171 (0.0427)	0.0365 (0.019)	21.6	0.464	0.081
Kc Pop Ins	0.323 (0.0411)	0.0351 (0.0211)	17.5	0.419	0.120	0.281 (0.0578)	0.045 (0.0262)	18.5	0.430	0.11
J-Integral PQ	201.7 (16.1)	-11.88 (8.263)	13.7	-0.370	0.174	229.7 (22.06)	-17.47 (9.982)	19.1	-0.437	0.104
J-Integral Pop Ins	544.69 (31.55)	-34.46 (16.22)	25.8	-0.508	0.053	628.02 (40.99)	-51.89 (18.55)	37.6	-0.613	0.015
GQ	135.8 (24.15)	13.05 (12.12)	8.8	0.297	0.303	102.35 (33.26)	20.80 (14.61)	14.4	0.380	0.18
Gc Pop Ins	262.3 (44.1)	20.72 (22.11)	6.8	0.261	0.367	212.45 (61.62)	30.99 (27.07)	9.8	0.314	0.275

Appendix 12.3: Continued

Osteoporotic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.212 (0.072)	0.0079 (0.0013)	72.9	0.854	<0.001	-5.1	2.528	76.4	<0.001	
Kc Pop Ins	-0.274 (0.0927)	0.011 (0.0017)	75.0	0.866	<0.001	-4.515	2.282	79.4	<0.001	
J-Integral PQ	100.16 (62.16)	2.08 (1.148)	20.2	0.449	0.093	1.332	0.5697	26.3	0.051	
J-Integral Pop Ins	628.5 (141.6)	-1.265 (2.616)	1.8	-0.133	0.637	2.859	-0.07	0.6	0.787	
GQ	-176.23 (80.15)	5.795 (1.53)	54.4	0.738	0.003	-5.529	4.355	72.6	<0.001	
Gc Pop Ins	-311.6 (143.3)	10.65 (2.736)	55.8	0.747	0.002	-4.244	3.795	75.4	<0.001	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.499 (0.053)	0.133 (0.023)	72.5	0.852	<0.001	0.262 (0.0181)	0.131 (0.021)	75.0	0.866	<0.001
Kc Pop Ins	0.687 (0.068)	0.1795 (0.029)	74.4	0.862	<0.001	0.364 (0.0252)	0.172 (0.0292)	72.7	0.853	<0.001
J-Integral PQ	290.02 (44.68)	36.17 (19.2)	21.4	0.463	0.082	220.5 (17.14)	24.2 (19.88)	10.2	0.320	0.245
J-Integral Pop Ins	510.9 (102.4)	-23.02 (44.04)	2.1	-0.143	0.610	541.5 (35.4)	-47.05 (41.07)	9.2	-0.303	0.273
GQ	343.67 (63.18)	96.82 (26.37)	52.9	0.727	0.003	176.4 (16.98)	106.95 (19.69)	71.1	0.843	<0.001
Gc Pop Ins	642.2 (113.6)	177.25 (47.39)	53.8	0.734	0.003	322.02 (33.05)	188.08 (38.34)	66.7	0.817	<0.001

Osteoporotic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-4.54 (1.24)	0.0031 (0.0008)	53.0	0.728	0.002	-102.86	31.98	60.6	0.001	
Kc Pop Ins	-5.90 (1.691)	0.004 (0.0011)	50.8	0.713	0.003	-91.22	28.39	60.8	0.001	
J-Integral PQ	-578.1 (877.8)	0.507 (0.565)	5.8	0.242	0.386	-12.08	4.508	8.1	0.303	
J-Integral Pop Ins	2503 (1778)	-1.25 (1.144)	8.4	-0.290	0.295	13.093	-3.24	6.2	0.371	
GQ	-3357 (1019)	2.24 (0.656)	49.3	0.702	0.005	-167.78	53.16	61.4	0.001	
Gc Pop Ins	-5888 (1902)	3.942 (1.23)	46.3	0.681	0.007	-144.023	45.82	62.4	0.001	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.6566 (0.1196)	0.1314 (0.0342)	53.1	0.729	0.002	0.318 (0.041)	0.116 (0.035)	45.8	0.667	0.006
Kc Pop Ins	0.8788 (0.1633)	0.171 (0.0468)	50.8	0.713	0.003	0.434 (0.056)	0.149 (0.048)	42.4	0.651	0.009
J-Integral PQ	284.6 (84.84)	21.71 (24.29)	5.8	0.241	0.388	232.99 (26.81)	23.76 (22.95)	7.6	0.276	0.319
J-Integral Pop Ins	376.3 (171.7)	-53.96 (49.16)	8.5	-0.291	0.292	513.12 (54.91)	-50.32 (47.01)	8.1	-0.285	0.304
GQ	454.8 (99.61)	96.32 (28.22)	49.3	0.702	0.005	209.24 (31.04)	90.90 (26.10)	50.3	0.709	0.005
Gc Pop Ins	822.1 (186.0)	169.5 (52.69)	46.3	0.680	0.007	389.3 (58.2)	159.4 (48.94)	46.9	0.685	0.007

Appendix 12.4: Osteoporotic Disks Ac

Osteoporotic Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.506 (0.207)	-0.004 (0.0025)	8.0	-0.283	0.144	1.976	-1.44	5.2	0.242
Kc Pop Ins	0.660 (0.257)	-0.0049 (0.0031)	8.4	-0.290	0.134	1.743	-1.244	4.6	0.271
J-Integral PQ	246.8 (96.75)	-0.969 (1.186)	2.4	-0.155	0.421	3.413	-0.632	4.1	0.294
J-Integral Pop Ins	171.94 (93.40)	2.11 (1.152)	12.3	0.350	0.079	1.632	0.472	10.8	0.101
GQ	287.5 (156.9)	-2.297 (1.92)	5.2	-0.228	0.242	5.416	-1.862	3.5	0.342
Gc Pop Ins	513.3 (261)	-4.054 (3.193)	5.8	-0.242	0.215	4.952	-1.47	2.6	0.413

Osteoporotic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.261 (0.556)	0.00011 (0.0001)	4.1	0.202	0.438	-11.05	2.97	4.4	0.421	
Kc Pop Ins	-0.239 (0.742)	0.0001 (0.0002)	2.8	0.168	0.520	-9.421	2.433	3.1	0.497	
J-Integral PQ	491 (234.4)	-0.07 (0.058)	9.4	-0.307	0.216	8.797	-1.811	10.2	0.197	
J-Integral Pop Ins	393.4 (288.7)	-0.015 (0.0715)	0.2	-0.049	0.841	3.51	-0.273	0.5	0.772	
GQ	-87.7 (410.4)	0.451 (0.102)	1.3	0.114	0.664	-7.956	2.721	1.4	0.654	
Gc Pop Ins	-26.7 (754.1)	0.05 (0.187)	0.5	0.069	0.791	-3.796	1.645	0.5	0.781	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.19 (0.0264)	0.0064 (0.014)	1.4	0.118	0.653	0.175 (0.025)	0.01 (0.015)	3.3	0.181	0.502
Kc Pop Ins	0.257 (0.035)	0.0059 (0.019)	0.7	0.082	0.756	0.242 (0.033)	0.012 (0.019)	2.6	0.162	0.550
J-Integral PQ	179.2 (10.75)	-8.24 (5.75)	11.4	-0.337	0.171	189.5 (10.44)	-3.11 (6.18)	1.7	-0.129	0.622
J-Integral Pop Ins	333.3 (13.12)	-1.197 (7.173)	0.2	-0.040	0.869	330.6 (12.49)	2.292 (7.302)	0.6	0.078	0.758
GQ	96.26 (19.31)	1.67 (10.24)	0.2	0.042	0.873	91.05 (18.28)	5.92 (10.56)	2.2	0.148	0.584
Gc Pop Ins	176 (35.37)	-0.48 (18.76)	0	-0.007	0.980	172.01 (33.56)	9.24 (19.38)	1.6	0.126	0.641

Appendix 12.4: Continued

Osteoporotic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.867 (0.274)	0.00028 (0.00007)	51.7	0.719	0.002	-23.477	6.35	50.8	0.002	
Kc Pop Ins	-1.057 (0.381)	0.00035 (0.0001)	46.2	0.680	0.004	-21.31	5.782	46.5	0.004	
J-Integral PQ	429.4 (179.3)	-0.064 (0.0474)	10.9	-0.330	0.195	7.41	-1.439	11.4	0.184	
J-Integral Pop Ins	502.7 (206.6)	-0.0447 (0.054)	4.1	-0.202	0.422	4.547	-0.567	4.4	0.405	
GQ	-508.5 (239.5)	0.161 (0.0632)	31.6	0.562	0.023	-27.197	8.136	37.6	0.012	
Gc Pop Ins	-796.6 (457.9)	0.26 (0.121)	24.8	0.498	0.05	-22.86	7.002	30.7	0.026	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.253 (0.025)	0.0385 (0.0123)	41.0	0.640	0.008	0.17 (0.0185)	0.0414 (0.0139)	40.6	0.637	0.011
Kc Pop Ins	0.337 (0.0348)	0.048 (0.017)	36.0	0.600	0.014	0.235 (0.025)	0.052 (0.0188)	37.4	0.611	0.015
J-Integral PQ	168.2 (14.61)	-11.13 (7.23)	13.7	-0.370	0.144	184.14 (10.18)	-0.148 (0.866)	0	-0.005	0.987
J-Integral Pop Ins	321.8 (16.55)	-7.16 (8.42)	4.3	-0.208	0.407	331.1 (12.52)	-0.555 (9.045)	0	-0.016	0.952
GQ	134.6 (21.13)	21.75 (10.29)	24.2	0.492	0.053	87.91 (14.68)	25.78 (11.05)	29.5	0.543	0.036
Gc Pop Ins	241.9 (40.03)	34.36 (19.49)	18.2	0.426	0.1	167.1 (27.55)	43.57 (20.74)	25.3	0.503	0.056

Osteoporotic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.648 (0.719)	0.00021 (0.00018)	9.5	0.308	0.265	-16.3	4.323	6.9	0.345	
Kc Pop Ins	-0.731 (0.956)	0.0025 (0.00024)	7.6	0.276	0.319	-14.34	3.816	5.9	0.382	
J-Integral PQ	634.6 (303)	-0.114 (0.0775)	13.5	-0.367	0.162	12.63	-2.887	16.3	0.121	
J-Integral Pop Ins	720.3 (364.6)	-0.0984 (0.093)	6.9	-0.263	0.307	7.249	-1.316	7.6	0.283	
GQ	-257.5 (544.9)	0.09 (0.1385)	3.2	0.178	0.525	-11.235	3.654	2.2	0.594	
Gc Pop Ins	-303.4 (997.2)	0.124 (0.254)	1.8	0.134	0.634	-7.31	2.64	1.3	0.686	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.197 (0.021)	0.033 (0.023)	13.6	0.369	0.176	0.157 (0.0357)	0.026 (0.022)	10.9	0.330	0.249
Kc Pop Ins	0.267 (0.028)	0.0396 (0.03)	11.5	0.339	0.216	0.217 (0.047)	0.034 (0.0286)	10.5	0.324	0.259
J-Integral PQ	182.5 (10.03)	-12.37 (10.37)	9.2	-0.304	0.253	179.8 (15.74)	4.45 (10.79)	1.3	0.114	0.687
J-Integral Pop Ins	331.1 (11.46)	-10.99 (11.99)	5.3	-0.230	0.374	333.79 (18.84)	-0.89 (11.92)	0	-0.20	0.942
GQ	101.4 (16.11)	15.19 (17.51)	5.5	0.234	0.401	80.28 (26.51)	15.45 (16.10)	7.1	0.267	0.356
Gc Pop Ins	187.9 (29.54)	22.81 (32.12)	3.7	0.193	0.490	150.9 (48.2)	27.92 (29.27)	7.0	0.265	0.359

Appendix 12.4: Continued

Osteoporotic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.133 (0.072)	0.001 (0.0014)	3.4	0.183	0.481	-1.154	0.218	2.2	0.573	
Kc Pop Ins	0.185 (0.095)	0.0013 (0.0018)	3.3	0.181	0.486	-1.016	0.219	2.3	0.557	
J-Integral PQ	204.4 (30.01)	-0.303 (0.565)	1.8	-0.133	0.599	2.397	-0.0764	1.8	0.596	
J-Integral Pop Ins	370.9 (34.48)	-0.706 (0.645)	6.6	-0.257	0.289	2.70	-0.11	7.6	0.252	
GQ	62.82 (52.31)	0.63 (1.003)	2.6	0.160	0.539	1.303	0.33	1.9	0.60	
Gc Pop Ins	121.57 (95.83)	1.1 (1.838)	2.3	0.153	0.558	1.578	0.332	2.0	0.587	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.224 (0.058)	0.0174 (0.0229)	3.7	0.193	0.459	0.197 (0.026)	0.0195 (.0216)	5.2	0.228	0.380
Kc Pop Ins	0.305 (0.077)	0.023 (0.03)	3.7	0.191	0.462	0.271 (0.034)	0.0274 (0.0285)	5.8	0.241	0.352
J-Integral PQ	176.5 (23.6)	-5.36 (9.42)	2.0	-0.141	0.577	190.7 (10.76)	2.51 (9.06)	0.5	0.069	0.786
J-Integral Pop Ins	305.9 (26.60)	-12.47 (10.74)	7.4	-0.271	0.262	330.8 (12.03)	-6.04 (10.39)	1.9	-0.140	0.569
GQ	121.1 (42.6)	11.26 (16.75)	2.9	0.171	0.512	105.5 (18.84)	14.85 (15.64)	5.7	0.238	0.357
Gc Pop Ins	223.9 (78)	19.89 (30.69)	2.7	0.165	0.527	198.5 (34.31)	29.17 (28.50)	6.5	0.256	0.322

Osteoporotic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.172 (1.112)	0.0002 (0.0007)	0.7	0.082	0.755	-3.73	0.923	0.1	0.899	
Kc Pop Ins	-0.222 (1.479)	0.00031 (0.00096)	0.7	0.082	0.754	-4.25	1.129	0.2	0.872	
J-Integral PQ	289.4 (495.2)	-0.065 (0.3198)	0.3	-0.051	0.842	3.065	-0.2499	0	0.931	
J-Integral Pop Ins	635.9 (555.5)	-0.194 (0.358)	1.7	-0.130	0.595	5.812	-1.03	2.0	0.567	
GQ	-105.3 (812.4)	0.129 (0.525)	0.4	0.063	0.81	-3.56	1.697	0.1	0.886	
Gc Pop Ins	-202 (1487)	0.245 (0.96)	0.4	0.066	0.802	-4.598	2.111	0.2	0.855	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.218 (0.113)	0.0099 (0.031)	0.7	0.082	0.754	0.174 (0.041)	-0.0077 (0.031)	0.4	-0.064	0.807
Kc Pop Ins	0.297 (0.15)	0.0132 (0.041)	0.7	0.082	0.753	0.239 (0.055)	-0.0096 (0.041)	0.4	-0.060	0.819
J-Integral PQ	178.8 (50.05)	-2.86 (13.77)	0.3	-0.052	0.838	194.3 (18.37)	4.55 (13.88)	0.7	0.082	0.747
J-Integral Pop Ins	305.1 (55.4)	-8.36 (15.42)	1.7	-0.130	0.595	332.5 (20.12)	-1.93 (15.61)	0.1	-0.030	0.903
GQ	114.2 (82.22)	5.57 (22.58)	0.4	0.064	0.809	90.31 (30.02)	-3.47 (22.47)	0.2	-0.040	0.879
Gc Pop Ins	214.3 (150.4)	10.53 (41.32)	0.4	0.066	0.802	171.4 (54.97)	-4.53 (41.14)	0.1	-0.028	0.914

Appendix 13: Osteoarthritic Group Fracture Toughness Testing Results vs. Clinical QUS Regressions

Appendix 13.1: Osteoarthritic Beams Ac

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.707 (0.252)	-0.005 (0.0038)	5.4	-0.232	0.156	1.128	-0.913	3.1	0.280
Kc Pop Ins	1.02 (0.35)	-0.008 (0.0053)	5.4	-0.233	0.154	1.07	-0.776	2.8	0.306
J-Integral PQ	201.2 (73.82)	-0.433 (1.113)	0.4	-0.065	0.699	2.51	-0.159	0.4	0.722
J-Integral Pop Ins	241.2 (340.1)	7.252 (5.121)	5.1	0.227	0.165	1.813	0.561	3.2	0.274
GQ	887 (360.1)	-9.11 (5.42)	6.9	-0.263	0.101	5.06	-1.537	2.9	0.290
Gc Pop Ins	1807.2 (698.4)	-17.93 (10.51)	7.1	-0.267	0.096	4.901	-1.242	2.5	0.334

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-4.05 (0.9395)	0.0011 (0.0002)	37.2	0.610	<0.001	-51.1	14.02	31.9	<0.001	
Kc Pop Ins	-5.93 (1.256)	0.0016 (0.00031)	41.6	0.645	<0.001	-47.55	13.1	34.5	<0.001	
J-Integral PQ	574.8 (314.1)	-0.0996 (0.078)	4.4	-0.209	0.208	12.37	-2.82	5.4	0.162	
J-Integral Pop Ins	4083 (1431)	-0.8319 (0.354)	13.0	-0.360	0.024	21.38	-5.14	12.7	0.026	
GQ	-5026 (1376)	1.315 (0.34)	28.2	0.531	<0.001	-70.5	20.19	24.2	0.001	
Gc Pop Ins	-10172 (2620)	2.672 (0.648)	30.9	0.556	<0.001	-62.54	18.07	24.8	0.001	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.428 (0.032)	0.094 (0.023)	30.7	0.554	<0.001	0.355 (0.0258)	0.0936 (0.031)	19.7	0.444	0.005
Kc Pop Ins	0.643 (0.043)	0.139 (0.031)	35.2	0.593	<0.001	0.534 (0.035)	0.141 (0.0421)	23.4	0.484	0.002
J-Integral PQ	164.5 (10.43)	-9.34 (7.47)	4.2	-0.204	0.219	171.4 (8.09)	-13.37 (9.19)	5.5	-0.236	0.155
J-Integral Pop Ins	671.3 (47.26)	-59.06 (35.45)	7.0	-0.264	0.104	714.1 (37.46)	-69.54 (43.11)	6.6	-0.256	0.115
GQ	380.5 (46.28)	111.5 (33.94)	22.1	0.470	0.002	293.95 (37.91)	111.4 (44.18)	14.3	0.379	0.016
Gc Pop Ins	819.5 (88.17)	230.1 (64.65)	25.0	0.500	0.001	640.7 (72.95)	227.3 (85.02)	15.8	0.398	0.011

Appendix 13.1:Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.762 (0.801)	0.00028 (0.0002)	4.9	0.221	0.176	-12.44	3.32	3.8	0.235	
Kc Pop Ins	-0.955 (1.112)	0.00038 (0.00029)	4.5	0.213	0.194	-.965	2.59	2.9	0.302	
J-Integral PQ	238.5 (245.1)	-0.0169 (0.063)	0.2	-0.045	0.790	4.90	-0.748	0.7	0.627	
J-Integral Pop Ins	3327 (1053)	-0.669 (0.27)	14.2	-0.377	0.018	15.89	-3.64	11.8	0.032	
GQ	-1586 (1146)	0.481 (0.294)	6.6	0.256	0.111	-19.27	5.998	4.1	0.211	
Gc Pop Ins	-3114 (2220)	0.9596 (0.5698)	6.9	0.264	0.1	-13.43	4.478	2.9	0.293	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.386 (0.037)	0.059 (0.033)	7.7	0.277	0.087	0.344 (0.029)	-0.01 (0.046)	0.1	-0.036	0.826
Kc Pop Ins	0.576 (0.051)	0.08 (0.046)	7.5	0.274	0.092	0.518 (0.0396)	-0.023 (0.0632)	0.4	-0.060	0.716
J-Integral PQ	170.8 (10.79)	-2.79 (10.15)	0.2	-0.046	0.785	172.86 (8.357)	-1.94 (14.17)	0.1	-0.023	0.892
J-Integral Pop Ins	650.1 (48.2)	-101.8 (46.34)	11.5	-0.340	0.034	725.4 (36.77)	-116.9 (58.72)	9.7	-0.311	0.054
GQ	350.4 (52.24)	90.35 (47.95)	8.5	0.292	0.067	284.2 (40.85)	15.84 (66.03)	0.2	0.039	0.812
Gc Pop Ins	755.4 (100.9)	183.7 (92.66)	9.4	0.306	0.055	621.2 (79.32)	23.1 (128.2)	0.1	0.029	0.858
Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.784 (1.157)	0.00029 (0.00029)	2.9	0.171	0.340	-4.52	1.111	0.2	0.789	
Kc Pop Ins	-1.573 (1.586)	0.0005 (0.0004)	5.3	0.230	0.198	-8.79	2.35	1.3	0.521	
J-Integral PQ	84.2 (328.6)	0.0219 (0.0835)	0.2	0.048	0.795	1.21	0.278	0.1	0.897	
J-Integral Pop Ins	400 (1718)	0.085 (0.436)	0.1	0.035	0.846	0.626	0.616	0.2	0.814	
GQ	-2039 (1634)	0.5883 (0.415)	5.9	0.243	0.166	-11.06	3.70	0.9	0.594	
Gc Pop Ins	-4683 (3103)	1.344 (0.789)	8.3	0.288	0.098	-18.19	5.79	2.9	0.337	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.3478 (0.036)	0.02 (0.037)	0.9	0.096	0.594	0.336 (0.03)	-0.027 (0.032)	2.2	-0.150	0.406
Kc Pop Ins	0.534 (0.0495)	0.044 (0.0515)	2.3	0.153	0.395	0.51 (0.042)	-0.028 (0.0445)	1.3	-0.112	0.534
J-Integral PQ	172.1 (10.15)	3.84 (10.52)	0.4	0.067	0.718	170.3 (8.79)	5.28 (9.18)	1.1	0.104	0.57
J-Integral Pop Ins	742.3 (50.18)	15.56 (54.09)	0.3	0.052	0.775	736.1 (43.69)	16.35 (45.91)	0.4	0.064	0.724
GQ	303.4 (50.22)	59.28 (52.89)	3.8	0.194	0.271	274.3 (43.96)	-3.11 (46.84)	0	-0.012	0.947
Gc Pop Ins	670.71 (95.75)	138 (100.8)	5.5	0.235	0.181	603.4 (84.59)	1.81 (90.13)	0	0.004	0.984

Appendix 13.1: Continued

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.311 (0.267)	0.0076 (0.0033)	16.7	0.408	0.031	-5.90	2.795	22.7	0.010	
Kc Pop Ins	-0.298 (0.369)	0.0094 (0.0046)	13.8	0.371	0.052	-4.465	2.142	17.5	0.027	
J-Integral PQ	294.4 (92.27)	-1.47 (1.147)	6.4	-0.253	0.213	3.628	-0.734	6.4	0.212	
J-Integral Pop Ins	1910.6 (416.2)	-14.06 (5.19)	22.7	-0.476	0.012	5.89	-1.586	21.3	0.015	
GQ	-307.4 (309.8)	6.466 (3.859)	9.7	0.312	0.106	-4.434	3.466	11.9	0.072	
Gc Pop Ins	-405.2 (618.9)	10.96 (7.71)	7.2	0.269	0.167	-1.557	2.16	6.2	0.201	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.368 (0.041)	0.124 (0.0546)	16.7	0.408	0.031	0.29 (0.031)	0.022 (0.048)	0.8	0.090	0.650
Kc Pop Ins	0.539 (0.056)	0.153 (0.075)	13.8	0.371	0.052	0.446 (0.0416)	0.0137 (0.0651)	0.2	0.041	0.835
J-Integral PQ	163.3 (14.05)	-23.96 (18.79)	6.3	-0.252	0.214	182.35 (10.21)	-17.76 (15.42)	5.2	-0.229	0.261
J-Integral Pop Ins	653.4 (64.13)	-229.6 (85.07)	22.6	-0.475	0.012	832.13 (44.22)	-185.04 (72.85)	20.5	-0.453	0.018
GQ	271.12 (47.04)	106.2 (63.2)	9.8	0.313	0.105	205.9 (34.16)	12.86 (53.48)	0.2	0.047	0.812
Gc Pop Ins	575.8 (93.96)	180.3 (126.2)	7.3	0.270	0.165	472.9 (67.37)	-7.0 (105.5)	0	-0.013	0.948

Osteoarthritic Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	3.26 (1.503)	-0.0012 (0.00095)	10.9	-0.330	0.061	30.78	-9.79	10.0	0.072	
Kc Pop Ins	4.74 (2.07)	-0.0027 (0.0013)	11.8	-0.344	0.05	29.45	-9.31	11.5	0.054	
J-Integral PQ	279.6 (501.9)	-0.0689 (0.316)	0.2	-0.040	0.829	4.95	-0.855	0.2	0.793	
J-Integral Pop Ins	3112 (2257)	-1.5 (1.43)	3.5	-0.186	0.30	12.46	-3.01	2.4	0.388	
GQ	3325 (2258)	-1.93 (1.43)	5.4	-0.232	0.186	57.46	-17.26	10.3	0.064	
Gc Pop Ins	6860 (4328)	-3.951 (2.732)	6.1	-0.248	0.158	54.39	-16.17	11.9	0.046	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.1197 (0.1155)	-0.0793 (0.041)	10.9	-0.330	0.061	0.287 (0.0384)	-0.088 (0.0447)	11.1	-0.334	0.058
Kc Pop Ins	0.1963 (0.159)	-0.115 (0.056)	11.9	-0.344	0.05	0.438 (0.053)	-0.129 (0.0616)	12.4	-0.352	0.045
J-Integral PQ	162.3 (37.44)	-2.96 (13.58)	0.2	-0.040	0.829	168.2 (11.63)	-3.99 (14.76)	0.2	-0.049	0.789
J-Integral Pop Ins	556.7 (175)	-64.44 (61.25)	3.4	-0.186	0.301	697.5 (58.36)	-64.1 (66.91)	2.9	-0.169	0.346
GQ	46.5 (173.9)	-82.82 (61.22)	5.4	-0.233	0.186	217.1 (57.37)	-99.04 (66.68)	6.4	-0.254	0.147
Gc Pop Ins	135.8 (333.3)	-169.9 (117.4)	6.1	-0.248	0.158	487.2 (110)	-200.8 (127.8)	7.2	-0.268	0.126

Appendix 13.2: Osteoarthritic Beams AL

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	1.763 (0.569)	-0.022 (0.008)	39.3	-0.627	0.022	11.03	-6.43	44.6	0.013
Kc Pop Ins	2.492 (0.798)	-0.0315 (0.0118)	39.3	-0.627	0.002	10.08	-5.81	41.4	0.018
J-Integral PQ	197.1 (367.7)	2.492 (5.432)	1.9	0.137	0.655	1.542	0.55	2.7	0.592
J-Integral Pop Ins	-790 (2557)	35.37 (37.77)	7.4	0.272	0.369	0.74	1.33	6.2	0.412
GQ	1178 (485.5)	-15.38 (7.17)	29.5	-0.543	0.055	17.91	-8.777	33.5	0.038
Gc Pop Ins	2393.8 (967.4)	-31.02 (14.29)	30.0	-0.548	0.053	16.0	-7.532	29.5	0.055

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-4.07 (1.03)	0.001 (0.0003)	63.1	0.718	0.002	-75.2	20.61	53.4	0.007	
Kc Pop Ins	-5.759 (1.45)	0.00149 (0.0004)	63.7	0.710	0.002	-68.78	18.89	51.3	0.009	
J-Integral PQ	1540 (1247)	-0.287 (0.306)	8.1	-0.419	0.371	15.18	-3.498	9.8	0.321	
J-Integral Pop Ins	14209 (8622)	-3.09 (2.12)	17.6	-0.284	0.175	28.77	-7.09	15.2	0.211	
GQ	-2462.4 (804.3)	0.629 (0.197)	50.4	0.798	0.010	-96.02	27.1	35.3	0.042	
Gc Pop Ins	-5043 (1617)	1.293 (0.397)	51.5	0.794	0.009	-83.18	23.64	32.4	0.053	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.282 (0.0373)	0.18 (0.042)	62.3	0.716	0.001	0.179 (0.039)	0.197 (0.045)	63.2	0.723	0.001
Kc Pop Ins	0.416 (0.052)	0.253 (0.059)	62.9	0.709	0.001	0.271 (0.0547)	0.278 (0.063)	63.9	0.716	0.001
J-Integral PQ	357.6 (28.82)	-41.20 (32.61)	12.7	-0.44	0.233	381.2 (30.83)	-45.2 (35.51)	12.9	-0.445	0.229
J-Integral Pop Ins	1528.8 (198.2)	-364.8 (224.2)	19.4	-0.356	0.132	1738.3 (211.7)	-401.9 (243.8)	19.8	-0.359	0.128
GQ	163.9 (33.9)	127.8 (38.35)	50.2	0.793	0.007	90.51 (35.91)	140.72 (41.36)	51.3	0.799	0.006
Gc Pop Ins	348.6 (67.09)	258 (75.9)	51.2	0.789	0.006	200.4 (71.09)	284.1 (81.87)	52.3	0.795	0.005

Appendix 13.2:Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-2.01 (2.06)	0.00058 (0.00053)	9.9	0.244	0.295	-29.21	7.93	7.9	0.352
Kc Pop Ins	-2.756 (2.888)	0.0008 (0.0007)	9.6	0.244	0.302	-23.97	6.53	6.1	0.417
J-Integral PQ	2399 (914.8)	-0.523 (0.235)	31.0	-0.579	0.048	22.09	-5.46	30.8	0.049
J-Integral Pop Ins	16718 (6430)	-3.889 (1.653)	33.5	-0.557	0.038	36.47	-9.28	35.4	0.032
GQ	-1250 (1664)	0.3574 (0.4277)	6.0	0.310	0.421	-29.56	8.755	3.9	0.519
Gc Pop Ins	-2478 (3327)	0.715 (0.855)	6.0	0.315	0.421	-19.07	5.936	2.1	0.634
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.317 (0.085)	0.11 (0.10)	9.2	0.233	0.313	0.257 (0.062)	0.048 (0.117)	1.5	0.072
Kc Pop Ins	0.4631 (0.12)	0.147 (0.141)	9.0	0.234	0.320	0.38 (0.087)	0.065 (0.163)	1.4	0.074
J-Integral PQ	303.3 (38.19)	-96.92 (44.86)	29.8	-0.572	0.054	346 (26.06)	-113.4 (48.88)	32.9	-0.551
J-Integral Pop Ins	1132.2 (267.7)	-726.7 (314.4)	32.7	-0.546	0.041	1464 (189.9)	-780.6 (356.3)	30.4	-0.573
GQ	181.6 (69.04)	64.61 (81.09)	5.5	0.299	0.442	144.15 (49.41)	22.77 (92.67)	0.5	0.118
Gc Pop Ins	383.3 (138.1)	129 (162.2)	5.4	0.304	0.443	308.4 (98.81)	44.5 (185.3)	0.5	0.124

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-3.71 (2.27)	0.001 (0.00057)	21.7	0.446	0.108	-55.48	15.21	21.0	0.115
Kc Pop Ins	-5.27 (3.16)	0.0014 (0.0008)	22.4	0.423	0.102	-50.3	13.82	19.7	0.129
J-Integral PQ	641 (1299)	-0.069 (0.327)	0.4	0.076	0.836	4.437	-0.525	0.2	0.882
J-Integral Pop Ins	-760 (9292)	0.593 (2.34)	0.6	-0.064	0.804	-2.754	1.644	0.8	0.771
GQ	-2705 (1838)	0.716 (0.462)	17.9	0.473	0.150	-83.88	23.82	20.8	0.118
Gc Pop Ins	-5698 (3629)	1.51 (0.913)	19.9	0.466	0.126	-73.5	21.04	19.4	0.132
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.278 (0.055)	0.121 (0.068)	22.5	0.455	0.102	0.26 (0.053)	0.114 (0.065)	21.7	0.445
Kc Pop Ins	0.411 (0.076)	0.172 (0.094)	23.2	0.431	0.096	0.386 (0.074)	0.162 (0.091)	22.4	0.422
J-Integral PQ	363 (31.53)	-9.06 (38.89)	0.5	0.074	0.820	364.3 (30.31)	-9.25 (37.43)	0.6	0.064
J-Integral Pop Ins	1612.6 (255.6)	68.1 (278.3)	0.5	-0.070	0.811	1601.9 (217.1)	57.2 (268.1)	0.4	-0.074
GQ	161.35 (44.42)	86.88 (54.79)	18.6	0.482	0.141	148.5 (42.92)	81.81 (53.0)	17.8	0.473
Gc Pop Ins	345.3 (87.68)	183.1 (108.2)	20.7	0.474	0.119	318.2 (84.79)	172.5 (104.7)	19.8	0.466

Appendix 13.2:Continued

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	1.04 (0.462)	-0.01 (0.0059)	21.3	-0.517	0.112	4.03	-2.52	13.9	0.210	
Kc Pop Ins	1.53 (0.641)	-0.0149 (0.0082)	23.1	-0.481	0.097	4.25	-2.54	16.0	0.176	
J-Integral PQ	256.4 (262.7)	1.398 (3.354)	1.6	-0.255	0.685	1.842	0.373	2.5	0.604	
J-Integral Pop Ins	3188 (1832)	-20.46 (23.40)	6.5	0.125	0.401	4.792	-0.863	5.3	0.448	
GQ	794.3 (361.5)	-8.41 (4.62)	23.2	-0.480	0.096	10.397	-4.518	17.9	0.149	
Gc Pop Ins	1707 (705.7)	-18.07 (9.01)	26.8	-0.462	0.07	10.84	-4.55	21.8	0.108	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.131 (0.086)	-0.166 (0.096)	21.2	-0.517	0.113	0.221 (0.051)	-0.198 (0.09)	30.7	-0.592	0.049
Kc Pop Ins	0.198 (0.12)	-0.242 (0.134)	23.0	-0.481	0.097	0.329 (0.07)	-0.286 (0.124)	32.7	-0.557	0.041
J-Integral PQ	381.3 (49.1)	22.7 (54.8)	1.5	-0.256	0.686	368.8 (30.8)	25.7 (54.1)	2.0	-0.188	0.644
J-Integral Pop Ins	1358.3 (342.2)	-3335.1 (382.1)	6.5	0.124	0.399	1561.9 (218.8)	-243.5 (384.2)	3.5	0.142	0.539
GQ	43.01 (67.55)	-137.1 (75.44)	23.1	-0.479	0.096	118.2 (40.27)	-157.2 (70.71)	31.0	-0.572	0.048
Gc Pop Ins	91.7 (131.9)	-294.8 (147.3)	26.7	-0.461	0.071	254.04 (78.16)	-334 (137.2)	35.0	-0.554	0.033

Osteoarthritic Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	1.734 (3.16)	-0.0009 (0.002)	2.0	-0.174	0.648	22.19	-7.17	3.0	0.574	
Kc Pop Ins	2.56 (4.42)	-0.0014 (0.0028)	2.2	-0.170	0.630	25.14	-8.03	4.2	0.501	
J-Integral PQ	2536 (1484)	-1.375 (0.939)	16.3	-0.366	0.171	20.13	-5.5	14.4	0.2	
J-Integral Pop Ins	15680 (10802)	-8.918 (6.839)	13.4	-0.404	0.219	33.24	-9.4	16.7	0.166	
GQ	1564 (2489)	-0.902 (1.576)	2.9	-0.148	0.579	43.33	-12.96	3.9	0.518	
Gc Pop Ins	3207 (4975)	-1.84 (3.15)	3.0	-0.140	0.571	49.24	-14.7	6.0	0.42	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.133 (0.253)	-0.041 (0.086)	2.0	-0.174	0.646	0.196 (0.0796)	-0.082 (0.0867)	7.5	-0.290	0.364
Kc Pop Ins	0.1986 (0.3537)	-0.0598 (0.12)	2.2	-0.171	0.629	0.294 (0.111)	-0.118 (0.12)	7.9	-0.285	0.351
J-Integral PQ	196.5 (118.6)	-59.03 (40.35)	16.3	-0.366	0.172	329.4 (39.12)	-55.87 (42.62)	13.5	-0.302	0.217
J-Integral Pop Ins	501.2 (863.5)	-383.1 (293.8)	13.4	-0.404	0.219	1386.2 (287.1)	-328.1 (312.8)	9.1	-0.368	0.317
GQ	29.2 (199)	-38.86 (67.7)	2.9	-0.148	0.578	97.04 (62.81)	-67.59 (68.42)	8.1	-0.282	0.344
Gc Pop Ins	74.2 (397.6)	-79.3 (135.3)	3.0	-0.141	0.570	213.1 (125.4)	-137.3 (136.6)	8.4	-0.274	0.337

Appendix 13.3: Osteoarthritic Disks Ac

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.713 (0.529)	-0.0075 (0.0076)	12.2	-0.349	0.358	0.957	-0.961	1.2	0.776
Kc Pop Ins	0.997 (1.261)	-0.0072 (0.182)	2.2	-0.147	0.705	-1.502	0.596	0.4	0.868
J-Integral PQ	-58.3 (159.3)	2.76 (2.298)	17.1	0.414	0.268	-0.347	1.335	16.2	0.282
J-Integral Pop Ins	174.6 (183.0)	1.762 (2.64)	6.0	0.245	0.526	1.66	0.44	6.1	0.520
GQ	252.3 (229.2)	-2.62 (3.306)	8.2	-0.287	0.454	0.208	0.789	0.3	0.887
Gc Pop Ins	175 (1415)	4.42 (20.41)	0.7	0.082	0.835	-4.71	3.902	5.9	0.528

Osteoarthritic Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-3.121 (1.298)	0.0008 (0.0003)	48.3	0.695	0.038	-52.08	14.22	25.3	0.167	
Kc Pop Ins	-5.33 (3.43)	0.0014 (0.00085)	29.2	0.540	0.133	-37.13	10.18	11.5	0.372	
J-Integral PQ	811.5 (496.5)	-0.168 (0.123)	21.1	-0.459	0.214	20.58	-5.123	22.3	0.199	
J-Integral Pop Ins	1002.6 (540.6)	-0.175 (0.134)	19.6	-0.443	0.233	12.01	-2.646	20.8	0.217	
GQ	-1232 (584.1)	0.323 (0.145)	41.6	0.645	0.061	-53.48	15.29	10.8	0.387	
Gc Pop Ins	-3116 (4326)	0.89 (1.07)	9.0	0.300	0.433	-23.58	7.22	1.9	0.724	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.255 (0.038)	0.0902 (0.0327)	52.1	0.722	0.028	0.187 (0.036)	0.104 (0.0498)	38.5	0.620	0.075
Kc Pop Ins	0.608 (0.0994)	0.171 (0.085)	36.8	0.607	0.083	0.481 (0.0919)	0.168 (0.129)	19.5	0.442	0.234
J-Integral PQ	123.6 (16.10)	-13.39 (13.73)	12.0	-0.346	0.362	134.3 (11.89)	-27.74 (16.64)	28.4	-0.533	0.139
J-Integral Pop Ins	286.6 (17.37)	-14.41 (14.82)	11.9	-0.345	0.363	298.1 (13.05)	-28.59 (18.26)	25.9	-0.509	0.161
GQ	95.96 (17.03)	36.40 (14.53)	47.3	0.688	0.041	68.84 (15.89)	40 (22.24)	31.6	0.562	0.115
Gc Pop Ins	567.9 (127)	128.5 (108.3)	16.7	0.409	0.274	476.1 (112.1)	76.9 (156.9)	3.3	0.182	0.639

Appendix 13.3: Continued

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = $a + b(\text{Proximal Phalanx SOS m s}^{-1})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Proximal Phalanx SOS m s}^{-1})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.803 (1.459)	0.0005 (0.0004)	21.1	0.459	0.213	-36.98	10.08	15.8	0.289
Kc Pop Ins	-3.384 (3.408)	0.001 (0.0009)	15.6	0.395	0.293	-28.39	7.798	8.4	0.451
J-Integral PQ	632.3 (472.7)	-0.129 (0.122)	13.8	-0.371	0.325	15.56	-3.749	14.8	0.306
J-Integral Pop Ins	717.8 (525.5)	-0.109 (0.136)	8.4	-0.290	0.449	7.966	-1.53	8.7	0.442
GQ	-392.2 (673.5)	0.1196 (0.174)	6.3	0.252	0.513	-31.07	9.122	4.8	0.572
Gc Pop Ins	-14 (4126)	0.127 (1.064)	0.2	0.045	0.908	-13.873	4.553	0.9	0.804
	Mechanical Parameter = $a + b(\text{Proximal Phalanx T-score})$					Mechanical Parameter = $a + b(\text{Proximal Phalanx Z-score})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.257 (0.058)	0.082 (0.055)	24.1	0.491	0.179	0.196 (0.045)	0.043 (0.107)	2.2	0.149
Kc Pop Ins	0.627 (0.134)	0.174 (0.127)	21.2	0.461	0.212	0.496 (0.103)	0.063 (0.243)	1.0	0.098
J-Integral PQ	122.97 (20.10)	-12.41 (19.03)	5.7	-0.239	0.535	129.99 (12.69)	-39.49 (29.95)	19.9	-0.446
J-Integral Pop Ins	288.25 (21.93)	-10.48 (20.77)	3.5	-0.187	0.629	294.11 (14.27)	-34.37 (33.68)	12.9	-0.360
GQ	89.84 (26.65)	23.86 (25.24)	11.3	0.337	0.376	70.21 (19.21)	-16.1 (45.35)	1.8	-0.133
Gc Pop Ins	545 (164.7)	82.6 (155.9)	3.9	0.196	0.613	466 (109.4)	-221.9 (258.2)	9.5	-0.309

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia SOS m s}^{-1})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Mid-Shaft Tibia SOS m s}^{-1})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.936 (1.486)	0.0003 (0.0004)	7.6	0.276	0.472	-18.68	4.971	4.4	0.590
Kc Pop Ins	-0.803 (3.457)	0.00033 (0.00088)	2.0	0.140	0.719	-10.293	2.75	1.2	0.781
J-Integral PQ	148.6 (479.1)	-0.004 (0.122)	0	-0.013	0.974	2.702	-0.166	0	0.963
J-Integral Pop Ins	254.7 (516.7)	0.011 (0.131)	0.1	0.030	0.938	2.003	0.129	0.1	0.946
GQ	-473.1 (621.9)	0.138 (0.158)	9.9	0.314	0.410	-34.69	10.11	6.7	0.502
Gc Pop Ins	-306 (3876)	0.1997 (0.9838)	0.6	0.076	0.845	-17.93	5.674	1.6	0.742
	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia T-score})$					Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia Z-score})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.209 (0.05)	0.031 (0.049)	5.5	0.235	0.543	0.193 (0.046)	-0.0009 (0.0517)	0	-0.007
Kc Pop Ins	0.503 (0.116)	0.024 (0.113)	0.6	0.079	0.840	0.48 (0.102)	-0.066 (0.1142)	4.6	-0.214
J-Integral PQ	131.8 (15.95)	-1.62 (15.49)	0.2	-0.040	0.919	131.6 (14.12)	-6.21 (15.86)	2.1	-0.146
J-Integral Pop Ins	296.6 (17.22)	0.49 (16.73)	0	0.011	0.978	295.99 (15.37)	-2.38 (17.27)	0.3	-0.052
GQ	78.83 (21)	15.25 (20.40)	7.4	0.272	0.479	71.37 (19.51)	0.47 (21.92)	0	0.008
Gc Pop Ins	481.7 (129.5)	1.8 (125.8)	0	0.006	0.989	461.7 (109.6)	-110.5 (123.2)	10.3	-0.321

Appendix 13.3: Continued

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.114 (0.34)	0.0034 (0.0042)	10.2	0.319	0.442	-2.849	1.041	3.1	0.674	
Kc Pop Ins	-0.258 (0.903)	0.009 (0.011)	9.2	0.303	0.466	-1.852	0.735	1.2	0.795	
J-Integral PQ	291.9 (124.4)	-1.892 (1.52)	20.5	-0.452	0.260	4.113	-1.042	20.6	0.259	
J-Integral Pop Ins	423.7 (112.4)	-1.45 (1.376)	15.6	0.395	0.333	3.24	-0.395	15.8	0.329	
GQ	41.3 (148.6)	0.214 (1.819)	0.2	0.048	0.910	3.735	-1.126	1.2	0.796	
Gc Pop Ins	413 (1176)	0.39 (14.39)	0	0.011	0.979	5.733	-1.74	2.0	0.737	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.193 (0.049)	0.057 (0.068)	10.4	0.323	0.436	0.165 (0.04)	-0.003 (0.061)	0	-0.017	0.967
Kc Pop Ins	0.512 (0.13)	0.142 (0.18)	9.4	0.306	0.461	0.442 (0.106)	-0.0075 (0.161)	0	-0.019	0.964
J-Integral PQ	122.7 (18.0)	-30.89 (24.91)	20.4	-0.452	0.261	144.36 (13.91)	-26.25 (21.12)	20.5	-0.452	0.260
J-Integral Pop Ins	294.13 (16.27)	-23.57 (22.52)	15.4	-0.393	0.336	311.72 (12.01)	-24.37 (18.23)	22.9	-0.479	0.230
GQ	60.52 (21.49)	3.75 (29.74)	0.3	0.051	0.904	62.28 (16.12)	-15.33 (24.47)	6.1	-0.248	0.554
Gc Pop Ins	449.2 (170.0)	7.9 (235.2)	0	0.014	0.974	472.8 (127.7)	-116.0 (193.8)	5.6	-0.237	0.571

Osteoarthritic Discs Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	1.874 (2.867)	-0.0011 (0.0018)	4.7	-0.216	0.576	41.79	-13.31	8.7	0.441	
Kc Pop Ins	4.91 (6.42)	-0.003 (0.004)	6.3	-0.252	0.513	50.28	-15.83	10.9	0.386	
J-Integral PQ	846.4 (686.9)	868.9 (0.546)	8.8	-0.297	0.438	17.83	-4.91	8.0	0.459	
J-Integral Pop Ins	681.7 (970.6)	0.242 (0.61)	2.2	-0.148	0.703	5.99	-1.1	1.4	0.761	
GQ	1675 (1086)	-1.01 (0.683)	23.8	-0.487	0.183	113.3	-34.88	22.1	0.201	
Gc Pop Ins	11911 (5985)	-7.185 (3.762)	34.3	-0.585	0.098	130.3	-39.93	22.8	0.194	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.076 (0.205)	-0.045 (0.077)	4.7	-0.216	0.576	0.174 (0.053)	-0.052 (0.0799)	5.7	-0.238	0.538
Kc Pop Ins	0.183 (0.46)	-0.119 (0.173)	6.3	-0.252	0.514	0.453 (0.121)	-0.103 (0.182)	4.4	-0.210	0.588
J-Integral PQ	82.75 (62.22)	-19.25 (23.46)	8.8	-0.296	0.439	128.6 (16.71)	-10.68 (25.18)	2.5	-0.158	0.684
J-Integral Pop Ins	269.5 (69.5)	-10.39 (26.21)	2.2	-0.148	0.704	294.6 (18.22)	-4.73 (27.45)	0.4	-0.065	0.686
GQ	-40.90 (77.77)	-43.32 (29.33)	23.8	-0.487	0.183	54.65 (20.25)	-44.62 (30.52)	23.4	-0.484	0.187
Gc Pop Ins	-318.1 (428.7)	-308.4 (161.6)	34.2	-0.585	0.098	384.3 (121)	-258.7 (182.3)	22.3	-0.473	0.199

Appendix 13.4: Osteoarthritic Disks AL

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.209 (0.162)	-0.0015 (0.0025)	6.8	-0.260	0.573	0.1998	-0.651	3.6	0.684
Kc Pop Ins	0.761 (0.573)	-0.0067 (0.0088)	10.6	-0.325	0.476	1.605	-1.179	8.7	0.521
J-Integral PQ	-113.4 (546)	9.620 (8.356)	21.0	0.458	0.302	0.184	1.385	27.4	0.228
J-Integral Pop Ins	777 (2202)	11.95 (33.70)	2.5	0.157	0.737	1.835	0.737	6.1	0.594
GQ	47.18 (61.89)	-0.331 (0.947)	2.4	-0.154	0.741	2.371	-0.57	1.1	0.825
Gc Pop Ins	544.1 (505.7)	-5.21 (7.74)	8.3	-0.288	0.531	5.181	-1.627	7.9	0.542

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.94 (0.592)	0.00026 (0.00015)	38.7	0.622	0.136	-35.01	9.431	34.5	0.166	
Kc Pop Ins	-4.28 (1.8)	0.001 (0.0004)	56.7	0.753	0.051	-48.64	13.33	50.9	0.072	
J-Integral PQ	-209 (2756)	0.1775 (0.678)	1.4	0.116	0.804	-2.497	1.438	1.4	0.804	
J-Integral Pop Ins	1468 (10077)	0.021 (2.48)	0	0.004	0.994	9.492	-1.752	1.6	0.789	
GQ	-159.4 (270.7)	0.046 (0.067)	8.6	0.292	0.524	-32.81	9.463	13.5	0.417	
Gc Pop Ins	-3623 (1662)	0.942 (0.409)	51.5	0.718	0.069	-60.06	17.26	40.6	0.124	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.124 (0.0176)	0.0189 (0.0146)	24.9	0.499	0.254	0.11 (0.0114)	0.035 (0.014)	56.5	0.752	0.051
Kc Pop Ins	0.38 (0.056)	0.089 (0.046)	42.2	0.650	0.114	0.315 (0.039)	0.133 (0.048)	60.7	0.779	0.039
J-Integral PQ	543.1 (69.97)	48.56 (58.14)	12.2	0.350	0.442	509.7 (61.65)	39.17 (75.32)	5.1	0.226	0.625
J-Integral Pop Ins	1602.5 (268.1)	75.9 (222.8)	2.3	0.151	0.747	1550.4 (228.9)	57.3 (279.6)	0.8	0.091	0.846
GQ	26.85 (7.55)	1.835 (6.28)	1.7	0.130	0.782	25.16 (5.57)	8.92 (6.81)	25.6	0.505	0.247
Gc Pop Ins	248.5 (53.22)	66.82 (44.22)	31.4	0.560	0.191	198.8 (33.48)	117.3 (40.91)	62.2	0.788	0.035

Appendix 13.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = $a + b(\text{Proximal Phalanx SOS m s}^{-1})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Proximal Phalanx SOS m s}^{-1})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.092 (0.496)	0.000005 (0.0001)	0	0.018	0.970	1.446	-0.675	0.4	0.890
Kc Pop Ins	-0.52 (1.756)	0.0002 (0.0004)	4.4	0.209	0.653	-5.95	1.51	1.5	0.791
J-Integral PQ	1434 (1774)	-0.2364 (0.4545)	5.1	-0.227	0.625	10.77	-2.249	7.8	0.544
J-Integral Pop Ins	3659 (6548)	-0.54 (1.68)	2.0	-0.142	0.761	10.51	-2.05	5.1	0.628
GQ	115 (181.5)	-0.023 (0.046)	4.6	-0.215	0.643	20.11	-5.23	9.7	0.495
Gc Pop Ins	-1 (1564)	0.053 (0.401)	0.3	0.059	0.900	5.328	-0.861	0.2	0.917
	Mechanical Parameter = $a + b(\text{Proximal Phalanx T-score})$					Mechanical Parameter = $a + b(\text{Proximal Phalanx Z-score})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.11 (0.023)	-0.002 (0.023)	0.2	-0.044	0.925	0.112 (0.017)	0.0016 (0.0245)	0.1	0.029
Kc Pop Ins	0.347 (0.081)	0.037 (0.081)	4.0	0.200	0.667	0.322 (0.062)	0.016 (0.089)	0.6	0.081
J-Integral PQ	501.4 (83.15)	-16.13 (83.64)	0.7	-0.086	0.855	513.7 (57.52)	-83.28 (82.03)	17.1	-0.413
J-Integral Pop Ins	1523.3 (302.3)	-46.7 (304.1)	0.5	-0.068	0.884	1557.6 (222.1)	-183.1 (316.7)	6.3	-0.250
GQ	21.25 (7.96)	-6.8 (8.01)	12.6	-0.355	0.434	25.66 (6.44)	0.293 (9.19)	0	0.014
Gc Pop Ins	205.9 (71.77)	0.51 (72.2)	0	0.003	0.995	205.4 (54.28)	7.03 (77.41)	0.2	0.041

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia SOS m s}^{-1})$					$\log(\text{Mechanical Parameter}) = a + b \log(\text{Mid-Shaft Tibia SOS m s}^{-1})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.371 (0.374)	0.00038 (0.00009)	79.9	0.894	0.016	-51.14	13.96	81.7	0.013
Kc Pop Ins	-5.57 (1.141)	0.0015 (0.00029)	87.1	0.933	0.007	-65.9	18.19	91.4	0.003
J-Integral PQ	576 (3096)	-0.01 (0.786)	0	-0.006	0.990	5.705	-0.832	0.5	0.897
J-Integral Pop Ins	-2632 (11766)	1.078 (2.985)	3.2	0.178	0.736	1.41	0.494	0.1	0.950
GQ	-287.7 (279.2)	0.08 (0.071)	24.2	0.492	0.321	-55.84	15.92	40.4	0.175
Gc Pop Ins	-4264 (1603)	1.139 (0.407)	66.2	0.814	0.049	-85.36	24.37	78.6	0.019
	Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia T-score})$					Mechanical Parameter = $a + b(\text{Mid-Shaft Tibia Z-score})$			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.14 (0.0058)	0.048 (0.0068)	92.6	0.962	0.002	0.121 (0.0086)	0.033 (0.0086)	78.7	0.887
Kc Pop Ins	0.419 (0.031)	0.177 (0.037)	85.3	0.924	0.008	0.35 (0.0496)	0.101 (0.05)	50.4	0.710
J-Integral PQ	522.6 (78.36)	-33.39 (91.76)	3.2	-0.179	0.734	532.8 (61.32)	-63.0 (62.0)	20.5	-0.453
J-Integral Pop Ins	1643.4 (306.2)	67.2 (358.6)	0.9	0.093	0.861	1612.1 (265.1)	-32.6 (268.1)	0.4	-0.061
GQ	33.7 (6.12)	12.97 (7.16)	45.0	0.671	0.145	28.88 (3.645)	12.38 (3.685)	73.8	0.859
Gc Pop Ins	286.1 (34.99)	144.6 (40.98)	75.7	0.870	0.024	229.9 (38.62)	96.19 (39.05)	60.3	0.776

Appendix 13.4: Continued

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.353 (0.161)	-0.003 (0.002)	34.7	-0.589	0.219	3.366	-2.274	38.5	0.189
Kc Pop Ins	0.944 (0.695)	-0.0076 (0.0087)	15.9	-0.398	0.434	3.756	-2.245	24.7	0.316
J-Integral PQ	-516.2 (516.8)	13.29 (6.49)	51.2	0.715	0.110	1.24	2.085	53.0	0.101
J-Integral Pop Ins	-1644 (2340)	41.12 (29.40)	32.8	0.573	0.235	-1.165	2.293	43.3	0.155
GQ	155.53 (42.08)	-1.609 (0.529)	69.8	-0.836	0.038	11.15	-5.15	75.0	0.026
Gc Pop Ins	1247.1 (412)	-12.92 (5.176)	60.9	-0.780	0.067	11.93	-5.09	60.8	0.067
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.089 (0.0255)	-0.0479 (0.033)	34.2	-0.585	0.223	0.1221 (0.0165)	-0.033 (0.031)	22.4	-0.474 0.343
Kc Pop Ins	0.2665 (0.1098)	-0.123 (0.143)	15.6	-0.395	0.438	0.355 (0.062)	-0.132 (0.115)	24.7	-0.497 0.316
J-Integral PQ	671.78 (81.69)	217 (106.4)	51	0.714	0.111	532 (68.07)	54.7 (126.4)	4.5	0.211 0.688
J-Integral Pop Ins	2032.7 (368.9)	674 (480.5)	33	0.574	0.233	1589.7 (259)	268.4 (480.9)	7.2	0.269 0.606
GQ	11.78 (6.7)	-26.21 (8.73)	69.3	-0.832	0.040	28.96 (6.71)	-9.87 (12.45)	13.6	-0.368 0.472
Gc Pop Ins	92.71 (65.34)	-210.6 (85.12)	60.5	-0.778	0.069	237.2 (47.04)	-150.2 (87.32)	42.5	-0.652 0.161

Osteoarthritic Discs AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-0.332 (0.791)	0.0003 (0.0005)	7.5	0.274	0.599	-10.34	2.936	3.7	0.715
Kc Pop Ins	-1.41 (3.01)	0.001 (0.0019)	7.8	0.280	0.591	-13.35	4.016	4.6	0.684
J-Integral PQ	1002 (3046)	-0.295 (1.929)	0.6	-0.076	0.886	8.235	-1.726	2.1	0.784
J-Integral Pop Ins	677 (11789)	0.594 (7.466)	0.2	0.040	0.940	3.424	-0.075	0	0.992
GQ	-68.6 (312.8)	0.061 (0.1981)	2.3	0.153	0.773	1.841	-0.142	0	0.991
Gc Pop Ins	-592 (2691)	0.516 (1.704)	2.2	0.150	0.777	-4.18	2.018	0.6	0.889
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.154 (0.064)	0.012 (0.0215)	7.5	0.274	0.60	0.122 (0.026)	0.004 (0.0253)	0.6	0.078 0.883
Kc Pop Ins	0.479 (0.244)	0.0475 (0.0818)	7.8	0.279	0.592	0.363 (0.098)	0.0278 (0.0957)	2.1	0.144 0.786
J-Integral PQ	500.8 (247.7)	-12.62 (82.88)	0.6	-0.076	0.886	545.46 (96.41)	11.69 (94.24)	0.4	0.062 0.907
J-Integral Pop Ins	1687.6 (958.6)	25.5 (320.7)	0.2	0.040	0.940	1653.3 (372)	54.3 (363.6)	0.6	0.074 0.889
GQ	35.58 (25.44)	2.622 (8.51)	2.3	0.152	0.773	27.02 (9.98)	-1.43 (9.76)	0.5	-0.073 0.890
Gc Pop Ins	286.9 (218.8)	22.08 (73.22)	2.2	0.149	0.778	220.3 (86.03)	-4.32 (84.09)	0.1	-0.026 0.961

Appendix 14: Osteoporotic +Osteoarthritic Group Fracture Toughness Testing Results vs. Clinical QUS Regressions

Appendix 14.1: Osteoporotic + Osteoarthritic Beams Ac

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.867 (0.114)	-0.0082 (0.0015)	22.8	-0.478	<0.001	3.433	-2.2	18.8	<0.001
Kc Pop Ins	1.299 (0.159)	-0.0123 (0.0021)	25.6	-0.506	<0.001	3.731	-2.27	21.1	<0.001
J-Integral PQ	404.1 (45.31)	-4.12 (0.607)	32.6	-0.571	<0.001	6.72	-2.585	27.1	<0.001
J-Integral Pop Ins	1672.5 (210.3)	-17.34 (2.813)	28.2	-0.531	<0.001	8.307	-3.14	29.1	<0.001
GQ	898.5 (146.2)	-9.434 (1.957)	19.0	-0.436	<0.001	8.138	-3.254	14.7	<0.001
Gc Pop Ins	1925.6 (285.6)	-20.23 (3.824)	22.0	-0.469	<0.001	8.70	-3.367	16.7	<0.001

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	-1.426 (0.585)	0.00042 (0.000145)	7.9	0.281	0.005	-22.07	5.934	5.5	0.020
Kc Pop Ins	-1.96 (0.834)	0.00058 (0.00021)	7.5	0.275	0.006	-18.11	4.88	3.9	0.050
J-Integral PQ	235.3 (256.2)	-0.0336 (0.063)	0.3	-0.055	0.597	6.261	-1.21	0.2	0.634
J-Integral Pop Ins	1421 (1165)	-0.256 (0.288)	0.8	-0.090	0.377	8.222	-1.6	0.3	0.592
GQ	-1815.2 (734.2)	0.499 (0.182)	7.1	0.267	0.007	-25.66	7.691	3.3	0.069
Gc Pop Ins	-3535 (1463)	0.982 (0.362)	7.0	0.264	0.008	-17.61	5.556	1.8	0.178
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.319 (0.0203)	0.0546 (0.0132)	15.1	0.388	<0.001	0.274 (0.0176)	-0.0172 (0.015)	1.4	-0.118 0.251
Kc Pop Ins	0.468 (0.029)	0.077 (0.0187)	14.8	0.385	<0.001	0.406 (0.025)	-0.028 (0.021)	1.8	-0.134 0.190
J-Integral PQ	100.23 (9.361)	0.780 (6.03)	0	0.013	0.897	112 (7.121)	-24.60 (5.963)	15.6	-0.395 <0.001
J-Integral Pop Ins	392.7 (41.91)	4.55 (27.49)	0	0.017	0.869	450 (31.82)	-116.86 (26.61)	17.0	-0.413 <0.001
GQ	262.2 (25.79)	59.98 (16.80)	11.5	0.339	0.001	211.63 (22.61)	-14.59 (19.06)	0.6	-0.078 0.446
Gc Pop Ins	552.8 (51.29)	120.36 (33.40)	11.7	0.342	<0.001	455.52 (44.86)	-37.15 (37.83)	1.0	-0.100 0.329

Appendix 14.1: Continued

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.541 (0.365)	0.00021 (0.0001)	5.0	0.223	0.031	-13.47	3.565	5.5	0.022	
Kc Pop Ins	-0.766 (0.521)	0.0003 (0.00014)	5.0	0.225	0.030	-12.396	3.317	5.0	0.029	
J-Integral PQ	-153.7 (158.4)	0.0665 (0.041)	2.9	0.169	0.108	-6.496	2.346	2.5	0.133	
J-Integral Pop Ins	-182.7 (720.1)	0.152 (0.187)	0.7	0.085	0.418	-5.753	2.294	1.8	0.205	
GQ	-742.7 (466.6)	0.2445 (0.121)	4.2	0.205	0.046	-16.25	5.106	4.0	0.052	
Gc Pop Ins	-1561.9 (925.9)	0.517 (0.240)	4.7	0.218	0.034	-14.04	4.588	3.4	0.073	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.309 (0.0223)	0.0459 (0.0138)	10.7	0.328	0.001	0.2777 (0.0183)	-0.0345 (0.016)	4.8	-0.220	0.035
Kc Pop Ins	0.458 (0.0318)	0.0666 (0.0196)	11.1	0.333	0.001	0.414 (0.026)	-0.053 (0.0228)	5.7	-0.238	0.023
J-Integral PQ	117.3 (9.734)	13.27 (6.075)	5.1	0.226	0.032	113.28 (7.873)	-18.886 (7.009)	7.7	-0.278	0.008
J-Integral Pop Ins	453.3 (44.38)	46.47 (27.79)	3.0	0.173	0.098	459.5 (34.01)	-106.6 (29.72)	12.6	-0.355	0.001
GQ	256.82 (28.59)	51.76 (17.77)	8.4	0.289	0.004	219.6 (23.55)	-35.97 (20.78)	3.2	-0.179	0.087
Gc Pop Ins	550.4 (56.56)	109.44 (35.16)	9.4	0.307	0.002	472.7 (46.65)	-77.71 (41.16)	3.8	-0.194	0.062

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.133 (0.285)	0.0001 (0.0001)	2.0	0.142	0.176	-7.461	1.883	2.3	0.149	
Kc Pop Ins	-0.107 (0.408)	0.00012 (0.0001)	1.5	0.124	0.238	-6.11	1.557	1.7	0.221	
J-Integral PQ	260.4 (120.1)	-0.042 (0.03)	2.2	-0.147	0.170	8.789	-1.92	2.6	0.130	
J-Integral Pop Ins	1151 (578)	-0.195 (0.145)	2.0	-0.141	0.182	10.78	-2.32	2.6	0.130	
GQ	-178.9 (361.3)	0.093 (0.091)	1.1	0.107	0.307	-7.674	2.702	1.7	0.218	
Gc Pop Ins	-249.5 (717.3)	0.166 (0.180)	0.9	0.096	0.360	-4.936	2.039	1.0	0.339	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.254 (0.0164)	0.0074 (0.009)	0.8	0.087	0.411	0.279 (0.0192)	-0.0186 (0.0094)	4.3	-0.207	0.050
Kc Pop Ins	0.376 (0.023)	0.0079 (0.0129)	0.4	0.065	0.541	0.416 (0.0271)	-0.030 (0.013)	5.7	-0.238	0.024
J-Integral PQ	94.95 (6.853)	-7.287 (3.731)	4.2	-0.205	0.054	113.3 (7.71)	-15.65 (3.71)	17.3	-0.416	<0.001
J-Integral Pop Ins	377 (32.36)	-35.74 (17.92)	4.3	-0.207	0.049	470.24 (35.73)	-79.85 (17.30)	19.7	-0.444	<0.001
GQ	191.21 (20.57)	6.59 (11.40)	0.4	0.061	0.564	217.6 (24.39)	-20.53 (11.94)	3.2	-0.179	0.089
Gc Pop Ins	408.99 (40.83)	9.51 (22.62)	0.2	0.044	0.675	470.14 (47.96)	-48.28 (23.48)	4.5	-0.213	0.043

Appendix 14.1: Continued

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.0669 (0.0524)	0.0031 (0.00084)	13.1	0.362	<0.001	-1.872	0.675	13.0	<0.001	
Kc Pop Ins	0.0837 (0.0735)	0.0048 (0.00117)	15.8	0.397	<0.001	-1.738	0.699	14.8	<0.001	
J-Integral PQ	-37.61 (19.12)	2.185 (0.305)	36.9	0.608	<0.001	0.225	0.941	26.9	<0.001	
J-Integral Pop Ins	-274.66 (89.85)	10.751 (1.431)	38.6	0.621	<0.001	0.307	1.212	30.6	<0.001	
GQ	16.40 (68.28)	2.886 (1.087)	7.1	0.267	0.009	0.453	0.907	8.3	0.005	
Gc Pop Ins	11.9 (133.7)	6.573 (2.129)	9.4	0.306	0.003	0.725	0.953	9.7	0.002	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.344 (0.029)	0.051 (0.014)	13.1	0.362	<0.001	0.254 (0.018)	0.0022 (0.0166)	0	0.014	0.893
Kc Pop Ins	0.518 (0.0407)	0.081 (0.0195)	15.9	0.398	<0.001	0.3786 (0.0256)	0.0092 (0.0237)	0.2	0.041	0.700
J-Integral PQ	158.2 (10.54)	36.3 (5.06)	36.9	0.607	<0.001	105.1 (7.12)	24.397 (6.494)	13.8	0.372	<0.001
J-Integral Pop Ins	689 (49.29)	178.7 (23.76)	38.6	0.621	<0.001	427.4 (33.88)	117.70 (31.62)	13.3	0.365	<0.001
GQ	275.3 (37.60)	48.07 (18.05)	7.2	0.267	0.009	187.6 (22.60)	-5.19 (20.93)	0.1	-0.026	0.805
Gc Pop Ins	601.71 (73.64)	109.6 (35.35)	9.5	0.308	0.003	406.65 (44.83)	-1.41 (41.53)	0	-0.004	0.973

OP + OA Beams Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.9397 (0.744)	0.00076 (0.00048)	2.7	0.165	0.112	-20.44	6.186	3.9	0.058	
Kc Pop Ins	-1.649 (1.054)	0.0013 (0.0068)	3.9	0.196	0.058	-22.85	6.995	5.2	0.027	
J-Integral PQ	-1221 (291.5)	0.841 (0.187)	18.6	0.431	<0.001	-38.64	12.69	17.2	<0.001	
J-Integral Pop Ins	-5089 (1427)	3.496 (0.913)	13.9	0.372	<0.001	-44.53	14.7	15.9	<0.001	
GQ	-1134.7 (940.2)	0.848 (0.602)	2.1	0.145	0.162	-23.54	8.012	2.3	0.144	
Gc Pop Ins	-2779 (1855)	2.04 (1.19)	3.1	0.175	0.089	-28.26	9.6	3.5	0.070	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.360 (0.069)	0.0328 (0.025)	2.7	0.165	0.112	0.272 (0.026)	0.0204 (0.0225)	0.9	0.094	0.368
Kc Pop Ins	0.557 (0.0975)	0.0557 (0.029)	3.9	0.196	0.058	0.408 (0.0371)	0.036 (0.032)	1.4	0.116	0.264
J-Integral PQ	210.78 (26.66)	36.2 (8.006)	18.7	0.432	<0.001	119.8 (10.45)	29.53 (9.187)	10.4	0.323	0.002
J-Integral Pop Ins	862.6 (131.7)	150.56 (39.22)	13.9	0.373	<0.001	473.45 (51.21)	113.10 (44.50)	6.6	0.257	0.013
GQ	309.27 (86.82)	36.43 (25.82)	2.1	0.145	0.162	208.2 (32.90)	19.70 (28.42)	0.5	0.072	0.490
Gc Pop Ins	693.8 (171.3)	87.66 (51.01)	3.1	0.175	0.089	454.5 (65.12)	51.50 (56.25)	0.9	0.095	0.362

Appendix 14.2: Osteoporotic + Osteoarthritic Beams AL

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.456 (0.158)	-0.0034 (0.00196)	4.2	-2.05	0.092	1.126	-1.031	2.5	0.192
Kc Pop Ins	0.833 (0.2085)	-0.0072 (0.0026)	10.3	-0.321	0.007	2.688	-1.775	8.7	0.014
J-Integral PQ	867.7 (105.5)	-9.07 (1.312)	41.6	-0.645	<0.001	9.671	-4.015	42.7	<0.001
J-Integral Pop Ins	3760 (557.3)	-39.54 (6.93)	32.7	-0.572	<0.001	10.8	-4.293	40.8	<0.001
GQ	181.8 (164.9)	-0.777 (2.051)	0.2	-0.046	0.706	2.794	-0.524	0.2	0.699
Gc Pop Ins	667.9 (290.1)	-5.609 (3.607)	3.5	-0.187	0.125	5.918	-2.012	4.0	0.10

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-1.724 (0.761)	0.00047 (0.0002)	13.6	0.369	0.017	-21.702	5.765	4.5	0.185	
Kc Pop Ins	-2.443 (1.064)	0.00066 (0.00026)	14.1	0.375	0.016	-21.31	5.71	5.3	0.148	
J-Integral PQ	-469.6 (799.2)	0.162 (0.197)	1.7	0.131	0.416	-13.59	4.371	3.4	0.251	
J-Integral Pop Ins	-231 (4027)	0.258 (0.993)	0.2	0.042	0.796	-10.86	3.788	2.3	0.343	
GQ	-1338.6 (594.8)	0.3519 (0.1467)	12.9	0.359	0.021	-23.72	7.035	2.4	0.333	
Gc Pop Ins	-2675 (1202)	0.7077 (0.2965)	12.7	0.357	0.022	-22.93	6.926	2.9	0.283	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.197 (0.025)	0.0442 (0.0186)	12.6	0.356	0.022	0.146 (0.0264)	0.0356 (0.0247)	5.3	0.230	0.158
Kc Pop Ins	0.295 (0.0347)	0.0636 (0.026)	13.3	0.365	0.019	0.224 (0.0371)	0.0483 (0.0347)	5.0	0.223	0.172
J-Integral PQ	210.15 (25.37)	30.27 (18.97)	6.1	0.248	0.119	208.3 (26.46)	-31.43 (24.73)	4.2	-0.205	0.212
J-Integral Pop Ins	885.2 (129.4)	93.93 (96.75)	2.4	0.154	0.338	937.4 (131.0)	-183.7 (122.4)	5.7	-0.240	0.142
GQ	111.4 (19.58)	31.28 (14.64)	10.5	0.324	0.039	70.09 (20.44)	33.01 (19.10)	7.5	0.273	0.092
Gc Pop Ins	241.44 (39.54)	63.29 (29.57)	10.5	0.324	0.039	158.71 (41.26)	64.47 (38.56)	7.0	0.265	0.103

Appendix 14.2: Continued

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.129 (0.554)	0.00001 (0.00014)	0	0.011	0.946	4.026	-1.372	0.6	0.630	
Kc Pop Ins	0.185 (0.778)	0.00002 (0.0002)	0	0.014	0.933	3.548	-1.185	0.5	0.654	
J-Integral PQ	129.9 (544.4)	0.016 (0.141)	0	0.019	0.910	-0.799	0.833	0.3	0.743	
J-Integral Pop Ins	1048 (2734)	-0.0561 (0.7085)	0	-0.013	0.937	-1.571	1.221	0.6	0.646	
GQ	124.2 (432)	-0.009 (0.112)	0	-0.013	0.937	13.71	-3.357	1.4	0.475	
Gc Pop Ins	297.2 (873.5)	-0.0259 (0.226)	0	-0.019	0.909	12.76	-2.983	1.3	0.485	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.174 (0.0322)	0.0069 (0.022)	0.3	0.051	0.758	0.182 (0.0249)	-0.031 (0.0224)	5.2	-0.228	0.174
Kc Pop Ins	0.262 (0.0453)	0.0104 (0.0313)	0.3	0.055	0.742	0.273 (0.0348)	-0.0458 (0.0314)	5.7	-0.239	0.154
J-Integral PQ	208.7 (31.44)	16.41 (21.71)	1.5	0.123	0.454	218.4 (22.82)	-59.25 (20.58)	19.2	-0.438	0.007
J-Integral Pop Ins	888.4 (158.5)	56.1 (109.5)	0.7	0.084	0.611	952.1 (117.5)	-260.1 (105.9)	14.7	-0.383	0.019
GQ	90.23 (25.14)	0.53 (17.36)	0	0.005	0.976	98.81 (19.69)	-19.69 (17.76)	3.4	-0.184	0.275
Gc Pop Ins	196.93 (50.83)	-0.28 (35.10)	0	-0.001	0.994	216.3 (39.59)	-42.66 (35.70)	3.9	-0.198	0.240

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.153 (0.398)	0.000003 (0.0001)	0	0.004	0.978	2.299	-0.889	0.4	0.683	
Kc Pop Ins	0.1856 (0.557)	0.00002 (0.00014)	0	0.018	0.912	0.326	-0.286	0.1	0.885	
J-Integral PQ	305.4 (390.9)	-0.0296 (0.098)	0.2	-0.048	0.764	3.677	-0.416	0.1	0.827	
J-Integral Pop Ins	1115 (1957)	-0.0753 (0.490)	0.1	-0.025	0.879	3.653	-0.236	0	0.906	
GQ	57.8 (309.3)	0.0076 (0.0775)	0	0.016	0.923	8.275	-1.837	0.7	0.611	
Gc Pop Ins	106 (624.8)	0.0221 (0.156)	0.1	0.023	0.888	4.33	-0.631	0.1	0.845	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.165 (0.0221)	-0.0048 (0.0135)	0.3	-0.056	0.726	0.18 (0.027)	-0.014 (0.0148)	2.3	-0.150	0.361
Kc Pop Ins	0.248 (0.031)	-0.0048 (0.019)	0.2	-0.040	0.802	0.269 (0.0374)	-0.0184 (0.021)	2.1	-0.144	0.382
J-Integral PQ	189.3 (21.53)	-12.29 (13.15)	2.2	-0.148	0.356	228.1 (24.22)	-39.38 (13.42)	18.9	-0.435	0.006
J-Integral Pop Ins	820.9 (108.3)	-41.11 (66.14)	1.0	-0.099	0.538	978.1 (126.3)	-152.5 (70.0)	11.4	-0.337	0.036
GQ	88.27 (17.20)	-2.04 (10.50)	0.1	-0.031	0.847	94.87 (21.07)	-5.91 (11.67)	0.7	-0.083	0.616
Gc Pop Ins	194.44 (34.76)	-2.82 (21.22)	0	-0.021	0.895	206.9 (42.44)	-11.33 (23.51)	0.6	-0.079	0.633

Appendix 14.2: Continued

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.078 (0.078)	0.0014 (0.001)	3.3	0.181	0.258	-1.523	0.353	4.6	0.180	
Kc Pop Ins	0.1335 (0.1098)	0.0019 (0.0017)	2.9	0.171	0.285	-1.175	0.267	3.2	0.267	
J-Integral PQ	-83.06 (63.92)	4.408 (1.001)	33.2	0.576	<0.001	1.162	0.578	16.1	0.009	
J-Integral Pop Ins	-182.3 (354.1)	16.25 (5.54)	18.1	0.425	0.006	2.03	0.439	8.5	0.065	
GQ	45.53 (61.43)	0.691 (0.962)	1.3	0.114	0.476	0.911	0.427	2.4	0.332	
Gc Pop Ins	117.4 (124.2)	1.248 (1.945)	1.0	0.102	0.525	1.608	0.256	1.1	0.515	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.203 (0.041)	0.0229 (0.0202)	3.2	0.179	0.264	0.166 (0.0252)	0.0038 (0.0234)	0.1	0.026	0.872
Kc Pop Ins	0.2996 (0.0572)	0.0304 (0.0284)	2.9	0.169	0.291	0.248 (0.0353)	0.0008 (0.0328)	0	0.004	0.981
J-Integral PQ	311.9 (33.27)	72.96 (16.52)	33.3	0.577	<0.001	208.2 (23.80)	39.90 (22.10)	7.7	0.278	0.079
J-Integral Pop Ins	1272.9 (184.4)	268.6 (91.57)	18.1	0.425	0.006	877.5 (122.1)	120.3 (113.4)	2.8	0.168	0.295
GQ	107.1 (32.01)	11.20 (15.89)	1.3	0.112	0.485	88.56 (19.58)	1.14 (18.18)	0	0.010	0.950
Gc Pop Ins	228.45 (64.74)	20.18 (32.14)	1.0	0.100	0.534	193.1 (39.55)	-1.88 (36.72)	0	-0.008	0.960

OP + OA Beams AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.79 (1.25)	0.00061 (0.0008)	1.5	0.121	0.451	-19.77	5.907	2.0	0.378	
Kc Pop Ins	-0.880 (1.76)	0.00072 (0.0011)	1.0	0.102	0.525	-10.95	3.207	0.7	0.600	
J-Integral PQ	-1532 (1211)	1.1 (0.775)	4.9	0.222	0.164	-25.94	8.804	5.8	0.128	
J-Integral Pop Ins	-4755 (6147)	3.562 (3.93)	2.1	0.144	0.370	-17.39	6.321	2.7	0.301	
GQ	-272.2 (980.2)	0.230 (0.627)	0.3	0.059	0.715	-17.73	6.07	0.8	0.587	
Gc Pop Ins	-331 (1982)	0.336 (1.267)	0.2	0.042	0.792	-0.086	0.671	0	0.946	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.249 (0.113)	0.0263 (0.0344)	1.5	0.122	0.449	0.16 (0.0373)	-0.0049 (0.038)	0	-0.020	0.899
Kc Pop Ins	0.348 (0.159)	0.0311 (0.0483)	1.1	0.103	0.524	0.236 (0.0522)	-0.0146 (0.053)	0.2	-0.044	0.786
J-Integral PQ	340.7 (109.1)	47.58 (33.25)	5.0	0.223	0.160	195.1 (36.66)	9.61 (37.39)	0.2	0.041	0.799
J-Integral Pop Ins	1312.4 (554.0)	154.5 (168.8)	2.1	0.145	0.366	810.8 (183.5)	-5.1 (187.1)	0	-0.004	0.978
GQ	120 (88.35)	9.94 (26.91)	0.3	0.059	0.714	80.17 (28.96)	-9.86 (29.54)	0.3	-0.053	0.740
Gc Pop Ins	240.9 (178.6)	14.54 (54.41)	0.2	0.043	0.791	172.94 (58.44)	-26.66 (59.59)	0.5	-0.071	0.657

Appendix 14.3: Osteoporotic + Osteoarthritic Disks Ac

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.242 (0.229)	-0.0002 (0.0029)	0	-0.013	0.943	-1.76	0.545	0.6	0.670
Kc Pop Ins	1.133 (0.372)	-0.0097 (0.0048)	11.9	-0.345	0.049	1.572	-1.099	2.7	0.362
J-Integral PQ	-448.4 (216.3)	8.795 (2.766)	24.6	0.496	0.003	-3.508	3.082	33.3	<0.001
J-Integral Pop Ins	-1402.6 (542.4)	25.79 (6.938)	30.8	0.555	0.001	-3.599	3.345	38.3	<0.001
GQ	-170.5 (154.9)	3.747 (1.977)	10.7	0.327	0.068	-4.863	3.578	9.4	0.087
Gc Pop Ins	853.7 (439.2)	-6.69 (5.606)	4.5	-0.213	0.242	2.011	0.182	0	0.927

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.92 (0.773)	0.00028 (0.00019)	8.5	0.292	0.157	-16.78	4.438	3.7	0.357	
Kc Pop Ins	-1.179 (1.456)	0.00038 (0.00036)	4.7	0.217	0.297	-9.80	2.573	1.3	0.592	
J-Integral PQ	723.9 (400.5)	-0.135 (0.099)	7.5	-0.274	0.186	14.19	-3.32	8.4	0.160	
J-Integral Pop Ins	1443 (1030)	-0.2436 (0.2541)	3.8	-0.196	0.348	11.17	-2.368	4.2	0.325	
GQ	-218.4 (538.3)	0.0804 (0.133)	1.6	0.128	0.552	-10.462	3.40	0.8	0.667	
Gc Pop Ins	-130 (1660)	0.115 (0.41)	0.4	0.060	0.782	2.61	-0.080	0	0.992	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.233 (0.0296)	0.0266 (0.0191)	7.8	0.279	0.177	0.197 (0.0293)	0.0163 (0.0184)	3.3	0.181	0.387
Kc Pop Ins	0.421 (0.0542)	0.0536 (0.035)	9.3	0.304	0.139	0.383 (0.055)	-0.0097 (0.0345)	0.3	-0.059	0.781
J-Integral PQ	163.4 (14.96)	-16.67 (9.650)	11.5	-0.339	0.097	179.0 (15.34)	-1.379 (9.655)	0.1	-0.030	0.888
J-Integral Pop Ins	422.03 (38.04)	-39.29 (24.54)	10.0	-0.317	0.123	447.1 (38.54)	11.08 (24.26)	0.9	0.095	0.652
GQ	110.76 (20.98)	4.23 (13.30)	0.5	0.068	0.753	98.12 (19.65)	11.51 (12.44)	3.7	0.193	0.365
Gc Pop Ins	363.6 (63.53)	32.00 (40.28)	2.8	0.167	0.435	359.38 (60.49)	-30.92 (38.30)	2.9	-0.170	0.428

Appendix 14.3: Continued

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.622 (0.626)	0.00021 (0.00016)	7.3	0.270	0.201	-20.84	5.596	9.0	0.153	
Kc Pop Ins	-1.472 (1.209)	0.00048 (0.003)	9.5	0.309	0.142	-21.31	5.797	9.5	0.142	
J-Integral PQ	409.4 (348.4)	-0.0595 (0.091)	1.9	-0.138	0.519	8.55	-1.763	3.7	0.371	
J-Integral Pop Ins	2023.6 (834.4)	-0.4067 (0.2172)	13.7	-0.371	0.074	15.25	-3.52	13.7	0.075	
GQ	-136.9 (439.9)	0.062 (0.1145)	1.4	0.117	0.594	-20.111	6.11	3.9	0.364	
Gc Pop Ins	-815 (1416)	0.2983 (0.3685)	3.0	0.174	0.427	-21.21	6.561	4.7	0.320	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.234 (0.375)	0.0278 (0.024)	5.8	0.240	0.259	0.189 (0.0273)	0.0224 (0.0243)	3.7	0.193	0.366
Kc Pop Ins	0.465 (0.0703)	0.083 (0.045)	13.4	0.366	0.079	0.377 (0.0541)	-0.0223 (0.048)	1.0	-0.098	0.648
J-Integral PQ	167.3 (20.55)	-11.39 (13.14)	3.3	-0.182	0.395	174.3 (14.72)	12.97 (13.10)	4.3	0.207	0.333
J-Integral Pop Ins	377.45 (47.93)	-70.40 (30.64)	19.4	-0.440	0.031	453.96 (38.22)	15.96 (34.03)	1.0	0.099	0.644
GQ	106.76 (26.43)	4.64 (16.80)	0.4	0.060	0.785	88.55 (18.08)	25.29 (16.01)	10.6	0.326	0.129
Gc Pop Ins	410.77 (82.78)	67.12 (52.61)	7.2	0.268	0.216	353.1 (61.04)	-45.54 (54.05)	3.3	-0.181	0.409

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.669 (0.471)	0.0002 (0.0001)	13.8	0.3725	0.074	-16.67	4.425	9.1	0.152	
Kc Pop Ins	-0.6695 (0.9047)	0.0003 (0.0002)	5.8	0.241	0.256	-13.31	3.56	6.2	0.241	
J-Integral PQ	466 (257.3)	-0.0734 (0.0651)	5.5	-0.234	0.272	9.226	-1.949	7.1	0.207	
J-Integral Pop Ins	1261 (647.1)	-0.205 (0.164)	6.6	-0.258	0.224	9.508	-1.914	6.7	0.221	
GQ	-324.3 (328.7)	0.11 (0.083)	7.7	0.278	0.199	-21.02	6.35	6.9	0.225	
Gc Pop Ins	-176 (1036)	0.1327 (0.2617)	1.2	0.110	0.617	-13.12	4.33	3.6	0.385	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.222 (0.024)	0.0287 (0.0146)	14.8	0.385	0.063	0.19 (0.028)	0.0276 (0.015)	12.8	0.357	0.087
Kc Pop Ins	0.391 (0.0475)	0.0268 (0.0286)	3.8	0.196	0.358	0.392 (0.0553)	-0.008 (0.03)	0.3	-0.056	0.794
J-Integral PQ	174.5 (13.46)	-7.916 (8.1)	4.2	-0.204	0.339	176.2 (15.73)	0.040 (8.597)	0	0.001	0.996
J-Integral Pop Ins	448.29 (34.04)	-20.56 (20.48)	4.4	-0.209	0.326	444.7 (39.66)	8.95 (21.67)	0.8	0.088	0.684
GQ	113.61 (16.97)	15.82 (10.08)	10.5	0.324	0.132	89.62 (18.24)	22.96 (9.802)	20.7	0.445	0.029
Gc Pop Ins	349.6 (54.52)	8.66 (32.41)	0.3	0.058	0.792	375.2 (61.23)	-29.63 (32.90)	3.7	-0.193	0.378

Appendix 14.3: Continued

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.071 (0.089)	0.0021 (0.0014)	9.4	0.307	0.144	-2.533	0.978	16.6	0.048	
Kc Pop Ins	-0.1134 (0.149)	0.0076 (0.0023)	33.5	0.579	0.003	-3.225	1.511	39.0	0.001	
J-Integral PQ	248.56 (48.39)	-1.075 (0.743)	8.7	-0.295	0.162	2.773	-0.304	6.6	0.227	
J-Integral Pop Ins	843.6 (98.09)	-6.065 (1.505)	42.5	-0.652	0.001	3.977	-0.753	37.7	0.001	
GQ	92.35 (63.94)	0.142 (0.988)	0.1	0.031	0.887	0.263	0.856	4.6	0.328	
Gc Pop Ins	-149.0 (177)	7.687 (2.734)	27.3	0.523	0.010	-1.243	1.996	25.7	0.014	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.2554 (0.044)	0.034 (0.0228)	9.2	0.303	0.150	0.214 (0.0238)	0.0565 (0.0298)	14.0	0.375	0.071
Kc Pop Ins	0.569 (0.073)	0.127 (0.038)	33.2	0.576	0.003	0.391 (0.0464)	0.113 (0.058)	14.7	0.384	0.064
J-Integral PQ	152.46 (23.64)	-17.79 (12.41)	8.5	-0.292	0.166	179.91 (13.87)	-4.84 (17.36)	0.4	-0.059	0.783
J-Integral Pop Ins	298.8 (47.69)	-101.8 (25.02)	43.0	-0.655	0.001	443.02 (32.39)	-85.25 (40.52)	16.8	-0.409	0.047
GQ	103.8 (31.98)	1.61 (16.50)	0	0.021	0.923	109.12 (17.54)	29.05 (22.02)	7.7	0.277	0.201
Gc Pop Ins	538.2 (88.81)	127.1 (45.83)	26.8	0.518	0.011	360.89 (55.93)	112.18 (70.21)	10.8	0.329	0.125

OP + OA Disks Ac	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-1.461 (1.177)	0.0011 (0.0075)	8.3	0.288	0.172	-35.89	10.99	9.7	0.139	
Kc Pop Ins	-4.24 (2.195)	0.0029 (0.0014)	16.7	0.408	0.048	-51.91	16.08	20.4	0.027	
J-Integral PQ	1023.5 (641.0)	-0.537 (0.41)	7.3	-0.270	0.202	18.76	-5.172	8.7	0.161	
J-Integral Pop Ins	5038 (1392)	-2.918 (0.888)	32.9	-0.574	0.003	35.06	-10.15	31.7	0.004	
GQ	-405.0 (831.7)	0.323 (0.53)	1.7	0.132	0.549	-28.08	9.348	2.6	0.466	
Gc Pop Ins	-3216 (2610)	2.262 (1.665)	8.1	0.284	0.189	-61.01	19.815	11.9	0.106	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.343 (0.1033)	0.0455 (0.032)	8.3	0.288	0.172	0.239 (0.0348)	0.051 (0.034)	9.2	0.303	0.151
Kc Pop Ins	0.759 (0.193)	0.126 (0.0601)	16.7	0.409	0.047	0.456 (0.066)	0.122 (0.0657)	13.5	0.368	0.077
J-Integral PQ	108.7 (56.24)	-23.17 (17.55)	7.3	-0.271	0.200	172.04 (19.57)	-12.04 (19.39)	1.7	-0.131	0.541
J-Integral Pop Ins	70.6 (122.1)	-125.6 (38.11)	33.1	-0.575	0.003	380.58 (44.53)	-109.8 (44.14)	22.0	-0.469	0.021
GQ	144.30 (73.26)	13.78 (22.79)	1.7	0.131	0.552	121.2 (24.31)	26.99 (23.92)	5.7	0.239	0.272
Gc Pop Ins	634.3 (229.9)	97.24 (71.52)	8.1	0.284	0.188	406.2 (78.01)	102.47 (76.76)	7.8	0.280	0.196

Appendix 14.4: Osteoporotic + Osteoarthritic Disks AL

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship			
	Mechanical Parameter = a + b(Age)					log(Mechanical Parameter) = a + b log(Age)			
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value
Kq	0.241 (0.139)	-0.0007 (0.002)	0.5	-0.069	0.688	-0.752	-0.026	0	0.972
Kc Pop Ins	0.864 (0.209)	-0.0073 (0.0027)	18.2	-0.427	0.009	2.262	-1.514	13.4	0.028
J-Integral PQ	948.8 (171.1)	-9.141 (2.186)	33.3	-0.577	<0.001	6.91	-2.439	37.7	<0.001
J-Integral Pop Ins	3202.6 (627.9)	-33.62 (8.095)	35.0	-0.592	<0.001	8.33	-3.00	39.2	<0.001
GQ	46.36 (97.65)	0.544 (1.247)	0.6	0.075	0.665	-0.546	1.229	2.8	0.330
Gc Pop Ins	672.2 (214.2)	-5.978 (2.736)	12.3	-0.351	0.036	5.48	-1.747	7.8	0.099

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Distal Radius SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Distal Radius SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.707 (0.554)	0.00022 (0.0001)	9.9	0.315	0.125	-18.33	4.853	8.8	0.150	
Kc Pop Ins	-1.929 (1.014)	0.0006 (0.00025)	17.4	0.417	0.038	-23.172	6.26	14.6	0.060	
J-Integral PQ	-150.9 (990.9)	0.107 (0.245)	0.8	0.089	0.665	-0.652	0.845	0.3	0.781	
J-Integral Pop Ins	-1437 (3599)	0.5225 (0.8881)	1.4	0.117	0.562	-7.214	2.751	1.7	0.519	
GQ	-208.1 (378)	0.071 (0.0933)	2.5	0.157	0.455	-12.71	4.00	2.0	0.503	
Gc Pop Ins	-1676 (1027)	0.467 (0.254)	12.8	0.358	0.079	-22.39	6.815	7.6	0.182	
	Mechanical Parameter = a + b(Distal Radius T-Score)					Mechanical Parameter = a + b(Distal Radius Z-Score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.188 (0.0232)	0.0157 (0.0137)	5.4	0.232	0.264	0.159 (0.022)	0.024 (0.0143)	11.2	0.335	0.110
Kc Pop Ins	0.346 (0.0421)	0.0496 (0.0248)	14.8	0.384	0.058	0.282 (0.0427)	0.0313 (0.028)	5.3	0.230	0.279
J-Integral PQ	304.6 (39.73)	22.39 (23.49)	3.6	0.191	0.350	302.7 (37.99)	-25.78 (25.46)	4.3	-0.207	0.322
J-Integral Pop Ins	766.9 (142.1)	92.32 (85.33)	4.5	0.211	0.290	763.9 (137.2)	-100.6 (90.47)	4.9	-0.221	0.277
GQ	81.96 (15.60)	2.934 (9.206)	0.4	0.066	0.753	70.46 (14.37)	14.30 (9.488)	9.4	0.306	0.146
Gc Pop Ins	251.6 (42.63)	40.27 (25.16)	10.0	0.317	0.123	197 (41.95)	31.94 (27.7)	5.7	0.239	0.261

Appendix 14.4: Continued

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Proximal Phalanx SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Proximal Phalanx SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-0.592 (0.38)	0.0002 (0.0001)	15.8	0.397	0.055	-15.19	4.016	13.6	0.076	
Kc Pop Ins	-1.385 (0.705)	0.0004 (0.0002)	20.8	0.456	0.025	-21.77	5.917	31.8	0.004	
J-Integral PQ	-424.7 (745.2)	0.186 (0.195)	3.8	0.195	0.350	-4.388	1.894	3.0	0.408	
J-Integral Pop Ins	-1953 (2577)	0.6901 (0.672)	4.2	0.205	0.314	-9.016	3.274	4.8	0.284	
GQ	-246.1 (263.8)	0.0858 (0.0689)	6.6	0.257	0.226	-7.674	2.634	2.0	0.513	
Gc Pop Ins	-1025.3 (739.3)	0.326 (0.193)	11.5	0.339	0.105	-20.816	6.435	19.0	0.033	
	Mechanical Parameter = a + b(Proximal Phalanx T-score)					Mechanical Parameter = a + b(Proximal Phalanx Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.2112 (0.0276)	0.0255 (0.0156)	10.8	0.329	0.117	0.166 (0.02)	0.038 (0.0176)	17.9	0.424	0.044
Kc Pop Ins	0.393 (0.05)	0.0663 (0.0283)	19.9	0.447	0.029	0.302 (0.0416)	0.030 (0.0364)	3.2	0.178	0.418
J-Integral PQ	342.04 (50.67)	42.90 (28.98)	8.7	0.295	0.152	304.6 (36.87)	-48.60 (35.71)	7.8	-0.279	0.187
J-Integral Pop Ins	884.0 (172.8)	153.6 (100.6)	8.8	0.297	0.140	776.4 (133.4)	-155.7 (111.2)	7.9	-0.280	0.175
GQ	93.35 (18.94)	8.78 (10.75)	2.9	0.172	0.423	73.28 (13.02)	26.60 (11.41)	20.6	0.453	0.030
Gc Pop Ins	282.9 (52.38)	47.55 (29.73)	10.4	0.323	0.124	217.4 (41.33)	25.59 (36.24)	2.3	0.152	0.488

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(Mid-Shaft Tibia SOS m s ⁻¹)					log(Mechanical Parameter) = a + b log(Mid-Shaft Tibia SOS m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	-1.17 (0.723)	0.00034 (0.00018)	15.0	0.387	0.075	-27.75	7.497	15.2	0.073	
Kc Pop Ins	-2.747 (1.376)	0.0008 (0.0003)	19.9	0.446	0.038	-32.16	8.788	20.2	0.036	
J-Integral PQ	-179 (1336)	0.1188 (0.3404)	0.6	0.076	0.731	0.702	0.471	0.1	0.908	
J-Integral Pop Ins	-2280 (4717)	0.755 (1.200)	1.8	0.133	0.536	-7.173	2.75	1.1	0.619	
GQ	-407.4 (501.5)	0.125 (0.127)	4.6	0.214	0.339	-23.75	7.1	4.9	0.324	
Gc Pop Ins	-2201 (1420)	0.616 (0.36)	12.8	0.357	0.103	-32.57	9.682	12.6	0.105	
	Mechanical Parameter = a + b(Mid-Shaft Tibia T-score)					Mechanical Parameter = a + b(Mid-Shaft Tibia Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.195 (0.02)	0.0503 (0.0226)	20.0	0.447	0.037	0.156 (0.0259)	0.032 (0.0179)	14.2	0.377	0.092
Kc Pop Ins	0.337 (0.0399)	0.0904 (0.045)	16.7	0.409	0.059	0.306 (0.054)	0.0141 (0.0375)	0.7	0.086	0.711
J-Integral PQ	281.7 (40.96)	-13.78 (44.47)	0.5	-0.067	0.760	359.7 (41.22)	-88.8 (31.33)	28.7	-0.535	0.010
J-Integral Pop Ins	684.8 (141.5)	-7.0 (154.9)	0	-0.010	0.964	939.5 (153.0)	-271.8 (108.1)	23.2	-0.481	0.020
GQ	89.28 (13.88)	22.98 (15.69)	9.7	0.311	0.159	63.66 (16.50)	23.73 (11.38)	18.6	0.431	0.051
Gc Pop Ins	246.1 (40.65)	74.58 (45.95)	11.6	0.341	0.120	215.5 (53.48)	18.92 (36.89)	1.4	0.117	0.614

Appendix 14.4: Continued

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(BUA dB MHz ⁻¹)					log(Mechanical Parameter) = a + b log(BUA dB MHz ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.198 (0.067)	-0.0003 (0.0011)	0.4	-0.066	0.760	-0.676	0.0773	0.3	0.805	
Kc Pop Ins	0.150 (0.127)	0.0026 (0.0021)	6.8	0.260	0.219	-1.313	0.418	7.6	0.191	
J-Integral PQ	-58.1 (89.20)	5.798 (1.46)	40.7	0.638	0.001	1.212	0.676	25.7	0.010	
J-Integral Pop Ins	-583.2 (322.5)	21.31 (5.284)	40.4	0.636	<0.001	0.9596	0.997	27.8	0.006	
GQ	122.6 (43.32)	-0.699 (0.7122)	4.2	-0.205	0.337	2.676	-0.529	4.5	0.319	
Gc Pop Ins	125.7 (127.6)	1.608 (2.098)	2.6	0.161	0.452	1.401	0.462	4.1	0.341	
	Mechanical Parameter = a + b(BUA T-score)					Mechanical Parameter = a + b(BUA Z-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.168 (0.0404)	-0.0055 (0.0185)	0.4	-0.064	0.768	0.176 (0.0236)	-0.004 (0.0222)	0.2	-0.041	0.847
Kc Pop Ins	0.388 (0.0762)	0.0443 (0.0348)	6.9	0.262	0.216	0.312 (0.0458)	0.0163 (0.043)	0.6	0.080	0.710
J-Integral PQ	461.9 (52.87)	96.73 (24.30)	40.8	0.639	0.001	311.02 (37.08)	61.21 (35.11)	11.7	0.342	0.095
J-Integral Pop Ins	1328.8 (190.4)	355.9 (87.94)	40.6	0.637	<0.001	757.1 (131.6)	202.7 (127)	9.6	0.310	0.124
GQ	60.34 (26.04)	-11.45 (11.89)	4.0	-0.201	0.346	79.97 (15.45)	-3.84 (14.54)	0.3	-0.056	0.794
Gc Pop Ins	270.29 (76.64)	27.07 (34.99)	2.6	0.163	0.447	222.83 (45.19)	7.15 (42.52)	0.1	0.036	0.868

OP + OA Disks AL	Linear Relationships					Power (log) Function Relationship				
	Mechanical Parameter = a + b(VOS Calcaneus m s ⁻¹)					log(Mechanical Parameter) = a + b log(VOS Calcaneus m s ⁻¹)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	p - value	
Kq	0.0972 (0.958)	0.0001 (0.0006)	0	0.018	0.933	0.793	-0.502	0	0.928	
Kc Pop Ins	-1.857 (1.811)	0.0014 (0.0012)	6.1	0.247	0.245	-19.02	5.775	4.7	0.310	
J-Integral PQ	-2513 (1582)	1.795 (1.016)	11.9	0.345	0.091	-23.99	8.263	11.8	0.093	
J-Integral Pop Ins	-9629 (5627)	6.606 (3.612)	12.2	0.350	0.080	-34.68	11.71	12.1	0.082	
GQ	364.8 (625.8)	-0.182 (0.402)	0.9	-0.096	0.656	22.52	-6.504	2.2	0.490	
Gc Pop Ins	-1273 (1810)	0.959 (1.162)	3.0	0.173	0.418	-17.11	6.052	2.3	0.482	
	Mechanical Parameter = a + b(VOS Calcaneus T-score)					Mechanical Parameter = a + b(VOS Calcaneus T-score)				
Parameter	a	b	r ² (%)	r	p - value	a	b	r ² (%)	r	p - value
Kq	0.186 (0.092)	0.0022 (0.0265)	0	0.018	0.934	0.166 (0.0361)	-0.012 (0.0289)	0.8	-0.087	0.687
Kc Pop Ins	0.505 (0.173)	0.0597 (0.05)	6.1	0.247	0.245	0.327 (0.07)	0.023 (0.056)	0.7	0.086	0.690
J-Integral PQ	542.2 (151.5)	77.39 (43.68)	12.0	0.347	0.090	351.9 (61.65)	68.61 (49.58)	7.7	0.277	0.180
J-Integral Pop Ins	1617.4 (534.2)	284.8 (155.2)	12.3	0.351	0.079	873.8 (215.4)	210.4 (176.5)	5.6	0.236	0.245
GQ	55.56 (59.85)	-7.84 (17.28)	0.9	-0.096	0.654	69.18 (23.52)	-12.43 (18.82)	1.9	-0.139	0.516
Gc Pop Ins	358.3 (173.1)	41.23 (49.95)	3.0	0.173	0.418	229.34 (69.35)	10.03 (55.49)	0.1	0.039	0.858

Appendix 15

The BOSCOS Project

Appendix 15: The BOSCOS Project

The following appendices contain the work that was performed and the documents that were written by the author for the purposes of the BOSCOS project. The documents were written at different stages of the project as it progressed and encompass a number of different aspects which required investigation.

Appendix 15.1: Review of Scanning Methodologies

The idea behind the BOSCOS project was the insertion of a scanning system into the motor vehicle so that the occupants could obtain a non-invasive measure of their bone quality. The information obtained from this investigation could then be utilised to provide the basis for any adjustments of the restraint system that were considered necessary so as to best protect the occupant in a crash situation. This document outlines the available scanning technologies available for the clinical determination of the skeletal condition, providing both pros and cons for each investigation and providing proof that quantitative ultrasound is the measurement of choice for this procedure.

Appendix 15.2: The Health Concerns and Dangers of the Different Scanning Systems

One of the major advantages of quantitative ultrasound over the other available systems is that it doesn't require the use of ionising radiation in order for its measurements to be performed; as such it constitutes the safest of the investigations which were presented in the previous document. Ultrasound is however not without its

dangers, and this document was written to highlight the possible effects that quantitative ultrasound could have on the body.

Appendix 15.3: Reading Across to the Upper Body and Thorax

After discussion within the consortium it was decided that the site of choice for the ultrasound investigation was the fingers, as they offered the most readily available site for investigation when an individual is within a motor vehicle. However at the time it was highlighted that the area of interest with respect to the biomechanics was the upper body and particularly the thorax, as this was the main area of loading in a frontal crash situation due to the seat belt and airbags.

This document therefore contains a literature review of all the previous biomechanical work that could be obtained for the biomechanics of the upper body and the effects that osteoporosis and bone loss might have on their biomechanics. Particular interest was given to the relationships between the effects seen at the thorax and those that were seen at the fingers.

Appendix 15.4: BOSCOS Prototype Analysis

As part of the BOSCOS consortium McCue Plc. developed a new prototype ultrasound finger scanner using the technology from within its clinical system the CUBA Clinical. This document outlines the initial testing of an exclusive group of 102 individuals, not used in the clinical studies that were presented in this thesis. The documents outlines the measurements that were performed, the parameters which were selected from the recorded waveforms, the relationship between the parameters and

DXA, as well as comparisons of their performance with respect to the two clinical QUS systems the CUBA Clinical and the Sunlight Omnisense.

Appendix 15.5: Sensitivity and Specificity of the BOSCOS Prototype Finger Scanner

Having provided the consortium with results with respect to the BOSCOS prototype analysis, the consortium requested that the sensitivity and specificity of the prototype system be determined. This document was produced to present the resultant sensitivity and specificity analysis for the prototypes results prediction of the DXA determined axial skeletal condition, in relation to the clinical systems.

Appendix 15.6: Biomechanics and Tissue Testing

The biomechanics document was written with the intention of presenting the expected drop that might be seen in the speed of sound results from the phalanx, and how it related to the corresponding drop in the mechanics of the cancellous bone from the femoral heads. The aim was to provide the individuals from the motor industry with a quantifiable reduction in the mechanics of the skeleton in osteoporosis, so they had a bench mark for the adjustment of the biomechanics of their model dummies within the crash scenario testing.

BOSCOS

Bone Scanning for Occupant Safety

Appendix: 15.1

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
DfT Contract Number PPAD 9/33/89

Report title Review of Scanning Methodologies

Author Richard B Cook
 Cranfield University at Shrivenham

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PROJECT REPORT
FORESIGHT VEHICLE LINK PROJECT
BONE SCANNING FOR OCCUPANT SAFETY
(BOSCOS)

Contract Number PPAD 9/33/89

1st February 2002 – 30th June 2005

Report to

Department for Transport

June 2005

For and on behalf of the Consortium, comprising:

Cranfield Impact Centre Ltd. – lead partner

Nissan Technical Centre – Europe Ltd.

TRW Automotive

Autoliv Ltd.

Cranfield University at Shrivenham, Centre for Materials Science and Engineering

Loughborough University, Vehicle Safety Research Centre

McCue plc (sub-contractor to lead partner)

DfT Project Officer

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Review of Scanning Methodologies

By Richard B Cook

Department of Materials & Medical Sciences

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1. Introduction.

Clinically it is possible to assess the quality of a patient's bone in different ways, these techniques range from X-ray absorptiometry to blood tests. The purpose of this document is to discuss the different scanning technologies in order to assess the best method for an in-car non-invasive bone quality assessment in-vivo.

2. Scanning Methodologies.

2.1. Radiology.

This technique uses standard x-ray films to provide information on the patient's bone. It is a non-quantitative method and its practical use is for the assessment of the cortical thickness of the bone, and the presence of fractures. This method can assess almost every bone in the body and can be used to assess vertebral and hip fractures, which can directly diagnose osteoporosis without need for bone mass measurements [N.A.Pocock (1998)].

There have been attempts to semi-quantify this technique, by the Singh Index [G.D.Krischak et al. (1999), N.J.Wachter et al. (2001)]. The system works by the classification of osteoporosis due to the visible rarefaction of trabecular structures into six grades, with one being severe osteoporosis, and six normal bone. The measurements are taken from the femoral neck of the intact side on a plain anterior-posterior-X-ray film.

2.2. Radiographic Absorptiometry.

Radiographic absorptiometry makes use of standard X-ray equipment. The system is used in the same way as in section 2.1, but with a standardised aluminium reference block, [N.A.Pocock (1998), S.Grampp et al. (1993), E.C.Mirsky et al. (1998)] or a calcium hydroxyapatite step phantom, [N.A.Pocock (1998)] next to the region of interest. By comparison of the bone with the aluminium or the calcium hydroxyapatite with an optical densitometer, it is possible to obtain a measure of bone density. The results are in aluminium equivalent values, or as measure of bone density compared to the step phantom.

2.3. Single-Photon (SPA) and Single X-ray (SXA) Absorptiometry.

Both of these systems works by the attenuation of a single energy beam, either photon or X-ray. In SPA scanners [S.Grampp et al. (1993)], a highly collimated photon beam from a radionuclide source (usually Iodine-125) is fired at the region of interest. The resultant level of attenuation is then converted to bone mineral content in grams or areal BMD in g/cm^2 using a known standard.

In SXA scanners [N.A.Pocock (1998), E.C.Mirsky et al. (1998)], a well-collimated low-energy X-ray beam, is fired at the region of interest, a scintillation detector measures the intensity of the radiation beam passing through the bone. The absorption can then be converted to a bone mineral content value by a known standard.

The absorption of the soft tissue has to be considered if a true value of BMD is to be gained. Water has similar absorption properties to soft tissue, so the soft tissue is

compensated for by submerging the region of interest in a water bath, with the transmitter and receivers on opposite sides.

2.4. Dual-Photon (DPA) and Dual-Energy X-ray (DXA) Absorptiometry

DPA was developed so that central sites, which SPA and SXA couldn't measure, could be assessed. DPA scanners [S.Grampp et al. (1993), M.Jergas et al. (1993)] work by having a radionuclide source with two effective discrete energy levels. Initially two sources were used together (Iodine-125 and Americium-241), but this was later replaced by a dual emitter Gadolinium-153 with energies of 44keV and 100keV¹.

DXA on the other hand has one X-ray source that emits X-rays at two principle energies. These two principle energies can be produced in different ways [E.C.Mirsky et al. (1998), G.M.Blake et al. (1997)]:

- **The energy switching.**

This system works by the switching of the high voltage generator between high and low KVp² during alternate half-cycles of the mains supply, this results in rapid pulses of different frequencies and different energy levels.

- **A rare earth filtered x-ray source.**

The different energy levels are emitted simultaneously; the output from a constant potential X-ray generator is passed through a rare earth filter with specific absorption characteristics resulting in energy output at different levels of voltage.

Both DXA and DPA work on the same principle; the attenuation coefficient is dependent on atomic number and photon energy. Measurement of the transmission factors at two energies enables the areal densities (i.e. mass per unit of projected area) of two different types of tissue to be inferred. These are taken to be bone mineral density (hydroxyapatite), and soft tissue respectively.

An edge detection algorithm is used to find the bone edges. The total projected area of bone is then derived by summing the pixels within the bone edges, and the reported value of bone mineral density (BMD) is calculated as the mean BMD over all the pixels identified as bone. [G.M.Blake et al. (1997)] BMD can be converted to bone mineral content (BMC) via equation 1

$$BMC = BMD \times Area$$

Equation taken from G.M.Blake at al. (1997)

Equation 1

¹ **Electronvolt** (symbol: eV) is a unit of energy. One eV is equal to the amount of energy one electron acquires by accelerating (from rest) through a potential difference of one volt. It is usually used as a measure of particle energies. $1 \text{ eV} = 1.602 \times 10^{-19} \text{ joule}$.

² **Kilovolts peak** (symbol kVp). The highest instantaneous energy across an X-ray tube, corresponding to the highest energy X-rays emitted.

DXA has two scanning modes, pencil beam and fan beam. [G.M.Blake et al. (1997)]

- **Pencil Beam.**

This was the first type of DXA scanner, that was clinically available, and it used a pinhole collimator. This produced a thin pencil like beam; due to the thin nature of the beam it had to pass back and forth over the surface, with the detector following, to building up a picture of the area. This resulted in long scanning times, and a reduction in the number of patient examinations feasible in a day.

- **Fan Beam.**

The fan beam system was developed to reduce the scanning times, and to increase the patient examinations per day. The pinhole collimator was changed to a slit; this meant that the beam spread out more into a fan shape. The beam has the ability to scan a larger area at once, so the required time for the scan is reduced.

Further advances have been made in the field of DXA, such as new solid state detectors, which improve the resolution of the scan, and in doing so help to improve the accuracy attainable.

2.5. Quantitative Computed Tomography (QCT)

CT scanners are frequently used in hospitals as an imaging tool, but the system has been adapted, so that while the region of interest is being scanned, a reference standard is being scanned simultaneously. The systems work by taking a digital radiograph of the site of interest; from this a region of interest can be chosen and measured. The results of the density measurements can then be compared to the results from the reference standard, the comparison allows for the calculation of the BMD [S.Grampp et al. (1993)]. The reference standards usually consist of either solid calcium hydroxyapatite of a known density, or a solution of dipotassium hydrogen phosphate K_2HPO_4 of a known concentration [R.B.Mazess et al. (1990)].

The results are given in Hounsfield units [E.C.Mirsky et al. (1998)]. A Hounsfield unit is a measure of X-ray attenuation for CT scans in which each pixel is assigned a value on a scale, with air being equivalent to -1000; water to 0; and compact bone being 1000 [S.I.Esses et al. (1989)]. The relationship between specimen apparent density and corrected Hounsfield units is described by the linear expression:

$$\rho = 1.9 \times 10^{-3} QCT + 0.105$$

Equation taken from S.I.Esses et al. (1989)

Equation 2

Where ρ is the apparent density (g/ml) and QCT is the corrected CT number in Hounsfield units as measured at each site.

QCT for the assessment of bone has two modes, single energy QCT (SEQCT) and dual-energy QCT (DEQCT), both methods can be used clinically and give different levels of precision, accuracy and radiation dose.

2.6. Quantitative Ultrasound.

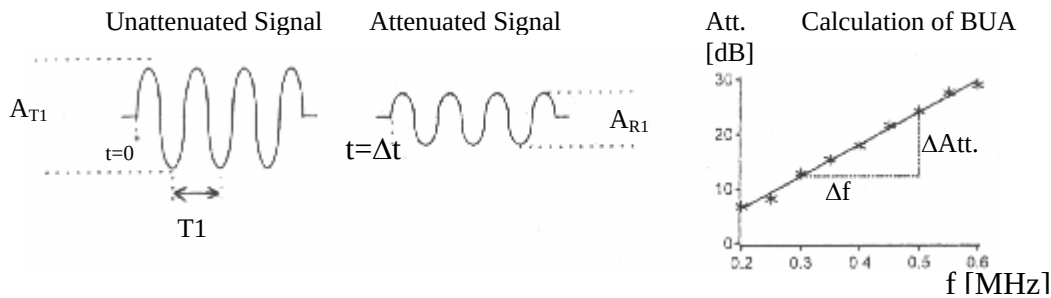
There are three main parameters which ultrasound can assess.

2.6.1. Broadband Ultrasound Attenuation. (BUA)

The idea behind BUA is that sound is a travelling mechanical vibration. As sound propagates, the mechanical properties of the medium progressively alter the shape, intensity and speed of the propagating wave. By observing the differences between the wave transmitted into the bone and the wave after interacting with the bone, one can obtain information about the bone's mechanical properties, specifically its stiffness and mass density. [G.H.Brandenburger et al. (1993)]

The measurement of BUA is most commonly measured across the calcaneus. There are two main types of system, the dry contact and the water bath systems, both measure the same value but in slightly different ways. Some try to compensate for the soft tissue to gain a more accurate assessment of the bone, while others ignore the soft tissue effects, as they are minimal.

During a measurement, [S.H.Prinns et al. (1998)] the machine takes a measure of peak-peak amplitude, A_{T1} , during a reference measurement either with no heel in the water bath or through a phantom. The heel is then inserted and the reading is retaken, the signal is attenuated and the received amplitude A_{R1} is recorded.



Taken from S.H.Prinns et al. (1998)

Figure 1.

The attenuation A_{tt} [dB] is calculated:

$$A_{tt} = 20 \log \frac{A_{T1}}{A_{R1}}$$

Equation taken from S.H.Prinns et al. (1998)

Equation 3

The frequency (f) is now increased during repeated measurements resulting in a corresponding increase in the calculated attenuation. The most generally used frequency range is between 0.2-0.6 MHz, although the frequency range 0.2-1.0 MHz was found to be the optimal for the determination of skeletal status due to the high attenuation of trabecular bone. [G.M.Blake et al. (1997), C.F.Njeh et al. (1997)]

When a sufficient number of measurement points have been obtained, they can be plotted in a graph of A_{tt} [dB] vs. f [MHz]. BUA is calculated as the slope of the line resulting from a simple linear regression. [Figure 1.]

$$BUA = \frac{\Delta A_{tt}(dB)}{\Delta f(MHz)}$$

Equation taken from S.H.Prinns et al. (1998)

Equation 4

The BUA can be adjusted for the heel width to give normalised BUA (nBUA, dB/MHz⁻¹cm⁻¹) by dividing the BUA by the heel width.

2.6.2. Speed of Sound. (SOS)

This measurement has a number of different identities, velocity of sound, apparent speed of sound, apparent velocity of ultrasound (AVU) and ultrasound transmission velocity. All these refer to the same generic ultrasound measurement.

There are different ways to measure SOS; the most simple is to calculate the time delay Δt , which it takes for a burst of ultrasound to travel from the transmitter to the receiver.

$$SOS = \frac{a}{\Delta t}$$

Equation taken from S.H.Prinns et al. (1998); C.F.Njeh et al. (1998)

Equation 5

Where **a** is the distance between the transducers. There are other methods for the calculation of SOS, based on the time of flight, TOF,

$$BoneVelocity = \frac{X_b}{T_b} = \frac{X - (s_1 + s_2)}{T_x - (t_1 - t_2)}$$

Equation taken from C.F.Njeh et al. (1998)

Equation 6

$$TOFvelocity = \frac{V_w X}{X - (\Delta t V_w)}$$

Equation taken from C.F.Njeh et al. (1998)

Equation 7

X = heel thickness including soft tissue.

X_b = the calcaneal thickness without overlying soft tissue.

T_x and T_b = are the corresponding transit times through X and X_b

s_1 and s_2 , t_1 and t_2 = the soft tissue thicknesses and the transit time through each of them.

V_w = the velocity of ultrasound through water.

Δt = the difference in transit time with and without the sample.

The three different measurement methods give slightly different values but they are all highly correlated to each other.

The Sunlight Omnisense™ [C.F.Njeh (2001)] works by having two transmitters and two receivers in the same probe. The two transmitters produce pulsed acoustic waves, at a centre frequency of 1.25 MHz (bandwidth 0.7-1.8 MHz). When the ultrasound waves are incident to the bone, the waves are reflected, refracted or transmitted, depending on the angle of incidence. It is the refracted wave that propagates along the sample that can be measured. One of the transmitters generates a predefined sequence of US pulses that are detected by one of the receivers. The transit time was defined as the time needed for the first detectable signal above noise to arrive at the receiving transducer. Because the transmitters and receivers are fixed in the probe the distance between them is constant, so the length of the ultrasound pathway is known and the velocity can be calculated.

The machine works by taking three sets of three hundred readings of velocity (m/s) each generating a representative SOS value. An internal algorithm checks the three sets of data for consistency, if the three sets are statistically inconsistent then the operator has to take a fourth set. The machine will only display a result when it has three statistically consistent SOS results.

2.6.3. Stiffness Index. (SI)

The stiffness index is provided by one clinically available calcaneal scanner called the Achilles (Lunar, Madison, WI, USA). The SI is calculated by a combination of the SOS value and the BUA value and is defined as:

$$SI = (0.67 \times BUA) + (0.28 \times SOS) - 420$$

Equation taken from S.H.Prinns et al. (1998), S.Sakata et al. (1997) and M.B.Mikhail et al. (1999)

Equation 8

It is claimed that SI improves the standard coefficient of variation of velocity or BUA alone.

2.7. Magnetic Resonance Imaging. (MRI)

'In performing MRI procedures, the patient's position is in an external magnetic field that causes the atomic nuclei with an odd number of protons to align and rotate around the axis of the magnetic field. It applies a radiofrequency pulse that causes the protons to resonate. When the radiofrequency pulse is removed, the protons "relax" back toward equilibrium. In so doing, energy is released that is detected as a radiosignal. Analysis of the amplitude and frequency of the emitted signal yields

information about the number and position of nuclei in the sample, from which the image is produced.’[Mosby’s Medical Encyclopedia (1997)]

Interest in this system came about when workers noted reduced signal intensity in gradient-echo images of substances in the presence of trabecular bone. It was also noted that this effect increased with increased trabeculation. The different diamagnetic susceptibilities of bone and marrow cause magnetic field inhomogeneities that affect the relaxation characteristics of trabecular bone. These local field inhomogeneities can be quantified by the measurement of T2*, [C.Kang (1999)] which is related to the spread in the magnetic field (ΔB) by:

$$\frac{1}{T2^*} = \frac{1}{T2} + \gamma \Delta B$$

Equation 9

$$\frac{1}{T2'} = \gamma \Delta B$$

Equation 10

Equations taken from C.Kang (1999)

Where T2 is the true transverse relaxation time reflecting signal decay in a perfectly homogenous magnetic field, and γ is the gyro-magnetic ratio. T2' represents the component of T2* due to magnetic field inhomogeneities alone.

What has been found is that in patients with osteoporosis, T2* and T2' are significantly higher, thought to be due to increased trabecular spacing, but it allows for a quantitative measure of osteoporosis to be produced.

3. Non-Scanning Methods of Bone Assessment.

3.1. ‘Simple Calculated Osteoporosis Risk Estimation.’ (SCORE)

The main method for the assessment of osteoporosis is densitometry, but due to the cost and lack availability of the machines, a system has been devised that identifies at risk patient via a questionnaire. The SCORE system was devised and validated by Dr. E.Ly dick et al. (1998). The system was devised to simply divide the women in into two sets, one group which is likely to have low BMD and the other which doesn't. Low BMD is set at less than 2 standard deviations below the young normal mean for women.

The SCORE system works by asking patients six questions, about there age, race, weight, rheumatoid arthritis, oestrogen use and there history of non-traumatic fractures post-45 years of age. These factors are given a point score, and any person with a high SCORE value (above 6) are likely to have low BMD, and any patient with Low SCORE values (6 or below) are likely to have higher BMD. The value SCORE calculation guidelines are below.

TABLE 1

Variable	Coefficient
Race	5 – If women is not black
Rheumatoid Arthritis	4 – If women has rheumatoid arthritis
History of nontraumatic fractures after age 45 years.	4 – For each type (wrist, rib, hip)
Age	3 Times the first digit of age in years
Oestrogen	1 – If women never received oestrogen therapy
Weight	-1 times weight in pounds divided by 10 and truncated to integer

SCORE calculation guidelines taken from W.B.Sedrine (2001)

3.2. Biochemical Markers for Diagnosis of Osteoporosis.

When bone is made and broken down, chemicals and enzymes are produced which can be measured. These markers are broken into two groups, markers of resorption and markers of formation.

TABLE 2

Markers of Formation.	Markers of Resorption
Serum.	Serum
Osteocalcin (OC) (Bone gla protein.)	Tartrate-Resistant Acid Phosphatase (TRACP)
Alkaline Phosphatase. (ALP)	Pyridinoline PYD and pyridinoline-containing peptides.
Procollagen Type I Propeptides (PINP)	Bone Sialoprotein.
	Urine
	Hydroxypyridinium Collagen Crosslinks (pyridinoline PYD and Deoxypyridinoline DPD)
	Hydroxyproline (Hyp.)
	Hydroxylysine-glycoside.

Biochemical markers of bone turnover adapted from P.D.Delmas (1993) and (2000)

These chemicals and proteins can all be measured either in the blood or in the urine of a patient. Resorption markers reflects the rate of bone loss and may identify a group of 'fast bone losers' who have an accelerated rate of bone loss, of greater than 3% per year, as measured by standard BMD. [L.K.H.Koh et al. (2002)]

4. Discussion.

The purpose of this article is to assess the different technologies that are available for the assessment of bone quality, in order to attain a technology that is best suited to the assessment of bone quality of the driver and passengers in a car environment.

4.1. Effective Radiation Dose.

Ideally it would be desirable to have a system that doesn't require the use of ionising radiation. Ionising radiation has the ability to break substances in their paths into ions. This can kill cells or slow their growth, but more seriously it can cause changes in the genetic makeup of the cells, which can lead to the formation of cancers. [Mosby's Medical Encyclopedia (1997)] The actual effective doses that the techniques give are generally low, and in a clinical environment would not be of concern. However in the car environment when a reading could be required every time the car is started, the repetitive doses will increase the risk of cancer development.

TABLE 3³

Technique	Effective Dose
Radiographic Absorptiometry. (RA)	~5 µSv
Single-Photon Absorptiometry. (SPA)	<1 µSv
Dual-Photon Absorptiometry. (DPA)	
Lumbar Spine	5 µSv
Proximal Femur	3 µSv
Single X-ray Absorptiometry. (SXA)	<1 µSv
Peripheral Dual-Energy X-Ray Absorptiometry (pDXA)	
Dual Energy X-Ray Absorptiometry (DXA)	
Pencil Beam.	
AP Spine	~1 µSv
Lat Spine	~3 µSv
Proximal Femur	~1 µSv
Whole Body	~3 µSv
Fan Beam.	50 µSv
Quantitative Computed Tomography (QCT)	
Single-Energy QCT (SEQCT)	50 µSv
Dual-Energy QCT (DEQCT)	100 µSv
Peripheral Quantitative Commuted Tomography (pQCT)	<2 µSv
Quantitative Ultrasound. (QUS)	
Broadband Ultrasound Attenuation (BUA)	0 µSv
Speed of Sound (SOS)	0 µSv
Magnetic Resonance Imaging (MRI)	0 µSv
Simple Calculated Osteoporosis Risk Estimation. (SCORE)	0 µSv
Biochemical Markers for Diagnosis of Osteoporosis.	0 µSv

Comparison of the effective radiation dose supplied by the different scanning techniques.

Table adapted from S.Grampp et al. (1993) and D.T.Baran et al. (1997)

³ Sievert (sv) New unit of absorbed dose-equivalent (1 Sv = 100 rems).

Rem: Roentgen equivalent man. The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest.

4.2. Precision and Accuracy of the Testing Method.

‘Precision errors have been defined to characterise the reproducibility of a diagnostic technique. Accuracy errors, on the other hand, reflect the degree to which the measured results deviate from the true values.’ [C.-C.Gl er et al. (1995)]. For the purpose of the car situation, it is important to have a technique that can give an accurate value after one quick measurement, the precision of the technique is less important but is desirable.

TABLE 4

Technique	Precision Error (%)	Accuracy Error (%)
Radiographic Absorptiometry. (RA)	1-2	5
Single-Photon Absorptiometry. (SPA)	1-2	4-6
Dual-Photon Absorptiometry. (DPA)		
Lumbar Spine	2-4	5-10
Proximal Femur	3-5	5-10
Single X-ray Absorptiometry. (SXA)		
Peripheral Dual-Energy X-Ray Absorptiometry (pDXA)	1-2	4-6
Dual Energy X-Ray Absorptiometry (DXA)		
AP Spine	1-1.5	4-10
Lat Spine	2-3	5-15
Proximal Femur	1.5-3	6
Whole Body	~1	3
Quantitative Computed Tomography (QCT)		
Single-Energy QCT (SEQCT)	2-4	5-15
Dual-Energy QCT (DEQCT)	4-6	3-10
Peripheral Quantitative Computed Tomography (pQCT)	0.5-1	2-8
Quantitative Ultrasound. (QUS)		
Broadband Ultrasound Attenuation (BUA)	0.4-4.0	NR
Speed of Sound (SOS)	0.15-1.9	NR
Magnetic Resonance Imaging (MRI)	3.9-4.8	NR
Simple Calculated Osteoporosis Risk Estimation. (SCORE)	NA	NA
Biochemical Markers for Diagnosis of Osteoporosis.	NA	NA

NR=Not Reported, NA= Not Applicable.

Precision and accuracy errors of the available testing techniques.

Table adapted from S.Grampp et al. (1993) and D.T.Baran et al. (1997)

4.3. Results.

When the bone quality of a patient is assessed in a clinical environment the results are given as a number. That number reflects in some way the quality of the bone that has been tested. The result can be expressed in three forms, the actual result, be that BUA, SOS, BMD or BMC or as a T-score or a Z-score.

$$T - Score = \frac{\text{Patients Measurement} - \text{Mean Peak Value For Normal Young Adults}}{\text{The Standard Deviation of the Peak Value For Normal Young Adults}}$$

Equation taken from E.C.Mirsky et al. (1998) and C.F.Njeh 2001

Equation 11

$$Z - Score = \frac{\text{Patients Result} - \text{Mean Value for Age.}}{\text{Standard Deviation of the Age Matched Mean}}$$

Equation taken from E.C.Mirsky (1998) and M.B.Mikhail (1999)

Equation 12

In the clinical environment the most commonly used result is the T-score, and it is around this result that the World Health Organisation based their definition of osteoporosis. For the purpose of the car, a result is required that gives a measure of bone quality, that can be related to the bones mechanical properties. The protection system can then be set up accordingly to minimise injury in a crash situation.

4.4. Measurement Sites.

The site at which the measurement is to be taken needs to be considered; as the different techniques have the ability to measure some sites but not others.

TABLE 5

Technique	Commonly Measured Sites
Radiology	Vertebral Column, Proximal Femur.
Radiographic Absorptiometry. (RA)	Metacarpal, Phalanges.
Single-Photon Absorptiometry. (SPA)	Distal or Ultradistal Radius, Calcaneus
Single X-ray Absorptiometry. (SXA)	Distal or Ultradistal Radius, Calcaneus
Peripheral Dual-Energy X-Ray Absorptiometry (pDXA)	Distal or Ultradistal Radius, Calcaneus
Dual-Photon Absorptiometry. (DPA)	Lumbar Spine, Proximal Femur
Dual Energy X-Ray Absorptiometry (DXA)	Lumbar Spine (L1-L4), Proximal Femur (Trans-Cervical Neck, Ward's Triangle, Trochanteric Region, Total Proximal Femur.) Total Body,
Quantitative Computed Tomography (QCT)	Lumbar Spine (L1-L4), Femur
Peripheral Quantitative Computed Tomography (pQCT)	Ultradistal Radius, Calcaneus
Quantitative Ultrasound. (QUS)	Calcaneus, Patella, 1/3 Radius, Phalanges, Tibia, Metatarsal
Magnetic Resonance Imaging (MRI)	Calcaneus, Lumbar Spine (L2-L4), Femoral Neck,
Simple Calculated Osteoporosis Risk Estimation. (SCORE)	NA
Biochemical Markers for Diagnosis of Osteoporosis.	NA

Table showing the measurement sites of the different techniques.

Table adapted from D.T.Baran et al. (1997) and S.Grampp et al. (1993)

The two considerations when choosing a site for the measurement to be taken are:

Accessibility.

The measurement site needs to be easily accessible, so that the occupants can do their assessments without having to remove clothing or jewellery. For example, the calcaneus is a popular and well-proven site for the assessment of bone status, but for use in a car it would require the occupant to remove their shoe and sock in order to take the measurement.

Correlation.

The measurement site is of importance, as the value that is obtained will give a value of the bone status at that site, which must correlate with the bone status at the other sites of the body. This is especially important if the strength of the bone is to be related accurately to it. This constitutes part of our on going work in Shrivenham.

The best site would be a peripheral site such as the distal radius or one of the phalanges. The correlation between the peripheral bone density and the axial skeleton is not high, and is worse if different scanning techniques are compared. The best measurement techniques for peripheral assessment are peripheral DXA, pQCT, RA, or QUS, as shown in Table 5.

4.5. Individual Technique Discussion.

4.5.1. Radiographic Absorptiometry.

This technique has the ability to quantitatively measure the peripheral skeleton, and one of two capable of measuring the phalanges. The radiation dose is minimal, but is higher than that for other peripheral techniques. The technique requires the use of a standard X-ray machine, that are large pieces of equipment that wouldn't fit into a car, but the precision and accuracy of the acquired results are comparable to the other peripheral techniques if performed and interpreted by a skilled operator. These factors render the system unsuitable for use in the car environment.

(-): requires an operator, ionising radiation, considerable set-up demands, weight, size, time.

4.5.2. Single-Photon and Single X-ray Absorptiometry.

This is a peripheral technique, which measures BMD with a good accuracy and precision. The radiation doses are two of the lowest of all the radiation-based systems, equalled only by pDXA. Of the two, the SXA system is preferable, as SPA requires a radionuclide source. These sources will emit radiation constantly, so must be enclosed when not in use, and suffers problems with degradation of the source, which cause measurement inaccuracies. The system doesn't require a skilled operator and most people can be trained to use a clinical system in a matter of hours. As mentioned in section 2.3., in order to account for the effects of the surrounding soft tissue the site of investigation must be submerged in a water bath. This requirement makes integration of the system into a car less feasible.

(-): requires an operator, ionising radiation, the use of a standard. SPA emits ionising radiation constantly, requires a water bath.

4.5.3. Dual-Photon Absorptiometry.

This technique measures the central skeletal sites, and in doing so requires a higher radiation dose than the peripheral absorptiometry techniques. The precision and accuracy of the results, aren't as good as for the peripheral techniques, but are comparable to the other techniques measuring central sites. The technique does require the use of a radionuclide source, like SPA [4.5.2.], and will have the same problems of constant radiation emission, and source degradation. The equipment for this system is

large, and the subjects positioning in relation to the transmitter and receiver are important, and would not be possible in a car situation and especially if it was required for more than one occupant.

4.5.4. Dual-Energy X-ray Absorptiometry.

This is the ‘Gold Standard’ for the measurement of the central skeleton. The radiation dose of the pencil beam system is low, but the scan takes a long time. In comparison the fan beam system has a much higher radiation dose, but lower exposure time. The accuracy and precision varies depending on the site, but are acceptable. The positioning of both the equipment and the subject is crucial, and the newer systems require a powerful computer in order to process the results. It is unfeasible to fit the required equipment into the car, with the desired positioning.

(-): both DPA and DXA have weight and size limitations, relatively expensive even in miniature form, ionising radiation, do not like vibration and noise, require regular safety checks. DPA constantly emits ionising radiation.

4.5.5. Quantitative Computed Tomography.

The radiation dose from this system is the highest of all the available systems, when used in the dual-energy form, but is comparable to fan beam DXA in the single-energy form. It is an accurate and precise method for the measurement of the central skeleton, but the equipment is too large for use in a car; and it wouldn’t be feasible to position either the occupant or the scanner correctly for data acquisition.

(-): QCT is the most accurate density assessment machine, but suffers at the same points as DPA and DXA.

4.5.6. Peripheral Dual-Energy X-ray Absorptiometry.

The radiation dose is equal with that from SPA and SXA, and is one of the lowest doses of the available X-ray systems. The system has the ability to measure peripheral sites, (Table 5) and has excellent precision and accuracy. The equipment varies in size; some pDXA systems are an additional programme on a normal DXA system, but there are smaller site-specific systems that are much smaller and portable, which may be adaptable for use in a car.

4.5.7. Peripheral Quantitative Computed Tomography.

The radiation dose supplied by these systems is low but not as low as pDXA, SXA or SPA. It has the ability to measure peripheral sites, with excellent precision and accuracy. It is however performed on a normal QCT scanner, using a different software package, this means that the same problems will arise with fitting the equipment into the car.

(-): same as QCT, but fragile and expensive.

4.5.8. Magnetic Resonance Imaging.

This is a radiation free method of scanning which is preferable due to the reduced risk of developing cancers from the ionising radiation. The precision is the worst of all the available systems, and there is no published information about its accuracy. It has the ability to measure the calcaneus, but apart from that it is only used to measure central skeletal sites. The system does have other problems, not least that the equipment is the largest of all, but the system works using high-powered magnets. In a

clinical environment all metallic objects are removed from the scanning room and the patient, as they may be forcefully attracted to the machine. Use of this system in the car, would result in the occupants' credit cards being blanked and special consideration would be required for any patients with metallic prosthesis. These problems mean that MRI is not a suitable option for use as a scanning system in the car.

(-): oversophisticated and expensive, not in standard use for assessing bone quality, time, space, money.

4.5.9. Quantitative Ultrasound.

This is a radiation free measurement system that has the ability to only measure peripheral sites, (Table 5), in particular though it can assess the phalanges, which are the most readily accessible site for measurement. The machines are small and light-weight (~10kg), and have the potential to be adapted for integration into a car. They have good precision, and the results have been found to correlate with other sites of the body. The systems require no extensive training in order to use them.

The systems do however require a coupling system with the skin; this used to be performed via a water bath, but a 'dry' system has been devised, that uses an ultrasonic gel to form the connection.

(-): requires database, requires gel coupling

(+): easy, simple, portable, small, cheap, robust, very compact.

4.5.10. Simple Calculated Osteoporosis Risk Estimation.

The 'SCORE' system is not a scanning technique, and so doesn't require any forms of medical equipment to be inserted into the car. However it is used in the clinical environment to reduce the numbers of people requiring expensive assessments of their bone quality.

The questionnaire provides a numerical value, which is an indication of the whole body bone status, not just a specific site. This value could be used to set up the occupants' protection; however, in clinical practise this method is only used as a means of ruling out patients requiring further expensive bone density investigations. Despite Dr. E.Lydyck's et al. (1998) validation of the scheme, subsequent investigations of the technique by W.B.Sedrine et al. (2001) and S.M.Cadarette et al. (1999) showed that the specificity of SCORE was poor and too low to be useful as a diagnostic tool for screening patients at high risk to later development of osteoporosis. The lack of accuracy of this system, despite the advantages of no radiation and giving a value related to the whole body, renders this system less desirable than many of the other available scanning techniques.

(-): does not provide an absolute measure, simpler than the Questionnaire we intend to use.

(+): it can be used to input one-off default data in the car at dealer level?

4.5.11. Biochemical Markers of Bone for Diagnosis of Osteoporosis.

The measurement of biochemical markers, although accurate in the assessment of the whole bodies bone turnover, is not a technique that gives rise to a value of bone quality or status. The measurement method requires the occupant to supply either a urine sample or a blood sample for testing, both of which are not suitable for use within

a car. This technique is useful in the clinical environment, for the monitoring of drug therapies, but will not supply the necessary information on bone quality that will aid the protection system to correctly restrain an occupant in a crash situation.

(-): solely hospital based, it gives a trend rather than the current state and condition of the body.

5. Conclusion.

The best technique for use in a car is a quantitative ultrasound system. It is radiation free, reducing the risk of occupants developing cancers from the repetitive exposure to ionising radiation that may occur with the X-ray based techniques. QUS has the ability to measure peripheral sites, with FDA approval, and with precision that is as good as any other scanning system. It requires the use of good databases that an occupants bone status can be compared against, so that the protection can be adjusted to suit that occupant. The only downside is the requirement of a gel coupling system and the power requirements for the system to run, which would be a factor in any system.

6. References

- D.T.Baran. et al. (1997) Diagnosis and Management of Osteoporosis: Guidelines for the Utilization of Bone Densitometry. **Calcified Tissue International**; Vol. 61, p. 433-440
- G.M.Blake et al. (1997) Bone Densitometry: Current Status and Future Prospects. **The British Journal of Radiology**; Vol. 70, Special Issue, p. S177-S186
- G.H.Brandenburger. (1993) Clinical Determination of Bone Quality: Is Ultrasound the Answer? **Calcified Tissue International**; Vol. 53, Suppl. 1, p. S151-S156
- S.M.Cadarette et al. (1999) Validation of the Simple Calculated Osteoporosis Risk Estimation (SCORE) for Patient Selection for Bone Densitometry. **Osteoporosis International**; Vol. 10, p. 85-90
- P.D.Delmas. (1993) Biochemical Markers of Bone Turnover for the Clinical Investigation of Osteoporosis. **Osteoporosis International**; Suppl. 1, p. S81-S86
- P.D.Delmas et al. (2000) The Use of Biochemical Markers of Bone Turnover in Osteoporosis. **Osteoporosis International**; Suppl.6, p. S2-S17
- S.I.Esses et al. (1989) Biomechanical Properties of the Proximal Femur Determined In-vitro by Single-Energy Quantitative Computed Tomography. **Journal of Bone and Mineral Research**; Vol. 4, No. 5, p. 715-721
- C.-C.Gl  ier et al. (1995) Accurate Assessment of Precision Errors: How to Measure the Reproducibility of Bone Densitometry Techniques. **Osteoporosis International**. Vol. 5, p. 262-270
- S.Grampp et al. (1993) Radiologic Diagnosis of Osteoporosis: Current Methods and Perspectives. **Endocrine Radiology**; Vol. 31, No. 5, p. 1133-1145
- M.Jergas et al. (1993) Current Methods and Recent Advances in the Diagnosis of Osteoporosis. **Arthritis and Rheumatism**; Vol. 36, No. 12, p. 1649-1662
- C.Kang et al. (1999) In Vivo MRI Measurements of Bone Quality in the Calcaneus: A Comparison with DXA and Ultrasound. **Osteoporosis International**; Vol. 9, p. 65-74

- L.K.H.Koh et al. (2002) Osteoporosis Risk Factor Assessment and Bone Densitometry-Current Status and Future Trends. **Annals of the Academy of Medicine Singapore**; Vol. 31, No. 1, p. 37-42
- G.D.Krischak et al. (1999) Predictive Value of Bone Mineral Density and Singh Index for the In Vitro Mechanical Properties of Cancellous Bone in the Femoral Head. **Clinical Biomechanics**; Vol. 14, p. 346-351
- E.Ly dick et al. (1998) Development and Validation of a Simple Questionnaire to Facilitate Identification of Women Likely to Have Low Bone Density. **The American Journal of Managed Care**; Vol. 4, Issue 1, p. 37-48
- R.B.Mazess. (1990) Bone Densitometry of the Axial Skeleton. **The Orthopaedic Clinics of North America**; Vol. 21, No. 1, p. 51-63
- M.B.Mikhail et al. (1999) Stiffness in Discrimination of Patients with Vertebral Fractures. **Osteoporosis International**; Vol. 9, p. 24-28
- E.C.Mirsky et al. (1998) Bone Densitometry in Orthopaedic Practise. **The Journal of Bone and Joint Surgery**; Vol. 80-A, No. 11, p. 1687-1698
- Mosby's *Medical Encyclopaedia*. Version 2.0 1997 TLC Properties Inc.
- C.F.Njeh et al. (1997) The Role of Ultrasound in the Assessment of Osteoporosis: A Review. **Osteoporosis International**; Vol. 7, p. 7-22
- C.F.Njeh et al. (2001) Assessment of Bone Status Using Speed of Sound at Multiple Anatomical Sites. **Ultrasound in Medicine and Biology**; Vol. 27, No. 10, p. 1337-1345
- N.A.Pocock. (1998) Quantitative Diagnostic Methods in Osteoporosis: A Review. **Australasian Radiology**; Vol. 42, p. 327-334
- S.H.Prinns et al. (1998) The Role of Quantitative Ultrasound in the Assessment of Bone: A Review. **Clinical Physiology**; Vol. 18, No. 1, p. 3-17
- S.Sakata et al. (1997) Ultrasound Bone Densitometry of Os Calcis in Elderly Japanese Women with Hip Fracture. **Calcified Tissue International**; Vol. 60, p. 2-7
- W.B.Sedrine et al. (2001) Evaluation of the Simple Calculated Osteoporosis Risk Estimation (SCORE) in a Sample of White Women from Belgium. **Bone**; Vol. 29, No. 4, p. 374-380
- N.J.Wachter et al. (2001) Predictive Value of Singh Index and Bone Mineral Density Measured by Quantitative Computed Tomography in Determining the Local Cancellous Bone Quality of the Proximal Femur. **Clinical Biomechanics**; Vol. 16, p. 257-262

BOSCOS

Bone Scanning for Occupant Safety

Appendix 15.2

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
DfT Contract Number PPAD 9/33/89

Report title The Health Concerns and Dangers of the Different
 Scanning Systems

Author Richard B Cook
 Cranfield University at Shrivenham

Date January 2003



PROJECT REPORT

FORESIGHT VEHICLE LINK PROJECT

BONE SCANNING FOR OCCUPANT SAFETY
(BOSCOS)

Contract Number PPAD 9/33/89

1st February 2002 – 30th June 2005

Report to

Department for Transport

June 2005

For and on behalf of the Consortium, comprising:

Cranfield Impact Centre Ltd. – lead partner

Nissan Technical Centre – Europe Ltd.

TRW Automotive

Autoliv Ltd.

Cranfield University at Shrivenham, Centre for Materials Science and Engineering

Loughborough University, Vehicle Safety Research Centre

McCue plc (sub-contractor to lead partner)

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The Health Concerns and Dangers of the Different Scanning Systems

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The Health Concerns and Dangers of the Different Scanning Systems.

1.Ultrasound.

If ultrasound is to be used for repeated scans, within the car environment, it is important to assess the possible risks that this may put the users under. Ultrasound is an inaudible sound wave, which can vary in amplitude; when an ultrasound wave enters the body, the soft tissue and bone will reduce the amplitude by either absorption or scattering of the wave.

1.1. Heating.

Absorption is the factor that causes the main concern. Ultrasound waves are a form of energy, and in order for the wave to be absorbed, and the amplitude reduced, this energy has to be dissipated, and the most common method is conversion into heat. 'Absorption is the mechanism that represents the portion of the wave's energy that is lost by conversion to heat.' R.Hershkovitz et al. (2002).

The absorption of ultrasound in biological tissues strongly depends on the molecular composition of the constituent tissue. The absorption coefficient increases as a function of protein content, with collagen having a particularly high specific absorption. The higher the absorption values, the greater the potential for undesirable ultrasound induced temperature increase. The highest absorption coefficient is obtained from mineralised bone (10dB/cm.MHz). (S.B.Barnett et al. 1997) This value is 30 times greater than for typical soft tissue, and the rate of ultrasound-induced heating may be 50 times faster. (S.B.Barnett et al. 1994) This is mainly due to the high collagen content and the lack of perfusion that can help to cool an area. The main area of concern when the heating effects are considered is during the scanning of embryos, where cell proliferation is occurring at a high rate. If the heating was to cause any damage to the cells the knock-on effect could lead to developmental problems, however, The World Federation for Ultrasound in Medicine and Biology (WFUMB) states. 'A diagnostic exposure that produces a maximum in situ temperature rise of not more than 1.5°C above normal physiological levels may be used without reservation on thermal grounds.' S.B.Barnett (1998).

In order to assess the risk of thermal damage the thermal index is used. The thermal index is a quantity related to calculated or estimated temperature rise under certain defined assumptions. The thermal index is the ratio of total acoustic power to the acoustic power required to raise the tissue temperature by 1°C under defined assumptions. In the calculation of the thermal indices, the average ultrasonic attenuation is assumed to be 0.3dB/cm. MHz along the beam axis in the body. (FDA 1997¹) The thermal index values for the bone densitometry machines are not published by the manufacturers.

The risk of thermal damage can however be assessed by looking at the output level of the different machines; the maximum outputs for modern imaging systems are

¹ Food and Drug Administration.

capable of depositing significant amounts of heat in biological tissues, resulting in temperature increases of 10°C in extreme cases.

Table 1. FDA approved intensity limits for specific applications.

Application.	FDA Approved Intensity Limit I_{SPTA}
Peripheral Blood Vessel.	720 mW/cm ²
Cardiac.	430 mW/cm ²
Fetal, Neonatal	94 mW/cm ²
Ophthalmic.	17 mW/cm ²

(S.B.Barnett et al. 2000)

Table 2

Machine	I_{SPTA} Value For The Machine.
CUBA Clinical	<10 μ W/cm ²
Sunlight Omnisense. 7000s	
CM probe (Distal Radius)	4.8mW/cm ²
CS probe (Proximal Phalanx)	4mW/cm ²

(Information taken from personal correspondence with Sunlight, and McCue)

Table 1 shows the FDA approved intensity limits for different ultrasound applications, and table 2 shows the values that relate to the ultrasound machines in use in the BOSCOS project. The values for I_{SPTA} for the CUBA clinical and the Sunlight Omnisense are well below the intensity limits set for peripheral ultrasound and are even below the limits of ophthalmic ultrasound.

1.2. Cavitation.

There are two main forms of cavitation, transient cavitation and stable cavitation.

Stable Cavitation: Most ordinary liquids contain stable microbubbles, or other minute nuclei around which bubbles of dissolved gas are found to grow during the negative pressure phase of a sound wave. After a critical size has been obtained, which is characteristic of the sound frequency, these bubbles exhibit mechanical resonance. This, together with the small-scale patterns of fluid movement or “microstreaming” that it induces, can lead to localised regions of high shear and stresses in the liquid sufficient to break subcellular structures (M.L.Baker et al. 1978)

Transient Cavitation: This is a more violent activity in which hot spots of high temperature, high pressure or both occur in short bursts of microseconds. These bursts are accompanied by the production of free oxygen radicals. (R.Hershkovitz et.al. 2002) These free radicals have the capability to interfere with DNA, causing chromosomal damage, although this has never been observed. (S.B.Barnett 1997).

In order to assess the risk of cavitation the mechanical index has been devised. **Mechanical index:** The spatial-peak value of the peak rarefactional pressure, derated by 0.3 dB/cm-MHz at each point along the beam axis, divided by the square root of the center frequency. (FDA 1997) The higher the mechanical index the greater the probability of a biological effect. Values of indices less than 1 are considered safe,

and ultrasound scans should not be withheld for fear of mechanically induced adverse effects. (S.B.Barnett et al. 2000)

Table 3

Machine	Mechanical Index Values.
Sunlight Omnisense 7000s	
CM probe (Distal Radius)	0.28
CS probe (Proximal Phalanx)	0.22
CUBA Clinical	0.27

(Information taken from personal correspondence with Sunlight, and McCue)

The values in table 3 show that the mechanical index of the bone ultrasound machines is well below the accepted risk level.

2. Ionising Radiation.

2.1. Doses. (FDA-CDRH²)

During a bone densitometry scan, the patient is exposed to a dose of radiation. The dose a patient receives can be viewed in three different ways; the absorbed dose, the equivalent dose and the effective dose.

The absorbed dose is the fundamental quantity for describing the effects of radiation in a tissue or an organ.

$$\text{Absorbed Dose} = \frac{\text{Energy deposited in a small volume of tissue by the radiation beam.}}{\text{Mass of the Tissue.}}$$

(FDA-CDRH)

Equation 1

The absorbed dose is measured in joules/kilogram, with 1joule/kilogram equalling a Gray (Gy).

The equivalent dose refers to the biological effects of an absorbed dose of a given magnitude. This is however dependant on the type of radiation i.e. X-rays, Gamma rays, Beta rays (electrons), alpha particles (neutrons, or other particulate radiation), as the different types of radiation interact with the tissues in different ways.

$$\text{Equivalent Dose (Sv)} = \text{Absorbed Dose (Gy)} \times \text{Radiation Weighting Factor. (W}_R\text{)}$$

(FDA-CDRH)

Equation 2

The radiation-weighting factor is a dimensionless constant that is specific to a type of radiation. The equivalent dose is measured in Sieverts (Sv). The energy weighting factors are as follows.

² Food and Drug Administration (FDA). Centre for Devices and Radiological Health.(C.D.R.H.)

Table 4

Radiation Type	Radiation Weighting Factor.
X-rays, Gamma Radiation.	$W_R = 1$
Neutrons (Energy 10KeV-100KeV)	$W_R = 10$
Alpha Particles.	$W_R = 20$

The effective dose refers to the risk of cancer induction from an equivalent dose, and is dependant on the organ/tissue receiving the dose.

$$\text{Effective Dose} = \frac{\text{Equivalent Dose To Each Organ}}{\text{Tissue x The Organ / Tissue Specific Weighting Factor}} \quad (\text{FDA-CDRH})$$

Equation 3

The organ/tissue specific weighting factor accounts for the variations in the risk of cancer induction or other adverse effects for the specific organ.

Table 5

Organ/Tissue.	Organ/Tissue Specific Weighting Factor.
Gonads	$W_T = 0.2$
Red Bone Marrow	$W_T = 0.12$
Breast	$W_T = 0.05$
Thyroid	$W_T = 0.05$
Skin	$W_T = 0.01$

The products of equivalent dose and tissue weighting factor are then summed over all the irradiated organs to calculate the “effective dose”. The effective dose is measured in sievert (Sv).

2.2. Risks.

The risk of developing a cancer depends on the amount of radiation absorbed, and the dosage supplied depends on the type of examination being performed. The doses supplied during a bone densitometry scan vary, according to the technique, but the values are generally low.

Table 6

Technique	Effective Dose
Radiographic Absorptiometry. (RA)	~5 μ Sv
Single-Photon Absorptiometry. (SPA)	<1 μ Sv
Dual-Photon Absorptiometry. (DPA)	
Lumbar Spine	5 μ Sv
Proximal Femur	3 μ Sv
Single X-ray Absorptiometry. (SXA)	
Peripheral Dual-Energy X-Ray Absorptiometry (pDXA)	<1 μ Sv
Dual Energy X-Ray Absorptiometry (DXA)	
Pencil Beam.	
AP Spine	~1 μ Sv
Lat Spine	~3 μ Sv
Proximal Femur	~1 μ Sv
Whole Body	~3 μ Sv
Fan Beam.	50 μ Sv
Quantitative Computed Tomography (QCT)	
Single-Energy QCT (SEQCT)	50 μ Sv
Dual-Energy QCT (DEQCT)	100 μ Sv
Peripheral Quantitative Commuted Tomography (pQCT)	<2 μ Sv
Average Annual Dose	2.6 mSv
Return Trans-Atlantic Flight.	60 μ Sv
Annual Dosage from Cosmic Radiation.	260 μ Sv
Concorde Flight	12-15 μ Sv per hour
Quantitative Ultrasound of Bone.	0 μ Sv

Comparison of the effective radiation dose supplied by the different scanning techniques.

Table adapted from S.Grampp et al. (1993) and D.T.Baran et al. (1997)

Table 4 shows the doses supplied by different medical techniques and some non-medical sources. The effective doses of the bone density scans is generally well below the effective dose that would be received for a trans-Atlantic flight. The risk that these radiation doses impart is difficult to clarify. “ Suppose two populations, each of 100,000 individuals distributed in age and gender similarly to the total US population, were followed there entire lives. The unexposed population would suffer 100,000 deaths, of which 18,330 would be due to cancer. An identical population exposed to a single acute dose equivalent of 0.1 Sv would suffer 100,000 deaths, but about 19,010 deaths would be due to cancer. The projected life time risk is thus 790 excess cancer deaths or an increase of about 4% above the normal.” (W.R.Hendree 1996)

Although the doses from the bone densitometer would be much less than 0.1 Sv, the information shows there is a definite risk of cancer development, with every dose of radiation. This means that the repeated scanning of the body using radiation, as with a radiation based BOSCOS scanning system, will dramatically increase the risk of the occupants developing a cancer.

3. Conclusion.

The use of ionising radiation for measuring bone, in a car environment is not a feasible option. The repetitive scanning with radiation, at the same site, would cause an unacceptable risk from cancer development.

Ultrasound is therefore the safest of the available technologies for the assessment of bone, in a car.

4. References

- S.B.Barnett et al. (1994) Is Diagnostic Ultrasound Safe? **The Medical Journal of Australia**; Vol. 160, p.33-37
- S.B. Barnett et al. (1997) The Sensitivity of Biological Tissue to Ultrasound. **Ultrasound in Medicine and Biology**; Vol.23, No.6, p.805-812
- S.B.Barnett et al. (1998) In: Proceedings of the Symposium on Safety of Ultrasound in Medicine, WFUMB (The World Federation for Ultrasound in Medicine and Biology). Recommendation on the Safe use of Ultrasound. **Ultrasound in Medicine and Biology**. Vol. 24, Suppl.1, xv-xvi
- S.B. Barnett et al. (2000) International Recommendations and Guidelines for the Safe use of Diagnostic Ultrasound in Medicine. **Ultrasound in Medicine and Biology**; Vol. 26, No. 3, p.355-366
- M.L.Baker et al. (1978) Biological Effects of Diagnostic Ultrasound: A Review. **Radiology**; Vol. 126, p.479-483
- R.Hershkovitz et al. (2002) Ultrasound in Obstetrics: a Review of Safety. **European Journal of Obstetrics and Gynecology and Reproductive Biology**; Vol.101, p.15-18.
- U.S. Department of Health and Human Services, Food and Drug Administration (FDA). Information for Manufacturers Seeking Marketing Clearance of Diagnostic Ultrasound Systems and Transducers. 510(k). 30th of September 1997
- U.S. Food and Drug Administration (FDA). Center for Devices and Radiological Health.(C.D.R.H.) <http://www.fda.gov/cdrh/ct/risks.html>
- U.S. Food and Drug Administration (FDA). Center for Devices and Radiological Health.(C.D.R.H.) <http://www.fda.gov/cdrh/ct/rqu.html>
- W.R. Hendee et al. Health Effects of Exposure to Low-Level Ionizing Radiation. **Institute of Physics Publishing** 1996.
- S.Grampp et al. (1993) Radiologic Diagnosis of Osteoporosis: Current Methods and Perspectives. **Endocrine Radiology**; Vol.31, No.5, p.1133-1145
- D.T.Baran et al. (1997) Diagnosis and Management of Osteoporosis: Guidelines for the Utilization of Bone Densitometry. **Calcified Tissue International**; Vol. 61, p.433-440

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Bone Scanning for Occupant Safety

Appendix: 15.3

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
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Report title Reading Across to The Upper Body and Thorax

Author R. Cook and P. Zioupos
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Date February 2005



PROJECT REPORT
FORESIGHT VEHICLE LINK PROJECT
BONE SCANNING FOR OCCUPANT SAFETY
(BOSCOS)

Contract Number PPAD 9/33/89

1st February 2002 – 30th June 2005

Report to

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For and on behalf of the Consortium, comprising:

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Cranfield University at Shrivenham, Centre for Materials Science and Engineering

Loughborough University, Vehicle Safety Research Centre

McCue plc (sub-contractor to lead partner)

DfT Project Officer

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Reading Across to The Upper Body and Thorax.

Report on literature search findings on the issue of reading biomechanical strength values across various sites in the body and in particular for the ribs and clavicle.

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Glossary of Terms

BMD: Bone Mineral Density: For pQCT units = grams per cubic centimetre (g/cm^3)
For DXA units = grams per centimetre square (g/cm^2)

DXA: Dual Energy X-ray Absorptiometry:

A clinical method for measurement of the density of bone, usually performed on the hip, lumbar spine and forearm, but can be used to assess the whole body and peripheral sites.

QCT: Quantitative Computed Tomography:

A clinical technique that can be used for measurement of the density of bone in 3D, usually performed on the axial skeleton.

pQCT: Peripheral Quantitative Computed Tomography:

Like QCT but designed for use on the peripheral skeleton.

QUS: Quantitative Ultrasound.

A technique that utilises ultrasound for the assessment of bone quality; restricted to peripheral bone sites due to its dependence on proximity of the measurement site to the skin.

SOS: Speed of Sound:

A measurement parameter of ultrasound, based on the speed of an ultrasound pulse transmission through the bone.

AD-SOS: Amplitude Dependant Speed of Sound:

A variation on SOS where the assessment of the time is dictated by the amplitude of the received pulse, in order to supply an end point of the measurement.

UBPI: Ultrasound Bone Profile Index:

A measurement parameter supplied by the DBM Sonic equipment based on a number of parameters related to the ultrasound pulse.

Modulus of Rupture

$\sigma = \text{PLC}/4I$ P = the load required to break the rib segment, in newtons.
I = is the bending moment of inertia (a function of the bone distribution with respect to the neutral axis) in mm^4 .
C = the perpendicular distance from the neutral axis to the furthest point on the rib surface at the cross-section under load, in mm.
L = the testing span, in mm.

Ward's Triangle and Trochanter: These are anatomical site of the proximal femur, used as sites of assessment during a DXA scan, as demonstrated by the image below:

Image taken from: www.skally.net/ppsc/ert.html



Periosteum: A layer of connective tissue on the outer surface (periosteal surface) of bone.

Endosteum: A layer of connective tissue on the inner surface (endothelial layer) that lies between the cortical bone and the marrow cavity.

Haversian Systems: Compact bone has a network of 'canals' running through it containing blood vessels and nerves, these are known as haversian canals. The walls of these canals are known as the haversian surfaces.

Introduction

Car crash situations can be traumatic events, causing high impact loading of the upper body via the seat belt restraint, air bag, an object intruding into the vehicle and contacting with the occupant. Using a three point belt restraint system requires the forces applied for deceleration, to be borne by the bones of the thorax and the clavicle. In occupants suffering from conditions that weaken the bones, the force required to fracture the bones is reduced. The result is that minor and low speed accidents, which would bring about little injury to an average occupant, can have the capability to cause traumatic fractures to a weak boned occupant.

Traffic accidents account for a large percentage ($\approx 70\%$, S.T. Liman et al., (2003)) of all blunt chest injuries dealt with by hospitals, with over half of those patients requiring hospitalization. J.B. Holcomb et al., (2003) investigated the rate of morbidity from rib fractures and conclude that the risk of morbidity from rib fracture increases after age 45, especially in those who sustain four or more rib fractures, at the same time. It is therefore important to consider those occupants with low bone quality, who are more at risk from rib fractures, to ensure they receive the highest level of protection possible.

The BOSCOS system aims to provide this protection by predetermining those occupants with low bone quality so that the method of deceleration in a crash situation can be adapted to minimise loading of the skeleton. The system aims to do this by assessment of the proximal phalanx of the hand, to give an indication of skeletal status.

The aim of this report is to review the literature and data available to us, to determine the ability of the phalanx to supply the necessary information on the skeleton of a person that is required in order for the BOSCOS system to function successfully.

The Anatomy

The Clavicle

The Clavicle runs between the scapula and the sternum, and acts to support the shoulder joint and hold the shoulders back. The clavicle bone is prone to fracture and can be broken by relatively low trauma falls onto an outstretched arm, where loading is likened to a side impact crash. However the loading of the clavicle from a seat belt in a head on crash situation differs from that of a fall, with loading occurring mid-shaft.

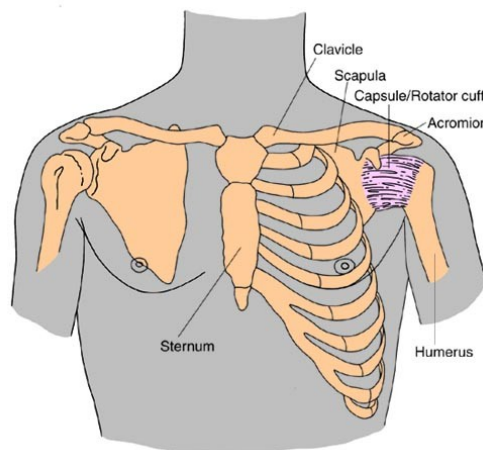


Figure 1. Diagrammatic representation of the anatomy of the clavicle, and its relation to bones of the upper body. (Image taken from www.luhhn.org/health)

There are different types of fracture that occur to the clavicle, and these were outlined by C.M. Robinson, (1998)(Figure 2). The fractures occur in three distinct areas, the two ends of the clavicle where articulation occurs with either the scapula, or the sternum, or in the mid-shaft region. The most common fracture is the type-2 fracture, or the fracture that occurs in the shaft of the clavicle, with type-3 fractures being the next most prolific and type one fracture the least frequent. Road traffic accidents account for approximately 27% of all clavicle fractures, with the majority of fractures occurring due to falls or sport related injuries. Of the injuries caused by road traffic accidents only 26% of the fractures were in car drivers or passengers, with pedestrians and cyclists accounting for most fractures. So from these statistics it would appear that the prevalence of clavicle fracture due to car crashes is relatively low.

However, fracture of the clavicle caused by a high trauma car crash has additional concerns. High impact loading has been shown to affect the body's ability to repair the bone. Increase in the healing time, and an increase in the number of delayed union and non-union of fractures was noted in subjects where the injuries were sustained in high trauma incidents.

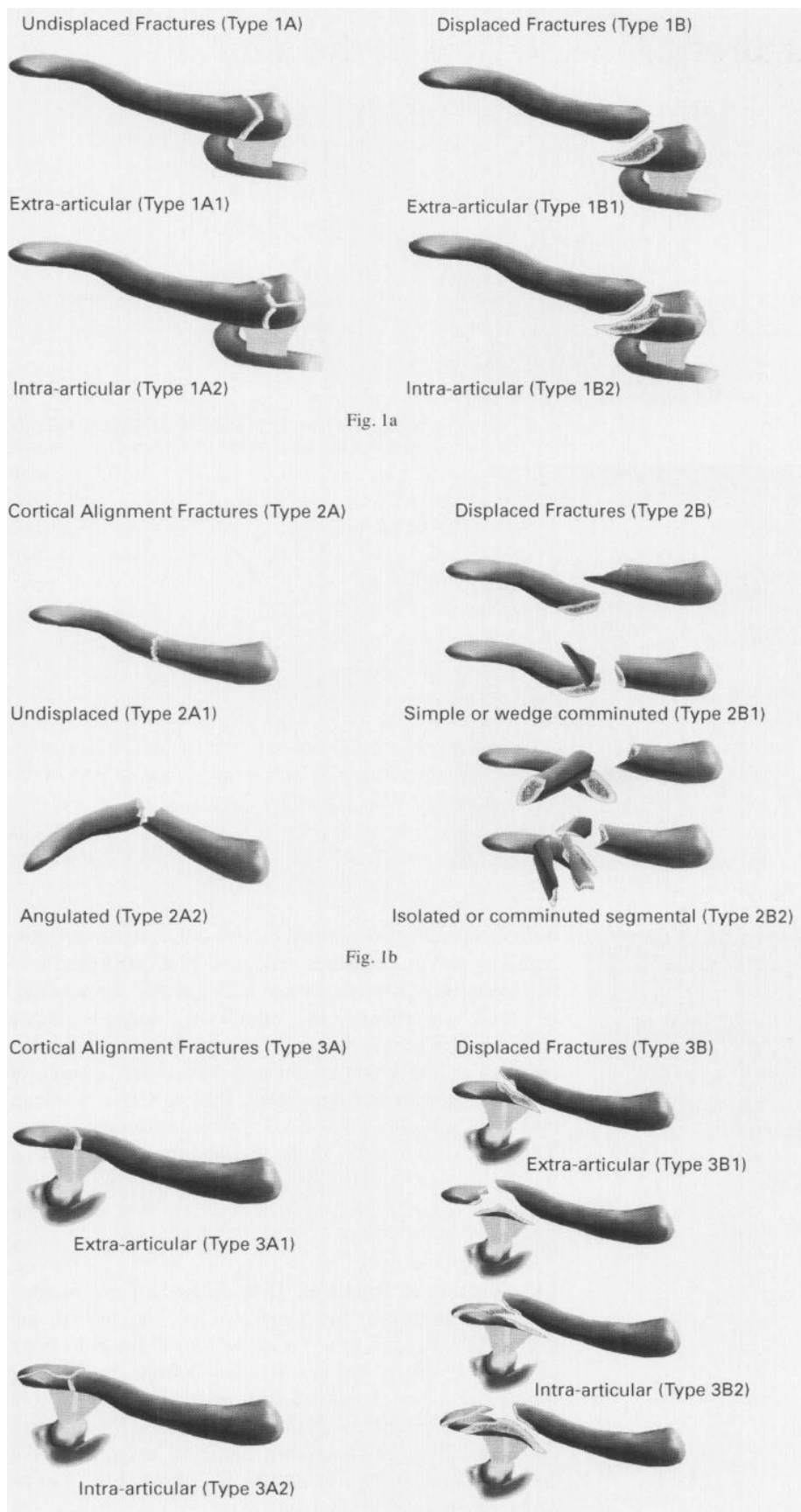


Figure 2. Diagrammatic representation of different clavicle fracture types.

The Ribs

The biomechanics of the ribs are very difficult to model and predict. Each rib differs in its geometry, cortical and cancellous bone composition and modes of attachment. Figure 3 shows a diagrammatic interpretation of the thorax. There are 12 pairs of ribs originating from the thoracic vertebrae, 7 of which are true ribs (ribs 1-7) and articulate with the sternum, and five are considered false ribs (ribs 8-12) due to their lack of articulation with the sternum, with the last two ribs (11 and 12) being named the floating ribs, as they only attach to the vertebrae. The lower numbered ribs are much shorter, and show a higher degree of curvature in comparison to the higher numbered ribs, the irregularity makes measurement of the standard mechanical properties of the ribs, such as tensile and compressive strength difficult as standard test samples can't be prepared.

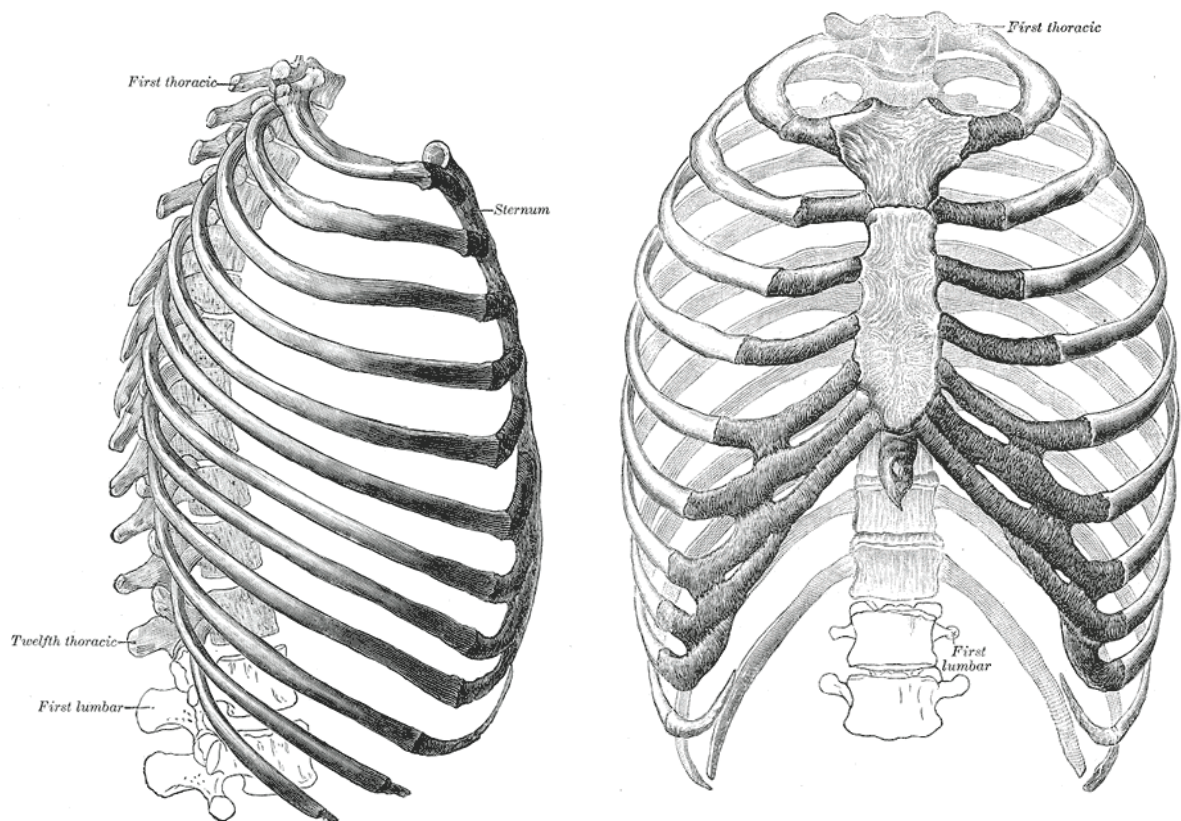


Figure 3. (Left) The thorax from the right. (Right) The thorax from the front.
(Images taken from The Bartleby.com edition of Gray's *Anatomy of the Human Body*)

The Sternum

The sternum is made up of three different parts:

- The Manubrium: The superior section of the sternum, which articulates with the clavicles and the first ribs.

- The Body: The mid region of the sternum, which articulate with rib pairs 2-7, the Manubrium, and the Xiphoid process.
- The Xiphoid Process: The inferior region of the sternum, which articulates with the Body of the sternum, the muscular diaphragm and the rectus abdominis muscles.

Anatomy Of The Hand Phalanges.

Phalangeal bones are found in both the feet and the hand, and are the bones found within the fingers and toes. The fingers consist of three phalangeal bones, the proximal, middle and distal phalanx, with the thumb only having two phalangeal bones, the proximal and distal.

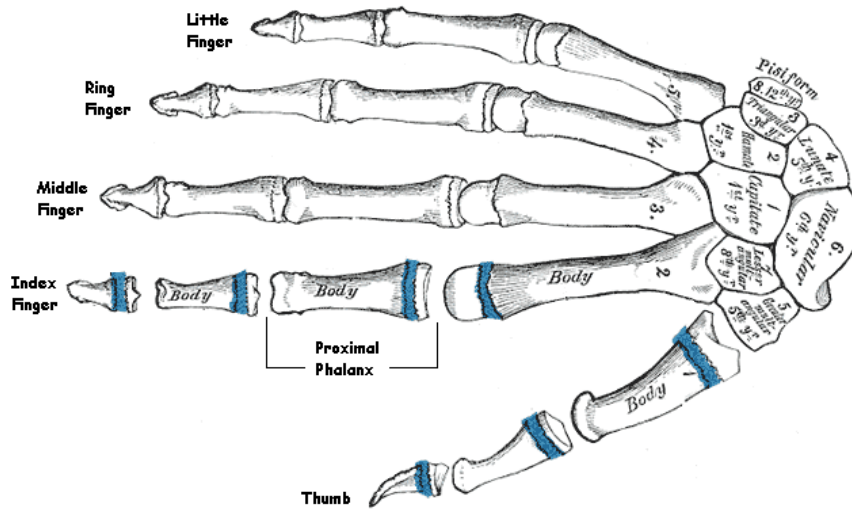


Figure 4. Anatomy of the hand showing the phalangeal bones.

Images Adapted from the Bartleby.com edition of Gray's *Anatomy of the Human Body*

For the purposes of the BOSCOS system, we are interested in the proximal phalanx, as it is the largest of the finger bones, which allows for a more accurate selection of the correct measurement site. It is also an easily accessible part of the body on which the measurement can be performed.

Ultrasound Of The Phalanges.

There are only two clinically available systems, which allow for the assessment of the phalangeal bones, for diagnosis of low bone density. The Sunlight Omnisense (Sunlight Technologies, Rehovot, Israel), an axial transmission based system, and the DBM Sonic (Igea, Carpi, Italy), a transmission based ultrasound system.

The Sunlight Omnisense.

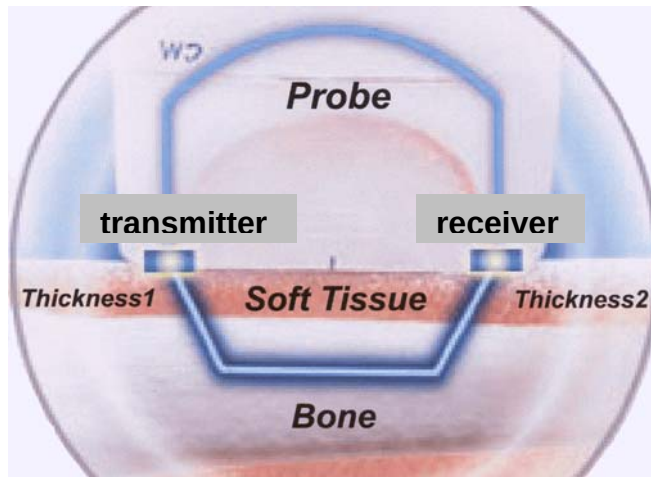


Figure 5. The Sunlight Omnisense Omnipath technology utilised for the measurement of Speed of Sound in Bone.

<http://www.sunlightmedical.com/international/html/tech.html>

The probe of the Sunlight system has four ultrasound transducers, two acting as transmitters, and two acting as receivers. The ultrasound pulse is propagated along the outer cortical bone, and measurement is taken of the time from the initiation of the ultrasound pulse to its arrival at the receiver. The time and signal is processed taking into consideration the angle of pulse entering and exiting the bone and the presence of the soft tissue. Ultrasound coupling gel is required to ensure propagation of the ultrasound to and from the probe. The measurements are supplied as speed of sound (SOS) (m/s), which can be compared against the systems database to produce the T-score and the Z-score, the standard values for evaluation of skeletal status.

DBM Sonic System

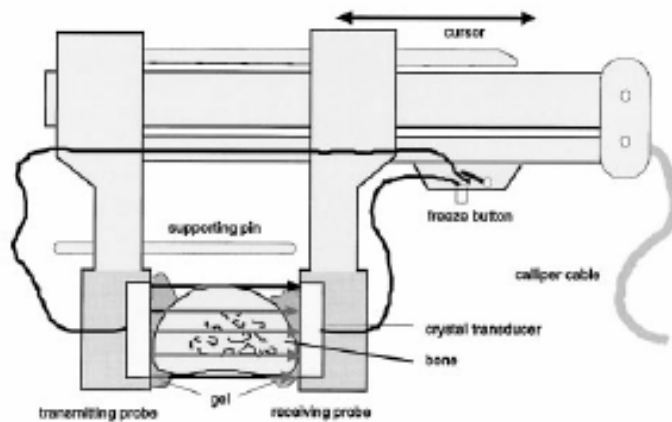


Figure 6. Schematic representation of ultrasound transmission through the fingers.
C. Wu et al., (2000)

The DBM Sonic works using the same principle that is used in the BOSCOS system, with slight differences, in that the BOSCOS system doesn't require the use of ultrasound gel as the silicon pads that contact with the skin provide enough coupling for the ultrasound transmission.

The systems work by positioning transducers on either side of the proximal phalanx of any finger, and ultrasound waves are passed through the finger and received by a second ultrasound transducer on the opposing side. The DBM Sonic has the ability to measure a number of parameters, the amplitude dependant speed of sound (Ad-SOS) (m/s), the dynamics of the ultrasound signal (SDy; $\text{mV}/\mu\text{s}^2$), time interval between the first and the fourth selected peaks (Time Frame [TF]; in μs), Signal energy (EN) normalized ($\text{mV}^2 \cdot \mu\text{s}$), maximum signal amplitude (UPA) in the TF (mV), and finally a combination of the above parameters, the ultrasound bone profile index (UBPI).

$$\text{UBPI} = 1/[1+\exp(-0.0018 \times \text{SDy} - 0.0560 \times \text{FWA} - 1.1467 \times \text{TF} + 3.03)]$$

Equation 1. Formulae for the calculation of the Ultrasound Bone Profile Index (UBPI)
R. Giardino et al., (2002)

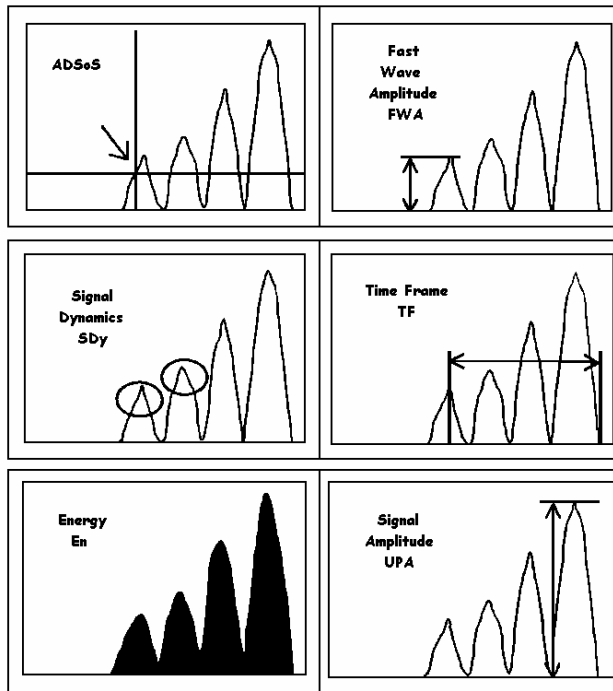


Figure 7. Physical parameters capable of measurement using the DBM Sonic.
C. Wüster et al., (2000)

The system also has the ability to reconstruct an image of the bone tissue at the measurement site, showing the size of the medullary canal and the cortical bone thickness.

The Effects of Ageing on the Human Skeleton.

- **Strength of Biological Materials.** H. Yamada, (1970b)

H. Yamada reviewed the average ratios for the changes in mechanical properties of human bone in relation to age. The research found that the mechanical properties of bone (combination of the properties of human femoral compact bone, intact long bones, and vertebrae) were greatest between the ages 20 and 29. Between the ages 10-19 the mechanical properties are capable of being equal, but are generally slightly lower. Between the ages 30-39, the average mechanical properties are reduced to 99% that of the 20-29 year olds, it falls to 90% between 40-49, to 86% between 50-59, 80% between 60-69, and 78% between 70-79 years of age. This shows a clear and steady decline in the mechanical properties of human bone with increasing age. Site specific reductions vary, with long bones only reducing to 83% in comparison to the peak by the age 70-79, whereas the vertebrae can reduce to as little as 70% by the same age.

Cartilage is also affected by age, the average mechanical properties of cartilage is greatest between the age 20-29. The ratio reduction in the mechanical properties for people aged 30-39 is 99%, between the ages 40-49 it's 79%, between 50-59 it's 74%, 60-69 it's 71% and between the age 70-79 it is 70%. Once again the percentage drop is dependant on the type of cartilage, (Hyaline cartilage, Costal cartilage, and intervertebral disks.) Costal cartilage is important as this is the type of cartilage that joins the ribs to the sternum; it has the greatest compressive mechanical properties

between the ages 20-39, the ratio is 86% between the ages 10-19, and is reduced to 71% by the age 40-79.

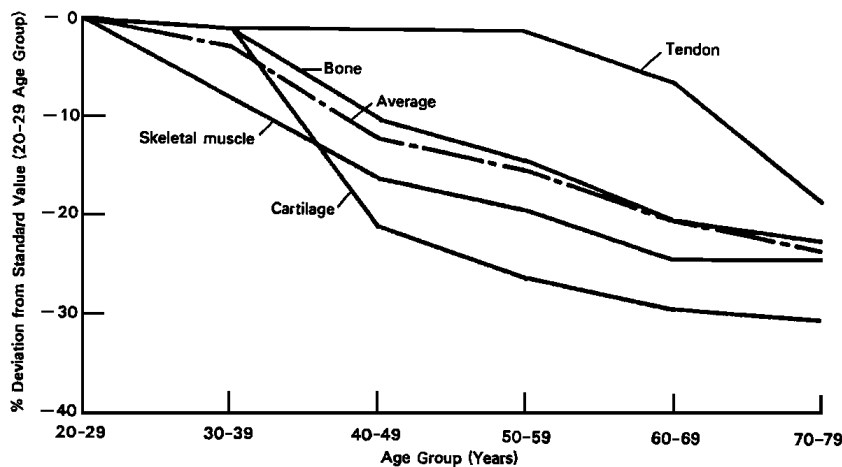


Figure 8. Aging rates for the strength of adult human locomotor organs and tissues.
H. Yamada, (1970a)

- **Age-independent consistency of mineral contents in human ribs.**

M. Utsumi et al., (1999)

The study population was mixed with both males and females, with the age of the population studied ranging from 65 and 93 years of age. The study concluded that the calcium and the phosphorus content did not decrease with aging in bone composed mainly of compact bone, whereas in bones composed mainly of spongy (trabecular) bone a decrease with age was noted.

- **Chapter 4: The adaptation of mechanical properties to different functions.**

J.D. Currey, (2002)

Chapter 4 considers the effect that variation in the mineral volume fraction of bone has on the mechanical properties of bone. By performing comparisons of different bones from different animals, that exhibit different mechanical properties, and different mineral, organic and water make-ups, it was possible to view the effects of changing compositions in bone, without artificial adjustment of the bone tissue. The mechanical properties discussed were Young's modulus, strength, and ultimate strain.

Young's modulus.

'Young's modulus is determined to quite a high degree by two variables only: calcium content (or mineral volume fraction) and porosity.' Figure 9 displays the correlation between mineral volume fraction, and young's modulus, showing a clear positive correlation. The addition of porosity in combination with mineral volume fraction would produce a much closer fit.

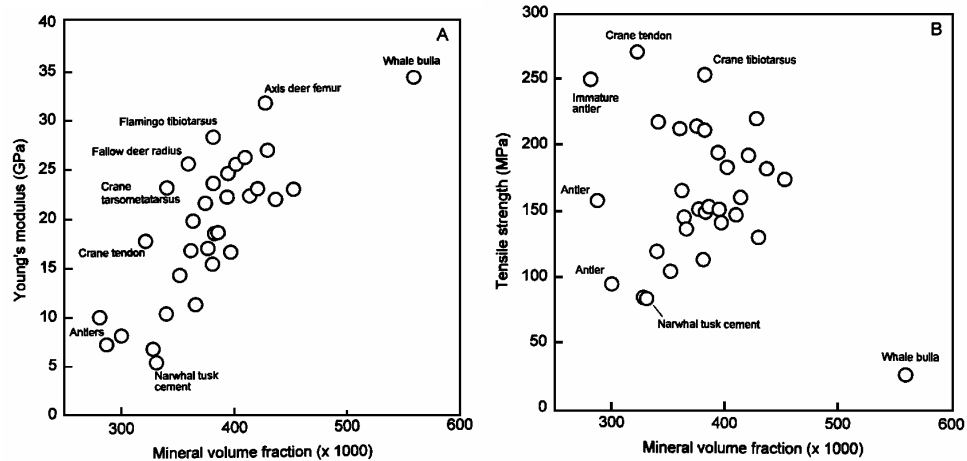


Figure 9. A) Young's modulus as a function of mineral volume fraction.
B) Tensile strength as a function of mineral volume fraction.
J.D. Currey, (2002)

Strength.

'Tensile strength shows no clear relationship with mineral volume fraction.'

Ultimate Strain.

Ultimate tensile strain is affected by mineral volume fraction; the greater the mineral content the lower the ultimate strain will be prior to failure.

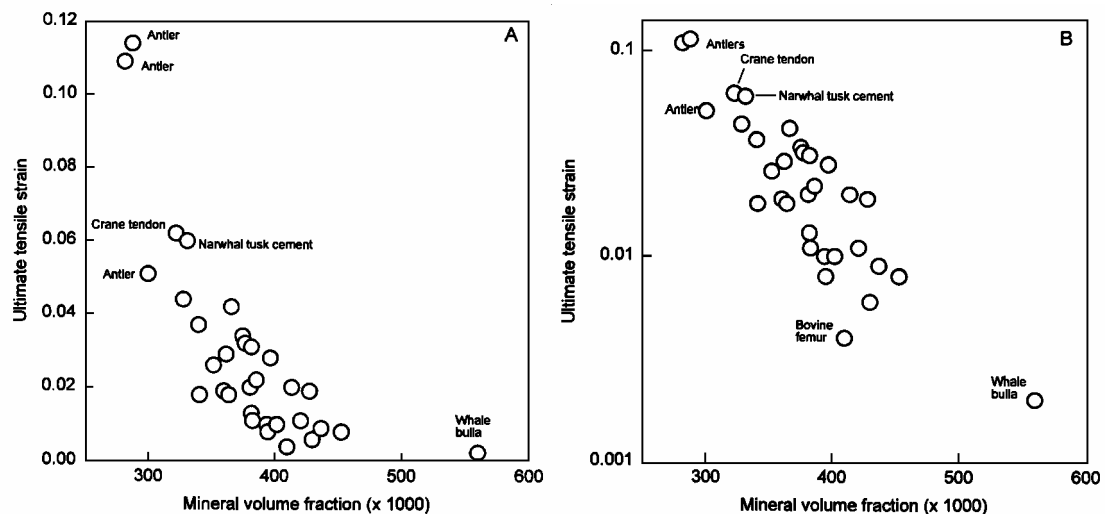


Figure 10. A) Ultimate tensile strain as a function of mineral volume fraction.
B) Ultimate tensile strain as a function of mineral volume fraction on a log scale. J.D. Currey, (2002)

- **The mechanical consequences of variation in the mineral content of bone.**

J.D. Currey, (1969)

The testing was performed on 23 pairs of third and fourth metatarsal bones from wild rabbits. The bones were made into test samples and mechanically tested in a three-point bend to produce values for Young's modulus, and ultimate tensile strength. In addition to this, samples were tested in impact, using a three-point bend, and assessment of the energy absorbed in breaking was determined.

The results showed that an increase in the ash content was positively linked to both ultimate strength and young's modulus, with regression equations of:

$$\text{Ultimate strength} = 1.75 \text{ ash} - 100.47$$

$$E \text{ (Young's Modulus)} = 197.32 \text{ ash} - 11.85$$

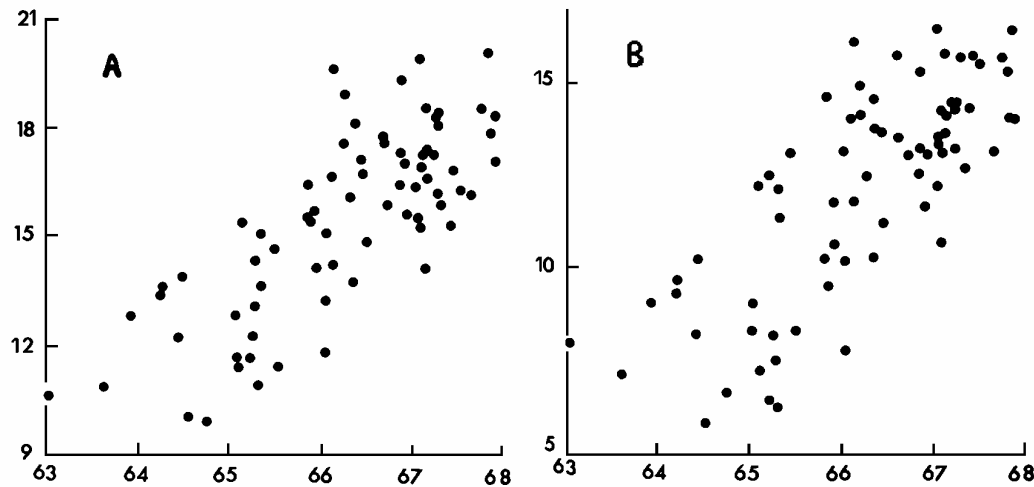


Figure 11. A) Relationship between ash content (weight percentage) and ultimate strength (kg/mm²).

B) Relationship between the modulus of elasticity (kg/mm²) x 10⁻¹ and ash content (weight percentage) J.D. Currey, (1969)

The relationship of ash content and modulus of impact (impact energy x depth of the section / $\sqrt{I}$) showed a quadratic fit, with an optimum ash content of between 66 and 67%. Even when the impact modulus was modified (impact energy x D/I) the trend and ash content was the same only the values of the modulus were reduced.

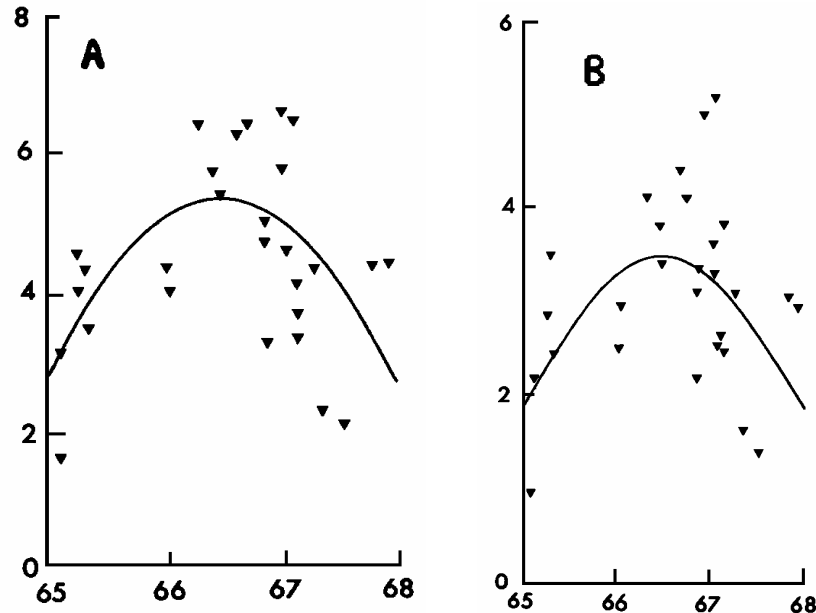


Figure 12.

A) Relationship between the modulus of impact (impact energy x depth of the section / $\sqrt{I}$) and ash content (weight percentage).

B) Relationship between the modulus of impact (impact energy x depth of the section / I) and ash content (weight percentage).

J.D. Currey, (1969)

The Effects of Age on Human Ribs

The ribs are in constant use through out life and are therefore less prone to osteoporosis caused by disuse. Any changes in the bone of the ribs will be mainly due to metabolic reasons, for this reason the ribs have a lower decline in density in comparison with age.

B.E.C. Nordin et al., (1996) showed that in a group of 47 postmenopausal women with vertebral fractures there was only a 15% difference between the BMD of the ribs between the study population and young reference values. In comparison to 40% at Ward's triangle, 30% at the lumbar spine (L1-L4) and 29% at the femoral neck. Three studies: F. Santoro and H.M. Frost, (1968), H. Takahashi and H.M. Frost, (1966), and E.D. Sedlin, (1964), have looked into the effects of age on the ribs, and more specifically in relation to osteoporosis. As with other bones within the human body the ribs are an active system, reabsorbing and remodelling through out life, with the peak amount of cortical bone in the ribs occurring between the ages of 15-22.

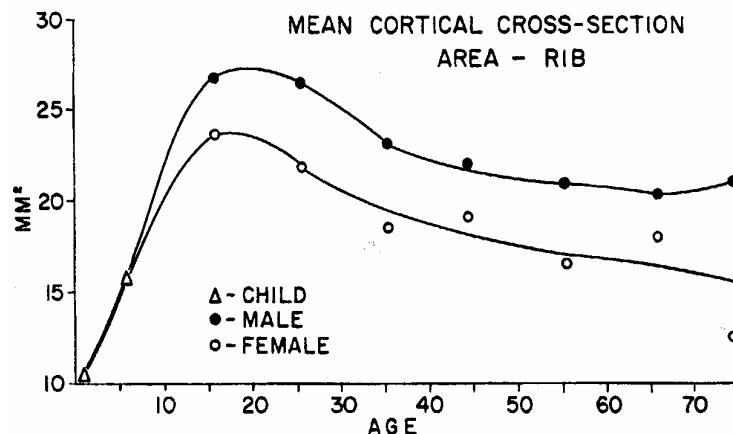


Figure 13. The variation in the mean cortical cross-sectional area of the rib vs. age. E.D. Sedlin, (1964)

The active reabsorbing and remodelling process occurs at three separate places within the rib, the periosteal surface, the endosteal surface and Haversian surfaces. However at these three separate sites the balance of the process is different; at the periosteal surface the balance is never negative; the balance is always preferential towards the laying down of bone, causing a gradual increase in the rib cross sectional area throughout life. The endosteal surface is however the reverse of this and the balance is never positive; this causes a steady increase in the size of the marrow cavity.

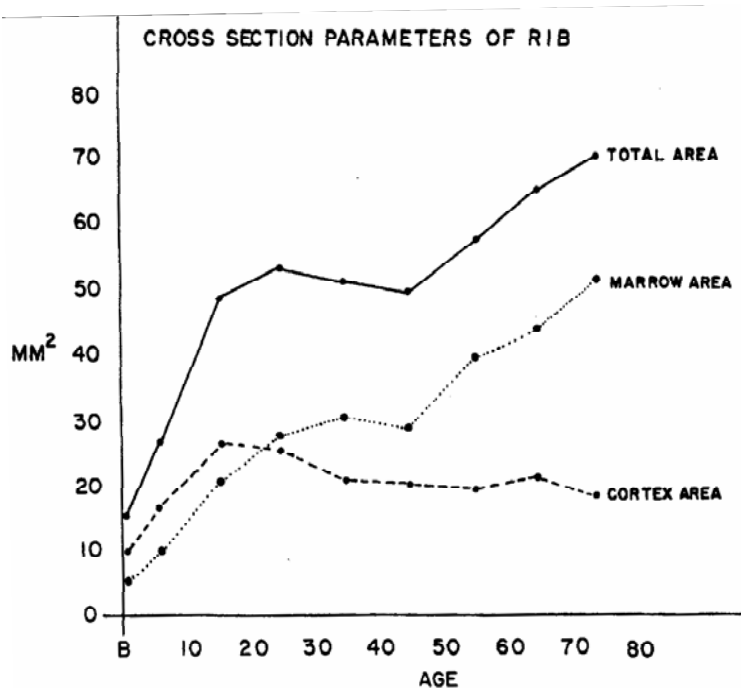


Figure 14. Change in the cross sectional parameters of the ribs with age.
E.D. Sedlin, (1964)

The Haversian surfaces are in normal balance during aging, and only become imbalanced when the patient is suffering from specific bone related disorders, but not osteoporosis.

The ribs of normal and osteoporotic subjects have been shown to have the same geometrical properties, but with the osteoporotic subjects having a reduced amount of cortical bone, and larger marrow cavities. G. Granik and I.D. Stein, (1973) showed that changes in the mechanical properties are mainly due to the compact/cortical bone (the spongy/trabecular bone having a negligible contribution to the ribs mechanical properties) hence a reduction in compact bone will reduce the mechanical properties of the ribs. H. Takahashi and H.M. Frost, (1966) quantified this loss and showed that the cortical area of the ribs reduces by approximately 25% from its peak, by the age of 65

Ageing Of The Phalanges.

Unlike the ribs, the phalanges of the hands are prone to variation in the density and bone mass due to age. Studies on large populations (Table 1) have shown significant negative correlations with age in both sexes, with old age, however the variation occurs throughout life with a gradual increase in density and mass till roughly the age of 30 in men, and the onset of the menopause in women, followed by a progressive reduction in density and mass. This trend is shown clearly in Figure 15.

Study	Population	Regression Equation	r-value	p-value
B. Drozdowska and W. Pluskiewicz, (2003)	1175 males from Poland, aged 7-80	Ad-SOS [m/s] = $1673.5 + \text{age [years]} - 0.203 \times \text{age [years]}^2 - 0.022 \times \text{age [years]}^3 + 0.00047 \times \text{age [years]}^4 - 0.000002731 \times \text{age [years]}^5$	0.55	<0.001
R. Giardino et al., (2002)	170 Postmenopausal women, aged 63 ± 7 years	Ad-SOS = $-5.80 (\text{age}) + 2251.4$ UBPI = $-0.02 (\text{age}) + 1.39$	-0.475 -0.595	<0.0005 <0.0005
M.D. Stefano and G.C. Isaia, (2002)	87 postmenopausal osteoporotic women, aged 49-81.	Ad-SOS UBPS	-0.53 -0.47	<0.001 <0.001
F. Duboeuf et al., (1996)	128 females aged 21-85 (mean 51.2 years)	AD-SOS = $2008.25 - 4.68 \text{ age}$	0.71	=0.0001
F.E. Alenfeld et al., (1998)	139 healthy Caucasian women aged 21-94	Ad-SOS	-0.73	<0.001
G. Guglielmi et al., (2003)	140 women aged 20-75 (mean 54 ± 11.1 years)	AD-SOS UBPI	-0.52 -0.35	<0.0001 <0.0001
J. Joly et al., (1999)	Females control group Postmenopausal group	AD-SOS = $-3.7 \text{ age} + 2230.3$ AD-SOS = $-4.83 \text{ age} + 2292.2$	-0.59 -0.51	<0.05 <0.05

Table 1. Correlation between quantitative ultrasound and age.

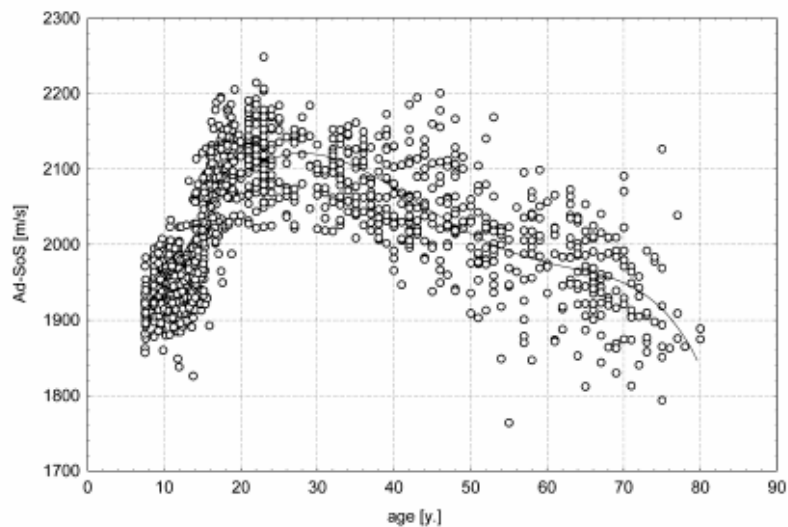


Figure 15. Ad-SOS versus age in a group of 1175 males, showing the trend of increase and decrease depending on age.

B. Drozdowska and W. Pluskiewicz, (2003)

Previous testing data of the thorax and axial skeleton

The biomechanics of the upper body and thorax are difficult to predict, as the skeleton will react in different ways depending on the load magnitude, rate and direction of application, but also the bone geometry and bone properties.

- **Chest deflection tolerance to blunt anterior loading is sensitive to age but not load distribution.** R. Kent and J. Patrie, (2004)

The study looked at four different types of loading:

1. Blunt hub loading: A 15.2cm circular steel plate was used to apply the load, with the load applied to the 4th interstitial space.
2. Seatbelt loading: This consisted of a 5cm wide belt passing over the thorax, originating at the left shoulder, and crossing the anterior thorax at 45° to the sagittal plane. Crossing the clavicle at the one third, crossed mid-sternally and finish at approximately the 9th rib.
3. Distributed loading: The load was applied using a 20.3cm wide belt traversing the thorax laterally roughly between the second and seventh ribs.
4. Diagonal belt loading: The load was applied via a four point belt using two 5cm wide belts running in opposite directions as described in the seatbelt loading.

Tests were performed on 93 cadavers, and showed that the chest deflection injury tolerance was insensitive to the loading condition. (Figure 16)

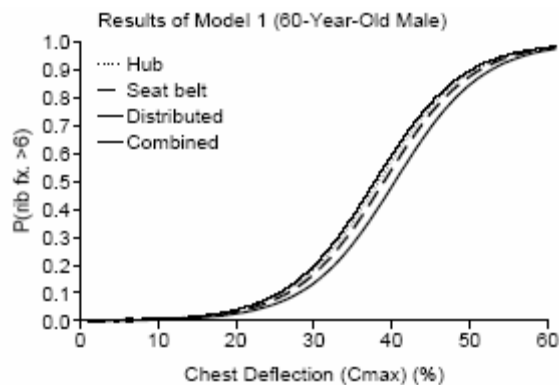


Figure 16. Chest deflection injury tolerance insensitivity to the loading condition.
R. Kent and J. Patrie, (2004)

However, when the risk of injury was compared to the age, increased age was found to reduce the chest deflection required for the infliction of an injury, with the probability of injury increased by both age and chest deflection.

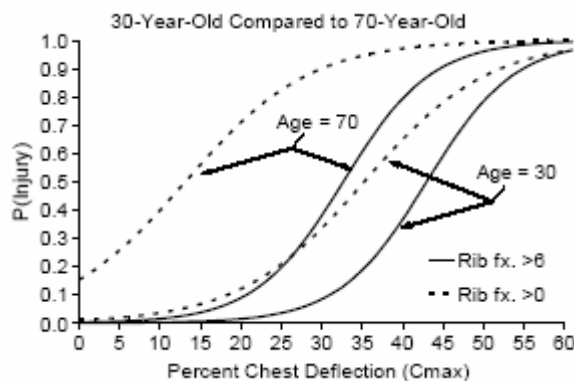


Figure 17. Comparison of injury risk onset and severe injury risk, for two ages.
R. Kent and J. Patrie, (2004)

- **Age-related changes in the effective stiffness of the human thorax using four loading conditions.** R. Kent et al., (2003)

The investigation used the four previously mentioned loading conditions, to investigate the age related changes in the effective stiffness of the thorax. The loading condition was found to affect the force required for deflection of the ribs:

1. Distributed load: 15,397N/100% deflection
2. 4-point belt load: 13,706N/100% deflection
3. Diagonal belt loading: 9,862N/100% deflection
4. Hub loading: 4,750N/100% deflection

The load required to attain 100% deflection was only mildly affected by age, with a slight but non-significant stiffness increase with increasing age.

- **Biomechanical properties of the male and female chest subjected to frontal and lateral impacts.** H. Kimpara et al., (2003)

An investigation into the biomechanics of human chests in frontal and lateral impacts, with specific interest in the gender differences. The conclusions from the study state that:

1. Female chest stiffness (267 ± 150 kN/m) was considerably lower than that of the males (476 ± 324 kN/m) in frontal impact, probably due to the smaller cross-sectional area of the female ribs.
2. There was no gender specific difference in the Young's modulus and bone mineral density based on isolated rib bending tests. However the cross-sectional area,

maximum bending force and stiffness of female ribs were approximately 19, 30 and 43% lower than those of male ribs respectively.

3. Linear regression analysis of data obtained from isolated rib bending tests did not correlate statistically the age, height, weight, chest depth and width of the cadavers tested for both males and females.

4. The maximum chest deflection, compression ratio and maximum force correlated linearly with impact energy for both males and females in frontal impact.

5. The slopes of maximum chest deflection and compression ratio versus impact energy for females are 37 and 31% steeper than those for males, respectively. In general the maximum deflection and compression ratio for females are considerably higher than those for males when subjected to the same impact energy.

- **Rib structure and bending strength: An autopsy study.**

I.D. Stein and G. Granik, (1976)

The study involved the testing of 218 ribs from male subjects in a three-point bend, at variable loading rates. The rate of loading was shown to have a positive correlation with rupture modulus (σ).

$$\sigma = PLC/4I$$

P= the load required to break the rib segment, in newtons.

I = is the bending moment of inertia (a function of the bone distribution with respect to the neutral axis) in mm^4 .

C = the perpendicular distance from the neutral axis to the furthest point on the rib surface at the cross-section under load, in mm.

L = the testing span, in mm.

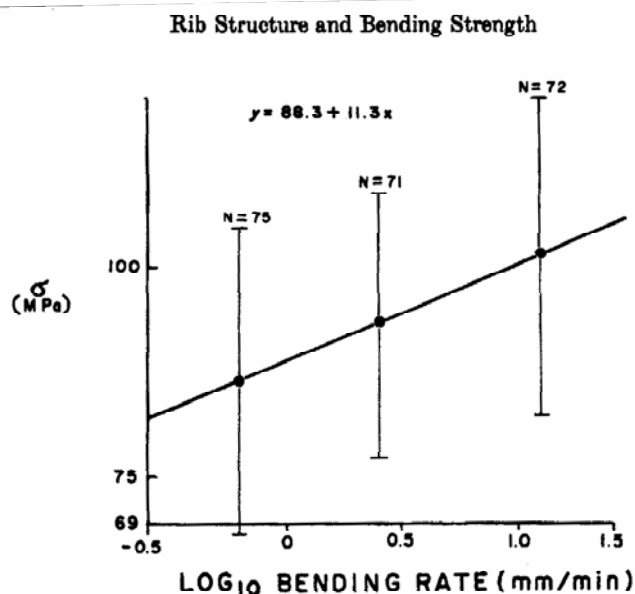


Figure 18. The relationship between $\log_{10}$ bending rate (rate of displacement at loading point) and the rupture modulus (σ). N= number of ribs tested. Error bars show ± 1 SD.

I.D. Stein and G. Granik, (1976)

The loading rates used in this testing show a far lower rate of loading than would be experienced in an impact situation such as a car crash situation, but show that with increasing loading rate the ribs are capable of sustaining a higher force prior to fracture.

Age showed a statistically significant ($p < 0.001$) negative correlation ($r = -0.534$) with breaking load (p), and also with rupture modulus ($r = -0.327$ $p < 0.01$)

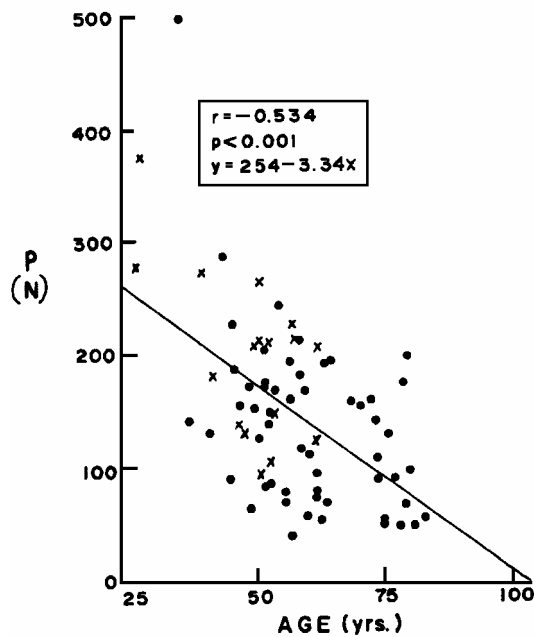


Figure 19. The relationship between patient age and breaking load, showing significant inverse correlation.

X= African-American origin.
Circles indicate Caucasian origin.
I.D. Stein and G. Granik, (1976)

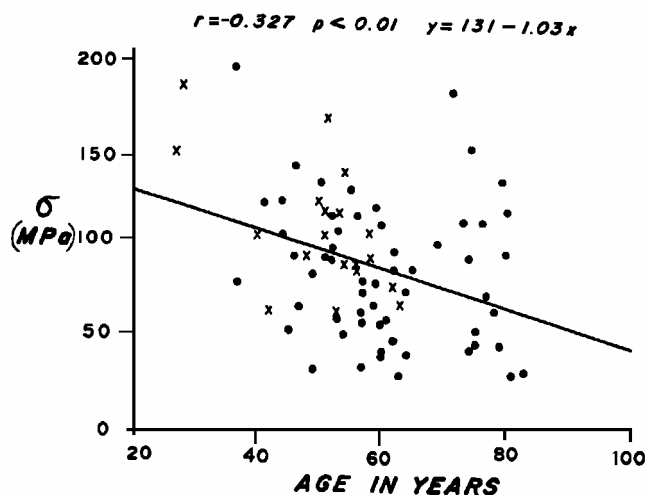


Figure 20. The relationship between patient age and modulus of rupture.

X= African-American origin. Circles indicate Caucasian origin.
I.D. Stein and G. Granik, (1976)

If these results (in particular the breaking load .vs. age) are viewed in relation to the results for the SOS (m/s) vs. the age (years), the correlation achieved is very similar to that of the breaking load for the ribs $r = -0.538$ ($p < 0.001$). The coefficient of variation (standard deviation over the mean) also seems to be of at least the same magnitude.

- **Regional bone mineral density interrelationships in normal and osteoporotic postmenopausal women.** B.E.C. Nordin et al., (1996)

The study investigated the bone mineral density (BMD) of different bone sites around the human body. The study investigated 131 postmenopausal women, with investigations being performed on the femoral neck, Ward's triangle, Trochanter, Lumbar spine (L1-L4), forearm, head, arms, legs, trunk, ribs and pelvis.

	Ribs	Forearm
Femoral neck	0.685	0.549
Ward's Triangle	0.662	0.594
Trochanter	0.748	0.639
L1-L4	0.709	0.648
Head	0.582	0.607
Arms	0.770	0.777
Legs	0.802	0.770
Trunk	0.921	0.689
Pelvis	0.810	0.647
Spine	0.848	0.698
Ribs		0.635
Forearm	0.647	

Table 2. Coefficients of correlation between BMD at different sites and regions in 131 postmenopausal women. (All $p < 0.001$)
B.E.C. Nordin et al., (1996)

These correlations show a moderate to good correlation between sites, and all with a high level of statistical significance. Despite this high correlation between sites, the ribs have a lower decline in density in comparison with age. The difference between the BMD of the ribs between the study population and young reference values was only 15%, in comparison to 40% at Ward's triangle, 30% at the lumbar spine (L1-L4) and 29% at the femoral neck, as mentioned previously.

- **Age-related bone loss: Relationships between age and regional bone mineral density.** T. Kamei et al., (1999)

The study investigated the head, arm, leg, thoracic and lumbar spine, ribs and pelvis with dual energy X-ray absorptiometry (DXA). The study cohort contained 985 women aged between 31 and 69 years of age.

	Arm years group	<50 age	Ribs <50 years age group	Arm years group	>50 age	Ribs years group	>50 age
Total Body	0.751		0.805	0.814		0.834	
Head	0.471		0.579	0.582		0.637	
Arm			0.729			0.827	
Leg	0.712		0.675	0.827		0.786	
Thoracic-Spine	0.637		0.712	0.722		0.792	
Lumbar-Spine	0.673		0.729	0.721		0.759	
Rib	0.729			0.827			
Pelvis	0.659		0.695	0.736		0.751	

Table 3 Pearson correlation coefficients (r) between measurements.
T. Kamei et al., (1999)

These correlations are in agreement with those of B.E.C. Nordin et al., (1996), as is the additional findings that BMD of the ribs reduces to a lesser extent than many other bones sites with a reduction of approximately 17%.

- **Differential changes in regional bone mineral density in healthy Chinese: Age-related and sex-dependant.** W.J. Yao et al., (2001)

The study investigated the changes in regional BMD in a group of 1265 Chinese men and women, and looked at the effects of age and sex.

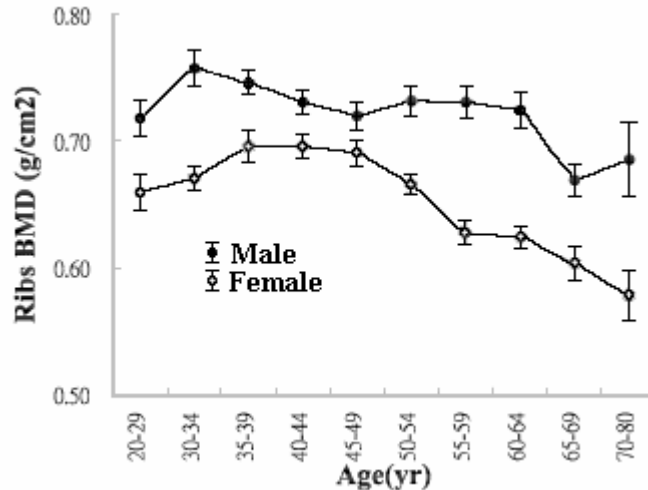


Figure 21. Age-related change in BMD of the Ribs in a group Chinese volunteers.
W.J. Yao et al., (2001)

Figure 21 shows that there is only a slight reduction in rib BMD with age, with a drop of 23.9% in women and 9.5% in men, between the ages 35-39 and 70-80, similar to that found in the previous two studies. The study also investigated the correlation between BMD at sites around the body and specifically the ribs, shows the results that are all statistically valid and show correlations similar to those of the two previous studies.

	Age	Weight	Height	BMI	Arms	Legs	Trunk	Pelvis	Spine	Head	Total
Rib BMD (Female)	-0.36	0.53	0.26	0.43	0.74	0.73	0.91	0.81	0.83	0.56	0.82
Rib BMD (Male)	-0.19	0.74	0.25	0.71	0.68	0.70	0.93	0.86	0.83	0.50	0.86

p<0.01

Table 4. Correlation coefficients of rib BMD in Chinese males and females.
W.J. Yao et al., (2001)

- **Rib-cage injuries indicating the direction and strength of impact.**
G. Schmidt, (1979)

An investigation into the hardness and loading capacity of hundreds of rib pairs, in comparison to the results from tests on 200 belt protected human cadavers. The effect of frontal impact on the ribs of 99 cadavers with a three-point belt restraint system is shown in Figure 22. The results showed that both an increase in age and an increase in speed caused a greater number of rib fractures.

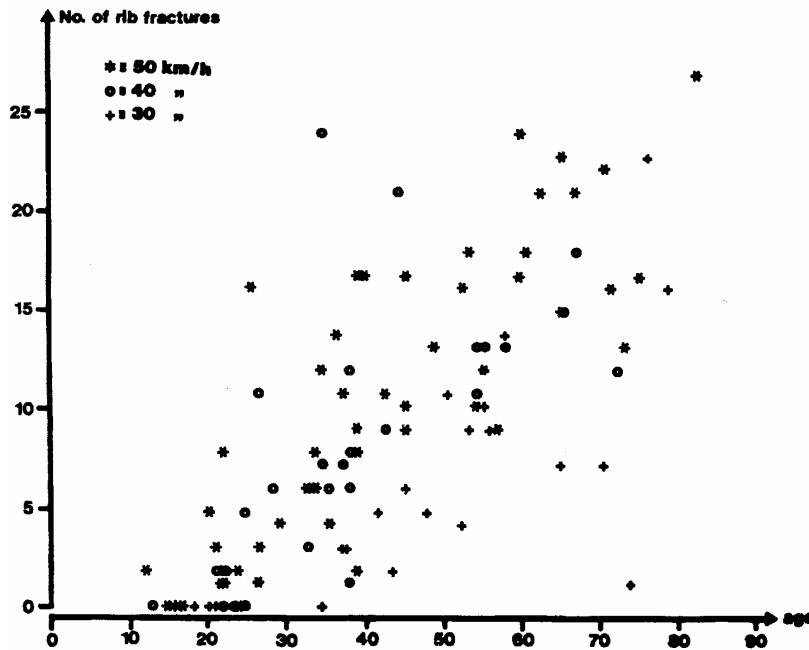


Figure 22. Results of rib fractures with 99 cadavers after frontal impact with a three-point belt. G. Schmidt, (1979)

The paper went on to investigate the loading capacity, and the effect of age on the compacta square measure (mm^2), a measure of the amount of compact bone present in the rib. The level of the compacta square measure varied with age (Figure 23) peaking as mentioned previously at between 12 and 22 years of age, with a steady decline occurring after this age. There was a discernable difference between the sexes, with males having a greater compacta square measure throughout life in comparison to age-matched females.

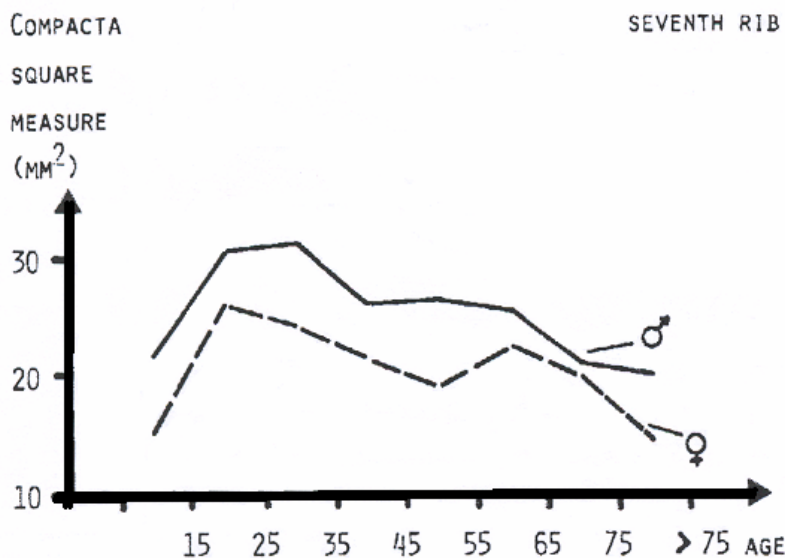


Figure 23. Compacta square measure (mm^2) of 7th rib from 110 corpses (average) as a function of age. G. Schmidt, (1979)

Not surprisingly, the loading capacity of the rib increased with higher compacta square values (Figure 24).

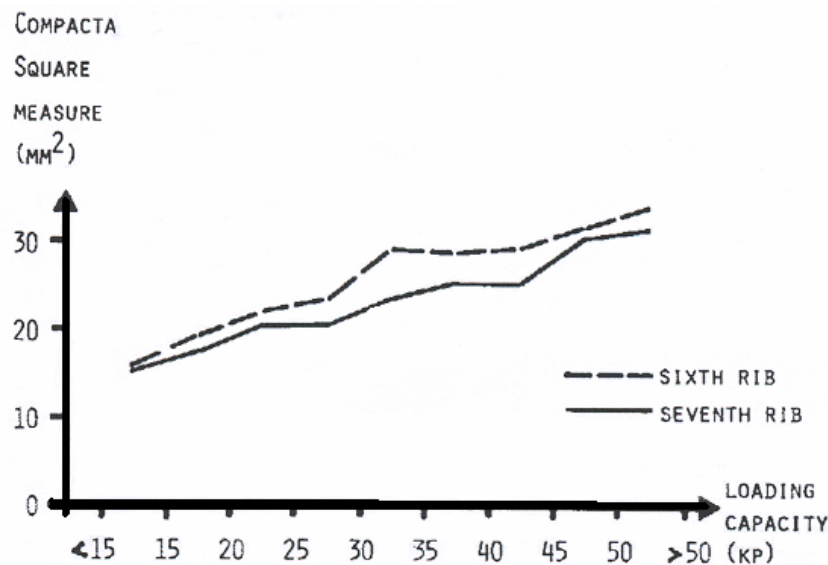


Figure 24. Loading capacity of ribs according to the compact square measure. The values are the means of 211 ribs: 6th rib, concave loading (force inflection from the concave side), 109 tests; 7th rib, convex loading, 102 tests. G. Schmidt, (1979)

When the results of these two graphs are combined, and the loading capacity for and average 20 year old male is compared with that of a 75 year old male the reduction in loading capacity is in the region of 55%.

- **Results of 49 cadaver tests simulating frontal collision of front seat passengers.**

G. Schmidt et al., (1994a)

The different tests used two different belt systems, a three point belt system, and a two point belt system with a knee bar to prevent submarining, the tests were performed at a simulated speed of 50km/h with a stopping distance of 40cm. The study looked at the effect of body weight on the shoulder belt force, which showed a significant rise with increased body weight in both the 2 and 3 point belt restraint systems. (Figure 25 A) The study also looked at the number of rib fractures the cadavers sustained, in accordance with the cadavers age and the seat belt restraint system utilised; the results showed a marked rise in the number of rib fractures with increasing age. (Figure 25 B)

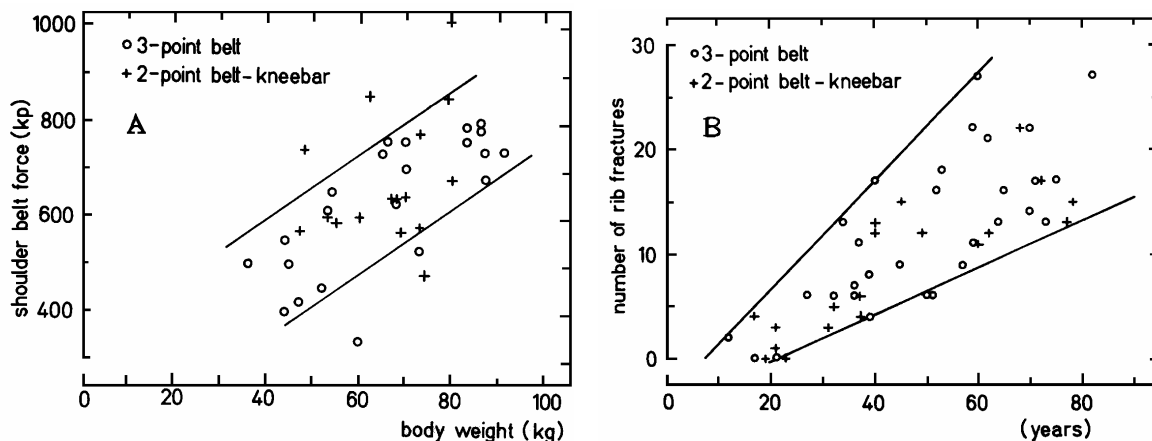


**Figure 25. A) Shoulder belt force dependency on weight.
B) Number of rib fractures in relation to age.
G. Schmidt et al., (1994a)**

The study then went on to investigate the ‘degree of injury’ in relation to the restraint system used and the age of the cadaver. The scale used was the ACIR-scale which denotes that: 0= no injuries, 1= slight injuries, 2= no dangerous injuries, 3= dangerous injuries, and 4= lethal injuries. The results showed that the cadavers aged over 40 were sustaining lethal injuries at 50km/h crash scenarios with both two and three point belt restraint systems, and a definite trend towards greater severity injuries in the elderly in comparison to youth, under the same crash parameters. (Figure 26)

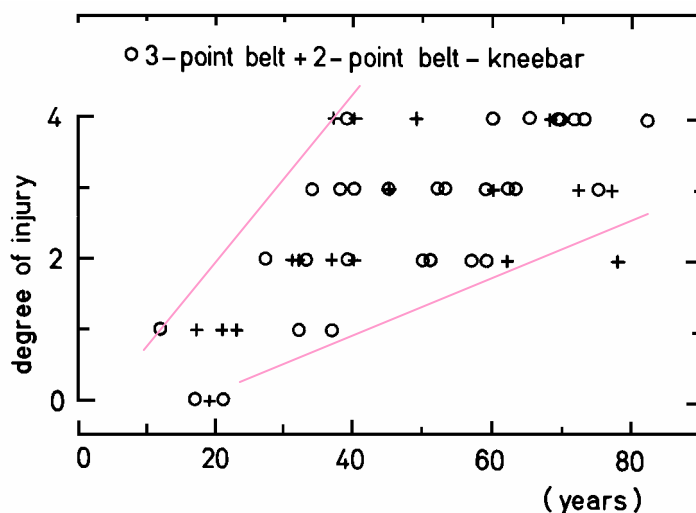


**Figure 26. Injury degree dependence on age, based on the ACIR-scale of injury.
G. Schmidt et al., (1994a)**

- **Neck and thorax tolerance levels of belt protected occupants in head-on collisions.** G. Schmidt et al., (1994b)

The testing was performed using fresh human cadavers aged between 12 to 82 years, in sled tests. The tests used either two or three point belt restraint systems, at three different impact velocities, 30, 40 and 50 km/h. The results from the testing showed that number of rib fractures was significantly affected by the age of the cadaver, with the

older cadavers sustaining higher numbers of fractures in comparison to the younger ones, regardless of the velocity test conditions (Figure 27).

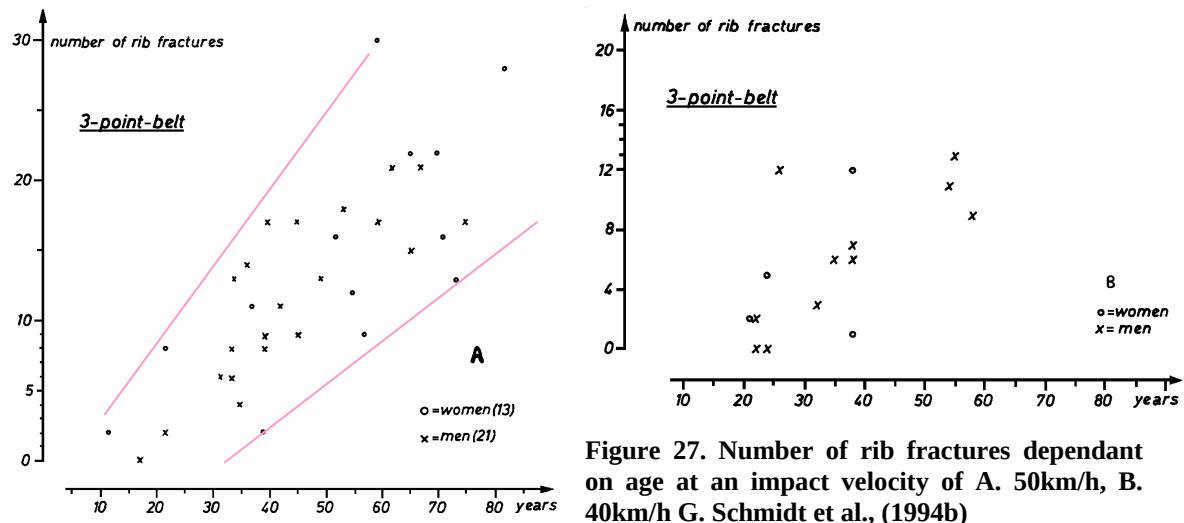


Figure 27. Number of rib fractures dependant on age at an impact velocity of A. 50km/h, B. 40km/h G. Schmidt et al., (1994b)

This trend can be explained by the load required to break the ribs, the paper looked at the breaking load of the 6th and 7th rib in relation to age, and showed that the breaking load reduced with age, (Figure 28).

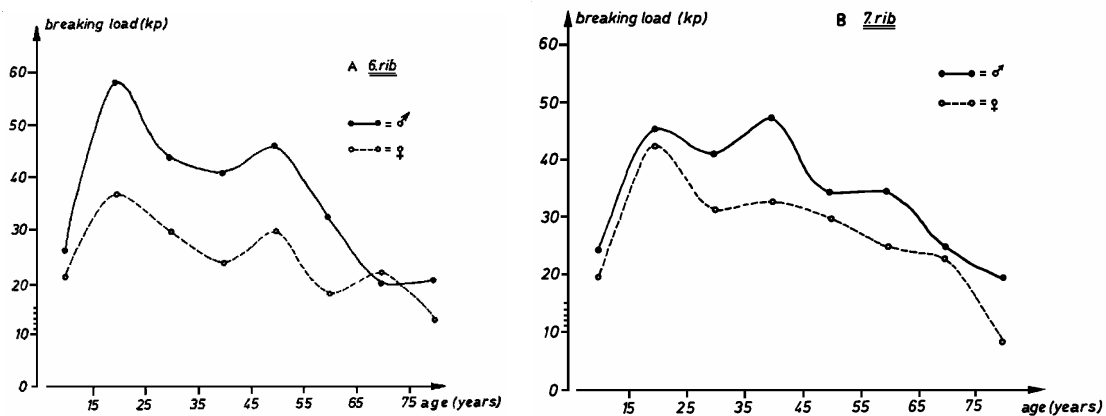


Figure 28. Average breaking load of A. 6th rib, B. 7th rib, and its dependence on both age and gender. G. Schmidt et al., (1994b)

As in the previous study, weight was shown to have an influence on the shoulder belt force, with the cadavers of greater body weight being subjected to greater shoulder belt forces than lighter cadavers under the same crash situations. (Figure 29)

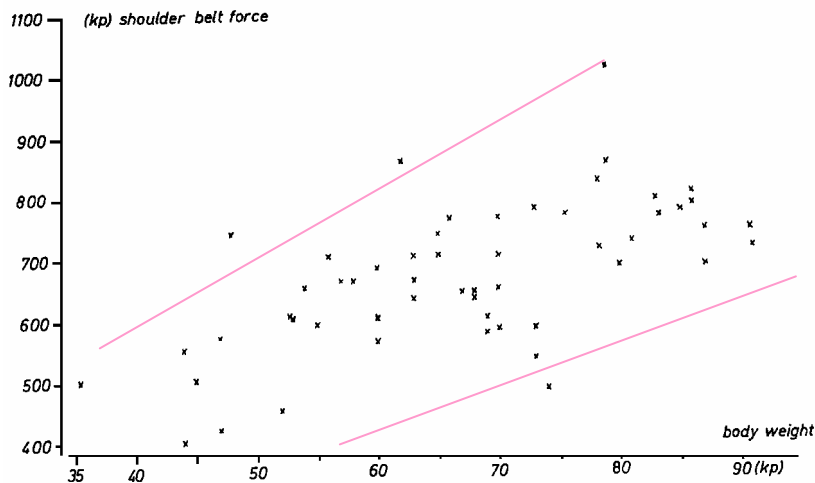


Figure 29. Shoulder belt force vs. weight of the occupant, in a three-point belt restraint.
G. Schmidt et al., (1994b)

Using the ACIR-scale, as described in the previous study; the effect of age on the degree of injury was investigated for the different crash scenarios. The study was able to show an increased degree of severity in accordance with age (Figure 30, Figure 31). However, the affects of gender and weight could not be proved in this study.

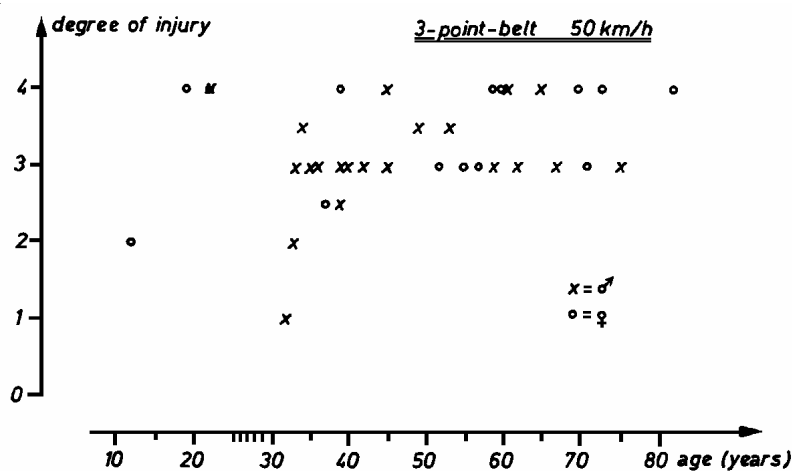


Figure 30. Degree of injury dependency on age.

G. Schmidt et al., (1994b)

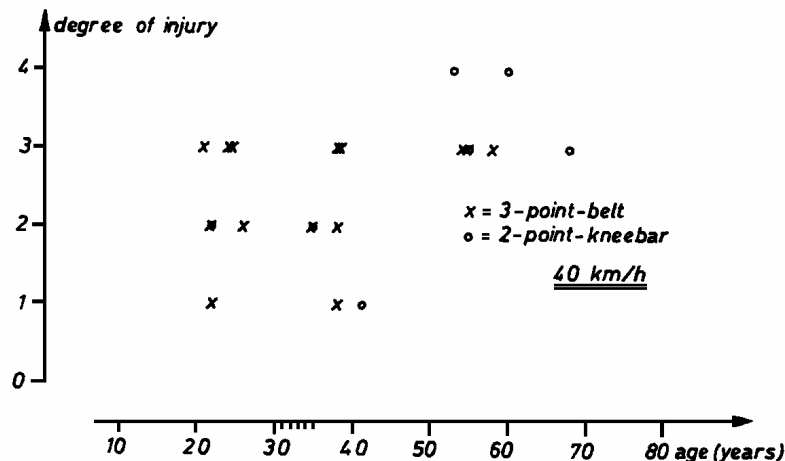


Figure 31. Degree of injury dependency on age.

G. Schmidt et al., (1994b)

- **Thorax of 3-point belt wearers during a crash (experiments with cadavers).**

A. Fayon et al., (1994)

The study investigated the effects on the thorax of three-point belt restraint, during crash tests on 31 human cadavers. The impact speed and the stopping distance varied between the different cadavers with impact speeds averaging 52.8 km/h, and the average stopping distance 715 mm. The belt restraints were all three point systems but with a variation in webbing width, belt pretensioner, and positioning of the belt in either the passenger or driver side. The variation in these parameters was designed to account for the difference in age of the cadavers, as it had been shown previously by G. Schmidt et al., (1994b) that age effects the thorax's ability to resist rib fracture when subjected to the same force.

The study looked at the number of rib fractures in relation to the shoulder restraint force (Figure 32) and the resultant force on the thorax (Figure 33). In both situations the number of rib fractures rose with increasing force.

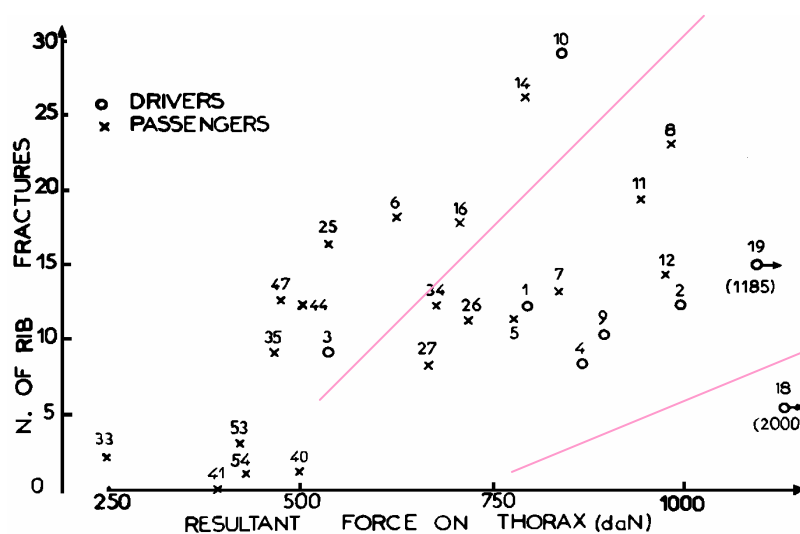
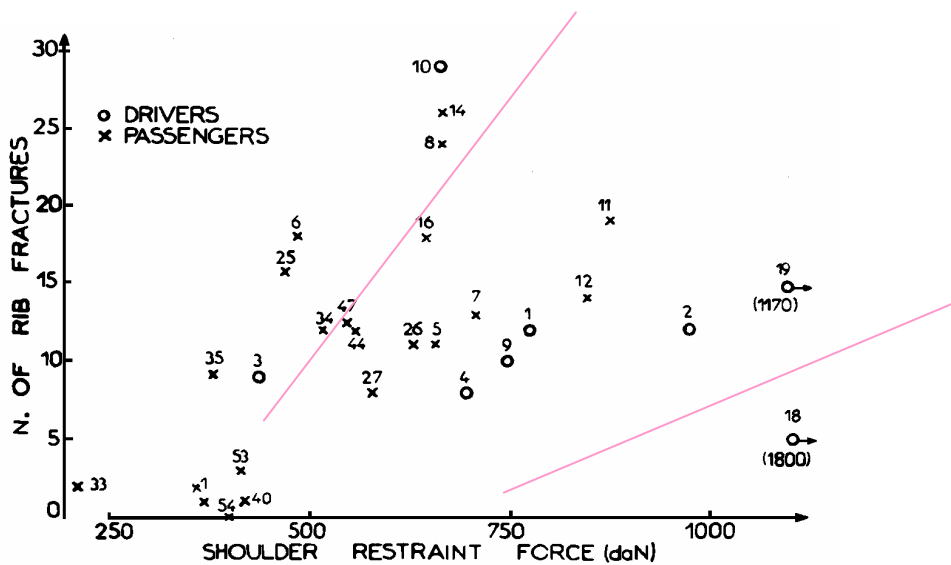


Figure 32. The effect of shoulder restraint force on the number of rib fractures sustained.

A. Fayon et al., (1994)



Research using Ultrasound of the Phalanges

- **Ultrasound velocity through the cortex of Phalanges, Radius, and Tibia in normal and osteoporotic postmenopausal women using a new multisite quantitative ultrasound device.** J.E. Damilakis et al., (2003)

The study looked at the relationship between the ultrasound velocity through the cortex of the phalanges in relation to other sites investigated by either QUS or densitometry. The correlation between the phalanx and the other sites is shown in Table 5. Despite the correlations being statistically significant, ($p < 0.001$), these results show a low correlation between the measurement sites, rendering SOS at the phalanx unsuitable for the prediction of axial skeletal properties.

	SOS _{Phalanx}
SOS _{Radius}	0.39
SOS _{Tibia}	0.28
BMD _{Lumbar Spine}	0.33
BMD _{Femoral Neck}	0.32
BMD _{Total Hip}	0.31

Table 5. Correlation between measurement of the proximal phalanx and other bone sites.
J.E. Damilakis et al., (2003)

The study additionally investigated the ability of SOS_{Phalanx} to differentiate between individuals with osteoporotic fractures and healthy control subjects. SOS_{Phalanx} measurements were found to be lower in individuals with fracture than the normal individuals, and SOS_{Phalanx} was the best of the QUS techniques investigated for this purpose, with an area under a receiver operator curve of 0.741 showing moderate clinical utility.

- **Discrimination of hip fractures by quantitative ultrasound of the phalanges and the calcaneus and dual X-ray absorptiometry.** J. Damilakis et al., (2004)

The study investigated the ability of QUS of the phalanges and the calcaneus to discriminate between patients with hip fractures, and healthy normals. Speed of sound at the phalanges (SOS_p) was only weakly correlated to BMD of the femoral neck BMD ($r = 0.35$, ($p < 0.001$)). As with J.E. Damilakis et al., (2003) SOS_{Phalanx} measurements were found to be lower in individuals with fracture than the normal individuals, and was the best of the QUS techniques investigated for this purpose, with an area under a receiver operator curve of 0.740 showing moderate clinical utility.

- **Estimation of wrist fracture load using phalangeal speed of sound: An in-vitro study.** C.F. Njeh et al., (2000)

An investigation of the relationship between phalangeal ultrasound and the fracture load of the wrist. The correlation between the variables is shown in Table 6.

	SOS _p	BMD _p	CCT _p
Fx-Load	0.60 (0.03)	0.60 (0.03)	0.65 (0.02)
Fx-Stress	0.74 (0.004)	0.51 (ns)	0.77 (0.002)
SOS _p		0.61 (0.03)	0.91 (0.000)
BMD _p			0.79 (0.001)

CCT=combined cortical thickness, (p-values), _p refers to the phalanx

Table 6. Pairwise correlation coefficients between variables measured on the third phalanx and fracture load (Fx-Load) and fracture stress (Fx-Stress) at the wrist.
C.F. Njeh et al., (2000)

The results show that the combined cortical thickness (CCT) has the best correlation with failure load and stress, with phalangeal speed of sound (SOS_p) out performing measurement of bone mineral density of the phalanx (BMD_p).

The best correlation was between CCT and SOS_p, this is not surprising as the Sunlight system works by measuring the SOS though the cortical bone of the phalanx.

- **Prediction of bone strength of distal forearm using radius bone mineral density and phalangeal speed of sound.** C. Wu et al., (2000)

The study investigated the bone strength of 13 cadaveric forearms and hands from people aged between 48-93 years of age. The DBM Sonic was used to assess the proximal phalanges of the index, middle and ring finger of each sample. The correlations between phalangeal speed of sound and the maximum load are shown in Table 7 with the middle finger showing the highest correlation, and the index finger the weakest.

Site of Measurement	R value
Index Finger	0.63
Middle Finger	0.72
Ring Finger	0.64
Average	0.71

Table 7. Spearman's correlation between maximum loading and bone measurements.
C. Wu et al., (2000)

The lack of correlation was put down to the size of the bone to be investigated, with the smaller bones such as the ring and index finger being harder to correctly assess. The SOS at the phalanx however did show a good correlation with the failure load of the radius.

- **Ability of ultrasound bone profile score (UBPS) to discriminate between fractured and not fractured osteoporotic women.**

M.D. Stefano and G.C. Isaia, (2002)

Studied the ability of the DBM Sonic to discriminate between fractured and non-fractured osteoporotic women, using a group of 87 women. The correlations between measurement at the phalanx, Lumbar spine and femoral neck were poorly correlated with both AD-SOS and UBPS failing to achieve a statistical significant correlation. The study reviewed the ability of the QUS system to select patients with vertebral fractures from those patients without vertebral fracture, and showed that patients with vertebral fracture had significantly lower UBPI than patients without fracture. AD-SOS however was not capable of showing the same differential ability.

- **Ultrasound measurements at the proximal phalanges in healthy women and patients with hip fractures.** F.E. Alenfeld et al., (1998)

The study investigated a group of healthy women and a group of patients with hip fractures using QUS of the phalanges. The correlations between measurement of the phalanges and the axial skeleton produced weak but statistically valid correlations of 0.36 ($p < 0.001$) and 0.37 ($p < 0.01$) with the BMD of the lumbar spine (L2-L4) and femoral neck respectively. The study showed that there was a statistically significant difference between the AD-SOS values for the patients with fracture and the normals ($p < 0.001$), which could be used to differentiate fractured patients from normals with good diagnostic accuracy (AUC 0.83 ± 0.06).

- **Ultrasound velocity through the phalanges in normal and osteoporotic patients.**

F. Blanckaert et al., (1999)

The study performed a comparison of the ultrasound velocity through the phalanges of the hand, in normal and osteoporotic patients. The correlation between measurements taken at the phalanx and the lumbar spine and femoral neck correlated moderately ($r = 0.45$ and $r = 0.44$ respectively [$p < 0.05$]). QUS of the phalanges showed a poor ability to predict osteoporotic patients from normals, (AUC = 0.57).

- **Quantitative ultrasound at the hand phalanges: comparison with quantitative computed tomography of the lumbar spine in postmenopausal women.**

G.P. Feltrin et al., (2000)

The investigation compared ultrasound of the phalanges with quantitative computed tomography of the lumbar spine. The correlations between the sites varied between the measurement techniques used, and the study cohort. For AD-SOS the correlation was $r = 0.54$ ($p < 0.0001$) in the normals, but was reduced to $r = 0.48$ in a purely osteoporotic group, and still significantly significant. For UBPS, the correlation in the normal population was 0.45 ($p < 0.0001$) and once again reduced but statistically significant in the osteoporotic subjects, to 0.23 ($p < 0.0001$).

- **Hand Ultrasound for Osteoporosis Screening in Postmenopausal Women.**

C.L. Benitez et al., (2000)

The study investigated the use of phalangeal ultrasound in a group of 206 postmenopausal women in relation to densitometry of the axial skeleton. The correlations between measurement sites were moderate ranging between 0.311 and

0.415 for the femoral neck and lumbar spine respectively. The diagnostic ability of the phalangeal ultrasound was tested for the correct selection of osteoporotic subjects from a population, the technique only achieved a moderate level of ability (AUC = 0.73).

Discussion

Ageing effects on Bone

There is a clear and measurable depreciation in the mechanical properties of the human skeleton with time, with bones only able to resist 78% of the mechanical forces applied to them by the age of 70-79, in comparison to their peak at 20-29. Cartilage shows a greater degree of reduction, only being capable of resisting 70% of their peak values by the ages 70-79.

Studies have shown that although human bone goes through phases of hypo- and hyper-mineralisation, there is no real change in the makeup and mineral characteristic of human bone matrix with age. So any variation in mechanical properties is down to mineral content/volume, apparent density and structure related changes.

The mineral volume fraction of bone has dramatic effects on bone, being positively correlated to Young's modulus, and ultimate strain, but not ultimate strength. However as mentioned above this changes very little in human bone with age.

When the mineral content of standard sized test samples is determined by ash content, the correlation with both modulus of elasticity and ultimate strength are both positive, with a quadratic fit being seen with impact energy, indicating a peak at an ash content of about 66.5%.

Ageing effects on the Ribs

The obvious ageing effects on the ribs are minimal due to their continuous usage through out life. The mechanical properties of the ribs peak between the ages of 15 and 22, as this is when the peak cortical cross section occurs, (the mechanical properties of the ribs mainly determined by the cortical bone with the trabecular bone having a lesser effect). The cortical area is predicted to reduce by 25% from its peak, with the BMD of the ribs declining by between 15-23.9% in women depending on race, and 9.5% in males. This reduction however goes with a steady increase in the actual size of the ribs, which helps to maintain some mechanical competence.

Ageing effects on the Phalanges

Ultrasound studies have shown a clear correlation between the aging of the human body and a reduction in the quality of bone in the phalanges, with correlation between age and bone quality ranging from $r = -0.35$ to -0.73 . The moderate correlation can be explained by the huge variation within the population, with two different people both aged 50, with one having bone quality considered normal for a 30 year old, and the other much lower with bone like a 70 year old.

Previous testing of the thorax

Most of the testing of the thorax has been performed with motor *vehicle safety* in mind; little to no work has been performed within the medical literature on the biomechanics of the ribs. The reasoning behind this trend is that medical biomechanics focuses on the areas of main medical concern, such as the spine, hip and forearm, the areas prone to osteoporotic fractures in the elderly that cost the most to contend with.

The *automotive biomechanics* supply a wealth of information. It is clear from the testing performed that the number of rib fractures sustained by an occupant, in a crash situation where the parameters are kept the same will be higher in a more elderly occupant.

Shoulder belt force and applied force to the thorax both have effects on the injuries sustained, with not surprisingly a greater degree of injuries seen by a higher force. The degree of injury was also increased by the degree of deflection of the rib cage, with greater deflection causing higher degree of injury, and this trend was once again age dependant, with older people more susceptible to injury, with injuries occurring at lower % deflections.

The *force on the thorax*, and the deflection caused are dictated by the loading method. Although the deflection required to cause injury doesn't change, the force required to cause the deflection does. During loading, the greater the area of contact with the body, i.e. the greater the surface area the load is applied to, the greater the load that is required to cause the deflection, so more severe crashes can be survived without injury.

The *rate of loading* was also found to affect the bending strength of the ribs, with a higher rate of loading increasing the bending strength; however the tests were performed at low rates of loading, from 0.4 to 1.2 mm/min, far lower than loading through impact in a crash situation. The breaking load of the rib decreased with age ($r = -0.534$ ($p < 0.001$)) with reductions in the average breaking load of the 6th and 7th ribs decreasing from between 42% and 66% between the ages of 20 and 70, in one study and 55% in another; and this is before consideration of those subjects deemed to be osteoporotic.

Gender differences were seen, with females having a lower chest stiffness, maximum bending force, and rib cross-sectional area, in comparison to men, These important factors, in the ability of the thorax to resist fracture, puts the female population at greater risk of injury in comparison to men in an identical crash scenario.

BMD of the ribs and the correlation with the axial skeleton and other regions was in general moderate to good with correlation ranging from 0.579 to 0.834 in a female Caucasian population, 0.56-0.91 in a female Chinese population, and 0.50-0.93 in a male Chinese population. No correlations could be found between the ribs and the phalanges, however the correlations between the ribs and the forearm was moderate ($r = 0.647$)

The main purpose for the measurement of bone quality at the phalanges is for the assessment of a subject's skeletal status, with particular respect to osteoporosis. In order for this to be achieved the correlation between measurement of the phalanx and measurement of the axial skeleton must be good. Studies utilising measurement of the phalanges, for the prediction of bone status at the axial skeleton, have shown poor correlations ($r = 0.23$ to 0.54), and when used to differentiate osteoporotic subjects from normals the diagnostic ability was only moderate ($AUC = 0.73$).

However phalangeal ultrasound has been used for other purposes than to predict the quality of the axial skeleton. The techniques showed a moderate ability to predict the failure load and stress of the radius, ($r = 0.60$ to 0.74); and good diagnostic accuracy (AUC 0.83 ± 0.06) when being used to differentiate patients with vertebral fractures from unfractured patients.

Conclusion

There is no data currently available within the literature that shows a direct link between the mechanical or densitometric properties of the ribs and the phalangeal bones of the hand. We know that reduction in the mechanical properties of the ribs is in the region of 50% between their peak values at 20-30 yr of age and 70yr of age. There is no information on this drop relationship to the velocity of sound through the phalanges.

A probable method for gaining this information would be to perform full body DXA or QCT scans on a large section of population at the ribs and the axial skeleton, and at the same session use either the BOSCOS prototype or a clinically available phalangeal assessment technique. This would supply information on the densitometric relationship between the sites, but, would still not supply information on the relationships to the in-situ mechanical properties.

In order to establish the relationship between the densitometry and the biomechanical parameters, a sample of bone would need to be donated from the individuals under going densitometry assessment. The sample would be used to determine the biomechanical properties of the bone, and would allow for direct comparison with the densitometric properties.

References

- F.E. Alenfeld, C. Wuster, C. Funck, et al. (1998) Ultrasound Measurements at the Proximal Phalanges in Healthy Women and Patients with Hip Fractures. **Osteoporosis International**; Vol. 8, p.393-398
- C.L. Benitez, D.L. Schneider, E. Barrett-Connor, et al. (2000) Hand Ultrasound for Osteoporosis Screening in Postmenopausal Women. **Osteoporosis International**; Vol. 11, p.203-210
- F. Blanckaert, B. Cortet, P. Coquerelle, et al. (1999) Ultrasound Velocity through the Phalanges in Normal and Osteoporotic Patients. **Calcified Tissue International**; Vol. 64, p.28-33
- J.D. Currey. (1969) The Mechanical Consequences of Variation in the Mineral Content of Bone. **Journal of Biomechanics**; Vol. 2, p.1-11
- J.D. Currey (2002) In *Bones: Structure and Mechanics* Princeton University Press, pp. 125-145

- J. Damilakis, G. Papadokostakis, K. Perisinakis, et al. (2004) Discrimination of Hip Fractures by Quantitative Ultrasound of the Phalanges and the Calcaneus and Dual X-ray Absorptiometry. **European Journal of Radiology**; Vol. 50, p.268-272
- J.E. Damilakis, G. Papadokostakis, H. Vrahoriti, et al. (2003) Ultrasound Velocity Through the Cortex of Phalanges, Radius, and Tibia in Normal and Osteoporotic Postmenopausal Women Using a New Multisite Quantitative Ultrasound Device. **Investigative Radiology**; Vol. 38, No. 4: p.207-211
- B. Drozdowska and W. Pluskiewicz. (2003) Skeletal Status in Males Aged 7-80 years Assessed by Quantitative Ultrasound at the Hand Phalanges. **Osteoporosis International**; Vol. 14, p.295-300
- F. Duboeuf, D. Hans, A.-M. Schott, et al. (1996) Ultrasound Velocity Measured at the Proximal Phalanges Precision and Age-Related Changes in Normal Females. **Revue Du Rhumatisme Engl. Ed.**; Vol. 63, No. 6: p.427-434
- A. Fayon, C. Tarriere, G. Walfisch, et al. (1994) In *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 341-369
- G.P. Feltrin, M. Nardin, A. Marangon, et al. (2000) Quantitative Ultrasound at the Hand Phalanges: Comparison with Quantitative Computed Tomography of the Lumbar Spine in Postmenopausal Women. **European Radiology**; Vol. 10, p.826-831
- R. Giardino, R. Rotini, F. Noia, et al. (2002) Phalangeal Ultrasonography in Forearm Fracture Discrimination. **Biomedicine and Pharmacotherapy**; Vol. 56, p.332-338
- G. Granik and I.D. Stein. (1973) Human ribs: Static Testing as a Promising Medical Application. **Journal of Biomechanics**; Vol. 6, p.237-240
- G. Guglielmi, C.F. Njeh, F. de Terlizzi, et al. (2003) Phalangeal Quantitative Ultrasound, Phalangeal Morphometric Variables, and Vertebral Fracture Discrimination. **Calcified Tissue International**; Vol. 72, p.469-477
- J.B. Holcomb, N.R. McMullin, R.A. Kozar, et al. (2003) Morbidity from Rib Fractures Increases After Age 45. **Journal of the American College of Surgeons**; Vol. 196, No. 4: p.549-555
- J. Joly, R. Westhovens, H. Borghs, et al. (1999) Reference Curve and Diagnostic Sensitivity for a New Ultrasound Device for the Phalanges, the DBMsonic 1200, in Belgian Women. **Osteoporosis International**; Vol. 9, No. 4: p.284-289

- T. Kamei, K. Aoyagi, T. Matsumoto, et al. (1999) Age-related Bone Loss: Relationships Between Age and Regional Bone Mineral Density. **Tohoku Journal of Experimental Medicine**; Vol. 187, No. 2: p.141-147
- R. Kent and J. Patrie. (2004) Chest Deflection Tolerance to Blunt Anterior Loading is Sensitive to Age but not Load Distribution. **Forensic Science International**; Vol. Article in Press
- R. Kent, C. Sherwood, D. Lessley, et al. (2003) In the International Conference on the Biomechanics of Impact (IRCOBI), pp. 249-263
- H. Kimpara, M. Iwamoto, K. Miki, et al. (2003) In International Research Committee On Biokinetics Of Impacts, Lisbon (Portugal), pp. 235-247
- S.T. Liman, A. Kuzucu, A.I. Tastepe, et al. (2003) Chest Injury due to Blunt Trauma. **European Journal of Cardio-thoracic Surgery**; Vol. 23, p.374-378
- C.F. Njeh, C. Wu, B. Fan, et al. (2000) Estimation of Wrist Fracture Load using Phalangeal Speed of Sound: An In-vitro Study. **Ultrasound and Medicine in Biology**; Vol. 26, No. 9: p.1517-1523
- B.E.C. Nordin, B.E. Chatterton, C.G. Schultz, et al. (1996) Regional Bone Mineral Density Interrelationships in Normal and Osteoporotic Postmenopausal Women. **Journal of Bone and Mineral Research**; Vol. 11, No. 6: p.849-856
- C.M. Robinson. (1998) Fractures of the Clavicles in the Adult: Epidemiology and Classification. **Journal of Bone and Joint Surgery (British Volume)**; Vol. 80, No. 3: p.476-485
- F. Santoro and H.M. Frost. (1968) Correlation of the Transverse Sizes of 6th and 11th Ribs in Normal and Osteoporotic Individuals. **Henry Ford Hospital Medical Journal**; Vol. 16, No. 1: p.87-96
- G. Schmidt. (1979) Rib-cage Injuries Indicating the Direction and Strength of Impact. **Forensic Science International**; Vol. 13, p.103-110
- G. Schmidt, D. Kallieris, J. Barz, et al. (1994a) In *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 311-316
- G. Schmidt, D. Kallieris, J. Barz, et al. (1994b) In *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 371-399
- E.D. Sedlin. (1964) The Ratio of Cortical Area to Total Cross-Section Area in Rib Diaphysis: A Quantitative Index of Osteoporoses. **Clinical Orthopaedics**; Vol. 36, p.161-168

- M.D. Stefano and G.C. Isaia. (2002) Ability of Ultrasound Bone Profile Score (UBPS) to Discriminate between Fractured and Not Fractured Osteoporotic Women. **Ultrasound and Medicine in Biology**; Vol. 28, No. 11/12, p.1485-1489
- I.D. Stein and G. Granik. (1976) Rib Structure and Bending Strength: An Autopsy Study. **Calcified Tissue Research**; Vol. 20, p.61-73
- H. Takahashi and H.M. Frost. (1966) Age and Sex Related Changes in the Amount of Cortex of Normal Human Ribs. **Acta Orthopaedica Scandinavica**; Vol. 37, No. 2, p.122-130
- M. Utsumi, S. Tohno, T. Minami, et al. (1999) Age-Independent Consistency of Mineral Contents in Human Ribs. **Biological Trace Element Research**; Vol. 67, p.165-171
- C. Wu, D. Hans, Y. He, et al. (2000) Prediction of Bone Strength of Distal Forearm Using Radius Bone Mineral Density and Phalangeal Speed of Sound. **Bone**; Vol. 26, No. 5, p.529-533
- C. Wüster, C. Albanese, D. De Aloysio, et al. (2000) Phalangeal Osteosonogrammetry Study: Age-related Changes, Diagnostic Sensitivity, and Discrimination Power. **Journal of Bone and Mineral Research**; Vol. 15, No. 8: p.1603-1614
- H. Yamada (1970a) In *Strength of Biological Materials*(Ed, Evan, F. G.) Williams and Wilkins Company, Baltimore, pp. 272-275
- H. Yamada (1970b) In *Strength of Biological Materials*(Ed, Evan, F. G.) Williams and Wilkins Company, Baltimore, pp. 255-271
- W.J. Yao, C.H. Wu, S.T. Wang, et al. (2001) Differential Changes in Regional Bone Mineral Density in Healthy Chinese: Age-Related and Sex-Dependant. **Calcified Tissue International**; Vol. 68, p.330-336
- P. Zioupos, J.D. Currey (1998) Changes in the stiffness, strength and toughness of human cortical bone with age. **Bone**, Vol. 22, p. 57-66

BOSCOS

Bone Scanning for Occupant Safety

Appendix: 15.4

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
DfT Contract Number PPAD 9/33/89

Report title BOSCOS Prototype Analysis
Author R. Cook and P. Zioupos
 Cranfield University at Shrivenham

Date February 2005



PROJECT REPORT
FORESIGHT VEHICLE LINK PROJECT
BONE SCANNING FOR OCCUPANT SAFETY
(BOSCOS)

Contract Number PPAD 9/33/89

1st February 2002 – 30th June 2005

Report to

Department for Transport

June 2005

For and on behalf of the Consortium, comprising:

Cranfield Impact Centre Ltd. – lead partner

Nissan Technical Centre – Europe Ltd.

TRW Automotive

Autoliv Ltd.

Cranfield University at Shrivenham, Centre for Materials Science and Engineering

Loughborough University, Vehicle Safety Research Centre

McCue plc (sub-contractor to lead partner)

DfT Project Officer

I. Knowles

BOSCOS PROTOTYPE ANALYSIS

R.Cook and P.Zioupou
Centre for Materials Science and Engineering
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1. DATA COLLECTION

Studies were undertaken on a group of 102 subjects, 7 males and 95 females, aged between 24 and 85 years of age (mean: 57 years).

For each individual patient the proximal phalanx of the index finger was assessed, and 10 waveforms with results were saved (figure 1).

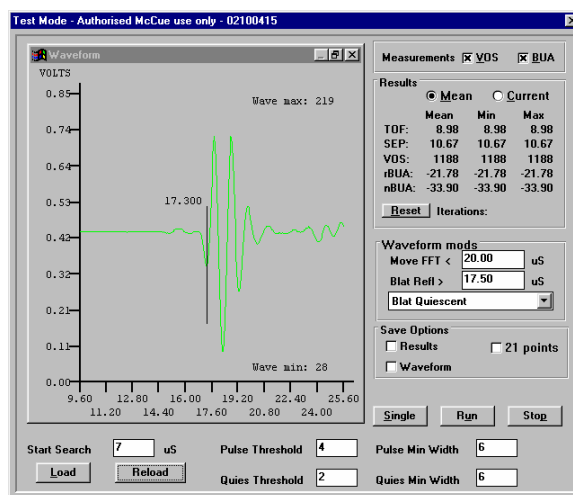


Figure 1. The original screen as seen when the measurement was performed.

The waveforms and results were sent to McCue plc for processing, and the results returned in spreadsheets and looked as follows :

412 Female 66

Data	Sep	TOF	VOS	BUA	Peak Time	Time Delta (μs)	Peak Value
134	11.37	0.000008	1432.36	-34.09	336		131
134					364	1.4	184
134					375	0.55	85
134					385	0.5	165
134					395	0.5	119
133					403	0.4	137
.					.	.	.
.					.	.	.
.					.	.	.

- Data: 2048 voltage values taken at intervals of 50ns from the receiving transducer.
- Sep: The separation (mm) between the two transducers, measured by a digital calliper.
- TOF: The time of flight of the ultrasound pulse, which is actually the adjusted TOF after taking the silicone pads into account, calculated as follows:

$$\text{TOFAdjSlope} = 9.196407\text{e-}9$$

$$\text{TOFAdjIntercept} = 8.413662\text{e-}6$$

$$\text{TOFAdjust} = \text{Separation} * \text{TOFAdjSlope} + \text{TOFAdjIntercept}$$

$$\text{Adjusted TOF} = \text{Raw TOF} + \text{TOFAdjust}$$
- VOS/BUA: Velocity of Sound/Broadband Ultrasound Attenuation, through the phalangeal bone, assessed using the CUBA Windows Software.
- Peak Time: The peak times are the times the peaks occur, recorded as the absolute measurement number.

- Time Delta: The time in microseconds between successive peaks.
- Peak Value: The absolute value of the peak in volts.

2. ANALYSIS OF VOS VALUES SUPPLIED BY M^CCUE

Behaviour of VOS versus age

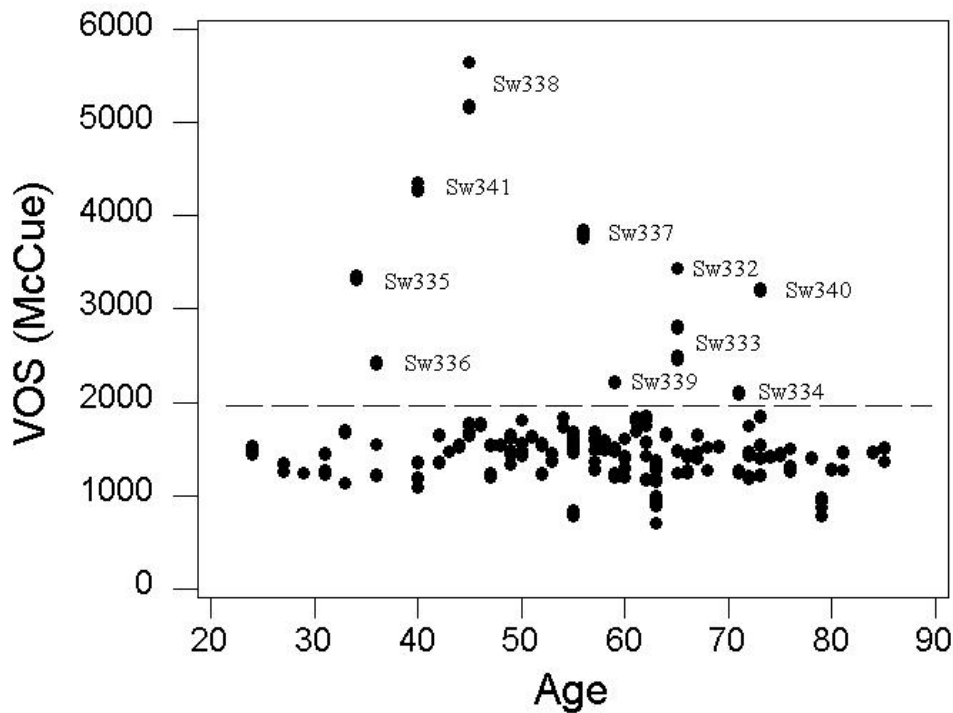


Figure 2. VOS values supplied by McCue vs. Age

The VOS results supplied with each waveform were investigated and any value found to be negative was removed from this analysis (5 patients removed). For each individual only 4 of the 10 waveforms were investigated, with the selected waveforms numbering 1, 3, 5 and 7. The values were plotted vs. age (Figure 2). The figure shows a close correlation between age and the measurement, but with a group of distinct outliers.

When investigation was performed the outliers were found to be a group of ten individuals from Sw332 – Sw341 inclusive, all of whom had separation values above and beyond that considered to be normal (22.3mm to 32.3mm). We took a closer look into the actual separation values for all individuals:

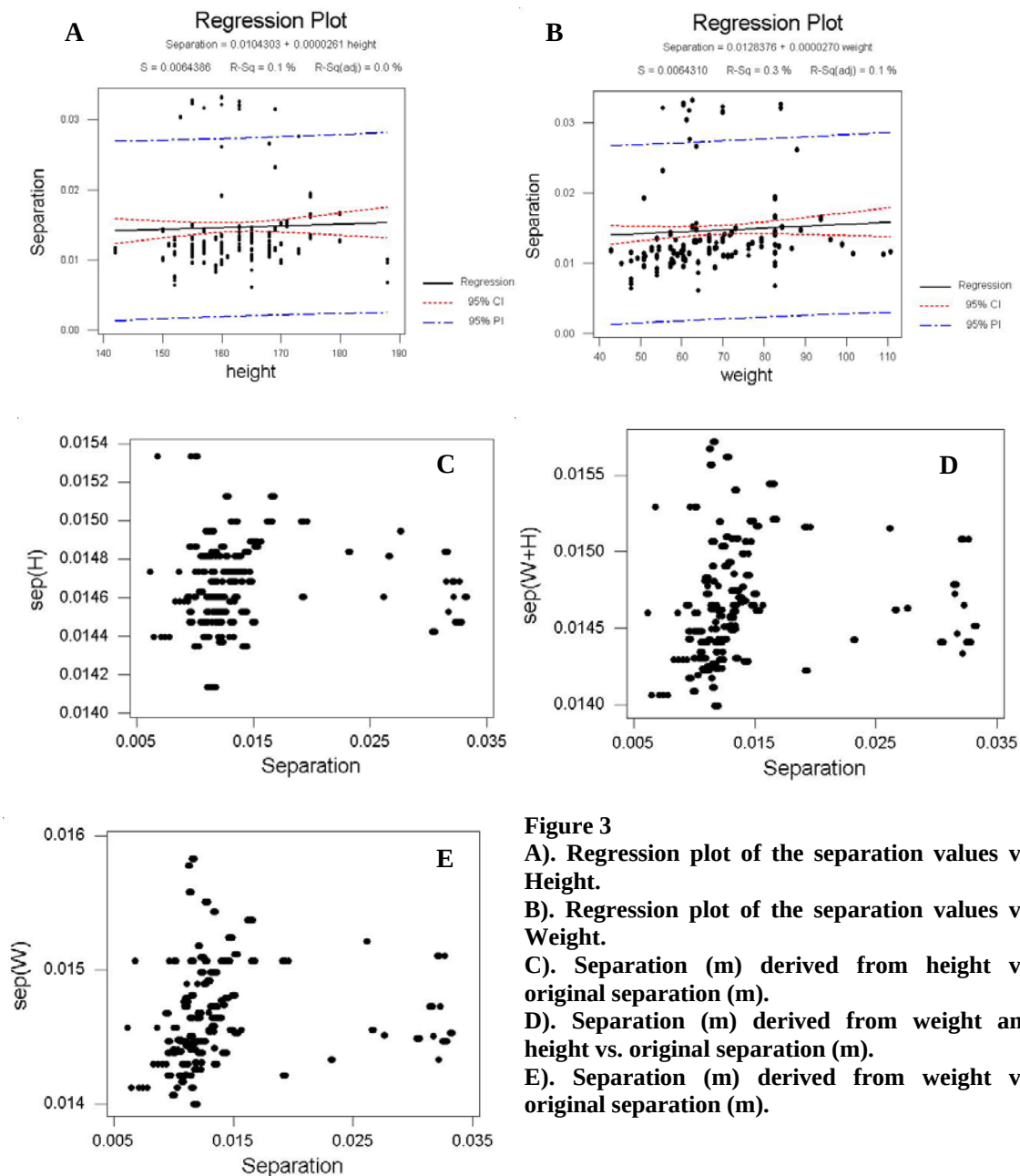


Figure 3

A). Regression plot of the separation values vs. Height.

B). Regression plot of the separation values vs. Weight.

C). Separation (m) derived from height vs. original separation (m).

D). Separation (m) derived from weight and height vs. original separation (m).

E). Separation (m) derived from weight vs. original separation (m).

In order to account for the error that was introduced due to the separation, new separation values were derived using the weight and height of the individual. (This meant reduced the size of the data as each individual had only one separation value rather than four, each one different for every waveform.) New VOS values were calculated and compared vs. age.

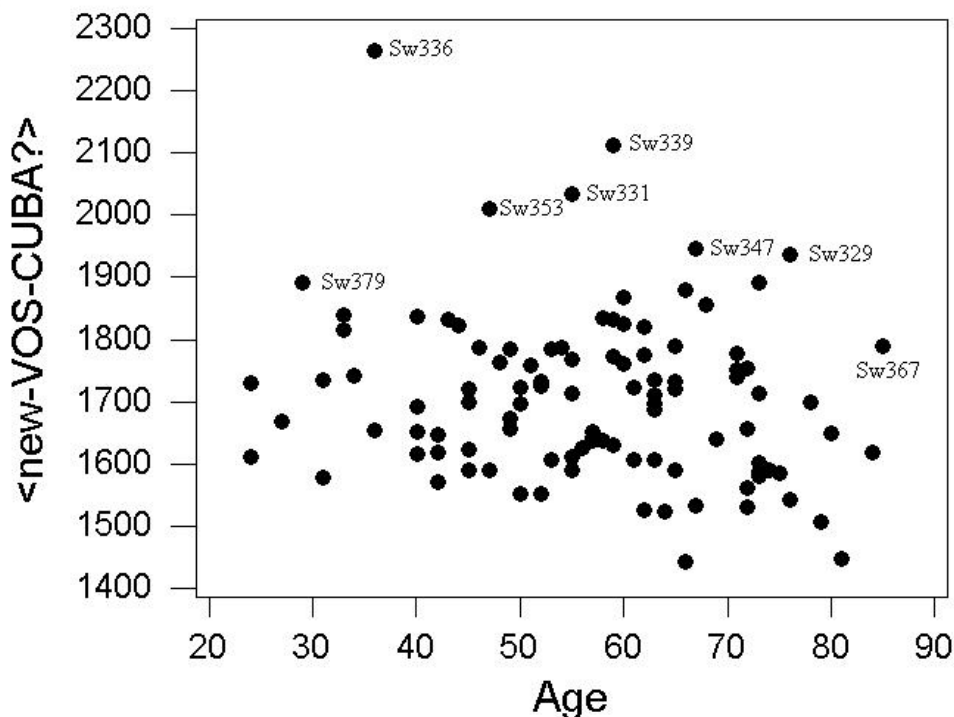


Figure 4. New-VOS values with adjusted separation vs. Age

The correlation was superior to that which was achieved previously during testing. However, once again distinct outlier points were noted. Further investigation showed those individuals to be at the extremes of the height and weight scales, and hence the outliers in these estimate values.

In conclusion: accurate separation values are crucial for this method and back-calculation of separation estimates (to remedy the errors) is not easy and cannot produce reliable values.

3. CLINICALLY VALID MEASUREMENTS

Diagnostic measurements were performed using three clinically available bone assessment systems: (1) a Hologic QDR-4500C, [Hologic Inc. Bedford, MA, USA] a Dual-energy X-ray absorptiometry machine able to measure the density of bone at the proximal femur and lumbar spine; (2) the Sunlight Omnisence (Sunlight Medical, Rehovot, Israel) and (3) the CUBA Clinical (McCue plc. Winchester, UK), both were quantitative ultrasound systems capable of measuring peripheral bone sites like the distal radius, proximal phalanx and the calcaneus.

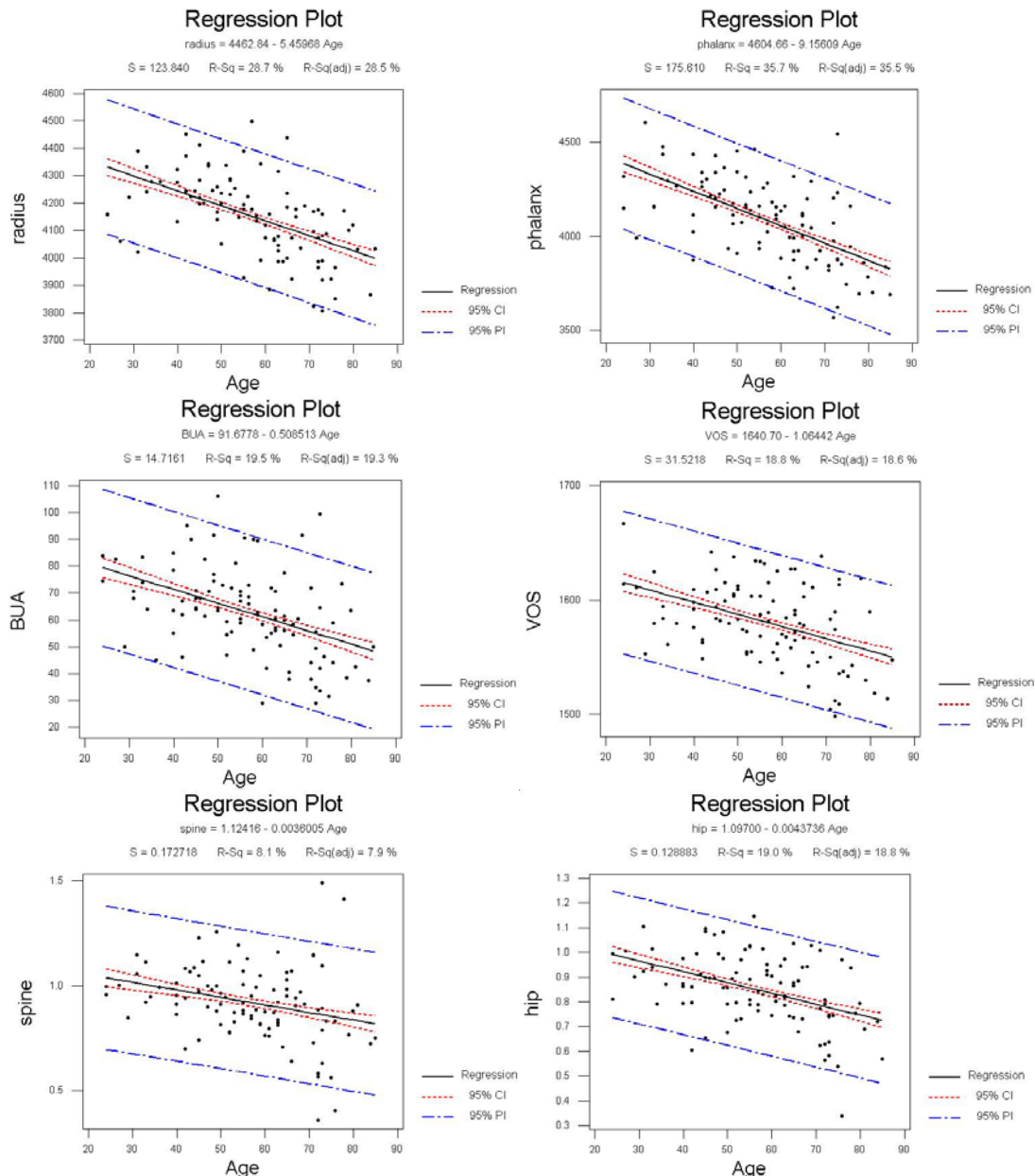


Figure 5. Regression plots of the results of clinical available bone assessment systems vs. age.

The regression plots in Figure 5 show that the bone assessment systems considered suitable for clinical use, display poor to moderate values between the measurement values and age, although these were superior to those achieved using the prototype system. It is worth noting that even the clinically available systems have distinct outlying values, which could be considered abnormal.

Table 1. Correlations: Age, VOS (McCue), height, weight, distal radius, proximal phalanx, BUA calcaneus, VOS calcaneus, lumbar spine, Total hip

	Age	VOS(McCUE)	Height	Weight	Radius	Phalanx	BUA	VOS	L.Spine
VOS(McCUE)	-0.119 0.022								
Height	-0.125 0.013	-0.017 0.742							
Weight	-0.136 0.007	-0.073 0.161	0.366 0.000						
Radius	-0.536 0.000	0.199 0.000	0.177 0.001	0.088 0.086					
Phalanx	-0.597 0.000	0.225 0.000	0.184 0.000	0.168 0.001	0.550 0.000				
BUA	-0.442 0.000	0.112 0.032	0.133 0.009	0.317 0.000	0.445 0.000	0.389 0.000			
VOS	-0.434 0.000	0.138 0.008	-0.014 0.785	0.037 0.468	0.431 0.000	0.371 0.000	0.812 0.000		
L.Spine	-0.285 0.000	0.123 0.018	0.222 0.000	0.335 0.000	0.465 0.000	0.354 0.000	0.551 0.000	0.530 0.000	
T.Hip	-0.436 0.000	0.093 0.073	0.176 0.001	0.510 0.000	0.458 0.000	0.332 0.000	0.573 0.000	0.519 0.000	0.695 0.000

Cell Contents: Pearson correlation
P-Value

All clinical data correlated with AGE and so did the original VOS McCue but only marginally. Interestingly the weight correlated well with AGE and the clinical instruments.

On the basis of this and since we do not actually know the precise condition of the bone we derived 3 'composite' parameters by combining the average of scaled values of (1) [age, weight, DXA]; (2) [Sunlight, CUBA, DXA]; (3) [age, weight, CUBA, Sunlight, DXA].

The correlation of these 3 new 'composite' parameters to weight and age is shown underneath:

Table 2. Correlations: Age, Weight, Age + Weight + DXA (AWD), Sunlight + CUBA + DXA (SCD), Age + Weight + All Clinical Measurements (AWA)

	Age	Weight	AWD	SCD
Weight	-0.136 0.007			
AWD	-0.747 0.000	0.611 0.000		
SCD	-0.552 0.000	0.416 0.000	0.833 0.000	
AWA	-0.752 0.000	0.541 0.000	0.963 0.000	0.927 0.000

Cell Contents: Pearson correlation
P-Value

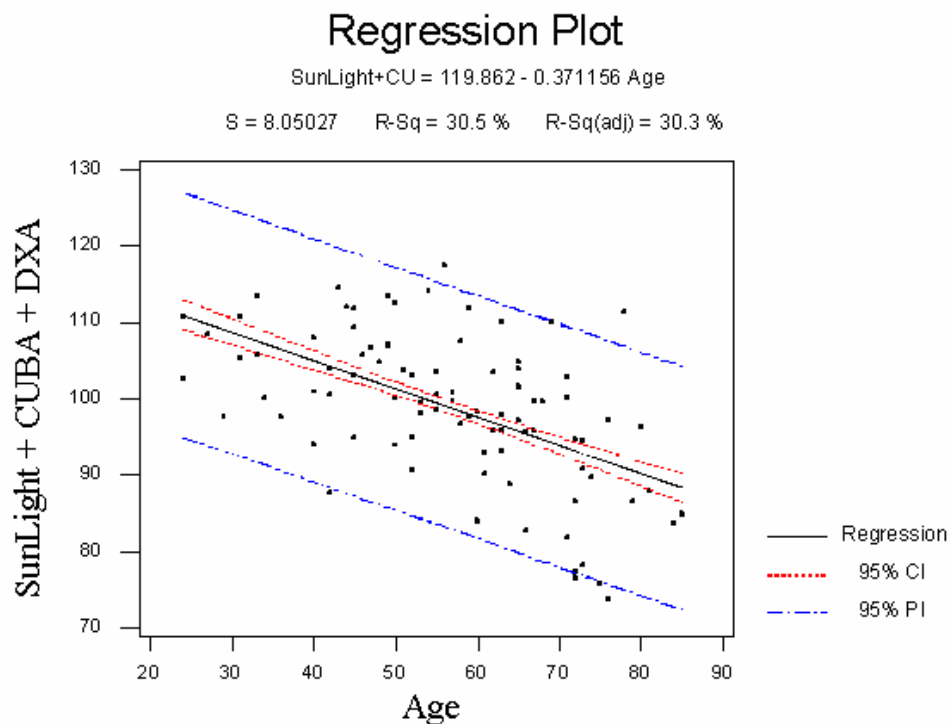


Figure 6. Regression plot of the combined [Sunlight, CUBA and DXA] measurements vs. age

The combined bone measurement value achieved a moderate statistically valid correlation with age and weight, but with poor R^2 values when regression was performed.

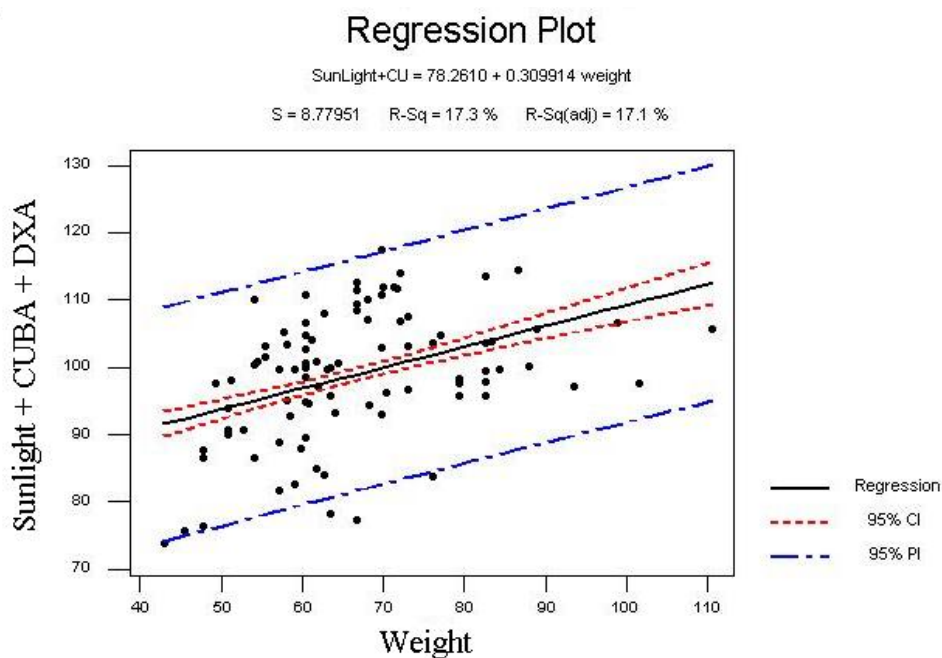


Figure 7. Regression plot of the combined [Sunlight, CUBA and DXA] measurements vs.weight.

4. THEORY OF ULTRASOUND TRANSMISSION THROUGH THE PHALANX.

Ultrasound transmission through the phalanx is complex, with the bone and soft tissue affecting the transmission time. The effects of this have been investigated by R. Barkmann et al. (2000) who looked at the transmission of ultrasound through the phalanges for the determination of phalangeal geometry.

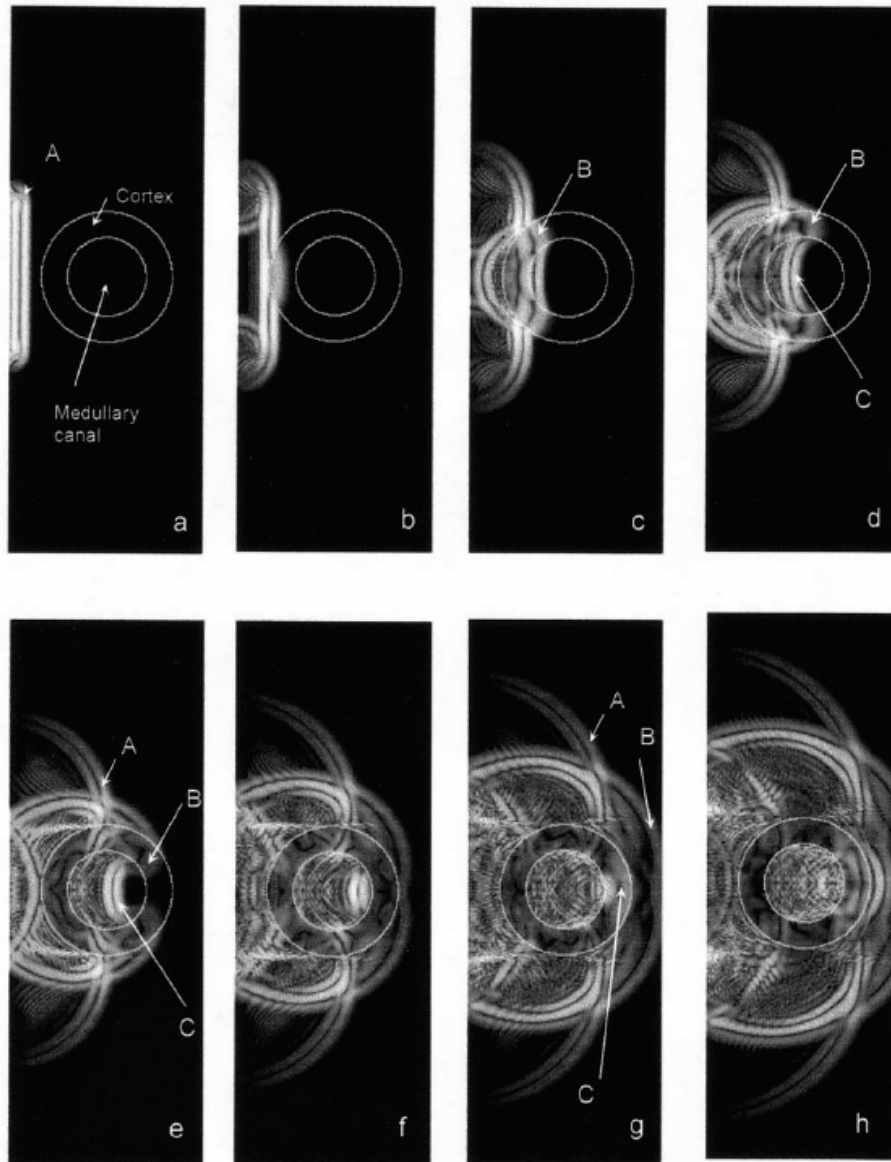


Figure 8. Transmission of an ultrasound pulse through a cross-section of bone, showing how the waveform is affected by the path of travel

(R. Barkmann et al. 2000)

Figure 8 shows a simulation of the propagation of an ultrasound pulse through bone. The simulation shows that the fastest travelling part of the pulse, is that which travels through the cortical bone, followed by the part which travels through the cortical bone and medullary canal, and the slowest path being that through the soft tissue. This gives important information for the

analysis of the received wave, indicating that assessment of the early to mid part of the received waveform is going to supply the greatest information about the bone.

The technique utilised by the BOSCOS prototype is in use clinically in a system called the DBM Sonic (IGEA, Carpi, Italy), which uses ultrasound transmission through the phalanges as a means of assessing the bone status of an individual.

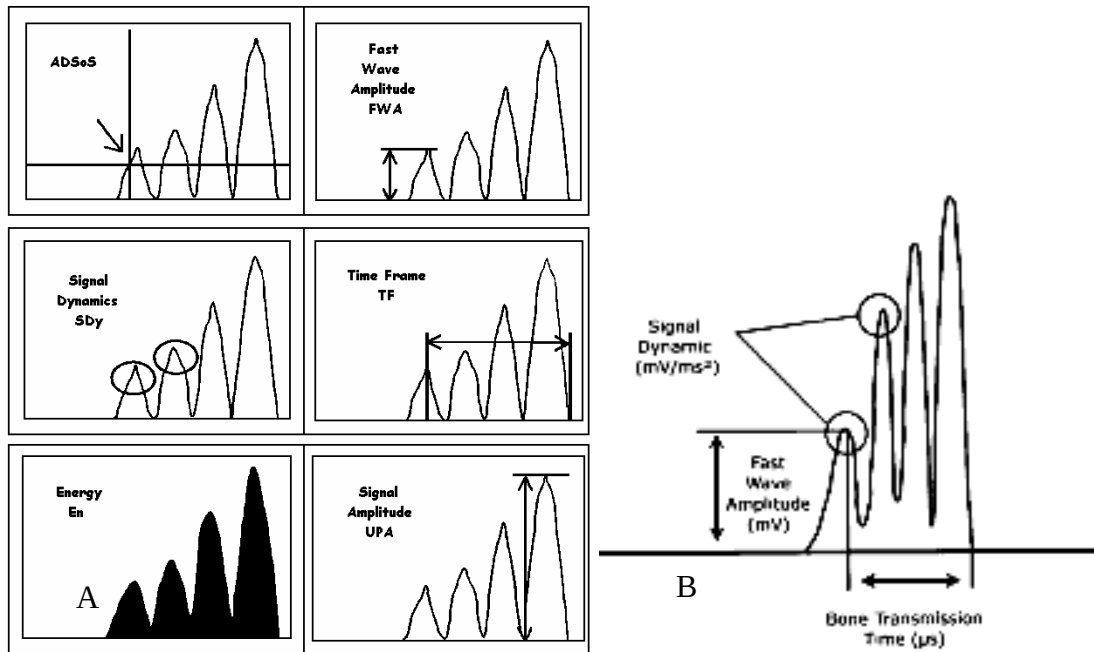


Figure 9. Physical parameters that can be assessed from a received ultrasound pulse.

A) C. Wüster et al. (2000) B) A. Montagnani et al. (2002)

The different parameters that can be assessed from a received ultrasound pulse have been reviewed in the literature previously, using the DBM Sonic system (Figure 9). The parameters are as follows: (A. Montagnani et al. 2002)

- Ad-SOS: Amplitude dependant speed of sound (m/s). The SOS taken at the point where the amplitude exceeds a certain threshold for the first time.
- SDy: The dynamics of the ultrasound signal ($\text{mV}/\mu\text{s}^2$). An expression of the second derivative of amplitude versus time of the fastest peak of the received US signal and represents the sharpness of the peak reflecting its frequency content.
- TF / BTT: Time Frame / Bone Transmission Time (μs). Time interval between the first received signal and the speed value of 1700m/s.
- EN: Signal Energy ($\text{mV}^2 \cdot \mu\text{s}$). The energy of the received pulse.
- UPA: Maximum Signal Amplitude (mV). The maximum signal amplitude within the TF.
- UBPI: Ultrasound Bone Profile Index. A combination of SDy, FWA and BTT,

$$\text{UBPI} = 1/[1+\exp(-0.0018 \times \text{SDy} - 0.0560 \times \text{FWA} - 1.1467 \times \text{TF} + 3.03)]$$

(A point to note here is that the quality of the signal improves dramatically when gel is used)

5. PROTOTYPE WAVEFORM ANALYSIS

The initial phase of the analysis was to transfer the first 800, of the 2048 data points of each individual waveform, from excel to separate sigma-plot files (Sigma-plot 8.0). As mentioned previously each data point was taken at an interval of 50ns, so each data point was converted to time by multiplying the spreadsheet row number by 5.0000e-9 seconds. The 800 data points were plotted against time to produce the original waveform as seen when the measurement was performed.

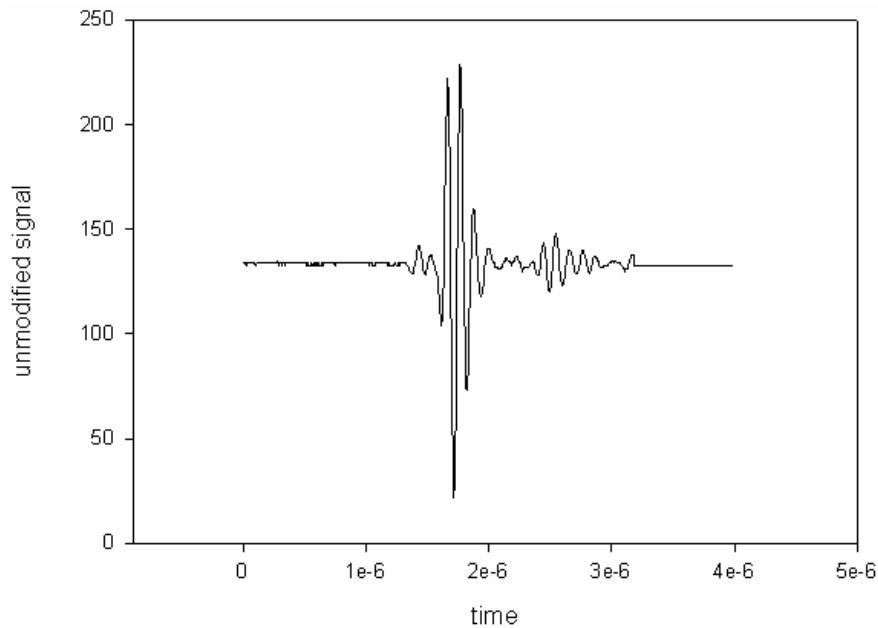


Figure 10. The 1st 800 data points vs. time, plotted to reproduce the original waveform.

The next phase was to convert the waveform from both positive and negative to all positive peaks. The transducers had a baseline potential voltage, which varied from 133 to 135 volts but mainly centred on 134. The first step was to compare the data point values with the relevant baseline to gain a new value of the deviation, both positive and negative. These new values were then squared and square rooted in order to convert the entire range into positive values, which were then plotted against time.

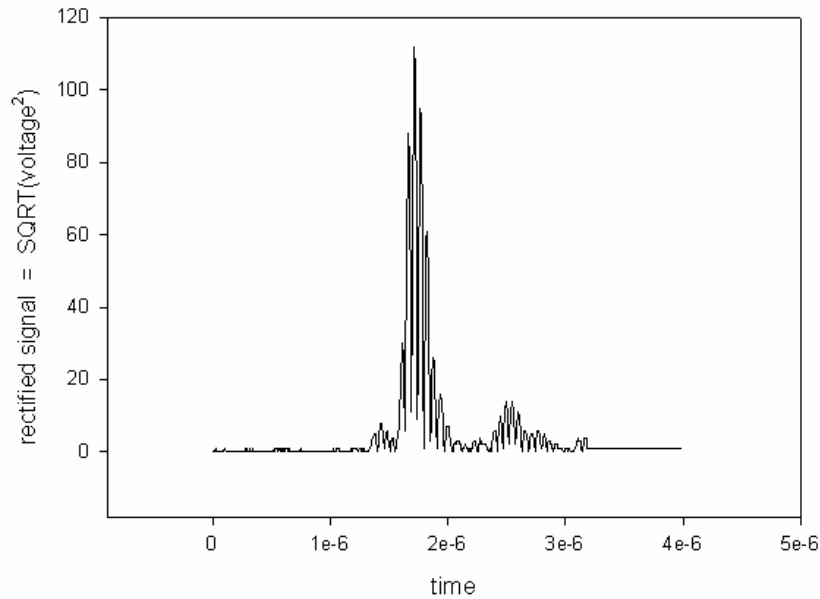


Figure 11. The rectified signal converted to all positive values

The next stage was to select the four largest peaks, and note both the time at which the peak occurred and the amplitude that the peak attained. This analysis was performed for four waveforms from each individual, ensuring that the waveforms were the same as those used in the previous analysis of the VOS values supplied by M^cCue plc.

The results of the 4 different peaks both amplitude and time were compared against the weight, height, age, VOS (M^cCue) and the clinical measurement results, in order to view which parameters showed any statistically valid correlation. (Appendix 1)

- The raw peak values (in essence times of flight data) did not correlate with the ultrasound systems, but showed correlations with the DXA values.
- The raw amplitude values correlated with all the ultrasound data and the DXA data.

With the data gained it was possible to perform analysis of parameters similar to those used by the DBM Sonic system.

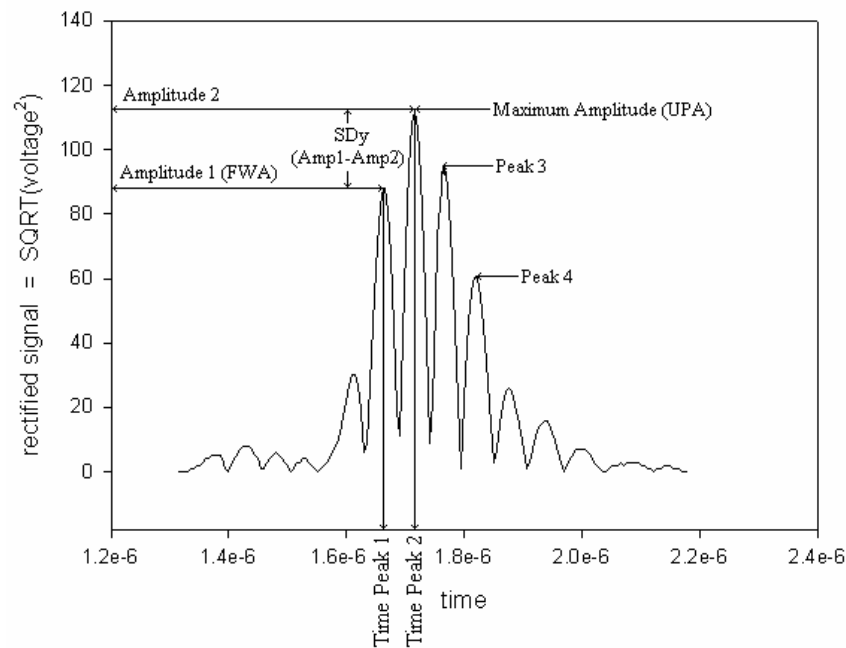


Figure 12. The measurement of ‘extrapolated’ parameters produced from the positive waveform.

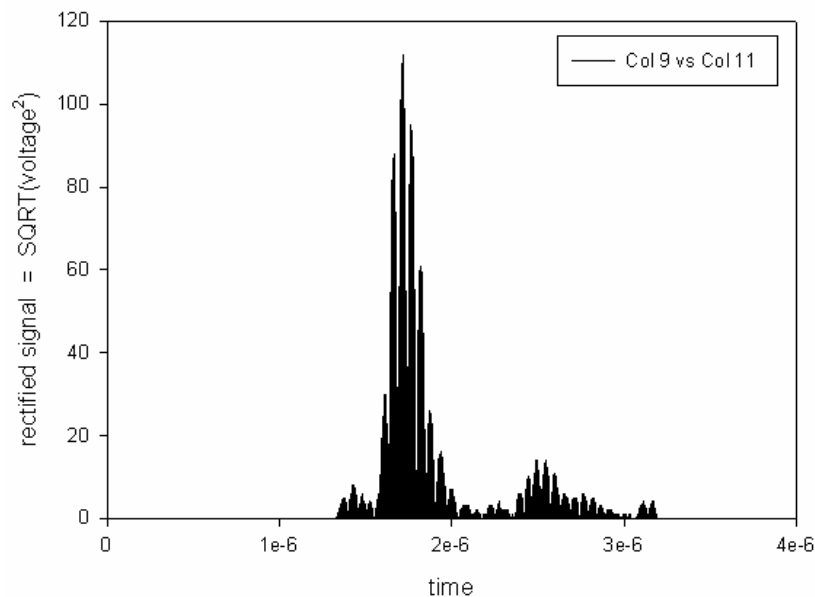


Figure 13. A graphic representation of the area measured, in the assessment of the energy value.

The list of produced ‘extrapolated’ parameters:

- Ad-SOS: The time of the first of the four greatest peaks measured. (Time 1: Figure 12)
- FWA: The amplitude of the first of the four greatest peaks measured.
- SDy: The difference in amplitude between the first and second of the four greatest peaks measured.
- UPA: The amplitude of the maximum peak of the four greatest peaks measured.
- Energy: The area under the positive waveform (Figure 13).
- TF: The time difference between the first and the last of the four greatest peaks measured. (Time Peak 4 – Time Peak 1)

The new ‘extrapolated’ parameters were compared against the clinical measurements, age, weight, height, and the VOS (M^cCue). (Appendix 2).

- TF and Ad-SOS (that is the time of flight based measurements, very much like the original McCue VOS values) failed to produce statistically valid correlations with any of the clinical measurements (with one exception of Ad-SOS vs. phalanx ($r = 0.104$, $p = 0.040$)).
- Meanwhile all the amplitude and energy values (FW, SDy, Energy and UPA) correlated well with all the clinical data. The highest significant correlation was $r=0.290$.

The next stage of the analysis was to compare the ‘extrapolated’ parameters against the previously mentioned ‘composite’ values for bone status (Appendix 3).

- Like before, the TF and Ad-SOS (that is the time of flight based measurements, very much like the original McCue VOS values) did not show promise as the correlations were weak although in cases still some were significant.
- Like previously all the amplitude and energy values (FW, SDy, Energy and UPA) correlated well with all the clinical data. The highest significant correlation was now $r=0.287$.

From this analysis we can perhaps summarise the findings as:

- ❖ Amplitudes and the energy of the received waves do carry some information reflecting the bone status and this should be taken into account in any future algorithm.
- ❖ At the same time, however, we cannot conclusively decide from these analyses that the *time of flight* values (and the consequently produced *speeds of sound* values) are unreliable bone status measurements. This is because the Speed of Sound data depends crucially on correct separation values and in this cohort we did not have available such reliable separation values that would allow us to arrive at an informed opinion on this particular aspect of the methodology.

6. PREDICTION ALGORITHMS BY STEP-WISE REGRESSIONS

By using the previous ‘extrapolated’ parameters and ‘weight’ (which showed the most promise by independently relating to bone status – and which is also incidentally able to be measured in-car) we produced a series of ‘step-wise’ regressions, in which the statistical software adds and subtracts parameters automatically from regressions to derive the best possible algorithms that are able to predict the ‘unknown’ variable.

The unknown variables were the DXA values for the hip, the spine and the 3 ‘composite’ parameters we introduced earlier and which are in general based on either/or hip, spine, ultrasound data, age, weight.

The stepwise regression shows, in order of predictive value, the best parameters for the prediction of a variable, and also the best combination of parameters

The list of the step-wise regression results follows underneath:

Lumbar Spine versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF (Appendix 4.1)

For the prediction of BMD at the Lumbar spine, the best predictive parameters are weight, SDy, ADSOS, FWA, UPA and Energy in that order. The addition of TF to the analysis had either no effect, or a negative effect on the prediction, and hence was excluded from the final results. The best R^2 value that could be attained by this analysis was 20.78%.

Total Hip versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF (Appendix 4.2)

For the prediction of BMD at the total hip, only three parameters had an effect on the predictive value, weight, SDy and ADSOS (in order of value). The best R^2 that could be obtained was 29.64%, displaying a superior predictive ability than was achieved for the Lumbar spine.

Age + Weight + DXA (AWD) versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF (Appendix 4.3)

For the prediction of the combined value AWD only weight and UPA had an affect on the prediction. Weight not surprisingly contributed the greatest prediction, as it was part of the initial variable being predicted. The R^2 value achieved was 41.69% the highest value achieved by these analysis.

Sunlight + CUBA + DXA (SCD) versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF (Appendix 4.4)

As with AWD, the combined value SCD was predicted best by weight and UPA, with weight once again supplying the greatest predictive value. The R^2 value was 22.14%.

Age + Weight + All Clinical Measurements versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF (Appendix 4.5)

AWA was best predicted by a combination of weight, UPA and ADSOS, with weight providing the greatest predictive value due to it's presence in both the variable and predictor. The R^2 value of 35.34% was the second highest value obtained.

7. SUMMARY OF RESULTS

The present examination of the BOSCOS prototype and its performance highlighted that the problems of the system are basically twofold: (1) the quality of the acquired signal and (2) the determination of the separation of the transducers.

The quality of the signal can be improved by either using gel as a coupling medium or by using more expensive transducers (i.e. Steveley ?).

- The use of gel would have better some of the quality characteristics of the system and thus would have made some predictions better, but this is not feasible in our application, so we cannot consider it further.
- The use of Stevealey transducers should be considered further and we are willing to consider further analysis and data collection to prove or disprove the feeling that more expensive transducers would perhaps improve the signal quality enough to counteract the absence of coupling gel.

Under the current set up and system characteristics the results' summary is:

- ❖ The list of the step-wise regression results showed that in the best of cases and by using the McCue prototype system, as it stands at the moment, we cannot predict bone status with an R^2 better than 50%.
- ❖ Employing a set of 'extrapolated' parameters (inspired from a system that is currently in clinical use) derived from the signal by simple processing methods is possible and these improve the predictive power of the current prototype system.
- ❖ Having better 'separation' values would alleviate some of the problems. The transducer that produced the separation values was clearly unreliable and/or malfunctioned easily and without the operator being aware that something was terribly wrong. In a fully automated system and in the absence of a fully trained and informed operator the system would be even more unreliable.
- ❖ On the other hand if the separation values can be made fully reliable it is conceivable that even better predictability of the bone status can be attained as the separation values

contribute in the time of flight data and the speed of sound data. In the current analysis SOS was unreliable and did not contribute in the algorithms. Had it been available it is possible that the actual algorithms would be more accurate.

8. REFERENCES

- R. Barkmann, S. Lüsse, B. Stampa, et al. (2000) Assessment of the Geometry of Human Finger Phalanges using Quantitative Ultrasound In Vivo. **Osteoporosis International**; Vol. 11, p.745-755
- R. Giardino, R. Rotini, F. Noia, et al. (2002) Phalangeal Ultrasonography in Forearm Fracture Discrimination. **Biomedicine and Pharmacotherapy**; Vol. 56, p.332-338
- A. Montagnani, S. Gonnelli, C. Cepollaro, et al. (2002) Graphic Trace Analysis of Ultrasound at the Phalanges May Differentiate Between Subjects with Primary Hyperparathyroidism and with Osteoporosis: A Pilot Study. **Osteoporosis International**; Vol. 13, p. 222-227
- C. Wüster, C. Albanese, D. De Aloysio, et al. (2000) Phalangeal Osteosonogrammetry Study: Age-related Changes, Diagnostic Sensitivity, and Discrimination Power. **Journal of Bone and Mineral Research**; Vol. 15, p.1603-1614

APPENDICES

Appendix 1.

Correlations of: Age, height, weight, VOS (McCue); the clinical systems measurement values *versus* the raw data for Peak times and Peak Amplitudes.

Height	Age																	
	-0.125	0.013																
Weight	Height																	
	-0.136	0.366																
VOS	Weight																	
	-0.119	-0.017	-0.073															
Peak 1	0.022	0.742	0.161															
	VOS (M ^c Cue)																	
Peak 1	0.140	0.430	0.448	-0.055														
	0.006	0.000	0.000	0.286														
	Peak 1																	
Peak 2	0.138	0.409	0.429	-0.062	0.963													
	0.006	0.000	0.000	0.234	0.000													
	Peak 2																	
Peak 3	0.131	0.343	0.349	-0.070	0.806	0.905												
	0.009	0.000	0.000	0.178	0.000	0.000												
	Peak 3																	
Peak 4	0.115	0.281	0.277	-0.070	0.651	0.740	0.944											
	0.022	0.000	0.000	0.178	0.000	0.000	0.000											
	Peak 4																	
Ampl-1	-0.272	-0.095	0.048	0.052	-0.273	-0.287	-0.295	-0.274										
	0.000	0.061	0.344	0.319	0.000	0.000	0.000	0.000										
	Ampl-1																	
Ampl-2	-0.284	-0.112	0.063	0.061	-0.293	-0.307	-0.317	-0.295	0.974									
	0.000	0.027	0.212	0.237	0.000	0.000	0.000	0.000	0.000									
	Ampl-2																	
Ampl-3	-0.295	-0.099	0.057	0.066	-0.289	-0.303	-0.312	-0.290	0.936	0.986								
	0.000	0.050	0.257	0.205	0.000	0.000	0.000	0.000	0.000	0.000								
	Ampl-3																	
Ampl-4	-0.279	-0.107	0.016	0.060	-0.296	-0.308	-0.313	-0.289	0.905	0.956	0.979							
	0.000	0.034	0.751	0.250	0.000	0.000	0.000	0.000	0.000	0.000	0.000							
	Ampl-4																	
Radius	-0.536	0.177	0.088	0.199	-0.003	-0.009	-0.029	-0.036	0.293	0.290	0.284	0.270	Radius					
	0.000	0.001	0.086	0.000	0.960	0.865	0.574	0.488	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>						
Phalanx	-0.597	0.184	0.168	0.225	0.023	0.017	-0.000	-0.011	0.294	0.295	0.284	0.249	0.550					
	0.000	0.000	0.001	0.000	0.649	0.732	0.996	0.821	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	0.000					
BUA	-0.442	0.133	0.317	0.112	0.071	0.069	0.054	0.044	0.204	0.212	0.207	0.186	0.445	0.389	Phalanx			
	0.000	0.009	0.000	0.032	0.161	0.172	0.285	0.391	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	0.000	0.000				
VOS	-0.434	-0.014	0.037	0.138	-0.072	-0.063	-0.041	-0.023	0.161	0.186	0.187	0.153	0.431	0.371	0.812	BUA		
	0.000	0.785	0.468	0.008	0.156	0.215	0.421	0.647	<u>0.001</u>	<u>0.000</u>	<u>0.000</u>	<u>0.003</u>	0.000	0.000	0.000			
L.Spine	-0.285	0.222	0.335	0.123	0.235	0.221	0.164	0.120	0.183	0.220	0.206	0.155	0.465	0.354	0.551	0.530	VOS	
	0.000	0.000	0.000	0.018	<u>0.000</u>	<u>0.000</u>	<u>0.001</u>	<u>0.017</u>	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	<u>0.002</u>	0.000	0.000	0.000	0.000		
T. Hip	-0.436	0.176	0.510	0.093	0.285	0.269	0.215	0.170	0.124	0.155	0.149	0.103	0.458	0.332	0.573	0.519	0.695	L.Spine
	0.000	0.001	0.000	0.073	<u>0.000</u>	<u>0.000</u>	<u>0.000</u>	<u>0.001</u>	<u>0.015</u>	<u>0.002</u>	<u>0.003</u>	<u>0.043</u>	0.000	0.000	0.000	0.000	0.000	

Cell Contents: Pearson correlation
P-Value

Correlations: of Age, VOS (McCue), height, weight, the clinical systems for radius, phalanx, BUA, VOS, hip and spine *versus* the new prototype analysis parameters (AdSOS; FWA; SDy; UPA; Energy; TF).

Cell Contents: Pearson correlation
P-Value

Appendix 3.

Correlations of: Age, [Age+Weight+DXA]=(AWD), [Sunlight+CUBA +DXA]=(SCD), [Age+Weight+All clinical measurements]=(AWA) versus ADSOS, FWA, SDy, Energy, UPA and TF

AWD	Age								
	-0.747								
	0.000								
SCD		AWD							
	-0.552	0.833							
	0.000	0.000							
AWA			SCD						
	-0.752	0.963	0.927						
	0.000	0.000	0.000						
ADSOS				AWA					
	-0.236	0.105	0.061	0.118					
	0.000	0.038	0.242	0.023					
FWA					ADSOS				
	-0.272	0.228	0.247	0.273	0.288				
	0.000	0.000	0.000	0.000	0.000				
SDy						FWA			
	0.198	-0.226	-0.221	-0.223	-0.247	-0.459			
	0.000	0.000	0.000	0.000	0.000	0.000			
energy							SDy		
	-0.283	0.214	0.248	0.265	0.322	0.962	-0.609		
	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
UPA								Energy	
	-0.281	0.249	0.264	0.287	0.313	0.973	-0.649	0.981	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
TF									UPA
	0.016	0.001	-0.005	-0.002	0.040	-0.090	0.049	-0.092	-0.089
	0.758	0.989	0.921	0.963	0.431	0.075	0.334	0.068	0.079
Cell Contents: Pearson correlation									
P-Value									

Appendix 4.1

Stepwise Regression:

Lumbar Spine versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is spine on 7 predictors, with N = 392

N (cases with missing observations) = 103 N (all cases) = 495

Step	1	2	3	4	5	6
Constant	0.6247	0.5927	0.7193	0.7308	0.7241	0.7590
weight	0.00437	0.00412	0.00406	0.00403	0.00401	0.00384
T-Value	7.03	6.78	6.69	6.67	6.72	6.37
P-Value	0.000	0.000	0.000	0.000	0.000	0.000
SDy		-0.00430	-0.00471	-0.00384	-0.02500	-0.02448
T-Value		-4.70	-5.00	-3.72	-4.15	-4.07
P-Value		0.000	0.000	0.000	0.000	0.000
ADSOS			-0.00006	-0.00007	-0.00006	-0.00005
T-Value			-1.73	-2.12	-1.83	-1.68
P-Value			0.084	0.035	0.068	0.094
FWA				0.00063	0.02164	0.02150
T-Value				2.04	3.67	3.65
P-Value				0.042	0.000	0.000
UPA					-0.0212	-0.0189
T-Value					-3.57	-3.12
P-Value					0.000	0.002
energy						-13028
T-Value						-1.72
P-Value						0.087
S	0.170	0.165	0.165	0.164	0.162	0.161
R-Sq	11.25	16.02	16.66	17.55	20.18	20.78
R-Sq(adj)	11.02	15.59	16.02	16.70	19.14	19.55
C-p	42.2	21.1	20.0	17.7	7.0	6.0

Appendix 4.2

Stepwise Regression:

Total Hip versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is hip on 7 predictors, with N = 388

N (cases with missing observations) = 107 N (all cases) = 495

Step	1	2	3
Constant	0.4934	0.4760	0.6276
Weight	0.00528	0.00515	0.00511
T-Value	11.65	11.48	11.48
P-Value	0.000	0.000	0.000
SDy		-0.00231	-0.00282
T-Value		-3.43	-4.07
P-Value		0.001	0.000
ADSOS			-0.00007
T-Value			-2.80
P-Value			0.005
S	0.123	0.121	0.120
R-Sq	26.01	28.20	29.64
R-Sq (adj)	25.82	27.83	29.09
C-p	19.2	9.3	3.4

Appendix 4.3

Stepwise Regression:

Age + Weight + DXA (AWD) versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is age + Weight + DXA on 7 predictors, with N = 388

N (cases with missing observations) = 107 N (all cases) = 495

Step	1	2
Constant	51.93	47.36
Weight	0.694	0.678
T-Value	15.15	15.31
P-Value	0.000	0.000
UPA		0.092
T-Value		5.40
P-Value		0.000
S	12.4	12.0
R-Sq	37.28	41.69
R-Sq (adj)	37.12	41.39
C-p	37.2	9.6

Appendix 4.4

Stepwise Regression:

Sunlight + CUBA + DXA versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is [SunLigh on 7 predictors, with N = 372

N(cases with missing observations) = 123 N(all cases) = 495

Step	1	2
Constant	78.26	75.76
Weight	0.310	0.292
T-Value	8.80	8.48
P-Value	0.000	0.000
UPA		0.060
T-Value		4.79
P-Value		0.000
S	8.78	8.53
R-Sq	17.30	22.14
R-Sq (adj)	17.08	21.71
C-p	28.7	7.5

Appendix 4.5

Stepwise Regression:

Age + Weight + All Clinical Measurements (AWA) versus Weight, ADSOS, FWA, SDy, UPA, Energy, and TF

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is [age+W+A on 7 predictors, with N = 372

N(cases with missing observations) = 123 N(all cases) = 495

Step	1	2	3
Constant	68.54	65.59	56.94
Weight	0.454	0.433	0.442
T-Value	12.38	12.19	12.40
P-Value	0.000	0.000	0.000
UPA		0.071	0.061
T-Value		5.47	4.43
P-Value		0.000	0.000
ADSOS			0.0038
T-Value			2.06
P-Value			0.040
S	9.14	8.80	8.76
R-Sq	29.30	34.60	35.34
R-Sq (adj)	29.11	34.24	34.81
C-p	39.2	10.7	8.4

BOSCOS

Bone Scanning for Occupant Safety

Appendix: 15.5

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
DfT Contract Number PPAD 9/33/89

Report title: Sensitivity and Specificity of the BOSCOS
Prototype Finger Scanner.

Author Richard B Cook
Cranfield University at Shrivenham

Date January 2003



PROJECT REPORT

FORESIGHT VEHICLE LINK PROJECT

BONE SCANNING FOR OCCUPANT SAFETY
(BOSCOS)

Contract Number PPAD 9/33/89

1st February 2002 – 30th June 2005

Report to

Department for Transport

June 2005

For and on behalf of the Consortium, comprising:

Cranfield Impact Centre Ltd. – lead partner
Nissan Technical Centre – Europe Ltd.
TRW Automotive
Autoliv Ltd.
Cranfield University at Shrivenham, Centre for Materials Science and
Engineering
Loughborough University, Vehicle Safety Research Centre
McCue plc (sub-contractor to lead partner)

DfT Project Officer

I. Knowles

Sensitivity and Specificity of the BOSCOS Prototype Finger Scanner.

R.Cook and P.Zioupou
of the Centre for Materials Science and Engineering
of Cranfield University at Shrivenham

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1. BOSCOS Individual Definition

The BOSCOS system requires that individuals are classified into groupings according to their QUS result. Depending on the grouping the individual falls into, adjustment of the restraint system can be performed to cater for the occupants bone status. In the clinical environment three bands are used, (Figure 1) and are designed to classify those individuals as either normal, which includes those individuals within 1 standard deviation below the young adult mean, and any one above average. The next banding is those individuals who fall between 1 and 2.5 standard deviation below the young adult mean, a condition known as Osteopenia, with the final groups being those individuals 2.5 standard deviations below the young adult mean, who are considered to be osteoporotic. These bandings are based around the world health organisation defined bandings, (Kanis et al. (1994)) that rely on 'T-score' values (Equation 1).

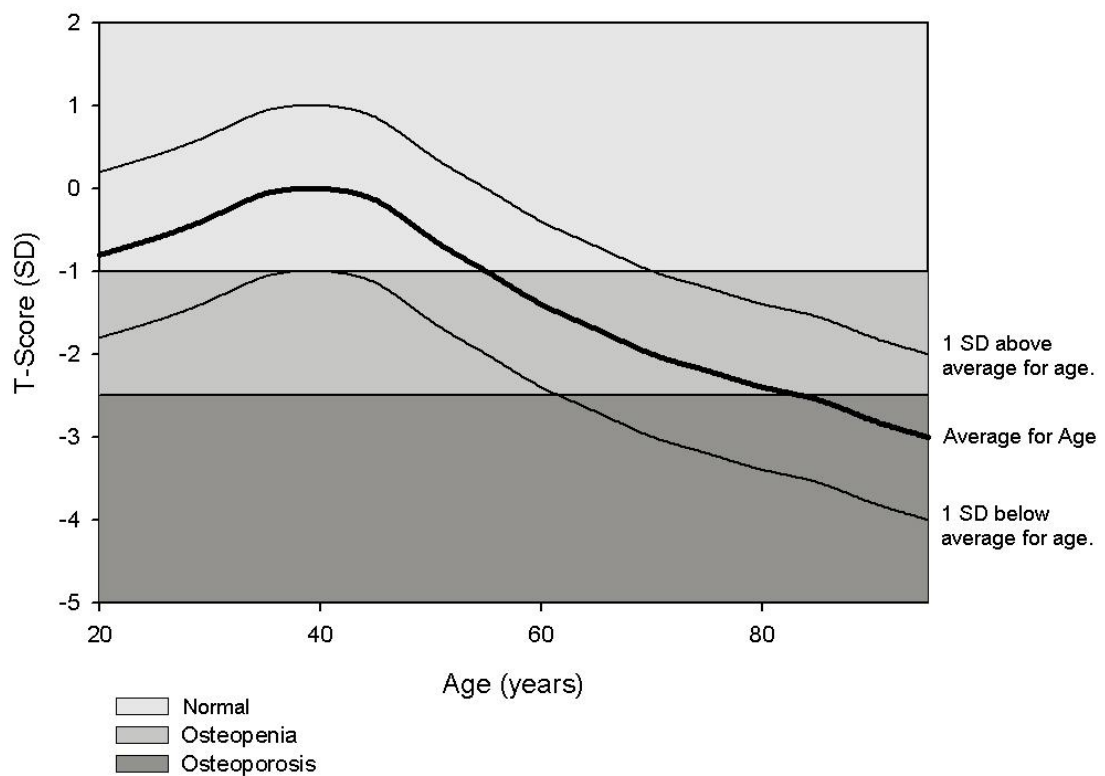


Figure 1. Diagrammatic representation of the clinical bands in relation to the expected value for individuals age.

T-score= (subject measurement – young adult mean) / (standard deviation young adult mean)

Equation 1. T-Score calculation.

This classification system shows that on average, everyone over the age of 60 can be considered to have low bone density or Osteopenia, and at age 80 and above the average individual will be suffering osteoporosis. This will vary depending on gender and ethnic origin.

However this system is based around assessment of the axial skeleton using DXA, and previous research (C.-C.Gluer (2000)) has shown it to require adjustment when using it to assess bone status of different bone sites, and in relation to different investigation techniques. This highlights the need for any BOSCOS system to have a population specific database, with predetermined cut-off levels. However any system, approved for use clinically, will have the ability to supply an individual with a specific value for there bone status, for that measurement site, and give information on the bone condition in relationship to their age and peak. But more importantly, the systems will be able to differentiate individuals into one of three bands, according to there bone quality.

2. Sensitivity and Specificity of the Prototype.

103 individuals were recruited from the DXA scanning clinics at the Great Western Hospital, Swindon. Six individuals were later excluded from this phase of the due to incomplete scan data. Information on the skeletal status of the individuals was assessed using the hospital DXA scanner, CUBA clinical and Sunlight Omnisense. Each individual was also scanned using the BOSCOS prototype system, and 10 waveforms were collected. Further information on the BOSCOS prototype, and the measurement parameters that were produced from the prototype waveforms, are described in the previous document, 'BOSCOS Prototype Analysis'.

Using Minitab™ Statistical Software version 13.31, stepwise regression was performed on the 97 individuals results, to identify the important prototype parameters for the prediction of the DXA result. Using regression analysis on the identified parameters, values specific to each individual were produced, which provided the highest predictive ability possible, for the determination of the DXA result, and therefore axial skeletal status.

Two different values were calculated for each individual. The first parameter was derived from stepwise regression of all the prototype parameters, and the second from all the prototype parameters but with the inclusion of weight as an additional parameter.

Sensitivity and specificity of a technique relate to its abilities to correctly predict a given result. The calculations are based around a 2x2 table (Table 1) The sensitivity is a measure of how good a test is at picking up people who have the condition and is calculated from the table as $A / (A+C)$. The specificity is a measure of how good a test can correctly exclude people without the condition, and is calculated as $D / (B+D)$.

Table 1. A 2x2 diagnostic table.

Diagnostic Tool Test Result	Disease Test Result		
	Positive	Negative	
Positive	A	B	A+B
Negative	C	D	C+D
	A+C	B+D	A+B+C+D

For the perfect screening test the sensitivity and the specificity should both be 100%, but with all tests there are some false positives and negatives. Generally there is a

balance between the sensitivity and specificity, with a high sensitivity relating to a low specificity, and visa-versa.

In order to compare different techniques, and gain information on the diagnostic ability, sensitivity and specificity values are used to plot receiver operating characteristic curves (ROC curves). In order to do this a range of values for sensitivity with their corresponding specificity from 1-0 must be calculated. The sensitivity is then plotted against 1-specificity to give a characteristic curve. Initial comparisons of the techniques abilities can be seen by the position of the curves, with the curves that lie closest to the top left corner of the graph having the highest diagnostic ability and those closer to the bottom left corner showing less. In order to quantify the diagnostic ability, the area under the ROC curve (AUC) is measured. The higher the value obtained, the greater the diagnostic ability. Kent R, Patrie J (2005) provide guidelines for the utility of discriminatory tools, based on areas below ROC curves. Systems with areas below 0.7 can be considered to have little or no utility, while systems show a moderate utility with values between 0.70-0.80, good utility between 0.80-1.

Using the Sensitivity and specificity values calculated for each technique for the prediction of DXA, three ROC curves, based on the prediction of three distinct DXA levels, DXA T-score of -2.5 (Osteoporosis) [Figure 2], -2 (Low Bone Density) [Figure 3] and -1 (Osteopenia) [Figure 4] were plotted. From this analysis was performed on the area below the ROC curve. The value for the area below the curve supplies information of the diagnostic ability of a technique.

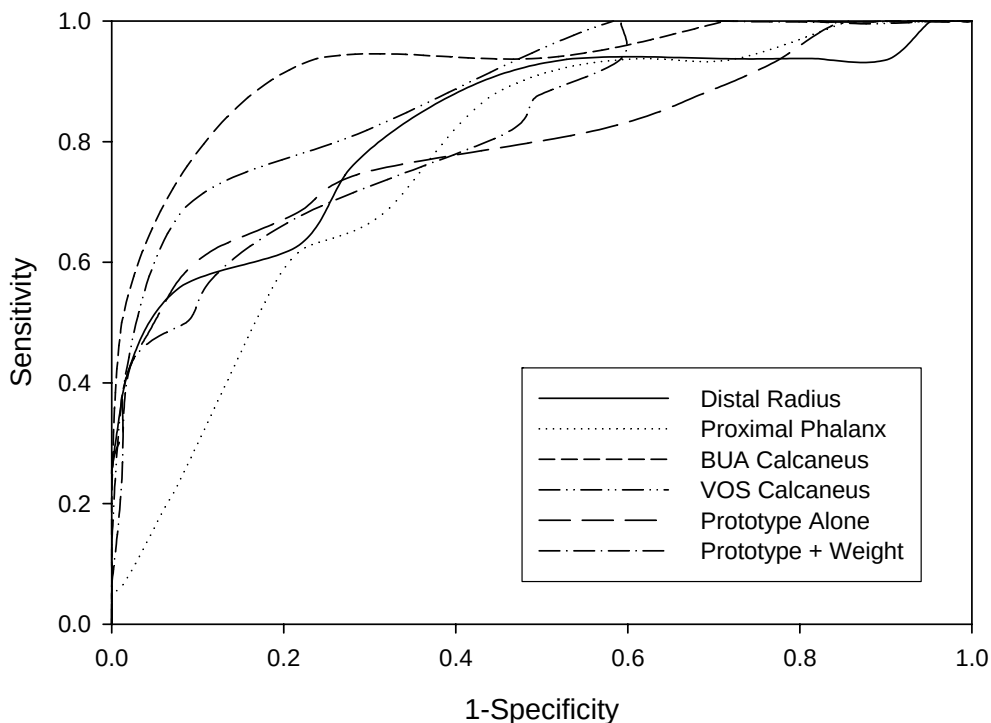


Figure 2. ROC curve for the prediction of DXA -2.5 (Osteoporosis)

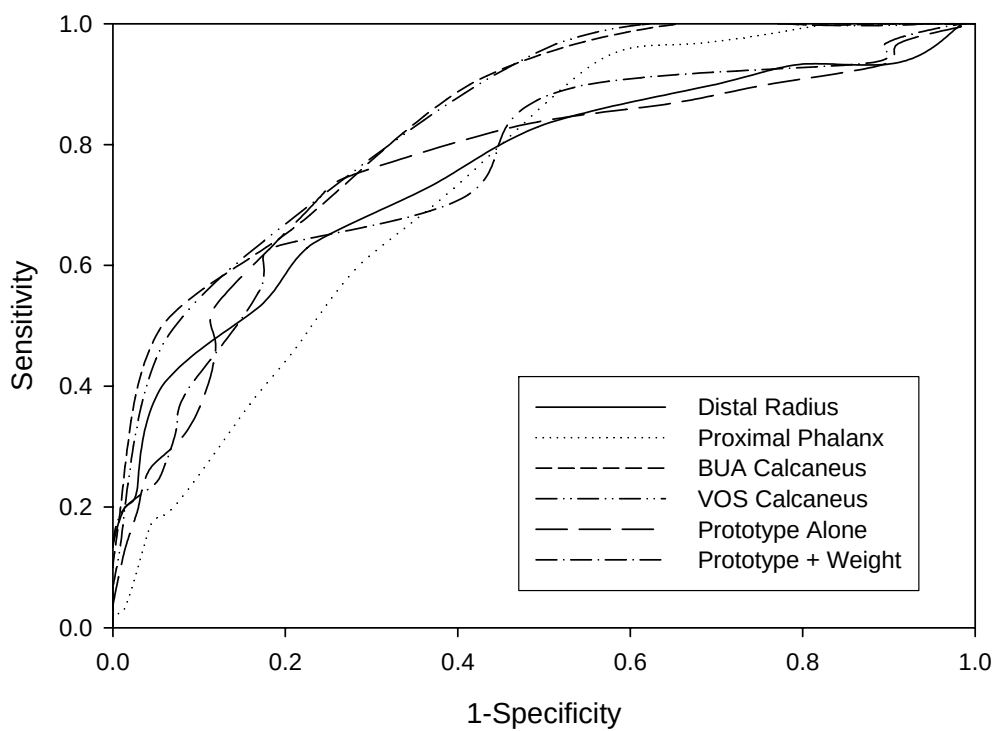


Figure 3. ROC curve for the prediction of DXA -2 (Low Bone Density)

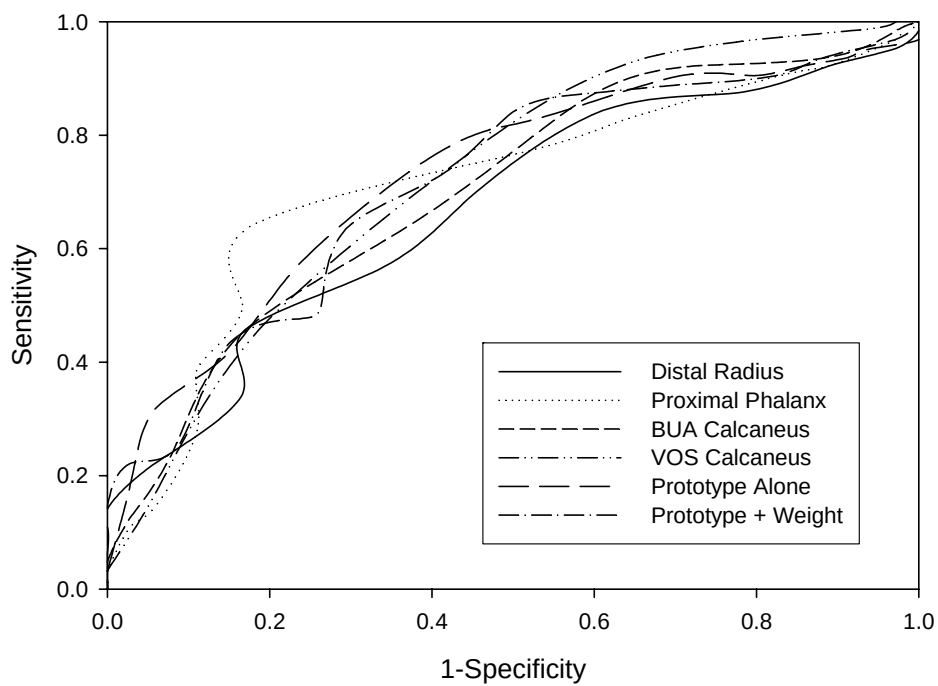


Figure 4. ROC curve for the prediction of DXA -1 (Osteopenia)

Table 2. Areas below the ROC curves for the three DXA cut-off levels.

	DXA -2.5	DXA -2	DXA -1
Distal Radius	0.82	0.75	0.67
Proximal Phalanx	0.76	0.74	0.71
BUA Calcaneus	0.92	0.84	0.70
VOS Calcaneus	0.88	0.84	0.72
Prototype Alone	0.80	0.76	0.73
Prototype + Weight	0.82	0.76	0.71

The results show that the systems, including the prototype, showed a moderate level of diagnostic ability, with BUA assessment of the calcaneus providing a good diagnostic ability. The ability of the prototype system surpassed that of the proximal phalanx assessment of the Sunlight system in all categories, and was the best technique for the prediction of individuals with axial skeletal T-score of greater than -1 (normal individuals).

3. Discussion

The results of this study show that, using a clinical system, it is possible to separate a population of people into three groups based around QUS assessment of the proximal phalanx. A larger cohort is required if the capabilities of the prototype systems to perform this same classification is to be assessed. Further work is also required to determine the best cut off points and levels of the three bands, especially if this is to be related to biomechanical properties of the skeleton.

When the systems were compared, using the same group of individuals, to assess the techniques diagnostic abilities, the prototype system performed well. It out performed the Sunlight Omnisense system in all bar one assessment, and was the best technique for the prediction of individuals with axial skeletal T-score of greater than -1 (normal individuals). With further development of the prototype systems these results show good potential for the prototypes abilities. These calculations were based around the assessments of 97 individuals, a small population for this type of investigation. Further work with a large population would once again be required to assess the true capabilities of the prototype technique, within a clinical environment.

4. Conclusions

Clinically based ultrasound systems have the ability to split a population of individuals into three bandings.

The prototype system as it stands shows good potential for its diagnostic abilities in relation to the axial skeleton.

5. References

- J.A. Kanis et al. (1994) The Diagnosis of Osteoporosis. **Journal of Bone and Mineral Research**; Vol.9, p.1137-1141
- R. Kent and J. Patrie. (2005) Chest Deflection Tolerance to Blunt Anterior Loading is Sensitive to Age but not Load Distribution. **Forensic Science International**; Vol.149, Issue 2-3, 10 May, p.121-128
- C.-C. Glüer. (2000) The use of Bone Densitometry in Clinical Practise. **Baillière's Clinical Endocrinology and Metabolism**; Vol.14, No.2, p.195-211

BOSCOS

Bone Scanning for Occupant Safety

Appendix: 15.6

A FORESIGHT VEHICLE LINK PROJECT
Research funded by the Department for Transport 2005
DfT Contract Number PPAD 9/33/89

Report title Biomechanics and Tissue Testing

Author R. Cook and P. Zioupos
 Cranfield University at Shrivenham

Date February 2005



PROJECT REPORT
FORESIGHT VEHICLE LINK PROJECT
BONE SCANNING FOR OCCUPANT SAFETY
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Loughborough University, Vehicle Safety Research Centre

McCue plc (sub-contractor to lead partner)

DfT Project Officer

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Biomechanics and Tissue Testing

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Centre for Materials Science and Engineering
Cranfield University at Shrivenham

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1. Data Collection

Bone was collected with the aid of Gloucestershire Royal Hospital orthopaedic department.

Study Group 1. Femoral heads from 20 osteoporotic individuals, who had suffered low trauma fractures of the femoral neck, and required hip replacement surgery. Each individual was scanned using the two quantitative ultrasound machines (CUBA Clinical and Sunlight Omnisense) at four body sites (Distal Radius, Proximal Phalanx, Mid-shaft Tibia, Calcaneus)

Study Group 2. Femoral heads taken from 8 osteoarthritic individuals who were undergoing elective surgery to replace there femoral heads with prosthesis. Each individual was scanned using the two quantitative ultrasound machines (CUBA Clinical and Sunlight Omnisense) at four body sites (Distal Radius, Proximal Phalanx, Mid-shaft Tibia, Calcaneus)

Study Group 3. A group of 17 osteoporotic femoral heads were collected from two UK NHS hospitals in Aberdeen and Gloucester, but without any additional data in the form of ultrasound assessments.

2. Sample Preparation

The Femoral heads were sectioned into slices using a band saw to provide slices of approximately 9mm in thickness. Care was taken to ensure that the heads were all orientated in the same direction during preparation.



Figure 1. Osteoporotic femoral head cut into four 9mm thick slices (top view)

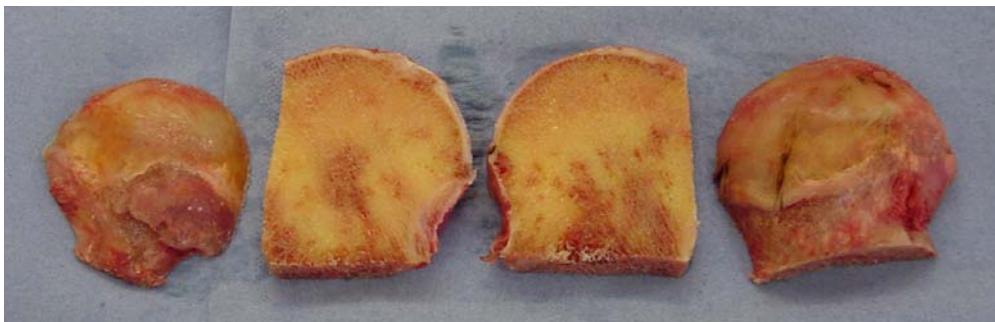


Figure 2. Osteoporotic femoral head cut into four 9mm thick slices (side view)

Figures 1 and 2 show a femoral head from study group 2 sectioned into 9mm thick slices. In this particular example the two middle slices were exactly 9mm thick

with parallel faces, and the two edge slices were one below and one above 9mm in thickness.

3. Sample Design

3.1 Compression cores

Compression cores were taken from the outer slices of the femoral heads, using a core drill with an internal diameter of 9mm. The ends of the cores were removed using a diamond circular saw to provide parallel surfaces.

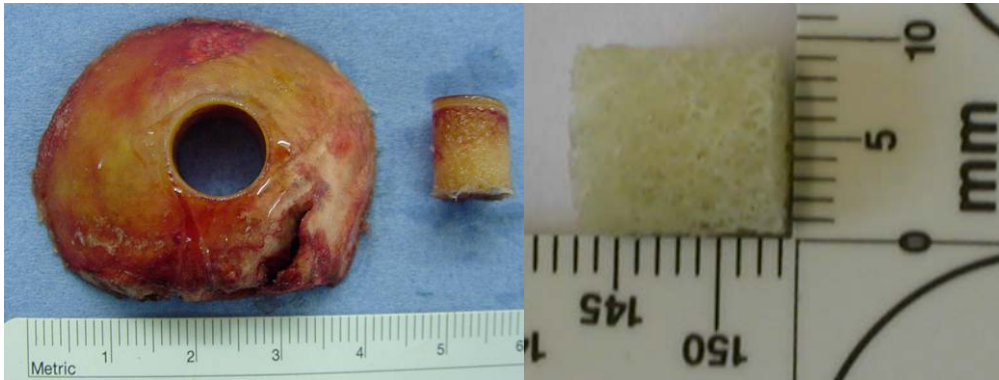


Figure 3. Compression core taken from the side slice of the hip

Figure 4. Compression core cleaned of marrow and articular cartilage

Each core was then cleaned of its marrow using the protocol laid out in section 4 leaving only the cancellous bone structure. The cores were then assessed for density using the protocol laid out in section 5.

The samples were then prepared for testing by the addition of wooden end-caps to either end of the sample, using superglue to form a permanent adhesive bond (Figure 5). These end-caps were used to ensure that the length of the specimen was such that the contact extensometer could be attached exclusively to the bone without interference from the loading platens, or testing rig.

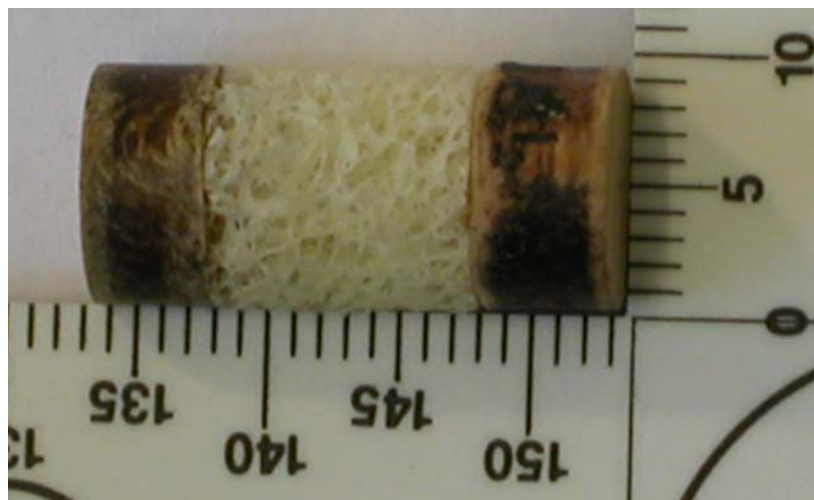


Figure 5. Compression core complete with wooden end-caps ready for testing.

3.2 Fracture Toughness Sample Design

The fracture toughness sample design was based around the guidelines set out in ASTM standard E399-90 Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials. The two sample designs used were the disc shaped compact specimen and the beam specimen.

3.2.1. Disc-Shaped Compact Specimen

The disc specimens were cut from the 9mm thick slices taken from the middle of the femoral head using a 20mm internal diameter diamond-edged core drill. The resultant discs had a W value of roughly 15mm, and after polishing from the original thickness of 9mm, a thickness (B) of 7.5mm.

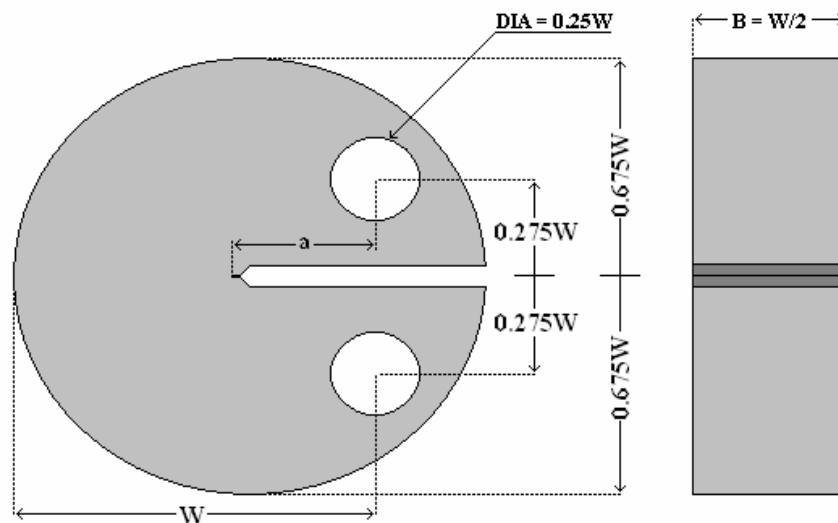


Figure 6. Schematic of the disc-shaped compact specimen redrawn from ASTM standard E399-90

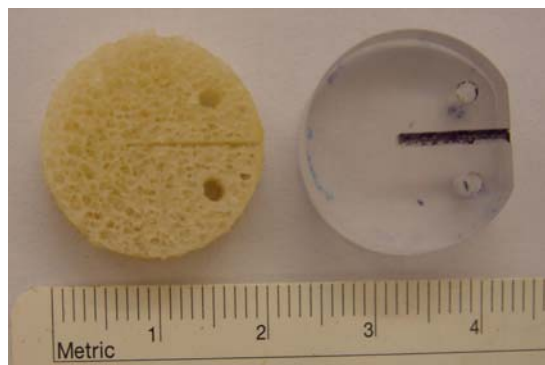


Figure 7. Disc-shaped specimen, and PMMA model

3.2.2. Beam Specimens

Beam specimens were prepared from the remaining bone tissue of the middle 9mm slices, after the disc specimens had been prepared. Beams were cut using the band saw, and then polished down to size to produce beams with $W = 6\text{mm}$ and $B = 3\text{mm}$.

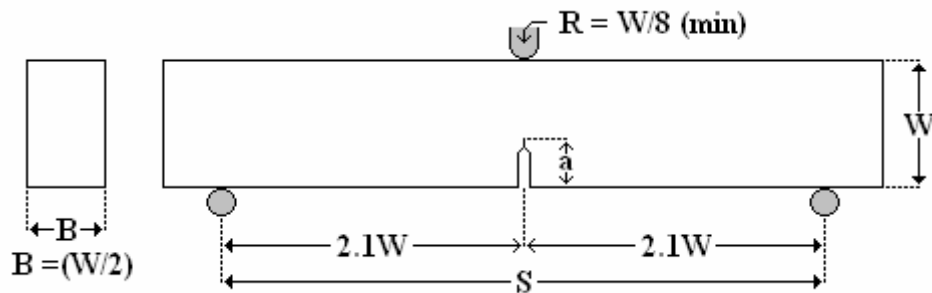


Figure 8. Schematic of the beam shaped specimen redrawn from ASTM standard E399-90

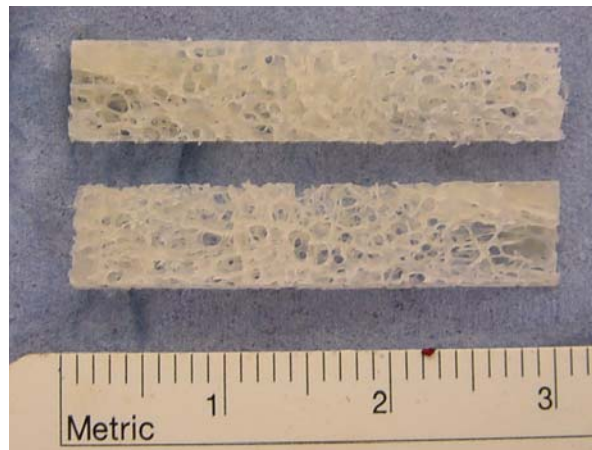


Figure 9. Cleaned osteoporotic beam samples

The fracture toughness samples were cleaned of marrow and fat using the protocol laid out in section 4 and the density of each sample was obtained using the protocol laid out in section 5.

Once the density of each sample had been determined, they were prepared for testing. For both the specimen designs, jigs had been prepared to ensure the accurate insertion of loading holes (disc-shaped compact specimens only), extensometer attachment holes and an initial notch. The jig allowed for the sample to be firmly held during preparation, and provided both pilot holes for drilling, and a slit to guide the cutting of the notch. The notch was inserted using a high speed diamond circular saw under constant irrigation to ensure cooling.

The disc samples were randomly split into four different groups, with each group having a different initial notch length. The beam specimens also had varied notch lengths, but the lengths were randomly varied to give a range.

Cancellous bone of the femoral head is an anisotropic material (different properties in different directions), and in order to take this property into consideration the samples were prepared in two different orientations depending on the orientation of the bones structure, with the initial notch either passing across (AC) the trabecular structure, or between the trabecular structures (AL). The samples were prepared so that the crack path from the initial notch was forced to pass between and along the trabecular structure or across it.



Figure 10. Beam samples showing the two trabecular orientations.
Top: Across AC **Bottom: Along AL**

4. Cleaning of Bone Samples

In order to test the mechanical properties of the cancellous bone materials the bone marrow and fat in between the trabecular struts was removed. The samples were cleaned using a high pressure water jet to remove the marrow from the pores. They were placed on blotting paper to remove any excess water from the pores and surface then placed into individual tubes and submerged in a solution of 1: 1 Chloroform and Methanol. The tubes were continuously agitated and left for 3 days to ensure all the remaining fat was removed from the samples. After the three days were over, the chloroform methanol solution was replaced with methanol for 24 hours, to remove any remaining chloroform. The methanol was diluted by water and thus the samples were rehydrated gradually and then submerged in Ringer's solution to reconstitute them in their physiological status.

5. Density Determination

The Archimedes principle was used to determine the apparent and material density along with the porosity of the bone samples. Each sample was submerged in distilled water and centrifuged at 30,000rpm for 3 minutes, to remove all air from the bone samples. The samples were then weighed while submerged in distilled water to give the submerged wet weight (W_{SUB}). The samples were wrapped in blotting paper and centrifuged again to remove any excess water and reweighed in a hydrated state to give the wet weight (WW).

The samples dimensions were determined using a digital vernier calliper, (accuracy 0.01mm), and used to calculate the volume (V_0) of the specimen sample. The apparent density (D_a) was calculated as:

$$(D_a) = \frac{(WW)}{(V_0)}$$

The material density (D_m) was calculated as:

$$(D_m) = \frac{(WW)}{(WW) - (W_{SUB})} * D_0$$

Where D_0 is the density of the liquid the sample was submerged in. In this case the sample was submerged in distilled water, so D_0 can be considered to equal 1.

The Porosity (P_o) of the sample is determined by:

$$P_o = 1 - (D_a / D_m)$$

6. Testing

All testing was performed on a 'Dartec Series HC25' materials testing machine driven by a '9610 series controller' unit and operated via a PC interface using the 'Workshop 96' software.

6.1. Compression

The compression tests were performed using a constant rate of 0.15mm/s (9mm/min), using a 5kN load cell.

Testing of the cores was performed using a specially designed test rig, with two stainless steel loading platens, the upper of which was articulated to allow for small deviations from linearity in the sample ends to be taken into account. Both upper and lower platens had 9mm wide by 1mm deep depressions in them which acted to constrain the sample ends and prevent any transverse movement during testing. The test samples were constantly irrigated with saline solution at 37°C during testing to mimic in-vivo conditions.

Sample deflection data was collected using three different devices:

1. Stroke control. The results obtained from the extensometer built into the materials testing machine.
2. Platens LVDT: This extensometer was attached between the two loading platens and measured their movement in relation to both loading and time.
3. Contact Extensometer: A miniature contact extensometer with a gauge length of 6mm was attached to the surface of the bone sample using orthodontic elastic bands and knife edges. This method provided the most accurate measure of the compression occurring in the central zone of the bone sample.

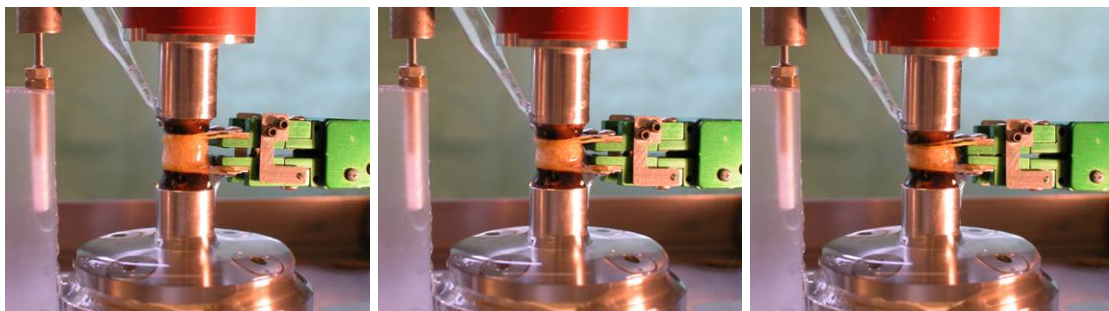


Figure 11. Compression testing

6.2. Fracture Toughness

The loading rate for the disc-shaped compact specimens, and the beam specimens was 0.05 mm/s (3mm/min). The load was monitored using a 500N load cell.

6.2.1. Disc-Shaped Compact Specimens

The disc shaped compact specimens were tested in tension using a specialised test rig. The crack mouth opening displacement (CMOD) was monitored using a miniature extensometer, fixed to the mouth of the crack. The sample was kept hydrated throughout testing with a constant flow of saline at 37°C, so as to mimic in-vivo conditions.

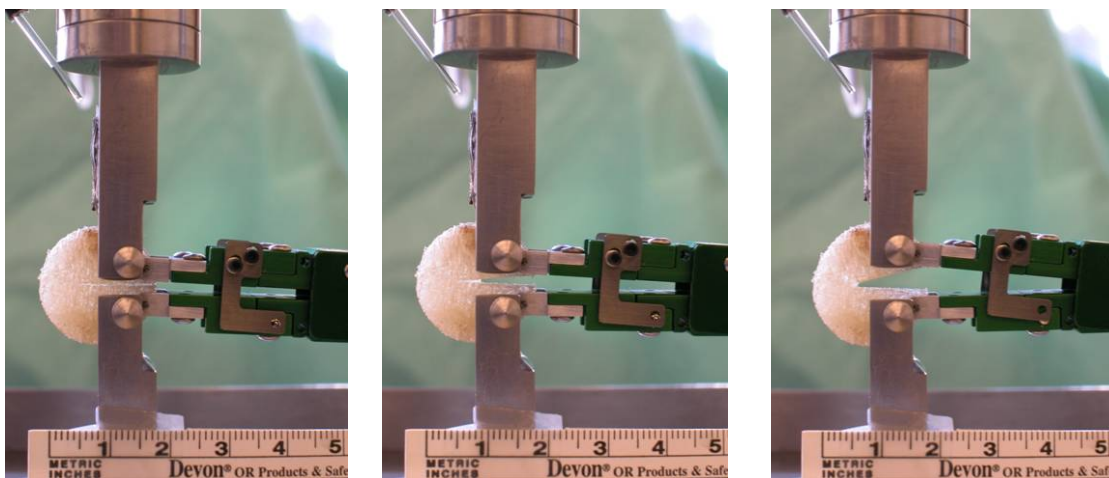


Figure 12. Testing of the disc-shaped compact specimens in tension.

6.2.2. Beam Specimens

The beam specimens were tested in three-point bending, in a purpose built test rig, with a span (S) of 24mm. The crack opening displacement was once again monitored using the miniature extensometer. The samples were tested fully hydrated in saline, but without constant irrigation.

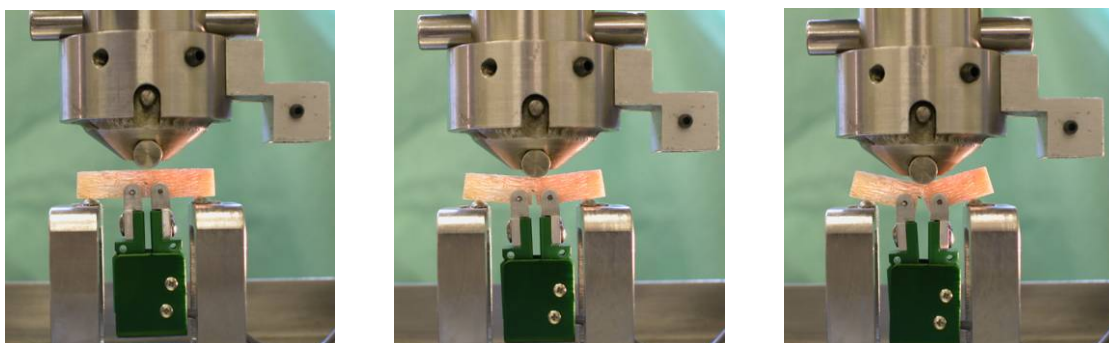


Figure 13. Testing of the beam shaped specimens in three point bend testing.

7. Results

7.1. Compression Testing

The results of the compression testing gave results in the form of a load-deformation curve. The curves varied depending on the extensometer that was used to obtain the results.

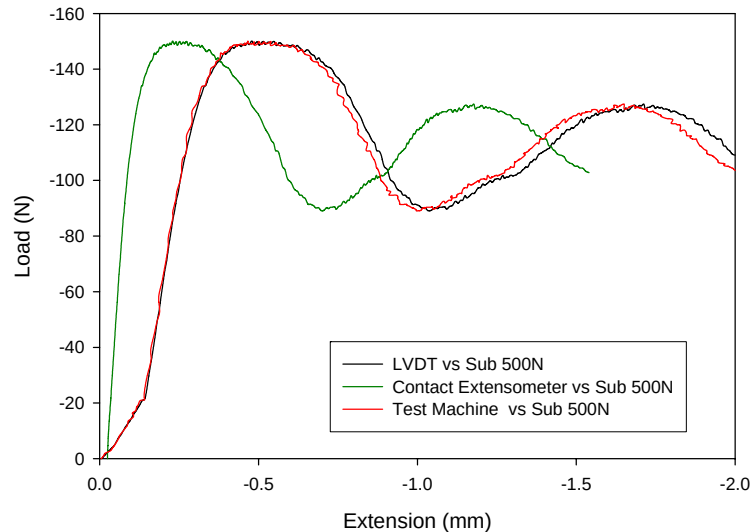


Figure 14. Load deformation curves from three different extensometers.

Both the LVDT attached to the platens and the extensometer built into the materials test machine frame showed an initial lag phase prior to compressive loading. This lag phase was due to the end effects caused by gripping and aligning the samples and of course was not present in the miniature extensometer data.

From the traces it was possible to determine two important parameters.

- Young's Modulus (material Stiffness)
 - The Young's modulus is the slope of the linear part of the stress-strain curve, or the result of the relationship between (nominal) stress (Load / Cross-sectional area of the test sample) divided by (engineering) strain (Change in length / Original Length).
- Strength
 - Strength is the maximum stress value in stress-strain curve (Maximum Load / initial undeformed Cross-sectional area).

7.1.1 Compression test results

Table 1. Mean and standard deviation values for density and compressive properties of cancellous bone cores from osteoporotic and osteoarthritic individuals.

	Apparent Density (g/cm ³)	Matrix Density (g/cm ³)	Porosity (%)	Young's Modulus Contact Extensometer (MPa)	Young's Modulus from the Platens (MPa)	Strength (MPa)
Osteoporotic (Group 1 + 3)	0.4040 (0.1526)	1.7673 (0.1646)	0.7641 (0.1157)	432 (381)	271.1 (172.4)	3.696 (2.544)
Osteoarthritic (Group 2)	0.587 (0.302)	1.7651 (0.1027)	0.6580 (0.1986)	411.4 (236.1)	416.7 (217.5)	6.92 (4.77)
ANOVA Test	p = 0.013	p = 0.971	p = 0.042	p = 0.891	p = 0.043	p = 0.007

Table 1 shows the mean and standard deviations of the compression testing results, and density of the samples from groups 1-3. The values obtained are similar to those published previously for the compressive properties of cancellous bone. [S.J.Brown et al. (2002), E.B.W.Giesen et al. (2001), D.L.Kopperdahl and T.M Keaveny (1998), M.-C. Ho Ba Tho et al. (1997)].

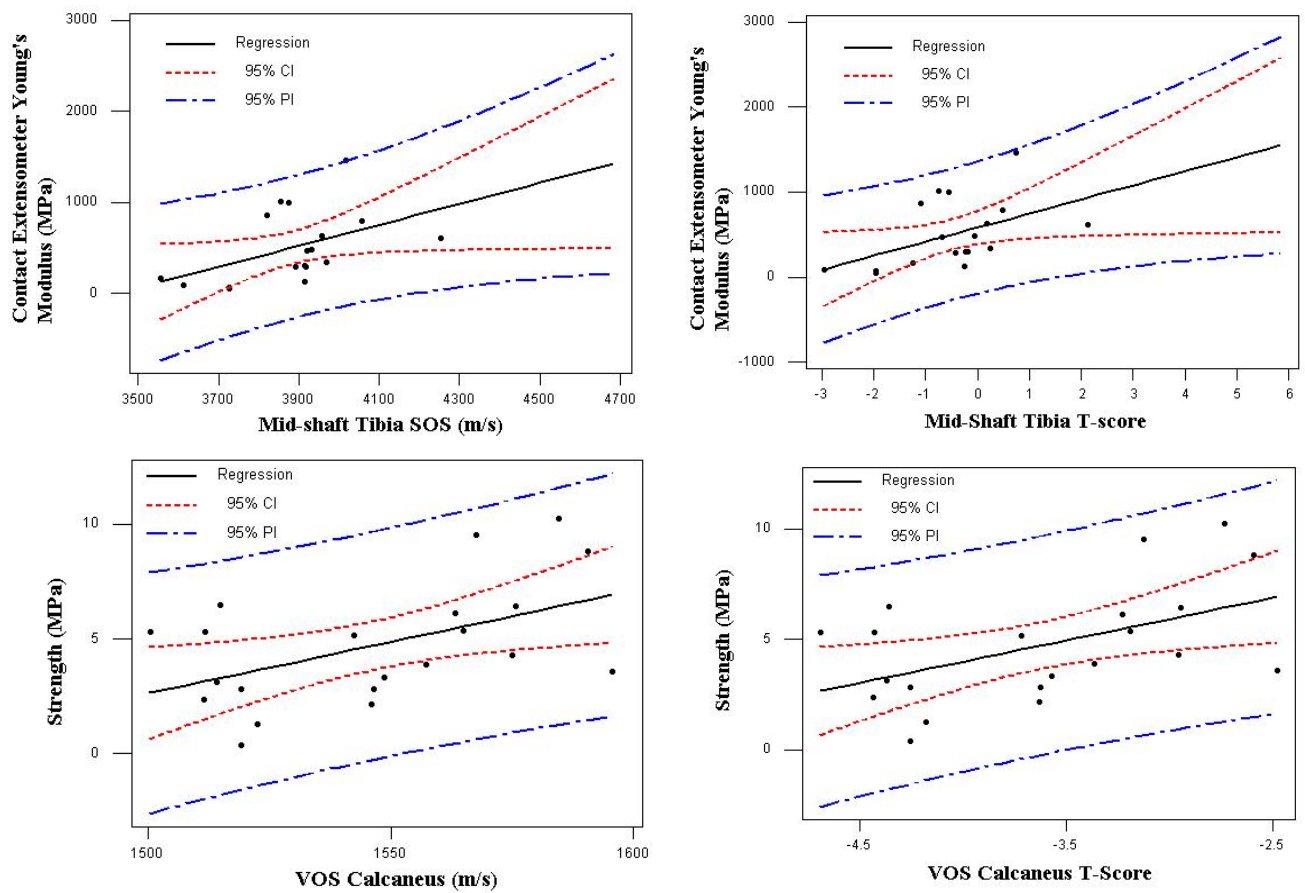
ANOVA testing was performed to investigate if there was a statistical difference between the study groups. The apparent density, platens Young's modulus and strength were all significantly ($p < 0.05$) higher in the osteoarthritic group in comparison to the osteoporotic. The matrix density was not significantly different between the groups as would be expected. However the non-significant difference between the means for the contact extensometer Young's modulus, indicate an error in the results. Although the results are within the range previously determined, the osteoporotic samples would have been expected to exhibit a lower Young's modulus than the osteoarthritic group.

7.1.2. Comparisons to QUS data

If we compare the results of the compression testing results against the clinical QUS assessment results from Groups 1 and 2 individually, we find that there are only a few significant correlations.

Table 2. Pearson's correlation coefficients between clinical ultrasound assessments and compressive testing parameters, from group 1.

	Mid-Shaft Tibia SOS	Mid-Shaft Tibia T-score	VOS Calcaneus	VOS Calcaneus T-score	BUA Calcaneus T-score
Young's Modulus Contact Extensometer	0.471 (p = 0.048)	0.481 (p = 0.043)			
Strength			0.506 (p = 0.019)	0.506 (p = 0.019)	0.431 (p = 0.051)



Figures 15. Regression plots for statistically significant correlations between QUS and compression testing results. Regression equations:

$$\text{E-Contact Extensometer} = -3964.82 + 1.151 \text{ MT-SOS} \quad r^2 = 22.2\%, p = 0.048$$

$$\text{E-Contact Extensometer} = 583.658 + 165.25 \text{ MT T-Score} \quad r^2 = 23.1\%, p = 0.043$$

$$\text{Strength} = -64.699 + 0.0449 \text{ VOS} \quad r^2 = 25.6\%, p = 0.019$$

$$\text{Strength} = 11.709 + 1.931 \text{ VOS T-Score} \quad r^2 = 25.6\%, p = 0.019$$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall

For group 1, the osteoporotic individuals, the Mid-Shaft Tibia SOS and T-score (For T-score definition see section 4.3 of the Review of Scanning Methodologies) both significantly correlated with the results of the contact extensometer, $r = 0.471$ and 0.481 , ($p < 0.05$) respectively. VOS Calcaneus and the corresponding T-score were significantly correlated to the strength, both $r = 0.506$, ($p < 0.05$). The T-score values corresponding to the BUA of the Calcaneus assessment almost achieved statistical significance vs. strength, $r = 0.431$, ($p = 0.051$).

For group 2, the osteoarthritic individuals, the only significant correlation was between Distal Radius SOS and strength, $r = 0.752$, ($p < 0.05$).

Table 3. Pearson's correlation coefficients between clinical ultrasound assessments and compressive testing parameters, from Group 2.

	Distal Radius SOS
Strength	0.752 (p = 0.032)

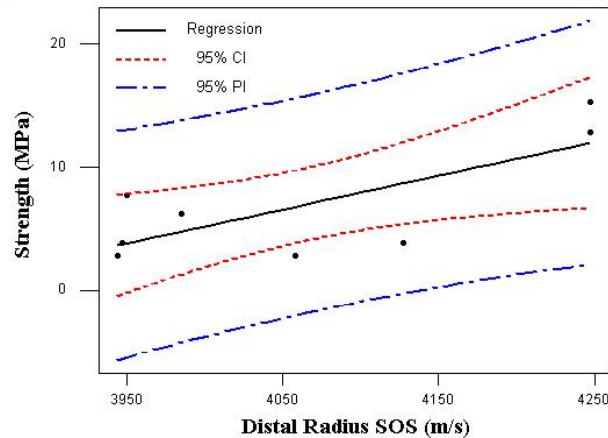


Figure 16. Regression plot of Distal Radius SOS (m/s) vs. compressive strength (MPa).

$$\text{Strength} = -104.686 + 0.0275 \text{ DR-SOS} \quad r^2 = 56.5\%, p = 0.032$$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall

However both study groups are very small, with only 29 samples in total being compared, with 21 in group 1 and 8 in group 2, a larger study cohort would most likely lead to an improvement of the statistics. A BOSCOS device, utilised in a car environment, wouldn't have the information available on the clinical nature of the individuals' conditions; all individuals would be considered normal till after the QUS assessment. To mimic this situation, groups 1 and 2 were combined; this combination resulted in a change in the correlations achieved. The QUS assessments failed to correlate with Young's modulus from either the contact extensometer or the platens extensometer. Strength however showed a number of significant correlations; the Proximal Phalanx SOS and T-score $r = 0.403$ and 0.4 respectively ($p < 0.05$); and VOS of the calcaneus and corresponding T-score both 0.372 ($p < 0.05$). In addition to this, the correlation between strength and SOS from the distal radius almost achieved significance $r = 0.362$ ($p = 0.054$). The moderate correlation between the proximal phalanx SOS and the strength of the test samples indicates that the assessment of the phalanx using the BOSCOS prototype system may have potential to provide information on the biomechanical competence of an individual's axial skeleton.

Table 4. Pearson's correlation coefficients between clinical ultrasound assessments and compressive testing parameters, from Groups 1 and 2.

	Distal Radius SOS	Proximal Phalanx SOS	Proximal Phalanx T-score	VOS Calcaneus	VOS Calcaneus T-score
Strength	0.362 (p = 0.054)	0.403 (p = 0.033)	0.400 (p = 0.035)	0.372 (p = 0.047)	0.372 (p = 0.047)

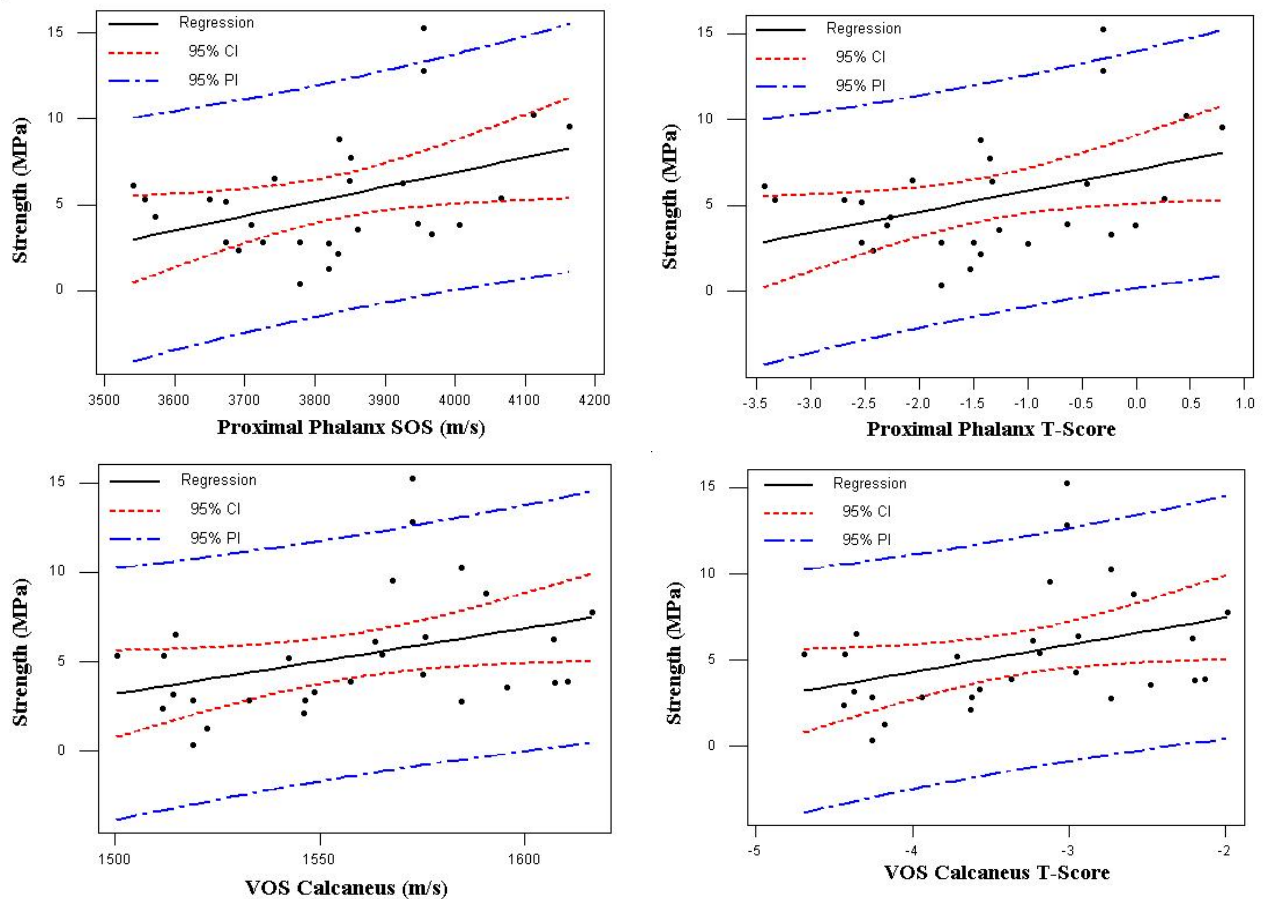


Figure 17. Regression plots for statistically significant correlations between QUS and compression testing results for Osteoporotic and arthritic combined. Regression equations:

$$\text{Strength (MPa)} = -27.121 + 0.0085 \text{ PP-SOS (m/s)} \quad r^2 = 16.2\%, p = 0.033$$

$$\text{Strength (MPa)} = 7.0784 + 1.226 \text{ PP T-Score} \quad r^2 = 16\%, p = 0.035$$

$$\text{Strength (MPa)} = -52.071 + 0.03684 \text{ VOS Calcaneus (m/s)} \quad r^2 = 13.8\%, p = 0.047$$

$$\text{Strength (MPa)} = 10.634 + 1.583 \text{ VOS T-Score} \quad r^2 = 13.7\%, p = 0.047$$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall.

7.2. Fracture Toughness Calculations

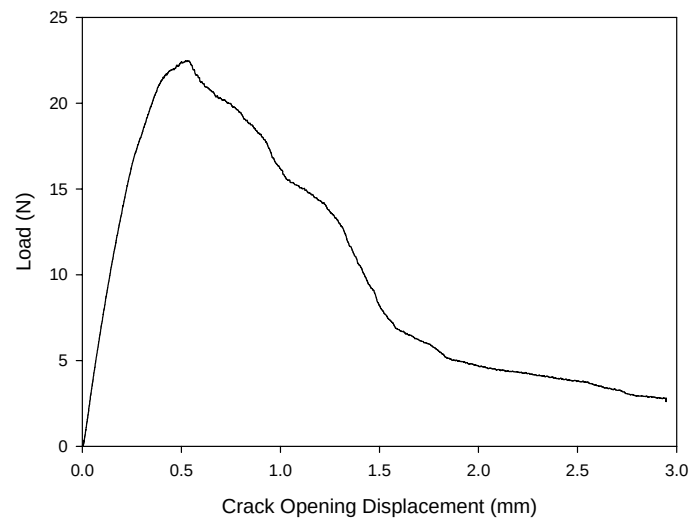


Figure 18. Load vs. crack opening displacement curve

The results from the fracture toughness testing gave results in the form of load vs. crack opening displacement. These traces allowed for the calculation of two parameters, K_Q and K_{IC} , both of which are related to the fracture toughness of the cancellous bone material (more accurately to the resistance to crack growth initiation)

7.2.1. K_Q

K_{IC} is the plane strain fracture toughness value; K_Q is a preceding value of fracture toughness used in the calculation of K_{IC} that under certain conditions equals K_{IC} .

The equations for the calculation of K_Q are laid out in ASTM standard E399-90 and require the determination of a load, P_Q . To determine P_Q , a secant line of 95% of the slope of the initial linear portion of the graph, must be plotted and the intersection P_5 between this secant line and the original curve represents the point from which load P_Q is determined. Figure 19 shows the adjustments, for the potential differences in the traces that may occur.

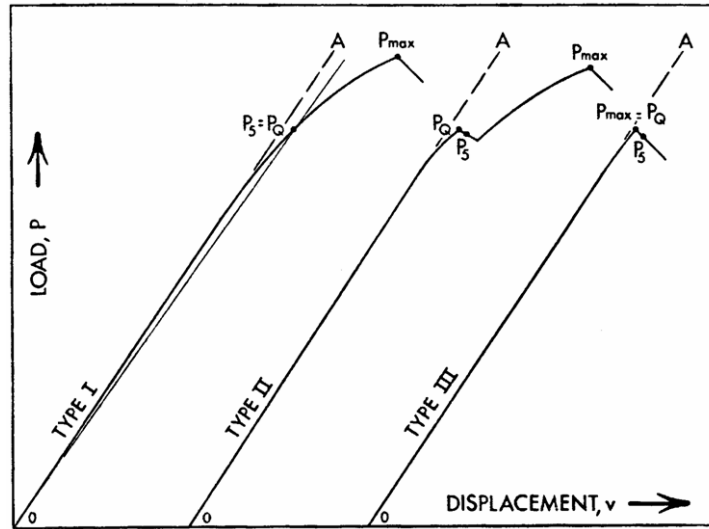


FIG. 8 Principal Types of Load-Displacement Records

Figure 19. Principle types of load-displacement curves for the determination of P_5 and P_Q .

The equations for the calculation of K_Q are dependant on the sample design. The equations are as follows:

Beam Samples:

$$K_Q = (P_Q S / BW^{3/2}) f(a/W)$$

Where P_Q is the load as explained above, S is the span of the test rig as shown previously, B is the specimen thickness, W is the specimen height, and $f(a/W)$ is a function of the initial crack length in relation to the specimens height, given by an additional equation:

$$f(a/W) = \frac{3(a/W)^{1/2} [1.99 - (a/W)(1 - a/W)(2.15 - 3.93a/W + 2.7a^2/W^2)]}{2(1 + 2a/W)(1 - a/W)^{3/2}}$$

Disk Samples:

$$K_Q = (P_Q / BW^{1/2}) f(a/W)$$

The parameters are the same as above, apart from the $f(a/W)$ which is given by a different equation:

$$f(a/W) = \frac{(2 + a/W)(0.76 + 4.8a/W - 11.58(a/W)^2 + 11.43(a/W)^3 - 4.08(a/W)^4)}{(1 - a/W)^{3/2}}$$

7.2.2. K_C

K_C is the fracture toughness value at the crack growth initiation, which here occurred at the point of maximum load attained by the sample (P_{max} value).

The relationship between the K_Q and the K_C values was linear and identical in the two different directions, with the K_C value being approximately double the K_Q value on average. (Figure 20)

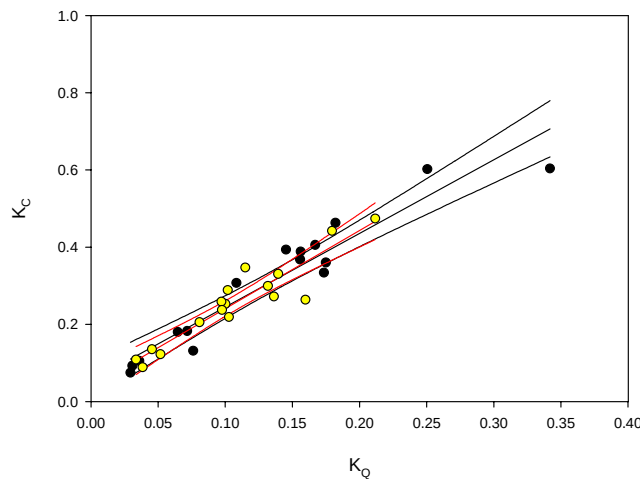


Figure 20. The linear relationship between K_Q and K_C from the osteoporotic disc samples in the AC direction (solid symbols) and the AL direction (open symbols).

Table 5 shows the averages of the densities, porosities and fracture toughness results of the different test sample designs and the different groups. Using ANOVA for comparison of the means, a number of different comparisons could be made.

Table 5. Mean and standard deviation values for density and fracture toughness properties of cancellous bone from osteoporotic and osteoarthritic individuals using two sample designs and two test directions.

	Apparent Density (g/cm³)	Material Density (g.cm³)	Porosity (%)	K_Q (MPa m^{1/2})	K_C (MPa m^{1/2})
Osteoporotic Group 1 + 3					
Disc Samples AC	0.4624 (0.1549)	1.6949 (0.1393)	0.7194 (0.1179)	0.1491 (0.0760)	0.3396 (0.1528)
Disc Samples AL	0.4808 (0.1501)	1.7258 (0.1443)	0.7139 (0.1153)	0.1167 (0.0601)	0.2672 (0.1168)
Beam Samples AC	0.4353 (0.1071)	1.8899 (0.0625)	0.7687 (0.0610)	0.1391 (0.0814)	0.3204 (0.1869)
Beam Samples AL	0.3906 (0.0838)	1.8321 (0.3082)	0.8196 (0.2343)	0.101 (0.0548)	0.2195 (0.1259)
Osteoarthritic Group 2					
Disc Samples AC	0.6242 (0.2669)	1.6702 (0.1061)	0.6183 (0.1846)	0.1935 (0.1268)	0.4937 (0.2854)
Disc Samples AL	0.6182 (0.2797)	1.7071 (0.2121)	0.6216 (0.2156)	0.1548 (0.1271)	0.4123 (0.2719)
Beam Samples AC	0.6065 (0.1764)	1.8537 (0.1017)	0.6689 (0.1123)	0.2327 (0.1226)	0.5442 (0.2841)
Beam Samples AL	0.5809 (0.2101)	1.8291 (0.0869)	0.6783 (0.1287)	0.1658 (0.1244)	0.3699 (0.2874)

7.3. Density and Porosity

Comparison between the apparent densities of the different sample designs within the osteoporotic group showed no statistically significant ($p>0.05$) difference in density between either of the disc samples or the beams samples AC. The beam samples in the AL direction were however statistically significantly less dense than the other osteoporotic samples ($p<0.05$). This difference in density is mimicked by the porosity, with the beam samples AL having a statistically significantly higher degree of porosity in comparison to the disc samples ($p>0.05$), but in this incidence the beam samples AC were not significantly different to any other group.

Comparison between the osteoporotic samples and the osteoarthritic showed that on average the osteoarthritic samples had a higher apparent density than the osteoporotic, however not all comparisons were significant. The beam samples from the osteoporotic group were significantly less dense than any of the osteoarthritic samples ($p<0.05$). However there was no significant difference between the osteoporotic disc samples, and the osteoarthritic samples ($p>0.05$) with the exception of the osteoarthritic beams AC which were shown to be significantly denser than any of the osteoporotic samples ($p<0.001$). This trend is reversed when porosity of the samples is compared; no significant difference was seen between the osteoporotic beams and discs samples, or between the osteoarthritic disc and beam samples. When the osteoporotic samples were compared to the osteoarthritic samples, there was no significant difference between the osteoporotic disk samples and any of the osteoarthritic samples, but the osteoporotic beams are significantly more porous than either the osteoarthritic discs or beams ($p<0.05$).

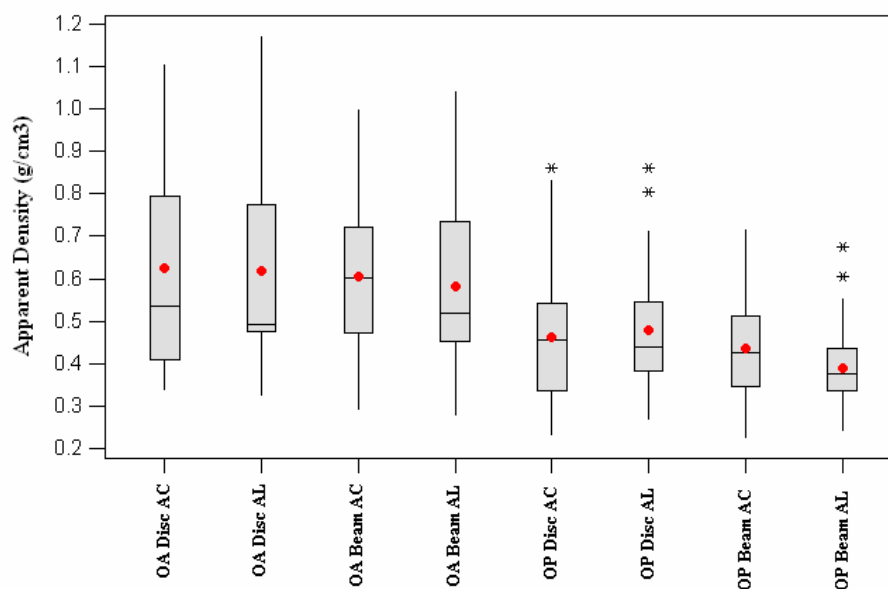


Figure 21. Box-plot for comparison of the average apparent densities (g/cm^3), with respect to the different groups and sample designs.

The box represents where 50% of the data falls, with the lines representing the further upper and lower 25%. The * symbol indicates an outlying value; the line within the box shows the median value for the data and the red dot is the mean of the values.

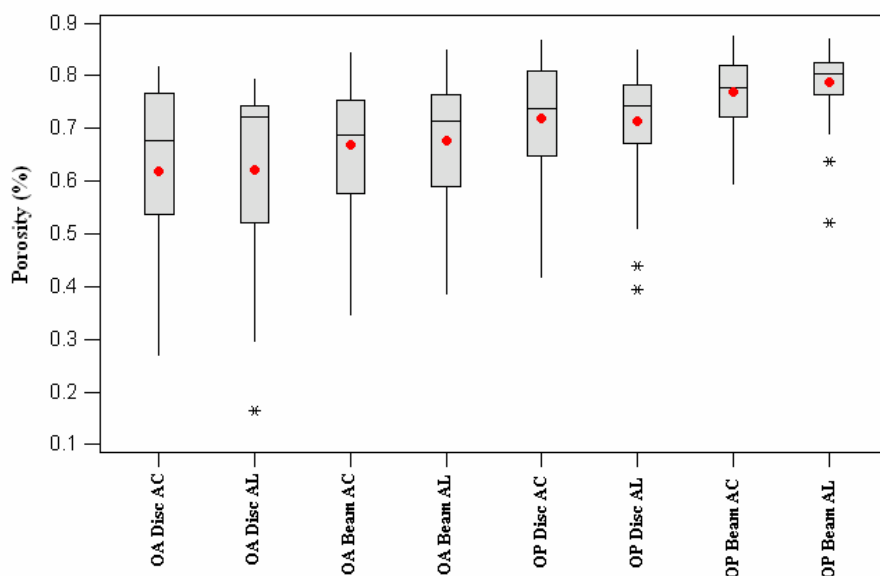


Figure 22. Box-plot for comparison of the average porosity (%), with respect to the different groups and sample designs.

The box represents where 50% of the data falls, with the lines representing the further upper and lower 25%. The * symbol indicates an outlying value; the line within the box shows the median value for the data and the red dot is the mean of the values.

The material density of the samples within the osteoporotic group showed statistically significant differences, with disc samples AC having a significantly lower material density in comparison to the beam samples AC and AL; the beam samples AC having a significantly higher material density than the disc samples AC and AL. But no statistically significant difference between the beam samples AL and the disc samples AL.

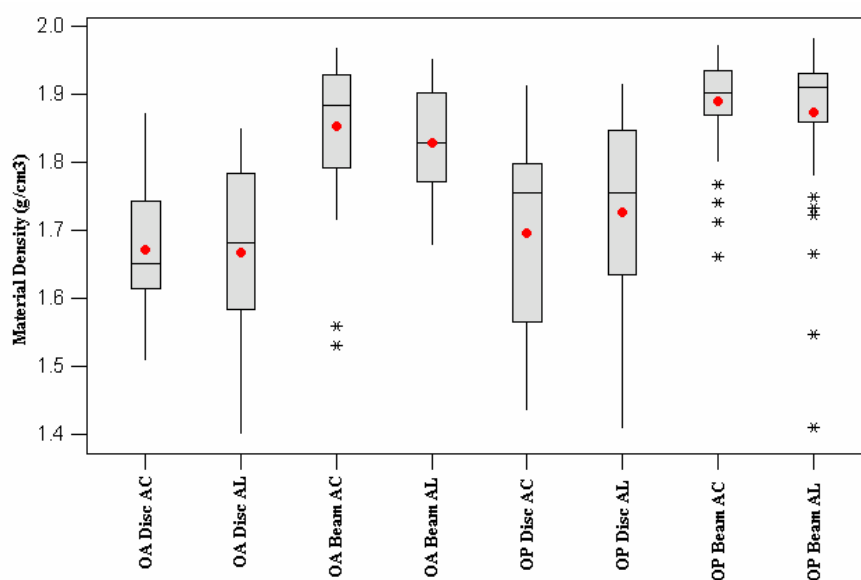


Figure 23. Box-plot for comparison of the average material density (g/cm³), with respect to the different groups and sample designs.

The box represents where 50% of the data falls, with the lines representing the further upper and lower 25%. The * symbol indicates an outlying value; the line within the box shows the median value for the data and the red dot is the mean of the values

The material density did not vary significantly between the beam samples of either the osteoporotic or osteoarthritic group ($p > 0.05$), and no significant difference was seen between the discs of either group. There was however significant differences between the discs and the beam samples, with the beams showing a significantly higher material density on average than the disc samples ($p < 0.05$), however the beams AL from the osteoarthritic group were not significantly different from the disc samples AL from the same group.

7.4. Fracture Toughness

The important comparisons for the fracture toughness data is between the different directions, the different sample designs and the different groups.

Direction

The results showed that on average the fracture toughness, both KQ and KC were greater in the AC direction than in the AL direction. However the difference was only statistically significant for the osteoporotic beams for the KQ and KC values. The other comparisons were close to statistical significance with most comparisons having p values of less than 0.09, except the osteoarthritic disc specimens which showed no statistical difference ($p > 0.5$).

Sample Design

Comparison of the results determined in the same orientation, but using different sample designs, failed to show any statistically significant differences, indicating that both sample designs were producing values of the same magnitude.

Different Groups

Comparison between the different groups, osteoporotic or osteoarthritic, keeping the sample design, and test direction, showed a number of significant differences. The average K_Q values between the discs in the AC and AL directions showed no statistically significant difference. All other comparisons showed that the osteoarthritic bone displayed a statistically significantly higher toughness in comparison to the osteoporotic bone.

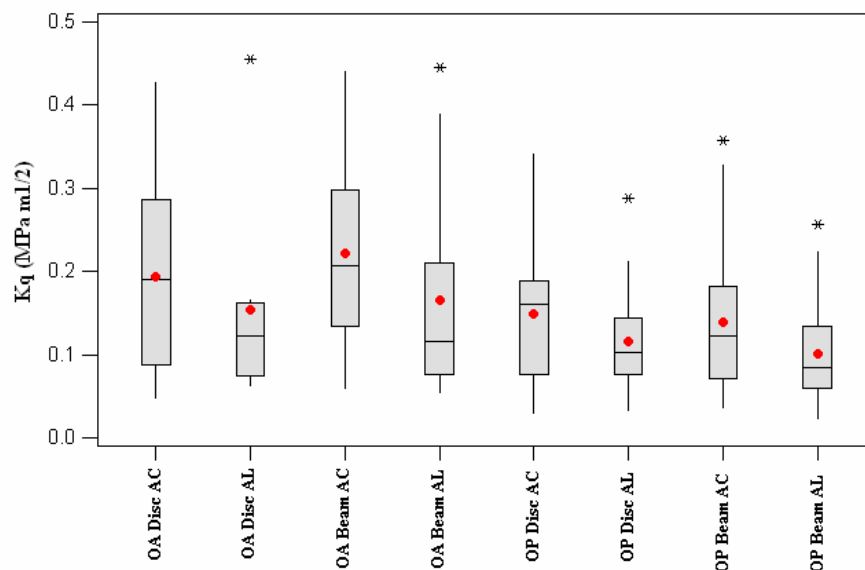


Figure 24. Box-plot for comparison of the average K_Q value ($\text{MPa m}^{1/2}$), with respect to the different groups and sample designs.

The box represents where 50% of the data falls, with the lines representing the further upper and lower 25%. The * symbol indicates an outlying value; the line within the box shows the median value for the data and the red dot is the mean of the values

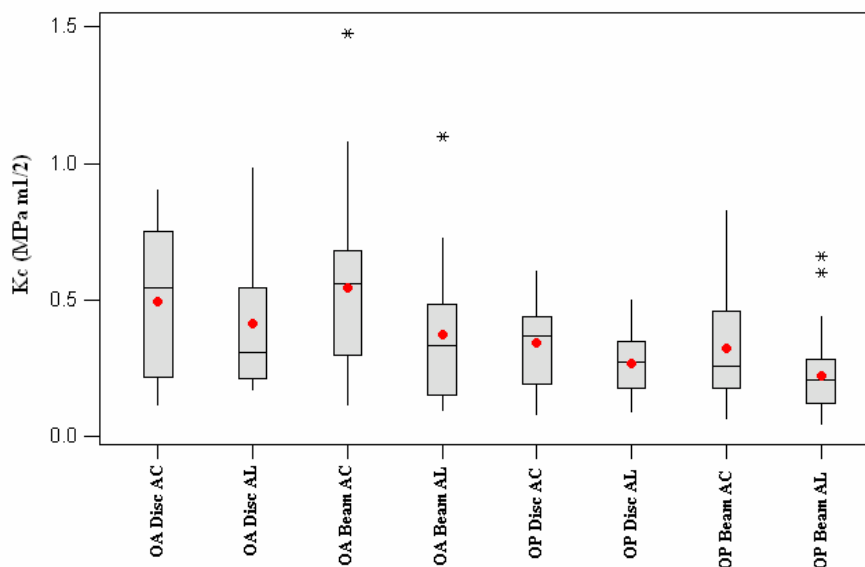


Figure 25. Box-plot for comparison of the average K_C value ($\text{MPa m}^{1/2}$), with respect to the different groups and sample designs.

The box represents where 50% of the data falls, with the lines representing the further upper and lower 25%. The * symbol indicates an outlying value; the line within the box shows the median value for the data and the red dot is the mean of the values.

7.4.1. Fracture Toughness vs. Age vs. Clinical QUS Assessment

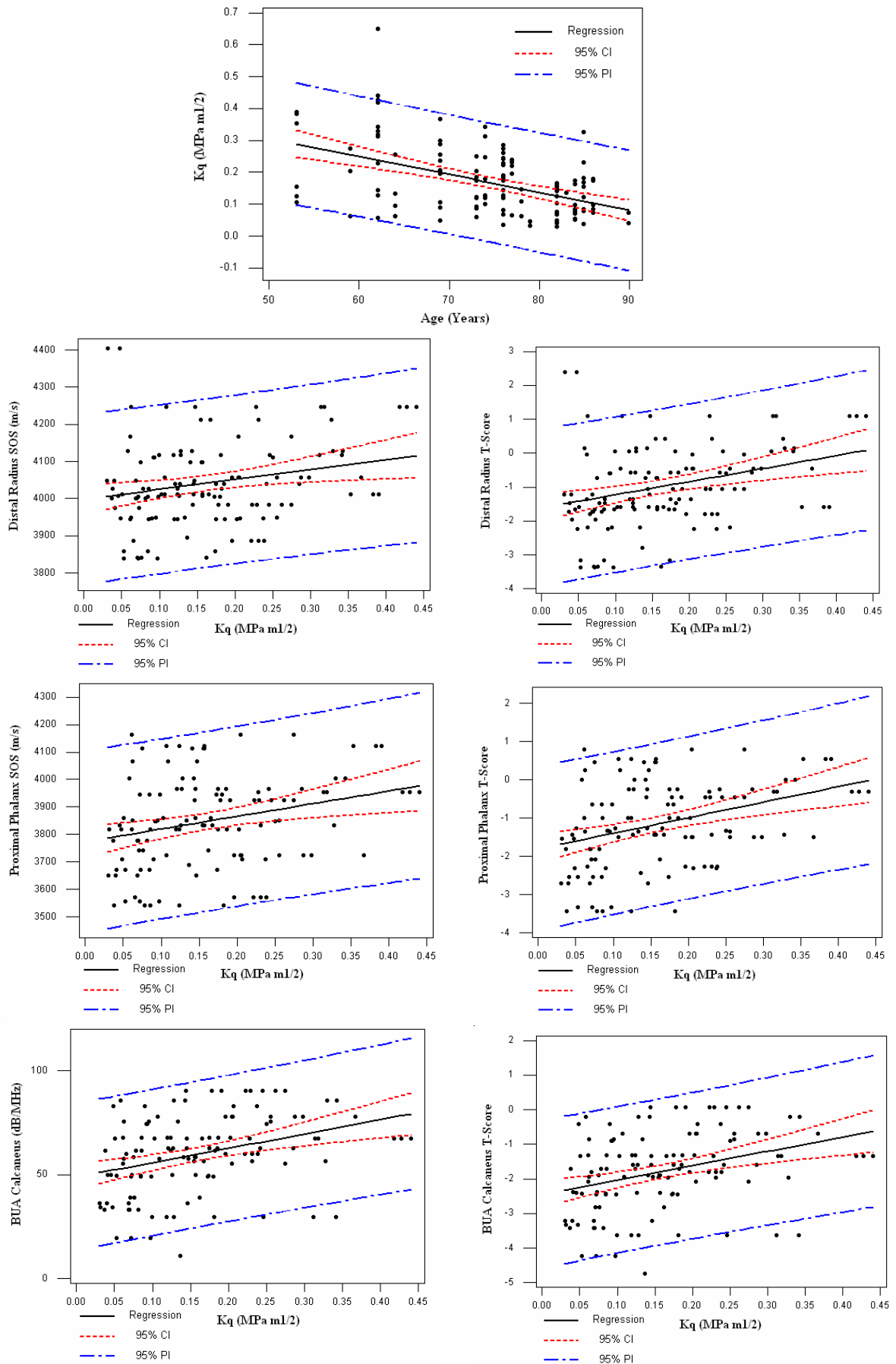
In order to assess the ability of QUS to predict the fracture toughness of cancellous bone, every fracture toughness result was compared against the QUS assessment result of the donor, from which the bone was sourced. Group 3 was excluded from the analysis as no QUS results were available.

The results from groups 1 and 2 were combined, so that all specimens, both discs and beams, tested in the AC direction were together, and all those tested in the AL direction were together.

Table 6. Showing the Pearson's correlation between fracture toughness values in the AC direction and in-vivo QUS values.

	Age	Distal Radius SOS	Distal Radius T-score	Proximal Phalanx SOS	Proximal Phalanx T-score	BUA Calcaneus	BUA Calcaneus T-score	VOS Calcaneus	VOS Calcaneus T-score
K _Q	-0.479*	0.266*	0.343*	0.265*	0.346*	0.328*	0.327*	0.192 ^Y	0.192 ^Y
K _C	-0.493*	0.257*	0.353*	0.240*	0.335*	0.377*	0.376*	0.212 ^Y	0.212 ^Y

P values: ^Y = p<0.05, * = p<0.01



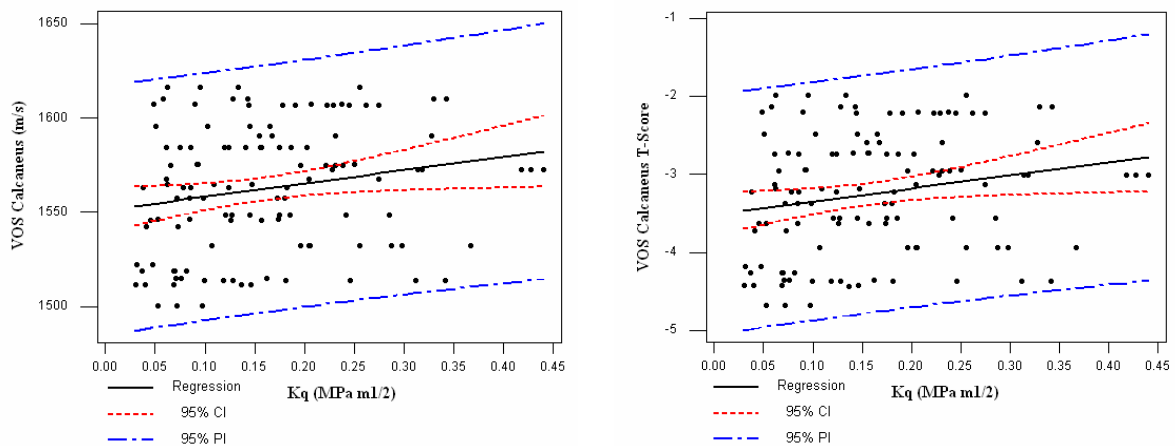
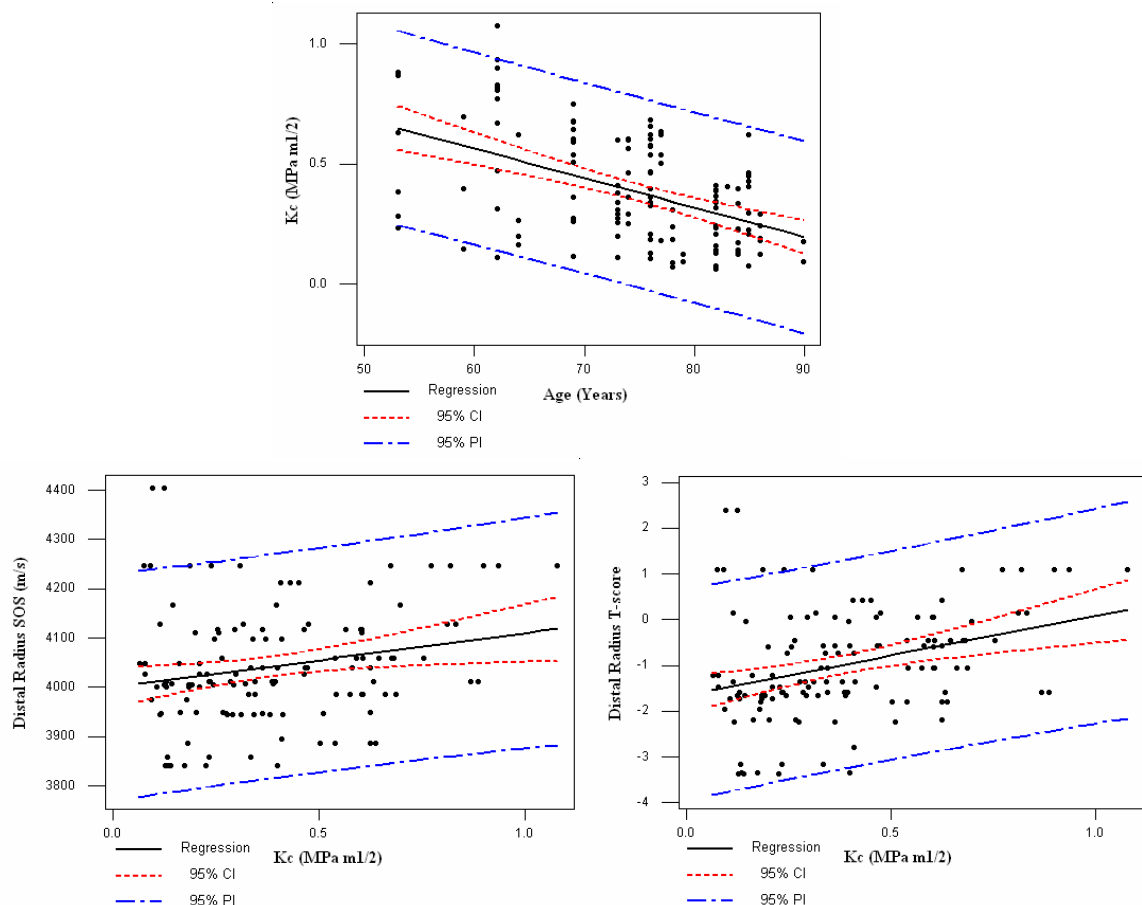


Figure 26. Regression plots of K_Q vs. age and QUS for samples fractured in the AC direction

$K_Q = 0.588510 - 0.0056408 \text{ Age}$	$r^2 = 22.9\%$	$p < 0.001$
$\text{DR SOS} = 3994.58 + 293.071 K_Q$	$r^2 = 7.1\%$	$p = 0.003$
$\text{DR T-Score} = -1.6098 + 3.846 K_Q$	$r^2 = 9.7\%$	$p < 0.001$
$\text{PP SOS} = 3773.87 + 461.255 K_Q$	$r^2 = 7.1\%$	$p = 0.004$
$\text{PP T-Score} = -1.801 + 4.0694 K_Q$	$r^2 = 12.3\%$	$p < 0.001$
$\text{BUA} = 48.9689 + 68.8125 K_Q$	$r^2 = 11.9\%$	$p < 0.001$
$\text{BUA T-Score} = -2.445 + 4.1345 K_Q$	$r^2 = 11.9\%$	$p < 0.001$
$\text{VOS} = 1551.13 + 70.8856 K_Q$	$r^2 = 4\%$	$p = 0.029$
$\text{VOS T-Score} = -3.513 + 1.650 K_Q$	$r^2 = 4\%$	$p = 0.029$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall.



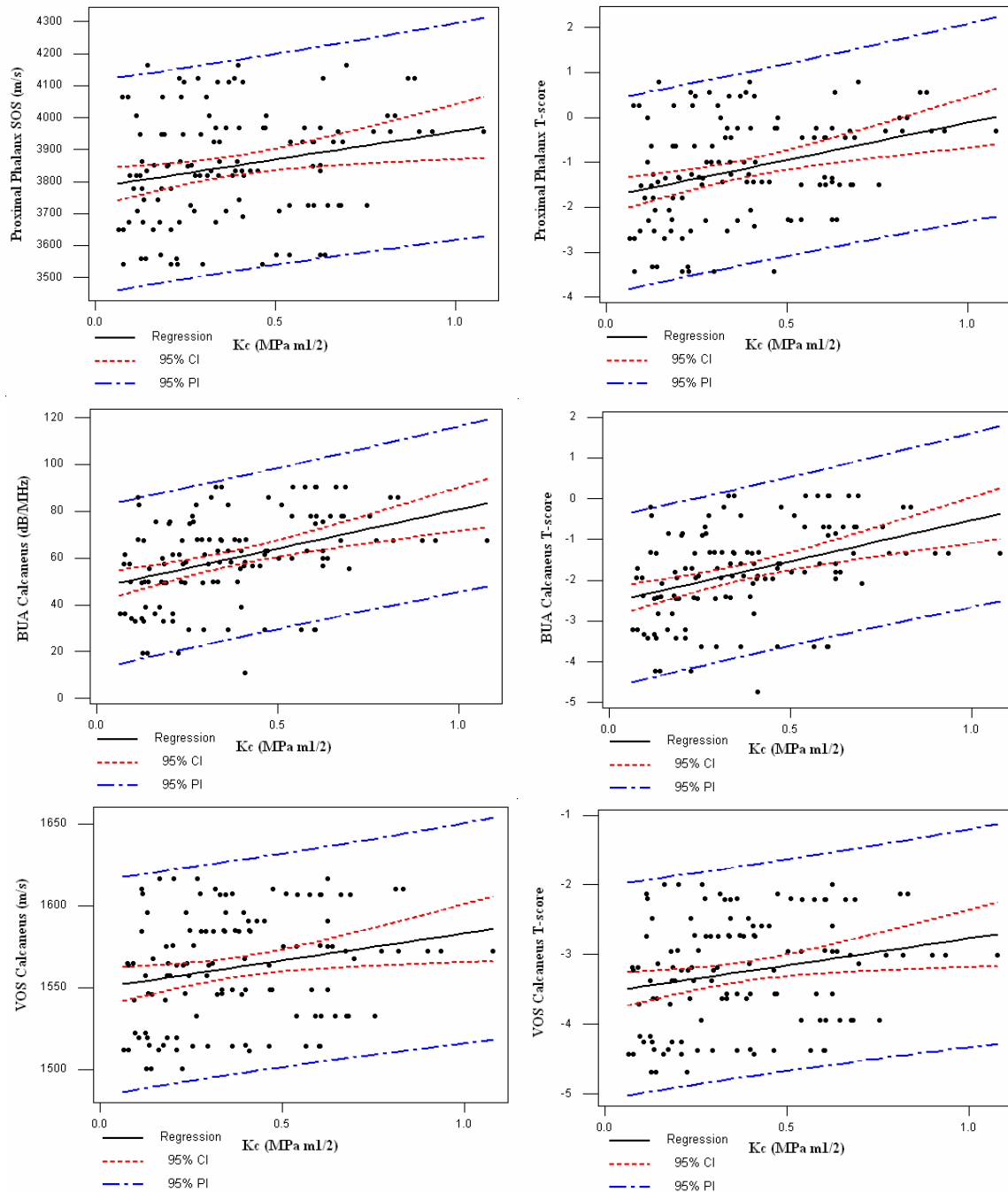


Figure 27. Regression plots of K_C vs. age and QUS for samples fractured in the AC direction

$$K_C = 1.30244 - 0.0122870 \text{ Age}$$

$$\text{DR SOS} = 3999.70 + 110.315 K_C$$

$$\text{DR T-Score} = -1.638 + 1.712 K_C$$

$$\text{PP SOS} = 3782.30 + 173.555 K_C$$

$$\text{PP T-Score} = -1.772 + 1.652 K_C$$

$$\text{BUA} = 47.3343 + 33.4827 K_C$$

$$\text{BUA T-Score} = -2.544 + 2.014 K_C$$

$$\text{VOS} = 1549.95 + 33.1584 K_C$$

$$\text{VOS T-Score} = -3.540 + 0.772 K_C$$

$$r^2 = 23.7\%, \quad p < 0.001$$

$$r^2 = 3.9\%, \quad p = 0.016$$

$$r^2 = 10.4\%, \quad p < 0.001$$

$$r^2 = 5.6\%, \quad p = 0.01$$

$$r^2 = 11.4\%, \quad p < 0.001$$

$$r^2 = 15.8\%, \quad p < 0.001$$

$$r^2 = 15.8\%, \quad p < 0.001$$

$$r^2 = 4.9\%, \quad p = 0.016$$

$$r^2 = 4.9\%, \quad p = 0.016$$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall.

	Age	Distal Radius SOS	Distal Radius T-score
K _Q	-0.370*	0.359*	0.319*
K _C	-0.409*	0.358*	0.323*

P values: * = p<0.01

Table 7. Showing the Pearson's correlation between fracture toughness values in the AL direction and in-vivo QUS values.

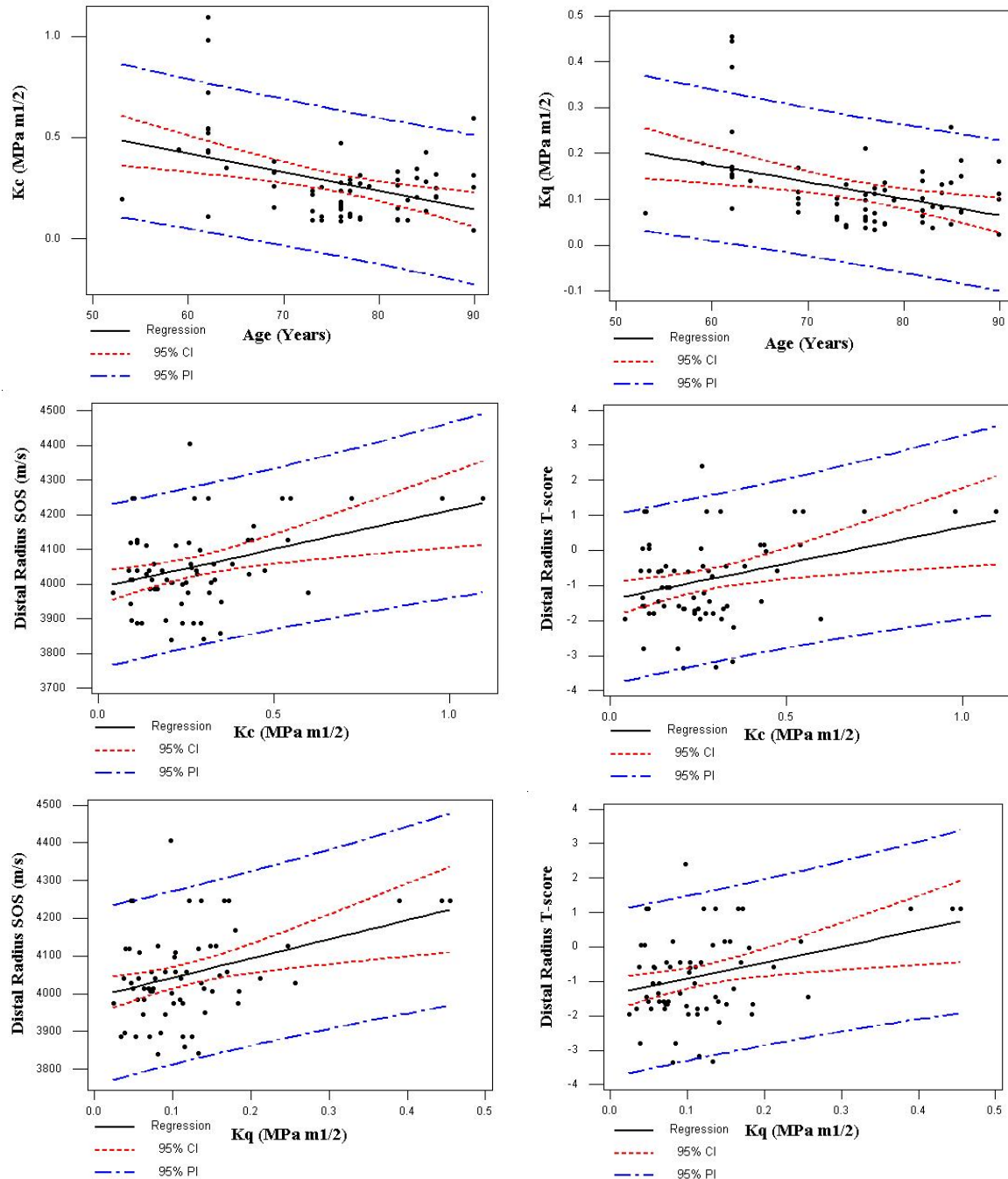


Figure 28. Regression plots of K_Q and K_C vs. age and QUS for samples fractured in the AL direction.

$$\begin{aligned}
 K_q &= 0.393529 - 0.0036480 \text{ Age} & r^2 &= 13.7\%, & p &= 0.002 \\
 K_c &= 0.972123 - 0.0092042 \text{ Age} & r^2 &= 16.7\%, & p &= 0.001 \\
 \text{DR SOS} &= 3991.33 + 509.315 K_q & r^2 &= 12.9\%, & p &= 0.003
 \end{aligned}$$

$$\begin{aligned} \text{DR T-Score} &= -1.379 + 4.642 K_Q \quad r^2 = 10.2\%, \quad p = 0.008 \\ \text{DR SOS} &= 3989.94 + 222.161 K_C \quad r^2 = 12.8\%, \quad p = 0.003 \\ \text{DR T-Score} &= -1.400 + 2.056 K_C \quad r^2 = 10.4\%, \quad p = 0.008 \end{aligned}$$

95% CI represents the 95% confidence intervals, which provide information of the possible range of values possible for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall.

The results show weak but statistically significant correlation between the non-invasive ultrasound based assessment and the toughness of cancellous bone as determined in-vitro.

8. Summary of Results

In conclusion, the best predictive relationships of:

- Compressive strength vs. Proximal Phalanx SOS had an r^2 of 16.2% ($p = 0.03$).
- Proximal Phalanx SOS values ranged between 3540.3 - 4163.7 m/s, using the regression data this equated to a percentage drop of 15%. Over the same range the compressive strength varied from 0.359 - 15.292 MPa, from the regression this equates to a 64.3% reduction.
- Using all samples together, no significant correlations with elastic modulus
- Fracture toughness showed a number of significant correlations and correlated weakly with the Proximal Phalanx SOS with an r^2 of 7.1% with K_Q and 5.6% with K_C .
- The range for the proximal phalanx varied from 3839.7 - 4405.7 m/s with a 12.8% drop. The corresponding fracture toughness results ranged for K_Q , from 0.0237 - 0.4546 MPa $m^{1/2}$, and K_C 0.0394 - 1.0971 MPa $m^{1/2}$. This equates to a drop of 56.3% for K_Q and 68% for K_C .

The results show the measurement of speed of sound at the phalanx is significantly, but weakly, correlated with both strength and fracture toughness of bone from the axial skeleton. This correlation is important in relation to the BOSCOS project, as it suggests that measurement of the phalanx using the BOSCOS system has potential to provide information on axial skeletal biomechanical properties.

9. References.

- S.J. Brown, P. Pollintine, D.E. Powell, et al. (2002) Regional Differences in Mechanical and Material Properties of Femoral Head Cancellous Bone in Health and Osteoarthritis. **Calcified Tissue International**; Vol. 71, p. 227-2342
- D.L. Kopperdahl and T.M. Keaveny. (1998) Yield Strain Behaviour of Trabecular Bone. **Journal of Biomechanics**; Vol. 31, p. 601-608
- M.-C. Ho Ba Tho, J.Y. Rho and R.B. Ashman. (1997) Anatomical Variation of Human Cancellous Bone Mechanical Properties In-vitro. **Studies in Health Technology and Informatics**; Vol. 40, p. 157-1734
- E.B.W. Giesen, M. Ding, M. Dalstra, et al. (2001) Mechanical Properties of Cancellous Bone in the Human Mandibular Condyle are Anisotropic. **Journal of Biomechanics**; Vol. 34, p.799-803

Appendix 16

Abstracts and Papers

Conference Presentations

Appendix 16.1

R. Cook, D. Collins, C. Curwen and P. Zioupos (2003) Comparison of Inter-Site Bone Densitometry Measurements, and the Short-Term Precision of Two Bone Quantitative Ultrasound Scanners. IPEM Annual Scientific Meeting, 15-17 September 2003, University of Bath, Bath, UK

Appendix 16.2

R. Cook, D. Collins, J. Tucker and P. Zioupos (2004) The Predictive Ability of Two Quantitative Ultrasound Bone Scanners in Comparison to DXA. ESB 2004, 4-7 July 2004, Hertogenbosch, the Netherlands

(This paper was one of three selected to compete for the Clinical Biomechanics Award, and was presented at a special plenary session at the meeting.)

Appendix 16.3

R. Cook, P. Zioupos, C. Curwen and T. Tasker (2005) Fracture Toughness of Femoral Head Cancellous Bone Material in Relation to Non-invasive Bone Assessment Measurements. Biomech (2005) Applied Biomechanics, 1 - 3rd July 2005, Regensburg, Germany

Poster Presentations

Appendix 16.4

R.B. Cook, D. Collins and P. Zioupos (2005) Comparison of Patient Screening Techniques for Dual-Energy X-ray Absorptiometry (DXA). National Osteoporosis Society, 10th Conference on Osteoporosis, 28th of November – 1st of December, Harrogate International Conference Center, Harrogate, UK

Automotive Conference Papers

Appendix 16.5

J.W. Watson, R.N. Hardy, R. Frampton, O. Williams, P. Zioupos, R. Cook, A. Kennedy, P. Sproston, B. Forrester and S. Peach (2004) BOSCOS Bone Scanning for Occupant Safety. Vehicle Safety Conference, Institute of Mechanical Engineers, December 2004.

Appendix 16.6

R.N. Hardy, J.W. Watson, R. Cook, P. Zioupos, B. Forrester, R. Frampton, M. Page, A. Kennedy, S. Peach and P. Sproston (2005). Development and Assessment of a Bone Scanning Device to Enhance Restraint Performance. Enhanced Safety of Vehicles (ESV) Conference, Washington June 2005

Appendix 16.7

R.N. Hardy, J.W. Watson, R. Frampton, M. Page, P. Zioupos, R. Cook, A. Kennedy, P. Sproston, B. Forrester and S. Peach (2005). BOSCOS - Development and Benefits of a Bone Scanning System. IRCOBI Conference, Prague September 2005

Peer Reviewed Journal Articles

Appendix 16.8

R.B. Cook, D. Collins, J. Tucker and P. Zioupos (2005) The Ability of Peripheral Quantitative Ultrasound to Identify Patients With Low Bone Mineral Density in the Hip or Spine. *Ultrasound in Medicine and Biology*; **Vol. 31**, No. 5, p.625-632

Appendix 16.9

R.B. Cook, D. Collins, J. Tucker and P. Zioupos (2005) Comparison of Questionnaire and Quantitative Ultrasound Techniques as Screening Tools For DXA. *Osteoporosis International*; **Article in Press**

Comparison of inter-site bone densitometry measurements, and the short-term precision of two bone quantitative ultrasound scanners.

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Background and Purpose.

The use of quantitative ultrasound [QUS] has become a widely accepted method of assessing human bone in-vivo. However it is mainly seen as a screening tool, which can assist in the management of osteoporosis. The rate of bone loss varies depending on both sex and the age of the patient, normal changes in bone occur at a rate of about 0.5-2% per year for most adults; however this can increase to 2-5% in early postmenopausal women.^[1] The purpose of the study was firstly, to calculate the short term-precision of two scanners, within a healthy group and a group considered to have a risk factor for osteoporosis. The risk factor group contained both healthy and osteoporotic individuals. The second purpose was to investigate the relationship between different measurement sites around the body. The two QUS devices used in this study are the Sunlight Omnisense [Sunlight Ultrasound Technologies Ltd., Rehovot, Israel.] and the CUBA Clinical [McCue Plc., Winchester, UK].

Materials and Methods.

The short-term precision was calculated using the guidelines laid out by C.-C.Gluer et al. [1995]^[2]. The healthy group consisted of 16 individuals, [10 males aged 25–58, and 6 females aged 25-58], four repeated scans were performed on each individual. The risk group consisted of 60 females aged between 33 and 80, with two measurements performed on each individual.

The inter-site correlation was calculated by comparison of the results of the risk group, at the different measurement sites, around the body.

Results.

Table 1. Short-Term Precision.

Short-Term Precision	Sunlight Omnisense		
	Distal Radius	Proximal Phalanx	Mid-Shaft Tibia
Risk Group	0.64%	0.98%	0.65%
Healthy Group	0.29%	0.55%	N/A

Short-Term Precision	CUBA Clinical	
	BUA	VOS
Risk Group	3.24%	0.12%
Healthy Group	2.88%	0.31%

Table one shows that the precision differed depending on the group. The healthy group showed better precision compared to those of the Sunlight Omnisense manufacturers guidelines and the previously published precision.^[3,4] The risk group

however showed lower precision than both the manufacturers guidelines and the previously published data.

In both groups the CUBA Clinical showed an inferior precision than supplied by the manufacturers, however the results were comparable to those reported in previous studies.^[5,6]

Table 2 Inter-site Correlations.

	Distal Radius	Proximal Phalanx	Mid-Shaft Tibia
Proximal Phalanx	0.567**		
Mid-Shaft Tibia	0.484**	0.261*	
BUA Calcaneus	0.441**	0.525**	0.338*
VOS Calcaneus	0.410**	0.532**	0.360*

*p<0.05, **p≤0.001

The results in table two showed a weak but statistically valid relationship between the different sites around the body, with the best being between the distal radius and proximal phalanx [r=0.567, p<0.001], and the worst being between the proximal phalanx and the mid-shaft tibia [r=0.261, p=0.046]

Conclusions.

The conclusions of this study are that greater care must be taken when measuring patients suspected of osteoporosis, to ensure the precision of the results. The correlation of bone sites shows that ultrasound is suitable for assessment of bone status within the population, but should be used as a screening tool and not as a definitive answer of a patients bone status.

Acknowledgements.

Funding was provided by the department of transport, through the BOSCOS project.

¹ S.Harris et al. Bone and Mineral. 1992; Vol.17: p.87-95.

² C.-C.Gluer et al. Osteoporosis International. 1995; Vol.5: p.262-270.

³ M.Weiss et al. Osteoporosis International. 2000; Vol.11: p.688-696.

⁴ W.M.Drake et al. Journal of Clinical Densitometry. 2001, Fall; Vol.4, No.3: p.239-248.

⁵ W.C.Graafmans et al. Bone. 1996, August; Vol.19, No.2: p.97-100

⁶ S.L.Greenspan et al. Journal of Bone and Mineral Research. 1997; Vol.12, No.8: p.1303-1313.

THE PREDICTIVE ABILITY OF TWO QUANTITATIVE ULTRASOUND BONE SCANNERS IN COMPARISON TO DXA.

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INTRODUCTION

Ultrasound measurement of bone has become a recognized method of screening patients at risk of osteoporosis. The Sunlight Omnisence (Sunlight Medical, Rehovot, Israel) and the CUBA Clinical (McCue plc. Winchester, UK) are two such ultrasound screening tools.

The ultrasound scanners, both use the T-Score method of classification of Osteoporosis as laid out by the World Health Organization, (Kanis et al. 1994), which allows for direct comparison of bone status at different measurement sites. Dual-energy x-ray Absorptiometry (DXA) is viewed as the gold standard for bone densitometry measurement, and supplies value of bone mineral density (BMD).

The aim of this study was to assess the ability of the two ultrasound scanners to differentiate patients with confirmed osteoporosis and osteopenia at the spine and hip.

MATERIALS AND METHODS

265 women [aged 28-87, mean age 57.5] were recruited from DXA scanning sessions, at GWH, Swindon. The patients received a DXA scan, followed by paired measurements on the two-ultrasound machines. 19 patients were excluded from the analysis of results due to incomplete sets of scans.

The hip and spine BMD investigations were examined. Two T-Score levels were used to identify patients with low BMD: T-scores of either -1 or -1.5. Two cut off levels were used to assess the potential of the ultrasound machines to detect low BMD, an ultrasound T-Score of -1 and -0.5.

RESULTS

The hip and spine BMD T-score of -1, classified 97, and 144 of the 246 patients as having low bone density at the hip, and spine respectively. The hip and spine BMD T-score of -1.5, classified 60, and 115 of the 246 patients as having low bone density at the hip, and spine respectively.

(i) Using the -0.5 ultrasound T-score cut off, and the -1 BMD T-score to denote low bone density: Combining all three Sunlight measurements, 17 women with low total hip BMD, and 24 women with

low spine BMD, would still be classified as normal. The CUBA Clinical BUA, using the same cut off points incorrectly identified 8 women with low spine BMD, but identified correctly all women with low hip BMD. (ii) Using the -0.5 ultrasound T-score cut off, and the -1.5 BMD T-score to denote low bone density: Combining all three Sunlight measurements, 8 women with low total hip BMD, and 24 women with low spine BMD, would be classified as normal. The CUBA Clinical BUA, using the same cut off points incorrectly identified 3 women with low spine BMD, but identified all women with low hip BMD correctly.

The results show that the specificity of the Sunlight Omnisence to pick up patients with osteoporosis and osteopenia is relatively poor.

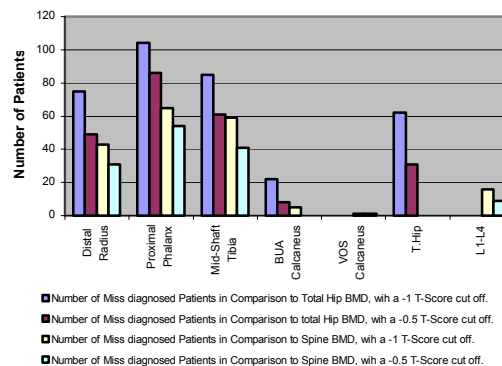


Figure 1: Graph to show the number of patients incorrectly diagnosed as normal.

CONCLUSIONS

Care should be taken when using ultrasound as an alternative to DXA diagnostic tool to ensure that patients with low hip and spine BMD are not incorrectly diagnosed in the screening process.

ACKNOWLEDGEMENTS

Support has been provided by the UK Dept. for Transport under the BOSCOS project.

REFERENCES.

Kanis et al. J. Bone Miner Res, 9:1137-1141, 1994.

Fracture toughness of femoral head cancellous bone material in relation to noninvasive bone assessment measurements

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Abstract

There have been a number of studies relating the biomechanical properties of human bone cancellous and cortical (mainly stiffness and strength) to quantitative non-invasive ultrasound (QUS). The best correlations are obtained when mechanical tests are compared vs. contact QUS in-vitro. Few studies attempted to relate noninvasive QUS on cadavers against excised material of the same donors. This study aims to assess the fracture toughness, in addition to stiffness and strength, of cancellous femoral head bone of donors that have gone QUS investigations in-vivo. Both the in-vivo aspect and the toughness measurements of bone are elements that have never been examined before.

Heads of femurs were collected from osteoporotic and osteoarthritic patients. QUS was performed by 2 different peripheral scanners on 4 different sites. Disc and bar-shaped samples were prepared from the femoral heads to material standards for fracture toughness measurements. The densities of samples have been measured to allow minimization of scatter due to varying density. The bar specimens were broken in 3-point bending and the disc shaped one in tension, in both the crack mouth opening displacement was measured. The aim of the study was to investigate whether reliable toughness measurements can be made on cancellous bone (a material capable of large elastoplastic deformations), their dependence on trabecular type and architecture, sample density and the relationship to QUS in-vivo. Such data is currently lacking in the literature.

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Comparison Of Patient Screening Techniques For Dual-Energy X-ray Absorptiometry (DXA)

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Attempts have been made to provide screening tools suitable for the selection of patients with low bone density, that require further diagnosis with DXA, and the exclusion of patients with normal bone density.

In this study we examined eight screening systems, the osteoporosis self-assessment tool (OST), the osteoporosis risk assessment instrument (ORAI), the osteoporosis index of risk (OSIRIS), a risk index derived using data from the study of osteoporotic fractures (SOF SURF), the simple calculated osteoporosis risk estimation (SCORE), body weight, along with two ultrasound based systems, the Sunlight Omnisense (Sunlight Medical, Rehovot, Israel) and the CUBA Clinical (McCue plc. Winchester, UK). The aim of the study is to assess the sensitivity and specificity of the different techniques, and their ability to act as screening tools in relation to DXA, in a group of 208 postmenopausal women.

The sensitivity and specificity of the different techniques in relation to DXA were plotted as receiver-operating characteristic (ROC) curves. The areas under the curves (AUC) were calculated and the values allowed for quantitative comparison of the techniques. The AUC values showed broadband ultrasound attenuation (BUA) at the calcaneus to consistently provides the highest AUC (0.77-0.81). The velocity of sound (VOS) of the calcaneus (AUC = 0.72-0.76) was equally good, but was out performed by some of the questionnaire systems (AUC = 0.66 – 0.79). Both the questionnaire systems and the CUBA Clinical out perform the Sunlight Omnisense (AUC = 0.58-0.7), which showed comparable performance with body weight. (AUC = 0.66-0.69)

The levels laid out by J.A.Swets (1988) for diagnostic accuracy of AUC values showed that the Sunlight Omnisense and body weight are of little diagnostic accuracy as a screening tools; the questionnaire systems and measurement of the calcaneus are of moderate diagnostic accuracy, with BUA of the calcaneus providing the best method for the screening of populations for DXA.

REF: Swets, J.A. Measuring the Accuracy of Diagnostic Systems. Science 1988 **240**: p. 1285-1293.

BOSCOS Bone Scanning for Occupant Safety

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SYNOPSIS

The objective of the BOSCOS project was to initiate development of a system that can make an assessment of the bone characteristics of each vehicle occupant in order to estimate their skeletal strengths. By modifying the seatbelt and airbag performance characteristics to account for instance a weak chested occupant, the restraint system can deliver optimum levels of protection specifically for each occupant. Recent analysis has shown that older people are at a greater risk of higher injury levels and are not fully considered in restraint systems. A system introduced into every UK vehicle has the capability of saving lives and reducing injury levels across the whole spectre of vehicle occupants.

1.0 BOSCOS OBJECTIVES

1.1 Background

Over the last decade the quest to improve the levels of vehicle safety has intensified dramatically and is now used as a sales feature by marketing departments. But as the criteria for vehicle crashworthiness have changed from vehicle deformations and decelerations to occupant related parameters (body accelerations, forces, deflections, etc.) a recognition of the implications of human diversity has been slow. This is illustrated by the fact that whilst there are child and adult anthropometric devices (dummies) available for use in vehicle testing, in the case of vehicle type approval (certification) test requirements are defined solely for a 50th percentile adult male driver representation. Consequently it is easy to perceive that the safety systems in motor vehicles are developed, tested and approved for optimum use by a narrow band of the driver population whose physical characteristics are not representative of the whole of the driver population.

With the mass of sensors that are now beginning to appear in motor vehicles, the ability to determine information about the driver, e.g. an indication of their mass, the position of the seat and the position of the driver on the seat, is much greater. However, even those parameters that can now be quantified give only limited information that can be used to extend the narrow optimum occupant protection band to a greater proportion of drivers. To successfully extend this band we need to have more information about the individual occupants of each car if they are also to be better protected. The type of information that is needed concerns the physical injury tolerance limits of each individual so that the restraint system or systems can be ‘tuned’ by on-board processing capability to deliver the optimum level of protection for a specific crash/impact event. This means that the maximum levels of protection can be delivered for each vehicle occupant improving the likelihood, not merely of survival of the event but of minimal injuries.

A preliminary assessment of technologies such as a “smart personal card” or a button transponder reveals considerable opportunity for misuse and inappropriate settings of the restraint system. The BOSCOS project (Bone Scanning for Occupant Safety) focuses on the development of a fully passive system which will ideally operate without the positive action of the seat user. The BOSCOS project is a Foresight Vehicle Project funded by the Department for Transport (DfT).

The intention of the Foresight programme is to bring together UK resources and expertise to create components and systems for the vehicles of the future. Within this programme, the specific aim of the BOSCOS project is to initiate development of a new product that will improve vehicle occupant safety (reducing fatalities and lowering the severity of injuries) and also have a direct influence on UK Health and Societal costs (hospital A & E services, rehabilitation costs, pain and suffering and industry costs associated with loss of personnel).

1.2 Overview of Phase 1

In the first Phase the possible technologies that are available were assessed for their suitability to an in-vehicle monitor system. Accident studies were conducted to create a baseline of statistics in terms of casualties and their injuries, followed by an extrapolation of this data

taking into account the effect of technologies already in vehicles but not yet providing sufficient statistics to quantify their effectiveness. Initial bone scanning studies began to build a database for use in later tasks. Further studies established the correlation between the scanning value and bone properties and the correlation between the bone properties and bone strength.

1.3 Overview of Phase 2

In the second Phase the technology was reviewed for its use in an in-vehicle application and the actions needed to achieve this were identified and followed through to establish the methods of accomplishing the objective. Computer based occupant mathematical modelling established the potential gains from a working system but also the requirements needed of the restraint systems to achieve these gains - these will serve as part of the specification for a successful system. Further bone scanning was conducted, leading to the specification of the most suitable car occupant bone(s) that can be scanned in a vehicle environment to provide data of the best quality to the electronic control unit (ECU) for optimisation of the restraint system.

2.0 SKELETAL PROPERTIES

The ultimate aim here is to establish specific algorithms and relationships able to accurately predict the condition of the bone based solely on non-invasively acquired data. Existing bio-mechanical data will be used as a reference point however it is anticipated that this will not relate quantitatively to the measurements gained from the selected technologies. The aim is to complete collecting data and material after 2 winter and 1 summer seasons followed by the material studies on the collected tissue, and correlation of the material properties with the clinical work.



Figure 1. Bone structure of 54 year old female (left) and a 74 year old female (right), spongy bone from the hip, showing the degeneration of both the structure and density.

2.1 Choice of Scanner Technology

The system must be simple and hassle free to use, non-invasive and harmless.

2.1.1 Non-invasive Bone Assessment

To ensure the accurate measurement of bone quality, the subjects bone needs to be assessed directly. There are ten methods that can perform assessments of bone non-invasively, however of the techniques available, 8 require the use of X-rays, and are therefore contribute too great a risk to the health of the subjects. The remaining two techniques are quantitative ultrasound (QUS) and magnetic resonance imaging (MRI). The practicality of placing a MRI machine into a motor vehicle renders it unsuitable for use. The system best suited to the BOSCOS design is quantitative ultrasound (QUS).

2.1.2 Health Concerns

According to popular belief ultrasound is relatively risk free. However, ultrasound waves are a form of energy, and in order for the wave to be absorbed, and the amplitude reduced, this energy has to be dissipated.

The two problems arising from this are heating and cavitation. Despite mineralised bone having the highest absorption coefficient (10dB/cm.MHz) [1] the intensity level of the ultrasound used in the assessment of bone is below the levels outlined by the Food and Drug Administration, as being safe from heating effects. The mechanical index indicates the risk of cavitation; the higher the mechanical index the greater the probability of a biological effect. The values published for the ultrasound of bone are between 0.22-0.28, with values below 1 considered to be safe [2].

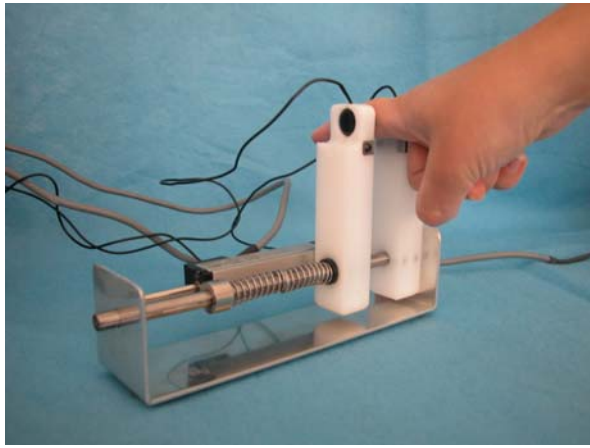
2.1.3 Ease of Use

In order to ensure that occupants use the system it must cause minimal inconvenience to the driver. For this reason the BOSCOS scan needs to be preformed on a readily accessible bone site, that is generally free from both clothing and jewelry. The finger, and in particular the proximal phalanx bones, are used in clinical tests as a means of assessing a patient's bone status, and have been shown to have an ability to predict fracture risk [3, 4, 5, 6].

2.1.4 The BOSCOS Device.

The ultrasound system has been developed by McCue plc. using technology from their commercially available CUBA Clinical™ system. The BOSCOS system is designed to measure the proximal phalanx of the index finger, on the non-dominant side of the subject. Figures 2 and 3. The system works by positioning two ultrasound transducers either side of the finger, and an ultrasound pulse is transmitted between the two transducers through the finger. The system takes a measurement of the separation of the transducers and the time taken for the ultrasound pulse to travel this distance. From this information the speed of sound can be calculated. The speed of the ultrasound pulse is affected by the quality of the bone it passes through, with good quality bone enabling the pulse to travel faster.

The BOSCOS system compares the newly measured speed to a reference database, allowing for a quantitative evaluation of the subject's bone status in comparison to an expected normal. If the result indicates the subject's measured bone speed of sound is below normal, the subject is deemed to have low bone quality and is therefore at higher risk of sustaining a fracture.



Figures 2 and 3. The BOSCOS Ultrasound Device

2.2 Initial Results

The best we can aim for is for the prototype to perform as well as the commercially available portable QUS scanners. We have therefore conducted extensive studies on the precision/accuracy and the sensitivity and specificity of two commercially available QUS scanners, the Sunlight Omnisense and CUBA Clinical along with the BOSCOS prototype.

The precision error of a bone scanning technique refers to its ability to produce the same result, when no change, apart from re-assessment, has occurred. [7] For the BOSCOS system the precision error needs to be minimal to ensure repeat measurements do not cause different restraints reaction scenarios. The perfect technique would present a precision error of 0% to show that measurements had no difference between them. Assessment of precision error showed the commercially available finger scanner was capable of a precision error of 0.55%, in comparison to the other techniques that ranged from 0.29-2.88%.

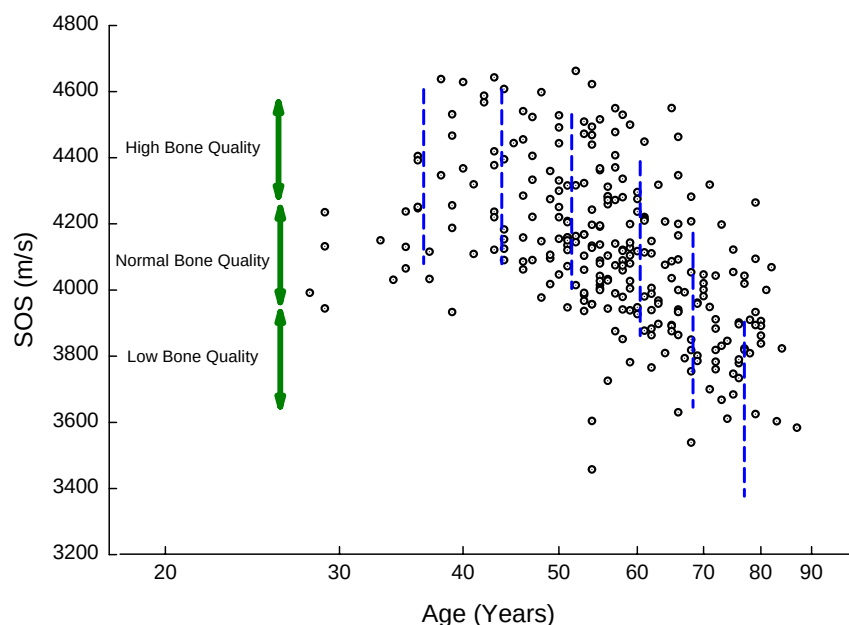


Figure 4. The speed of sound (SOS) measurement values from a commercially available finger scanner versus age for 295 volunteers, showing how the system could be used to sub-classify the population into at least three groups.

Using data obtained from 295 subjects, the finger showed the highest correlation with age 0.533 (p value < 0.001). See Figure 4. The p-value is the level of statistical significance, a value below 0.05 (95% confidence) is considered to be of statistical significance.

3.0 REAL-WORLD INJURY ASSESSMENTS

3.1 Real-world data

The primary reason for the use of accident data in BOSCOS is to identify the types of crashes and occupants who would most likely benefit from the system in order to address conditions where real people in real crashes are being injured. The accident data was to provide a basis for the modelling of the current injury situation. This baseline was to be the starting point from which to assess the potential effectiveness of modifying restraint system performance parameters based upon an estimate of occupant bone strength. The real-world data used within the BOSCOS project was collected by the Co-Operative Crash Injury Study (CCIS), which samples accidents based on vehicle age, vehicle damage and injury outcome. To be included in the database, the accident must have included at least one car that was at most seven years old at the time of the crash, was towed away from the accident scene and in which an occupant of the car was injured. The data are also collected within a stratified sample which is biased towards 'fatal' and 'serious' injury outcome crashes. Of all crashes occurring in the geographical sampling regions, approximately 80% of all fatal and serious accidents, and 10-15% of slight injury crashes are investigated.

Because of the bias within the CCIS data towards serious and fatal injury outcomes, it is necessary to weight the data so that it is representative of the whole population of injury, tow-away accidents. To do this, weighting factors were calculated which correct the under-representation of slight injury accidents.

3.2 Problem Definition

3.2.1 Impact type

During the initial stages of the project it was intended to examine as many different impact types as possible. 73% of belted front seat occupants who sustained an AIS 2+ injury were involved in either frontal or side impacts. Impacts such as rollovers and under-runs were not considered, since not only is occurrence of these impact types low, but modelling of such impacts is very difficult due to their inherent variability.

Although side impacts make up around 23% of injured (MAIS 2+) occupants, it was decided not to attempt to apply the BOSCOS system to side impacts at this stage for the following reasons:

- Side restraint systems have far less time in which to operate, hence the extent to which their deployment can be adjusted to differing scenarios and occupant types is limited.
- Due to its retrospective nature, the CCIS data contains relatively few crashes with cars fitted with side airbags, hence making an assessment of the effectiveness of the BOSCOS device compared to current technology is difficult.

Therefore at this stage it was decided to restrict the investigation to frontal crashes only, which still covers 57% of the occupants in the database. However, it is anticipated that the application of BOSCOS to side impacts could provide the basis for further development work in the future.

3.2.2 Body regions and types of injury

The next stage of problem definition was to identify the body regions and types of injury that were most likely to be mitigated with the introduction of a BOSCOS system. Since the basis of such a device is to adapt the restraint system according to the bone strength of the occupant, it follows that skeletal injuries are those most likely to be reduced. Obviously a reduction in skeletal injury resulting from “softer” restraints is also likely to be accompanied by a reduction on the occurrence of soft tissue injuries, although the exact influence on these types of injuries will be harder to determine.

Figure 5 shows the location of skeletal injuries for belted drivers with airbags. It is clear that the body regions of concern in this context are the chest and upper and lower extremities. Since injuries to the chest are likely to pose a higher threat to life than those to the extremities, chest injuries will provide the focus for the initial development of BOSCOS.

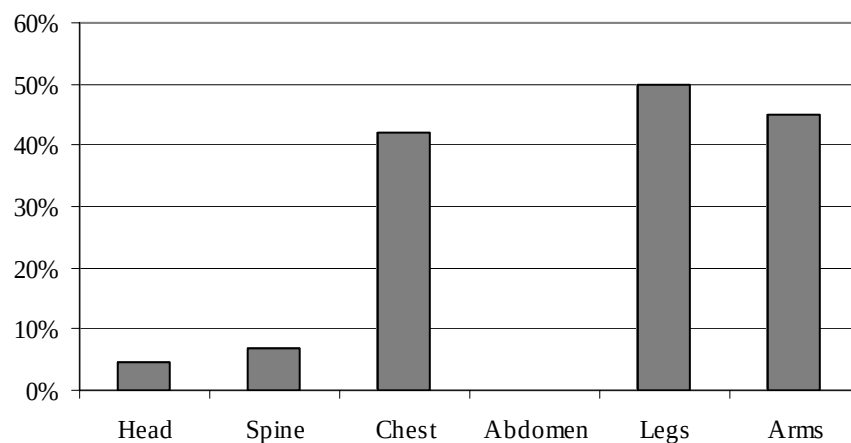


Figure 5. Location of skeletal injury for belted drivers with airbags

71% of all serious (AIS 2+) chest injuries for belted drivers are fractures to the ribs or sternum. Of these skeletal injuries, 66% were considered to have been caused by the restraint system (either belt or airbag), whilst 53% of all AIS 2+ chest injuries were attributed to the restraint system. In crashes where the crash severity, as determined by an (ETS) calculation is known, 75% of injuries occur at speeds lower than 56km/h, the current basis for legislative testing. ETS is the vehicle delta v, calculated on the assumption that deformation was caused by impact with a fixed rigid barrier [8]. Since 96% of these cases below 56km/h sustained little or no facia intrusion (< 4cm) it is clear that there is the potential for an adaptive restraint system to provide significant benefit to chest injury risk.

3.2.3 Occupant types

It is widely accepted that human bone strength decreases with age, and as such it is expected that the benefits of a BOSCOS system will be of greater magnitude to the elderly. With the

aging population of the UK, the societal benefit as a whole will increase as more and more older drivers and passengers become exposed to the increased risk of injury attributable to a decrease in bone strength.

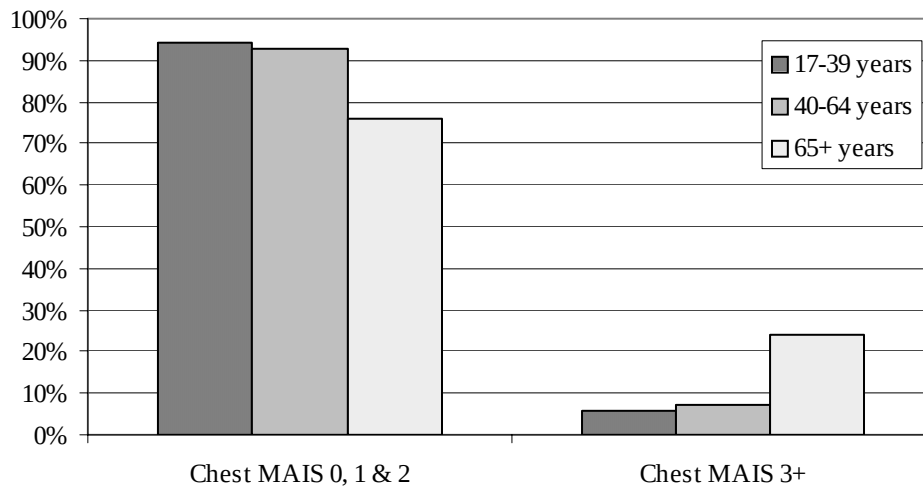


Figure 6 Distribution of maximum chest AIS of belted drivers by age group

Figure 6 shows the distribution of maximum chest AIS for belted drivers of varying age groups. It is apparent that injury risk remains constant for the 17-39 and 40-64 age groups, but that there is a clear shift towards more AIS 3+ injuries for the 65+ age group. However, it is expected that a BOSCOS system will also be of benefit to younger occupants.

Although risk of chest injury in AIS terms is similar for ages 17 to 64, a number of clinical studies [9, 10] show that morbidity from rib fractures can increase from a much younger age, possibly as young as 40 onwards. As such, although the risk of specific injuries may not increase in the 40-64 age group, the risk of complications and associated increased costs of treatment (and ultimately cost to society) can increase.

The ability of the BOSCOS system to measure bone strength means that sufferers of conditions such as osteoporosis will be detected, and the restraint system tailored to them as much as is practicable.

3.3 Development of accident matrix

Analysis of the real-world data presents an obvious target group, for which a BOSCOS system should provide an improvement in occupant protection. This group was broadly defined as belted drivers and front seat passengers, in vehicles fitted with pretensioners, and who sustained an injury attributed to the restraint system. Whilst it is likely that others outside this target group would also benefit from BOSCOS, this group was the most appropriate on which to base the next stage of work – development of a matrix of accident scenarios.

One of the limitations of mathematical modelling is that models have to be validated by full-scale crash tests to ensure that the results produced are valid. Since the motor industry has a need to optimise performance for legislative and consumer tests, there is no guarantee that

extrapolating the models outside these types of impact will produce valid results. For this reason, the BOSCOS target group was categorised into the following impact types:

- Full overlap – This type of model will be used to represent all the real-world impacts with an overlap greater than 85%. The ETS selected for this group were 25km/h and 45km/h, since these were the 25thile and 75thile respectively of the real-world full overlap crashes.
- Offset – Since an offset test is designed to test the crash performance assuming that one longitudinal member absorbs the majority of the impact energy, this type of model will represent all real-world impacts with an overlap up to 55%. 90% of the real-world offset crashes fell between 23km/h and 33km/h and therefore a median speed of 28km/h was chosen to represent this group. Impacts to poles and trees only represented 4% of the BOSCOS group. The data was insufficient to develop a scenario for modelling. Improving safety in a small offset impact should, however, also address some of these narrow object impacts.
- The remaining group consists of crashes where only one of the longitudinals was directly loaded, but a significant proportion of the energy was absorbed by loading of the engine block. In effect, a wide overlap impact but directly impacting only one longitudinal. An overlap of 75% and ETS of 40km/h was deemed suitable to model this group of crashes.

5.0 CONCLUSION

The BOSCOS project to-date has set out to identify the best means of calculating the bone strengths of vehicle occupants. It has selected Ultrasound technology as being the most effective and safe tool to use and highlighted its benefits through scans of human subjects. Different ultrasound devices have been evaluated and a new prototype device has been built which could be adapted for in-car use. Real world vehicle accident data has been assessed to determine which accidents are causing rib fractures. A number of accident scenarios have been highlighted and they these have been initially evaluated using finite element models.

6.0 ACKNOWLEDGEMENTS

The collaborators in this project are **Cranfield Impact Centre, Cranfield University** (Department of Materials and Medical Sciences (DMMS) at the Royal Military College of Science (RMCS)), **Vehicle Safety Research Centre** (Loughborough University), **Nissan Technology Centre Europe, TRW, Autoliv** and **McCue**.

7.0 FUTURE WORK

In the last Phase the technical issues that need to be addressed in the use of the bone scanning technology in a vehicle will be investigated to provide input to the development of the system. During the course of this Phase this process will be reviewed as other tasks define particular aspects of the technology. Final bone scanning will be completed leading to the definition of the bone property ranges that can be successfully identified by the scanning

techniques chosen. A study will establish the sensitivity of the scanner device in a vehicle environment as influenced by factors such as the bone selected for scanning, the possible locations of the device in the vehicle, ambient conditions in the vehicle and occupant diversity. Also mathematical occupant modelling will predict the likely improvements in occupant crash survival given the ranges of bone properties that can be identified.

8.0 REFERENCES

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- ¹ Barnett, S.B., et al., The Sensitivity of Biological Tissue to Ultrasound. *Ultrasound in Medicine and Biology* 1997 **23**(6): p. 805-812.
 - ² Barnett, S.B., et al., International Recommendations and Guidelines for the Safe Use of Diagnostic Ultrasound in Medicine. *Ultrasound in Medicine and Biology* 2000 **26**(3): p. 355-366.
 - ³ Ekman, A., et al., Dual X-ray Absorptiometry of Hip, Heel Ultrasound, and Densitometry of Fingers Can Discriminate Male Patients with Hip Fractures from Control Subjects. *Journal of Clinical Densitometry* 2002 **5**(1): p. 79-85.
 - ⁴ Mele, R., et al., Three-Year Longitudinal Study with Quantitative Ultrasound at the Hand Phalanx in a Female Population. *Osteoporosis International*, 1997. **7**: p. 550-557.
 - ⁵ Montagnani, A., et al., Usefulness of Bone Quantitative Ultrasound in Management of Osteoporosis in Men. *Journal of Clinical Densitometry* 2001 **4**(3): p. 231-237.
 - ⁶ Benitez, C.L., et al., Hand Ultrasound for Osteoporosis Screening in Postmenopausal Women. *Osteoporosis International* 2000 **11**: p. 203-210.
 - ⁷ C.-C. Glüer, G. Blake, Y. Lu, B.A. Blunt, M. Jergas, H.K. Genant Accurate assessment of precision errors: How to measure the reproducibility of bone densitometry techniques. *Osteoporosis International (Osteoporos Int.)* 1995; **5**, p.262-270
 - ⁸ Lenard, J., Hurley, B., Thomas, P. The Accuracy of CRASH3 for Calculating Collision Severity in Modern European Cars. *Procs 16th ESV Conf*, Windsor, 1998.
 - ⁹ Holcomb, J.B., McMullin, N.R., Kozar, R.A., Lygas, M.H., Moore, F.A., "Morbidity from rib fractures increases after age 45", *J Am Coll Surg*, 2003.
 - ¹⁰ Easter, A., "Management of patients with multiple rib fractures", *Am J Crit Care* 2001;**10**:320-329

DEVELOPMENT AND ASSESSMENT OF A BONE SCANNING DEVICE TO ENHANCE RESTRAINT PERFORMANCE

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ABSTRACT

The objective of the BOSCOS (BOne SCanning for Occupant Safety) project was the development of a system that can make an assessment of the bone characteristics of each vehicle occupant in order to estimate their skeletal strengths. The seatbelt and airbag characteristics can then be adjusted to deliver optimum levels of protection specifically for each occupant. A system introduced into every vehicle has the capacity to save lives and reduce injury levels across the whole spectrum of vehicle occupants. This paper describes the contributions from academic and industrial partners to this UK Department for Transport funded project.

Commercial pressure focuses restraint design on meeting legal requirements for vehicle approval, but legal requirements use dummies which do not represent the range of car occupant shapes, sizes, and driving positions. A person with lower skeletal characteristics may not be able to withstand the current fixed levels of restraint without sustaining injuries. Conversely, a person with greater skeletal characteristics may be capable of withstanding greater levels of restraint.

Possible technologies that are available have been assessed for their suitability for an in-vehicle monitoring system. Accident studies have been conducted to create a baseline of statistics in terms of casualties and their injuries. Initial bone scanning studies have utilised different types of

equipment and a new prototype scanner has been developed for use in a vehicle environment using ultrasound technology.

Computer based occupant mathematical modelling has been used to establish the potential gains from a working system and also the requirements needed of the restraint systems to achieve these gains. In addition, bone scanning has been conducted, to determine a method to read across from scan values to skeletal condition to provide data for the optimisation of the restraint system.

BOSCOS OBJECTIVES

Background

Over the last decade the quest to improve the levels of vehicle safety has intensified dramatically and is now used as a sales feature by marketing departments. But as the criteria for vehicle crashworthiness have changed from vehicle deformations and decelerations to occupant related parameters (body accelerations, forces, deflections, etc.) a recognition of the implications of human diversity has been slow. This is illustrated by the fact that whilst there are child and adult anthropometric devices (dummies) available for use in vehicle testing, in the case of vehicle type approval (certification) test requirements are defined solely for a 50th percentile adult male driver representation. Consequently, it is easy to perceive that the safety systems in motor vehicles

are developed, tested and approved for optimum use by a narrow band of the driver population whose physical characteristics are not representative of the whole of the driver population.

With the mass of sensors that are now beginning to appear in motor vehicles, the ability to determine information about the driver, e.g. an indication of their mass, the position of the seat and the position of the driver on the seat, is much greater. However, even those parameters that can now be quantified give only limited information that can be used to extend the narrow optimum occupant protection band to a greater proportion of drivers. To successfully extend this band we need to have more information about the individual occupants of each car if they are also to be better protected. The type of information that is needed concerns the physical injury tolerance limits of each individual so that the restraint systems can be 'tuned' by on-board processing to deliver the optimum protection for a specific crash/impact event. This means that the maximum levels of protection can be delivered for each vehicle occupant improving the likelihood, not merely of survival, but of minimal injuries.

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In the first Phase, the possible technologies that are available were assessed for their suitability to an in-vehicle monitoring system. Accident studies were conducted to create a baseline of statistics in terms of casualties and their injuries, followed by

an extrapolation of this data, taking into account the effect of technologies already in vehicles but not yet providing sufficient statistics to quantify their effectiveness. Initial bone scanning studies began to build a database for use in later tasks. Further studies established the correlation between the scanning value and bone properties and the correlation between the bone properties and bone strength.

Overview of Phase 2

In the second Phase the technology was reviewed for its use in an in-vehicle application and the actions needed to achieve this were identified and followed through to establish the methods of accomplishing the objective. Computer based occupant mathematical modelling established the potential gains from a working system but also the requirements needed of the restraint systems to achieve these gains - these will serve as part of the specification for a successful system. Further bone scanning was conducted, leading to the specification of the most suitable car occupant bone(s) that can be scanned in a vehicle environment to provide data of the best quality to the electronic control unit (ECU) for optimisation of the restraint system.

SKELETAL PROPERTIES

Existing biomechanical data relating to human bone, has shown that with old age, there are statistically significant reductions in load carrying capability, when compared with youth [1]. Yamada showed that bones were only able to resist 78% of the mechanical forces applied to them by the age of 70-79, in comparison to their peak at 20-29.

This reduction in biomechanical competence is supported by data from cadaver crash tests, which show that increasing age leads to greater probability of injury in the thorax and abdomen [2, 3, 4].

The reason for this reduction in the mechanical properties is due to a multitude of factors combining a reduction of the overall density, and structural competence (See Figure 1), combined with changes in the biochemical makeup of the bone.

The easiest parameter for assessment of bone status is the reduction in density. This is the parameter used in the clinical environment for the diagnosis of low bone density and osteoporosis. There are different systems clinically available for the measurement of the bone density, the technique

considered to be the gold standard is dual energy X-ray absorptiometry (DXA). Others are available such as radiographic absorptiometry (RA), single photon absorptiometry (SPA), dual-photon absorptiometry (DPA), single X-ray absorptiometry (SXA), quantitative ultrasound (QUS), magnetic resonance imaging (MRI) and quantitative computed tomography (QCT).

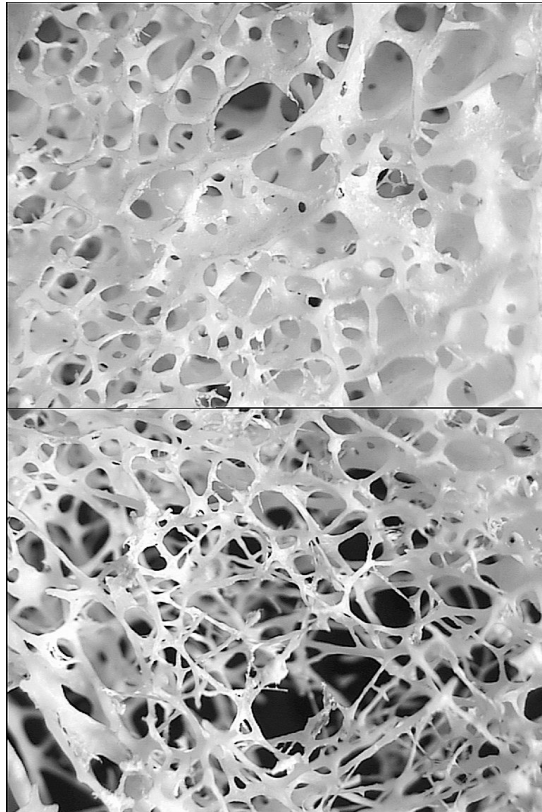


Figure 1. Bone structure of 54 year old female (top) and a 74 year old female (below), spongy bone from the hip, showing the degeneration of both the structure and density.

The ultimate aim was to establish specific algorithms and relationships between one of the clinically available techniques so as to accurately predict the condition of the bone based solely on non-invasively acquired data. Existing bio-mechanical data was used as a reference point; however it was anticipated that this was not related quantitatively to the measurements gained from the selected technologies. The aim was to complete collecting data and material after two winter and one summer seasons followed by the material studies on the collected tissue, and correlation of the material properties with the clinical work.

Non-invasive Bone Assessment

To ensure the accurate measurement of bone quality, the subjects bone needs to be assessed

directly. Of the techniques mentioned previously, DXA, SXA, SPA, DPA, RA and QCT are either out-dated, too inaccurate or require the use of X-rays, and therefore contribute too great a risk to the health of the subjects. The remaining two techniques are quantitative ultrasound (QUS) and magnetic resonance imaging (MRI). The practicality of placing a MRI machine into a motor vehicle renders it unsuitable for use. The system best suited to the BOSCOS design is quantitative ultrasound (QUS).

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According to popular belief ultrasound is relatively risk free. However, ultrasound waves are a form of energy, and in order for the wave to be absorbed, and the amplitude reduced, this energy has to be dissipated.

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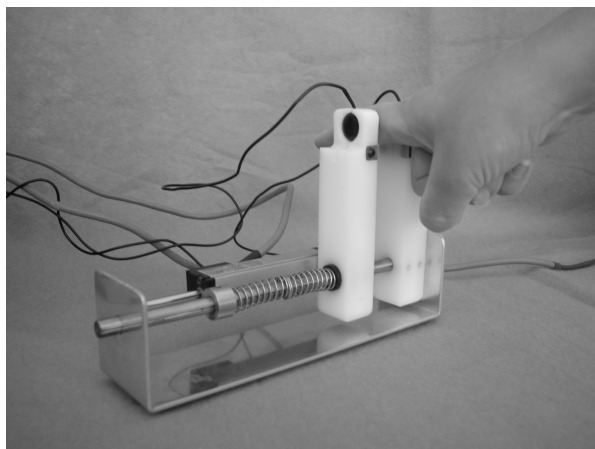
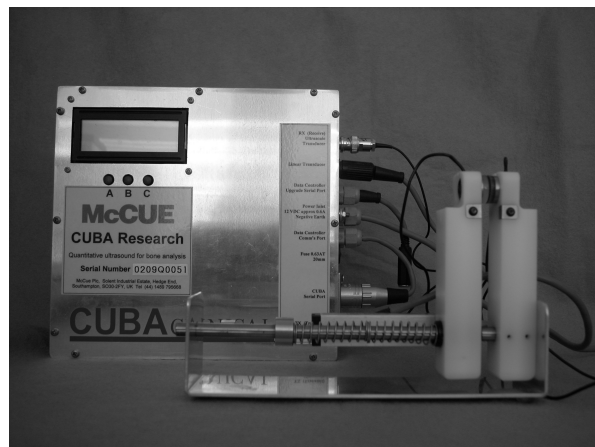
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Figures 2 and 3. The BOSCOS Ultrasound Device.

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precision/accuracy and the sensitivity and specificity of two commercially available QUS scanners, the Sunlight Omnisense and CUBA Clinical along with the BOSCOS prototype.

The precision error of a bone scanning technique refers to its ability to produce the same result, when no change, apart from re-assessment, has occurred. [11] For the BOSCOS system the precision error needs to be minimal to ensure repeat measurements do not cause different restraints reaction scenarios. The perfect technique would present a precision error of 0% to show that measurements had no difference between them. Assessment of precision error showed the commercially available finger scanner was capable of a precision error of 0.55%, in comparison to the other techniques that ranged from 0.29-2.88%.

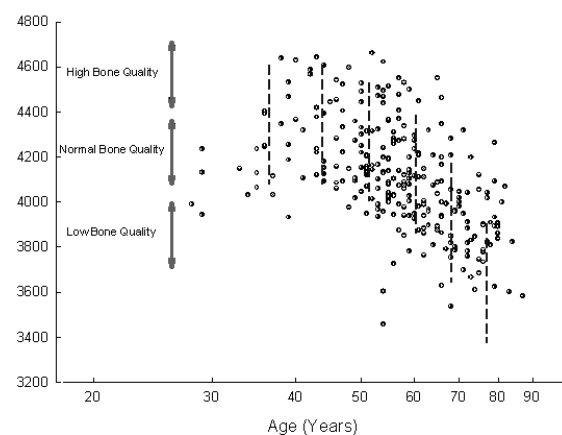


Figure 4. The speed of sound (SOS) measurement values from a commercially available finger scanner versus age for 295 volunteers, showing how the system could be used to sub-classify the population into at least three groups.

Using data obtained from 295 subjects, the finger showed the highest correlation with age 0.533 (p value < 0.001) (See Figure 4). The p -value is the level of statistical significance; a value below 0.05 (95% confidence) is considered to be of statistical significance.

The prototype system was used along side DXA assessment of the total hip and lumbar spine (Hologic QDR-4500C; Hologic Inc. Bedford, MA, USA); QUS assessment of the calcaneal (heel) bone (CUBA Clinical; McCue plc. Winchester, UK), proximal phalanx and distal radius (Sunlight Omnisense; Sunlight Medical, Rehovot, Israel), in a study on a group of 102 subjects (7 males, 95 females) aged between 24 and 85 years of age (mean: 57 years). The correlation between the new phalangeal assessments and age gave a correlation

of $r = -0.597$ (p value < 0.001), and regression analysis (See Figure 5) gave the relationship:

$$\text{Phalanx SOS} = 4604.66 - 9.15609 \text{ age}$$

$$R^2 = 35.7\%$$

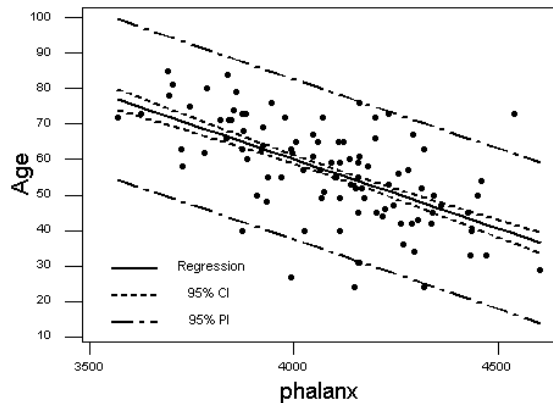


Figure 5. Regression plot of age vs phalangeal SOS

Not knowing the actual condition of the bone the performance of the prototype was assessed against a 'composite' parameter by combining the average of scaled values of the CUBA clinical, Sunlight Omnisense and DXA.

For each individual patient the proximal phalanx of the index finger was assessed using the BOSCOS system, and 10 waveforms with results were saved (See Figure 6).

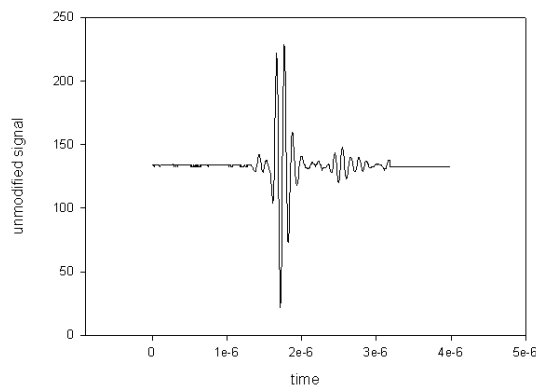


Figure 6. A representative ultrasound pulse after transmission through bone.

The pulses were converted to absolute values in relation to the baseline and the time and amplitude of the four greatest peaks was noted (See Figure 7). The ultrasound pulse was analysed by retrieving information about:

- The time incident of the first of the four greatest peaks assessed.
- The time and amplitude difference between the first and second peaks.

- The time between the first and fourth greatest peak
- The area under the waveform.
- The amplitude of the biggest of the four peaks. (The maximum amplitude)

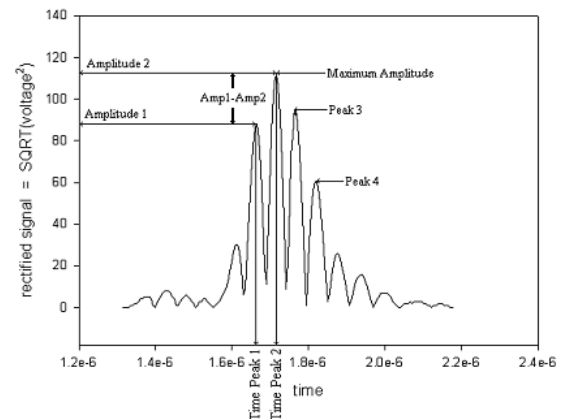


Figure 7. The 'extrapolated' parameters produced from the positive waveform.

These parameters were used alone and in combination with weight and age for the assessment of the composite measure.

The results showed that a combination of the ultrasound parameters with weight and age enabled the BOSCOS system to predict the status of a persons bone with an R^2 of not better than 50% (the R^2 represents the coefficient of determination, which is a measure of how well the regression model defines the data). However, by making use of available superior technology, the predictive ability of the system may well be improved, which could enable the differentiation of individuals into groupings according to their bone status. Further work is required to enable an understanding of what the measurement value (taken from the phalanx) means, in terms of actual bone properties, with respect to the rest of the skeleton.

REAL-WORLD INJURY ASSESSMENTS

Real-world data

The primary reasons for the use of accident data in BOSCOS were to identify the types of crashes and occupants who would most likely benefit from the system in order to address conditions where real people in real crashes were being injured. The accident data was to provide a basis for the modelling of the current injury situation. This baseline was the starting point from which to assess the potential effectiveness of modifying restraint system performance parameters based upon an estimate of occupant skeletal strength. The real-world data used within

the BOSCOS project was collected by the UK Co-Operative Crash Injury Study (CCIS), which samples accidents based on vehicle age, vehicle damage and injury outcome. To be included in the database, the accident must have included at least one car that was at most seven years old at the time of the crash, was towed away from the accident scene and in which an occupant of the car was injured. The data are also collected within a stratified sample which is biased towards 'fatal' and 'serious' injury outcome crashes. Of all crashes occurring in the geographical sampling regions, approximately 80% of all fatal and serious accidents, and 10-15% of slight injury crashes were investigated.

Because of the bias within the CCIS data towards serious and fatal injury outcomes, it was necessary to weight the data so that it was representative of the whole population of injury, tow-away accidents. To do this, weighting factors were calculated which correct the under-representation of slight injury accidents.

Problem Definition

Impact Type

During the initial stages of the project it was intended to examine as many different impact types as possible. 73% of belted front seat occupants who sustained an AIS 2+ injury were involved in either frontal or side impacts. Impacts such as rollovers and under-runs were not considered, since not only is occurrence of these impact types low, but mathematical modelling of such impacts is very difficult due to their inherent variability.

Although side impacts make up around 23% of injured (MAIS 2+) occupants, it was decided not to attempt to apply the BOSCOS system to side impacts at this stage for the following reasons:

- Side restraint systems have far less time in which to operate, hence the extent to which their deployment can be adjusted to differing scenarios and occupant types is limited.
- Due to its retrospective nature, the CCIS data contained relatively few crashes with cars fitted with side airbags, hence making an assessment of the effectiveness of the BOSCOS device compared to current technology is difficult.

Therefore, at this stage it was decided to restrict the investigation to frontal crashes only,

which still covered 57% of the occupants in the database. However, it was anticipated that the application of BOSCOS to side impacts could provide the basis for further development work in the future.

Body Regions and Types of Injury

The next stage of problem definition was to identify the body regions and types of injury that were most likely to be mitigated with the introduction of a BOSCOS system. Since the basis of such a device was to adapt the restraint system according to the skeletal strength of the occupant, it follows that skeletal injuries are those most likely to be reduced. Obviously a reduction in skeletal injury resulting from "softer" restraints is also likely to be accompanied by a reduction on the occurrence of soft tissue injuries, although the exact influence on these types of injuries will be harder to determine.

Figure 8 shows the location of skeletal injuries for belted drivers with airbags. It is clear that the body regions of concern in this context were the chest and upper and lower extremities. Since injuries to the chest are likely to pose a higher threat to life than those to the extremities, chest injuries provided the focus for the initial development of BOSCOS.

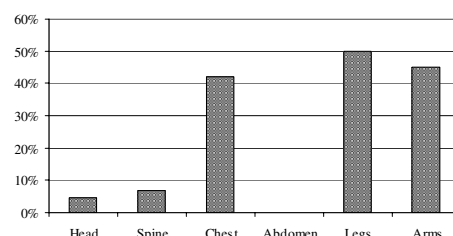


Figure 8. Location of skeletal injury for belted drivers with airbags.

71% of all serious (AIS 2+) chest injuries for belted drivers were fractures to the ribs or sternum. Of these skeletal injuries, 66% were considered to have been caused by the restraint system (either belt or airbag), whilst 53% of all AIS 2+ chest injuries were attributed to the restraint system. In crashes where the crash severity is known, as determined by an ETS calculation, 75% of injuries occurred at speeds lower than 56km/h, the current basis for legislative testing. ETS is the vehicle delta v, calculated on the assumption that deformation was caused by impact with a fixed rigid barrier [12]. Since 96% of these cases below

56km/h sustained little or no facia intrusion (<4cm) it is clear that there is the potential for an adaptive restraint system to provide significant benefit to chest injury risk.

Occupant Types

It is widely accepted that human bone strength decreases with age, and as such it is expected that the benefits of a BOSCOS system will be of greater magnitude to the elderly. With the aging population of the UK, the societal benefit as a whole will increase as more and more older drivers and passengers become exposed to the increased risk of injury attributable to a decrease in bone strength.

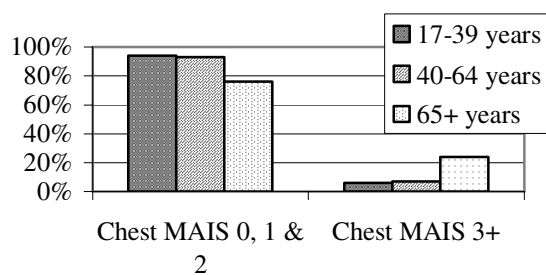


Figure 9. Distribution of maximum chest AIS of belted drivers by age group.

Figure 9 shows the distribution of maximum chest AIS for belted drivers of varying age groups. It is apparent that injury risk remains constant for the 17-39 and 40-64 age groups, but that there is a clear shift towards more AIS 3+ injuries for the 65+ age group. However, it is expected that a BOSCOS system will also be of benefit to younger occupants.

Although risk of chest injury in AIS terms is similar for ages 17 to 64, a number of clinical studies [13, 14] show that morbidity from rib fractures can increase from a much younger age, possibly as young as 40 onwards. As such, although the risk of specific injuries may not increase in the 40-64 age group, the risk of complications and associated increased costs of treatment (and ultimately cost to society) can increase.

The ability of the BOSCOS system to measure bone strength means that sufferers of conditions such as osteoporosis will be detected and the restraint system tailored to them as much as is practicable.

Development of Accident Matrix

Analysis of the real-world data presents an obvious target group, for which a BOSCOS system should provide an improvement in occupant protection. This group was broadly defined as belted drivers and front seat passengers in vehicles fitted with pre-tensioners and who sustained an injury attributed to the restraint system. Whilst it is likely that others outside this target group would also benefit from BOSCOS, this group was the most appropriate on which to base the next stage of the work – development of a matrix of accident scenarios.

One of the limitations of mathematical modelling is that models have to be validated by full-scale crash tests to ensure that the results produced are valid. Since the motor industry has a need to optimise performance for legislative and consumer tests, there is no guarantee that extrapolating the models outside these types of impact will produce valid results. For this reason, the BOSCOS target group was categorised into the following impact types:

- Full overlap – This type of model will be used to represent all the real-world impacts with an overlap greater than 85%. The ETS selected for this group were 25km/h and 45km/h, since these were the 25% percentile and 75% percentile respectively of the real-world full overlap crashes.
- Offset – Since an offset test is designed to test the crash performance assuming that one longitudinal member absorbs the majority of the impact energy, this type of model will represent all real-world impacts with an overlap up to 55%. However, 90% of the real-world offset crashes fell between 23km/h and 33km/h and therefore a median speed of 28km/h was chosen to represent this group. Impacts to poles and trees only represented 4% of the BOSCOS group. The data was insufficient to develop a scenario for modelling. Improving safety in a small offset impact should, however, also address some of these narrow object impacts.
- The remaining group consists of crashes where only one of the vehicle's longitudinals was directly loaded, but a significant proportion of the energy was absorbed by loading of the engine block.

In effect, a wide overlap impact but directly impacting only one longitudinal. An overlap of 75% and ETS of 40km/h was deemed suitable to model this group of crashes.

BASIS OF COST BENEFIT STUDY

Background to Cost Benefit Study

In order to assess the potential benefits of BOSCOS, it was necessary to evaluate changes in injury risk and their associated costs. In this way, any benefits can be shown clearly as monetary values, which are directly comparable to costs incurred by proposed BOSCOS systems.

‘Willingness to Pay’ Approach

Several cost benefit scales were considered including the HARM concept developed in the US by Malliaris et al in the early 1980s [15] and Miller et al, 1991 [16]. HARM was considered inappropriate for use in BOSCOS because injury costs in Europe do not exist in a form usable by HARM. For this reason, it was decided to consider the ‘Willingness to Pay’ approach, which was developed by the UK Department for Transport (DfT) to calculate costs of injury in the UK.

The Willingness to Pay approach to injury costing was first used in 1988 by DfT to value the cost of road accident fatalities. The concept behind it is to consider what people would be prepared to pay in order to reduce the risk of being killed in a road accident. According to TRL Report 163 [17] this approach is ‘consistent with cost benefit analysis, in that decisions reflect the preferences and attitude to risk of people who are likely to be affected by them.’ In 1993 the same method was used to revise the values for non-fatal road accidents and in 1994 other accident costs were also derived. There are two areas of costs which have been defined; casualty related costs which include lost output, human costs and medical and support costs and accident related costs which encompass property damage, insurance administration and police costs.

Severity of an accident is defined as fatal, serious or slight. A serious injury is defined in TRL Report 163 as covering a wide range ‘from a fractured finger, to those resulting in severe permanent disability, or death more than 30 days after the accident.’

Serious injuries were divided into sub-groups according to treatment length, extent and duration of pain and recovery time.

Table 1.
Injury State Descriptors, Hopkirk & Simpson, 1995

Injury Code	Injury State
F	Recover 3-4 months (Out-patient)
W	Recover 3-4 months (In-patient)
X	Recover 1-3 years
V	Mild permanent disability (Out-patient)
S	Mild permanent disability (In-patient)
R	Some permanent disability with scarring
N	Paraplegia/Quadriplegia
L	Severe head injuries

The Willingness to Pay approach was implemented to determine the ‘human cost’ of an accident. A Standard Gamble questionnaire was used to carry out a survey of 450 people, asking them how much they would be willing to pay to reduce the risk of injury, relative to the cost of a fatality.

The respondents ranked the injury states and placed each one on a scale from 0-100. The majority regarded injury state L as being as bad as or worse than death and injury state N as only slightly better than death. The respondents were also asked to specify the level of risk at which they would opt for treatment of an injury. It was then possible to convert the survey results into values relative to the value of death and as a percentage value of death. Therefore the human cost of each injury state can be expressed as a percentage of the human cost of a fatality. The cost for a slight injury, including whiplash, has also been determined.

New injury costing method – VSRC

Medical researchers at the VSRC have mapped 300-400 trauma injuries from the CCIS database from the AIS level (AIS 1990 revision), [18] to the injury states defined by Hopkirk and Simpson in TRL Report 163. This enables the calculation of the human cost of a trauma injury according to its AIS code. In TRL Report 163, complete lists are given for slight and serious injury costs as a percentage of the overall value of a fatality in 1994. The 2003 figure for a fatal casualty is given in Road Casualties Great Britain 2003: Annual Report and therefore all 2003 human costs for an injury can be calculated [19].

Cost benefit calculations

Using the injury costs defined by the VSRC, it is possible to give a monetary value to reductions in injury risk achieved by the BOSCOS project.

For example, if simulations are performed using increasing load limiter settings, on a strong and a weak occupant (in terms of skeletal strength), then the different chest injury risks can be assessed for each occupant using appropriate risk curves. The risk of head injury with the differing load limiter values can also be simulated. The costs can be derived for each type of injury, according to occupant strength and load limiter. The optimum load settings can then be determined for each type of occupant depending on skeletal strength. Using the proposed BOSCOS system, it would be possible to adjust the level of the load limiter as required, depending on what is most beneficial in terms of occupant injury, therefore reducing potential injury costs.

NEW TECHNOLOGIES OF RESTRAINT SYSTEMS

The present protection system on front seats features a belt system, incorporating a pretensioner, a load limiter, and an airbag. This protection system is not capable of changing its performance characteristics during a crash event. The ability of an occupant protection system to adapt itself to dominant crash condition parameters, such as impact speed and type, occupant size and mass, bone characteristics offers a great improvement in occupant protection for a wider range of crash conditions, as well as occupants.

New technologies are being rolled out to address these issues. These technologies will require new sensors in order to detect certain parameters e.g. the BOSCOS scanner and new actuators in order to protect the occupant.

The car occupant restraint industry has so far mainly focused on “In-crash systems” aimed at mitigating the consequences of an accident. However, for example, Autoliv’s Total Safety System concept has widened the scope of safety enhancing areas to include both “pre-crash systems” and “post-crash systems”. The pre-crash systems are often active systems that are aimed at preparing the safety systems for an imminent crash or, preferably, avoiding the crash altogether. Post-crash systems are devised to increase the

occupant’s chances of surviving after a serious accident.

Components and sub-systems must therefore be designed to interact with each other as one system. Seat belt pretensioner and frontal airbags, for instance, are tuned to complement each other via the same electronic control unit to give the best possible protective effect. In addition, the deployment of the frontal airbags should be adjusted depending on crash severity, seat belt use and occupant characteristics.

Future restraint systems should provide protection for all kinds of occupants in various seat positions with or without seat belts (infants, elderly people, petite females, and large males).

In real life, crashes are almost never “head-on” frontal collisions into a rigid unmoveable object at one specific speed (as in most crash tests required by the government regulators). Consequently, future safety systems should be able to do more than just determine if an accident is a frontal crash, a side impact, a rear-end collision or a rollover.

An ideal system should be able to identify and provide protection to car occupants in collisions with various types of vehicles and objects (car-to-car, car-to-truck, etc.) up to a collision speed where there is still a survivable space in the vehicle’s compartment. New technologies may include the concepts described below.

Smart Seat Belt

In a crash, a smart belt starts by tightening the belt, using a pyrotechnic pre-tensioner. This eliminates slack and makes it possible to release some webbing at a later stage, if the load on the occupant becomes too high. The airbag is instead used to absorb more load.

In a traditional system, the loads to the occupant from the seat belt and the airbag are added to each other, when the airbag also starts to restrain the occupant. But in the smart belt, the system just shifts into the second lighter gear so that the load on the occupant’s body can be maintained at a relatively constant level.

Equally important is the fact that the force of the combined systems – and thus the load on the occupant – can be tuned to the severity of each crash. Many future vehicles will have advanced occupant weight sensing systems. In those vehicles, a smart belt could be tuned to each occupant individually. This will be particularly

important for occupants who are more susceptible to high chest loads.

Pre-Pretensioning

The pre-pretensioner will give a more gentle load distribution on the occupants chest in the event of a car crash. The device will tighten the seat belt as early as one tenth of a second before a likely crash, using a fast electrical motor.

The elimination of slack in the belt system can therefore start earlier, even before a crash and the system can be made reversible. Consequently, it is possible to "strap in" the occupant more gently. It also makes it possible to tighten the belt, as a precaution when it is difficult to predict whether there will be a crash or not. The new system will be especially effective in preventing occupants from being thrown forward during severe braking.

Pre-Crash Sensing

In a few tenths of a second before a crash, radar sensors are capable of identifying the relative speed towards an object and the estimated time of impact. This will allow better discrimination of the crash severity and events identified in the BOSCOS accident studies.

Secondly, this will enhance the detection capability and timing of existing safety systems, particularly for relatively small, narrow objects, such as a corner of another vehicle, or pole or lamppost. The pre-crash sensing system will be especially useful in combination with pre-pretensioning.

Even if this pre-crash system gives just a few more milliseconds to inflate the airbags, it could open the possibility to make the airbags "softer" during deployment without compromising their protection capability.

PARAMETRIC MODELLING

In phase 2 of the project a series of mathematical modelling parametric studies were conducted to investigate different accident scenarios. The different scenarios were generated from the accident analysis performed by VSRC and have identified crash configurations where there are AIS 2+ chest injuries attributed to the seat belt. These injuries are in the form of broken bones as well as other soft tissue injuries. Dummy models were used to develop a generic seating and interior design to enable comparisons between different models to be evaluated.

The dummy models are able to predict the levels of acceleration, belt loads and trajectories of certain body parts. For each different configuration these criteria indicate the severity of the crash pulses. Parameters such as the seat belt tension and pre-tensioners were incorporated into the model to represent the range of safety restraint systems which are currently available. An airbag was included in the model, as they play an important role in the protection of vehicle occupants.

Initial simulation results with the selected accident scenarios predict injury indices below those allowed in the higher speed legal or EuroNCAP tests.

CONCLUSIONS

The BOSCOS project to-date has set out to identify the best means of calculating the bone strengths of vehicle occupants. The ultrasound technology has been selected as the most effective and safe tool to use and highlighted its benefits through scans of human subjects. Different ultrasound devices have been evaluated and a new prototype device has been built which could be adapted for in-car use. Real world vehicle accident data has been assessed to determine which accidents are causing rib fractures. New restraint technologies have been identified which could be enhanced with the addition of BOSCOS type technology. A number of accident scenarios have been selected and they have been used in the initial mathematical modelling.

ACKNOWLEDGEMENTS

The collaborators in this project are **Cranfield Impact Centre, Cranfield University** (Department of Materials and Medical Sciences (DMMS) at the Royal Military College of Science (RMCS)), **Vehicle Safety Research Centre** (Loughborough University), **Nissan Technology Centre Europe, TRW Automotive, Autoliv and McCue**. The project was funded by the UK Department for Transport.

FUTURE WORK

In the last phase of the BOSCOS project the technical issues that need to be addressed in the use of the bone scanning technology in a vehicle will be investigated to provide input to the development of the system. During the course of this Phase this process will be reviewed as other tasks define particular aspects of the technology. Final bone scanning will be completed leading to

the definition of the bone property ranges that can be successfully identified by the scanning techniques chosen. A study will establish the sensitivity of the scanner device in a vehicle environment as influenced by factors such as the bone selected for scanning, the possible locations of the device in the vehicle, ambient conditions in the vehicle and occupant diversity. Mathematical modelling will predict occupant injury indices with the new technologies. A cost benefit study will utilise these results to deliver an indication of change in injury risk and the potential gains from a BOSCOS system.

REFERENCES

- [1] Yamada, H. (1970), Strength of Biological Materials (Ed, Evan, F. G.) Williams and Wilkins Company, Baltimore, pp. 255-271.
- [2] Kent, R. and Patrie, J. (2004), Forensic Science International, Article in Press.
- [3] Schmidt, G., Kallieris, D., Barz, J. and Mattern, R. (1994), Biomechanics of impact injury and injury tolerances of the thorax-shoulder complex, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 311-316.
- [4] Schmidt, G., Kallieris, D., Barz, J., Mattern, R. and Klaiber, J. (1994), Biomechanics of impact injury and injury tolerances of the thorax-shoulder complex, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 371-399.
- [5] Barnett, S.B., et al., The Sensitivity of Biological Tissue to Ultrasound, Ultrasound in Medicine and Biology 1997 23(6): p. 805-812.
- [6] Barnett, S.B., et al., International Recommendations and Guidelines for the Safe Use of Diagnostic Ultrasound in Medicine, Ultrasound in Medicine and Biology 2000 26(3): p. 355-366.
- [7] Ekman, A., et al., Dual X-ray Absorptiometry of Hip, Heel Ultrasound, and Densitometry of Fingers Can Discriminate Male Patients with Hip Fractures from Control Subjects, Journal of Clinical Densitometry 2002 5(1): p. 79-85.
- [8] Mele, R., et al., Three-Year Longitudinal Study with Quantitative Ultrasound at the Hand Phalanx in a Female Population, Osteoporosis International, 1997. 7: p. 550-557.
- [9] Montagnani, A., et al., Usefulness of Bone Quantitative Ultrasound in Management of Osteoporosis in Men, Journal of Clinical Densitometry 2001 4(3): p. 231-237.
- [10] Benitez, C.L., et al., Hand Ultrasound for Osteoporosis Screening in Postmenopausal Women, Osteoporosis International 2000 11: p. 203-210.
- [11] Glüer, C.-C, Blake, G., Lu, Y., Blunt, B.A., Jergas, M., Genant, H.K., Accurate assessment of precision errors: How to measure the reproducibility of bone densitometry techniques, Osteoporosis International (Osteoporos Int.) 1995; 5, p.262-270.
- [12] Lenard, J., Hurley, B., Thomas, P. The Accuracy of CRASH3 for Calculating Collision Severity in Modern European Cars, Procs 16th ESV Conf, Windsor, 1998.
- [13] Holcomb, J.B., McMullin, N.R., Kozar, R.A., Lygas, M.H., Moore, F.A., Morbidity from rib fractures increases after age 45, J Am Coll Surg, 2003.
- [14] Easter, A., Management of patients with multiple rib fractures, Am J Crit Care 2001;10:320-329.
- [15] Malliaris A. C. et al., Harm Causation and Ranking in Car Crashes. SAE 850090, Society of Automotive Engineers, Warrendale, PA, 1985.
- [16] Miller T. R. et al., Motor Vehicle Injury Costs by Body Region and Severity, Proceedings of the Annual Conference of the Advancement of Automotive Medicine, 34, Scottsdale, AZ, 1990.
- [17] Hopkin J. M. & Simpson H., Valuation of Road Accidents, TRL Research Report 163, Transport Research Laboratory, Crowthorne.
- [18] VSRC Injury Costings, developed by VSRC for use in the DFT Secondary Safety Priorities (SSP) Project.
- [19] Road Casualties Great Britain 2003: Annual Report, Department for Transport, National Statistics, 2004.

BOSCOS - Development and Benefits of a Bone Scanning System

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ABSTRACT

The objective of the BOSCOS (BOne SCanning for Occupant Safety) project was the development of a system that can make an assessment of the bone characteristics of each vehicle occupant in order to estimate their skeletal strengths. The seatbelt and airbag characteristics can then be adjusted to deliver optimum levels of protection specifically for each occupant. A system introduced into every vehicle has the capacity to save lives and reduce injury levels across the whole spectrum of vehicle occupants. This paper describes the contributions from academic and industrial partners to this UK Department for Transport funded project.

Keywords: BONE STRENGTH, FRONTAL IMPACTS, RESTRAINT SYSTEMS, CHEST DEFLECTION, ULTRASOUND

Commercial pressure focuses restraint design on meeting legal requirements for vehicle approval, but legal requirements use dummies which do not represent the range of car occupant shapes, sizes, and driving positions. A person with lower skeletal characteristics may not be able to withstand the current fixed levels of restraint without sustaining injuries. Conversely, a person with greater skeletal characteristics may be capable of withstanding greater levels of restraint.

Possible technologies that are available have been assessed for their suitability to an in-vehicle monitoring system, including health issues. Protocols have been developed and ethical issues addressed in building relationships with Hospital Trusts to integrate the project's bone scanning activities with routine scanning procedures and hence correlate results across different technologies. Pre-operative in-vivo measurements were then available for tissue samples that could then be tested in-vitro to quantify mechanical characteristics following surgical procedures.

A prototype scanner based on the use of ultrasound technology has been developed for use in an in-vehicle environment to take measurements from one of the phalanges of the hand. Techniques to correlate such measurements with skeletal condition/characteristics have been examined and quantified in order to provide data for the optimisation of a restraint system.

Accident studies have been conducted to create a baseline of statistics (in terms of casualties and their injuries) and to identify scenarios where an optimised restraint technology could be employed to deliver improved safety benefits. Following these, computer based occupant mathematical modelling has been used to establish the potential gains from a working system but also the requirements needed of the restraint systems to achieve these gains. The correlation of computer simulation injury indices with AIS injury risk predictors has enabled a cost benefit analysis to be conducted that shows a reduction in personnel and societal injury costs for a modest outlay in in-vehicle hardware.

Issues relating to the integration of systems based on the prototype equipment have been examined from a technological and consumer acceptance perspective. Whilst technology issues can be addressed, consumer acceptance would need to be tackled on the basis of improved safety benefits and the perception of a high (information) technology fitment (gadget).

This project was developed under the Foresight Vehicle funding scheme in the UK whereby organisations can put commercial considerations to one side since the project has essentially been of a pre-competitive nature. Whilst the basis of the technology has been established and demonstrated by the Partners, exploitation as a commercial venture is in the future when greater refinement has been added to the hardware and software needed as the basis of a BOSCOS based optimised restraint system. In particular, further development of the ultrasound technology and the read across techniques to determine bone strength will be needed to refine the separation of the population into groups with well defined skeletal capabilities.

SKELETAL PROPERTIES

Existing biomechanical data relating to human bone has shown that with old age, there are statistically significant reductions in load carrying capability, when compared with youth (Yamada, 1970). Yamada showed that bones were only able to resist 78% of the mechanical forces applied to them by the age of 70-79, in comparison to their peak at 20-29.

This reduction in biomechanical competence is supported by data from cadaver crash tests, which show that increasing age leads to greater probability of injury in the thorax and abdomen (Kent et al, 2005, Schmidt et al, 1994 a, b).

The reason for this reduction in the mechanical properties is due to a multitude of factors combining a reduction of the overall density, and structural competence (Figure 1), combined with changes in the biochemical makeup of the bone.

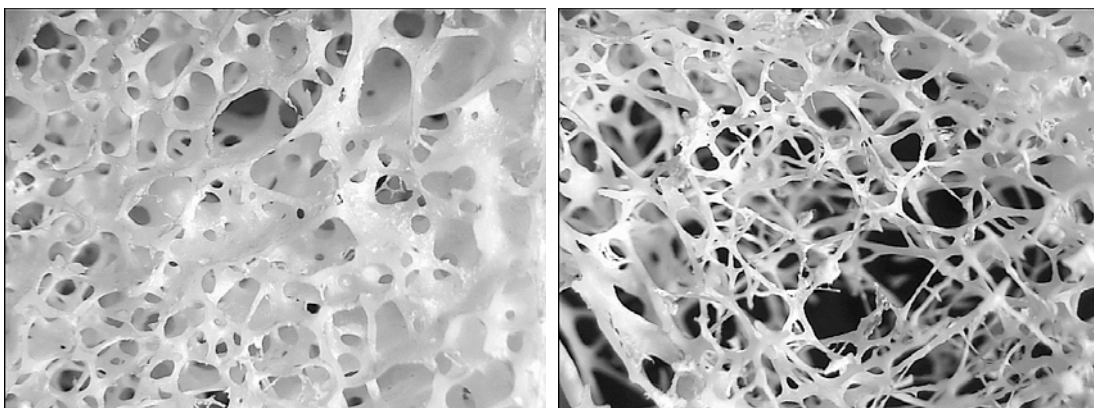


Figure 1. Bone structure of 54 year old female (left) and a 74 year old female (right), spongy bone from the hip, showing the degeneration of both the structure and density.

The easiest parameter for assessment of bone status is the reduction in density. This is the parameter used in the clinical environment for the diagnosis of low bone density and osteoporosis.

There are different systems clinically available for the measurement of the bone density, the technique considered to be the gold standard is dual energy X-ray absorptiometry (DXA). Others are available such as quantitative ultrasound (QUS), magnetic resonance imaging (MRI) and quantitative computed tomography (QCT).

The ultimate aim was to establish specific algorithms and relationships between one of the clinically available techniques so as to accurately predict the condition of the bone based solely on non-invasively acquired data. Existing bio-mechanical data was used as a reference point; however it was anticipated that this was not related quantitatively to the measurements gained from the selected technologies. Data and material was collected during two Winter and one Summer seasons, followed by the material studies on the collected tissue and correlation of the material properties with the clinical work.

THE BOSCOS DEVICE

The prototype system has been developed by McCue plc. using technology from their commercially available CUBA ClinicalTM system – an ultrasound system offering weight benefits and minimal health risks. The system is designed to assess the proximal phalangeal bone of the hand (Figure 2). The reasons for the selection of the finger, and in particular the proximal phalanx bones, for the measurement site are two fold. Firstly the proximal phalanx is used in clinical tests as a means of assessing a patient's bone status, and has been shown to have an ability to predict fracture risk (Ekman, 2002). Secondly it is the most readily available site for assessment of an individual in a car.

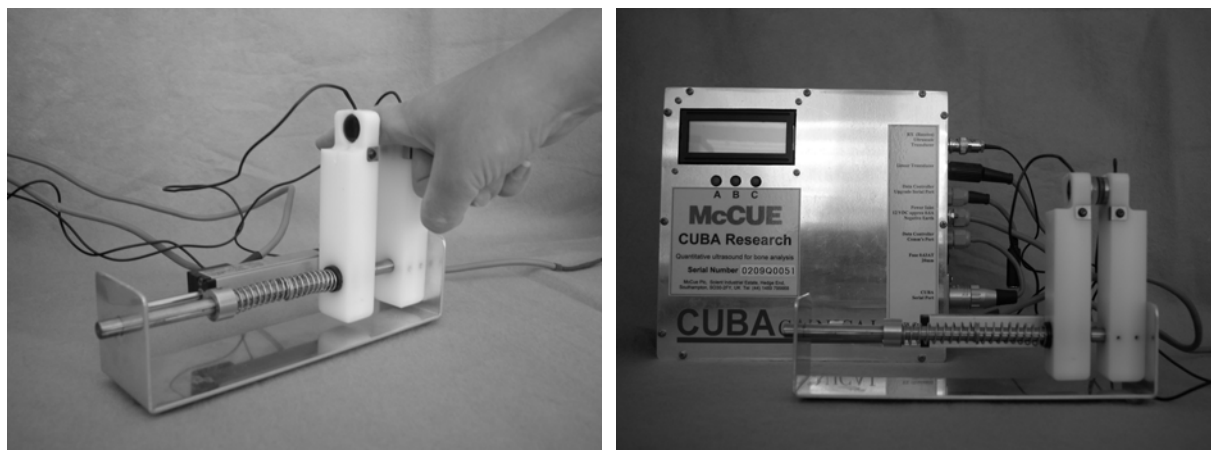


Figure 2. The BOSCOS Ultrasound Device

The system works by positioning two ultrasound transducers either side of the finger and an ultrasound pulse is transmitted between the two transducers through the finger. From the received pulse information on the condition of the bone can be determined from the amplitude of the received wave, and the time taken for the wave transmission through the finger. The prototype system was used to perform investigation on 102 subjects (7 males, 95 females) aged between 24 and 85 years of age (mean: 57 years). 10 waveforms were obtained from each individual, and analysed to give parameters relating to:

- The time incident of the first of the four greatest peaks assessed.
- The time and amplitude difference between the first and second peaks.
- The time between the first and fourth greatest peak.
- The area under the waveform.
- The amplitude of the biggest of the four peaks. (The maximum amplitude).

These parameters were used alone and in combination for the prediction of the bone status of the axial skeleton, as determined by DXA. The results showed that the best combination of the ultrasound

parameters with inclusion of an individual's age and weight, enabled the BOSCOS system to predict the status of a person's bone with an R^2 of not better than 50% (R^2 reflects the percentage of variability in the data that can be explained by the regression model). This is as good an R^2 value as those of the various clinically used commercial systems although such systems work without need of knowing the age and weight of the subject. When the prototype's best combined parameter (ultrasound+age+weight) was statistically analysed to assess the sensitivity and specificity of the prototype system, the prototype achieved AUC (area under curve) values in the region of 0.73-0.80 for the system's ROC (receiver operator characteristic) curve. Kent R, Patrie J (2005) have provided guidelines for the utility of discriminatory tools, based on AUC values of ROC curves. Systems with AUC below 0.7 can be considered to have little or no utility, in between 0.70-0.80 moderate utility; and in between 0.80-1.0 good utility. The BOSCOS system as it stands at the moment, shows a moderate level of diagnostic ability. But with the implementation of alternative superior (and more expensive) ultrasound transducers the diagnostic ability of the system will improve.

TISSUE ASSESSMENT

To investigate the relationship of clinical ultrasound and the biomechanics of human bone femoral heads were collected from 20 osteoporotic individuals undergoing hip replacement surgery due to broken necks of femur and 8 arthritic individuals undergoing elective surgery. Each individual was assessed using a CUBA Clinical system and a Sunlight Omnisense, to supply information on the bone status at the distal radius, proximal phalanx of the middle finger, mid-shaft tibia and calcaneus. The Sunlight Omnisense system had to be used instead of the BOSCOS prototype for ethical reasons. All scans were performed within three days after the operation had been performed.

Cores, 9mm in diameter, were taken from femoral head of each individual. The cores were cleaned of any marrow and fat using a high pressure water jet and washing in a 1:1 mixture of chloroform and methanol. Each core was then assessed for apparent and material density as well as porosity using the Archimedes principle and volume measurement using a micrometer. Each sample was then extended in length by the addition of a hard wood cap on either end (Figure 3).

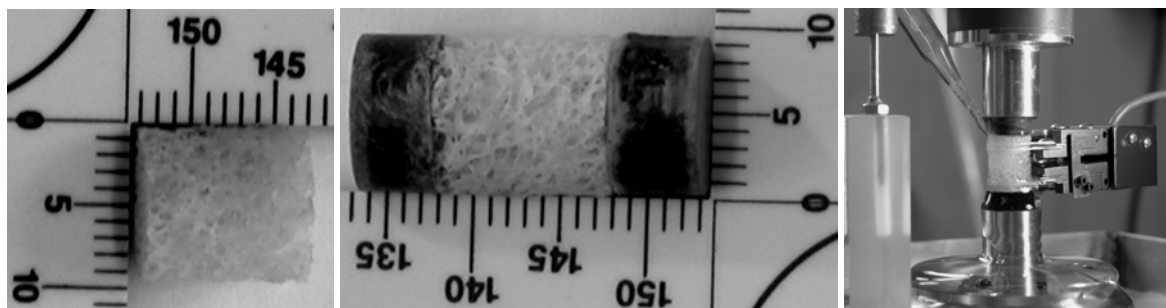


Figure 3a, b, c. Compression sample and test rig design.

Positioning of the samples between the platens was ensured by a 1mm deep depression on both loading platens, which constrained the samples and ensured that the sample was vertically aligned. The samples were preconditioned sinusoidally at 1Hz and a stroke of 50 microns and then tested in compression at a rate of 0.15mm s^{-1} (strain rate $\sim 1\% \text{ s}^{-1}$). In order to gain data relating to the change in length of the specimen during testing three transducer readings were used: (i) a miniature extensometer with a 6mm gauge length, was attached directly to the sample surface; (ii) a Linear Variable Differential Transformer (LVDT) attached between the loading platens; (iii) another LVDT was built into the testing rig to control stroke motion.

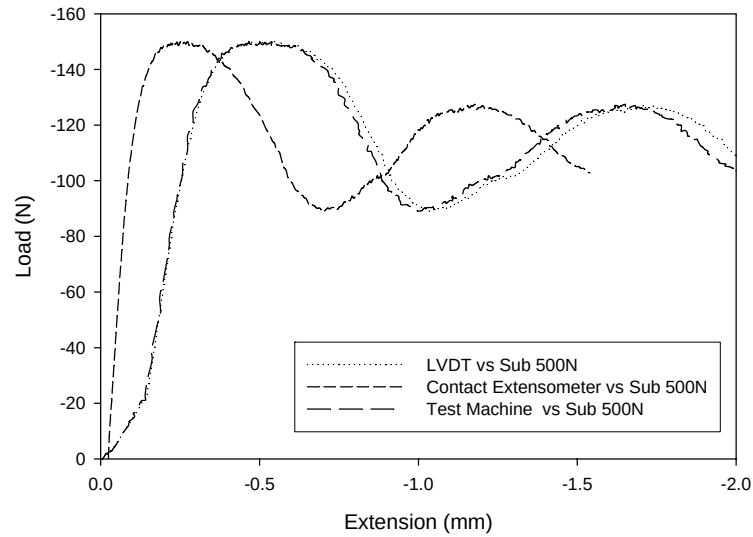


Figure 4. Comparative output of force/deformation curves from the 3 extension transducers.

From the resultant load extension curves (Figure 4) it was possible to obtain reliable values of Young's Modulus, yield and failure strain and yield and failure stress.

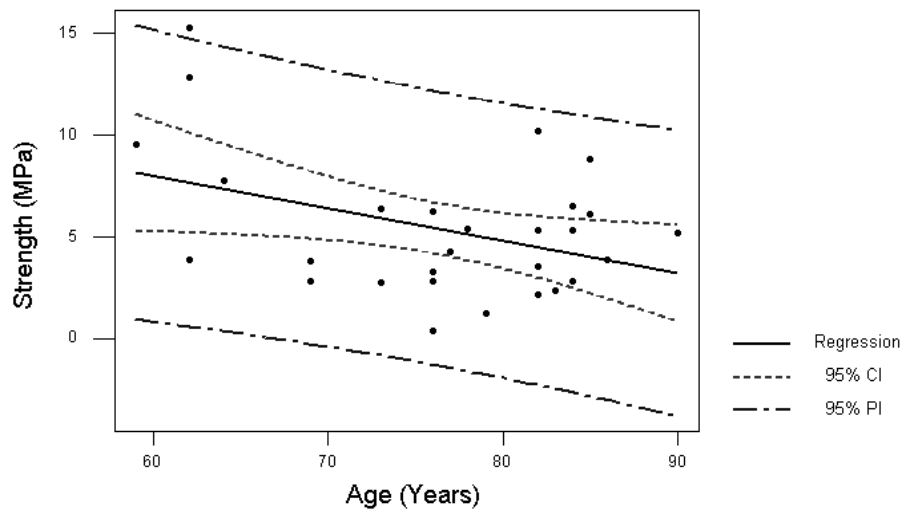


Figure 5. Comparison of strength with age.

Note: 95% CI represents the 95% confidence intervals, which provide information of the range of possible values for a data set, with 95% of the results falling within these bands.

95% PI represents the 95% prediction intervals, which provide boundaries into which 95% of any new values added would be predicted to fall.

Figure 5 shows a clear reduction (statistically significant, $p < 0.05$) in the strength of the trabecular bone in relation to age. When the strength is compared against the ultrasound assessment of the proximal phalanx (Figure 6) a positive statistically significant ($p < 0.05$) relationship is seen between the two variables.

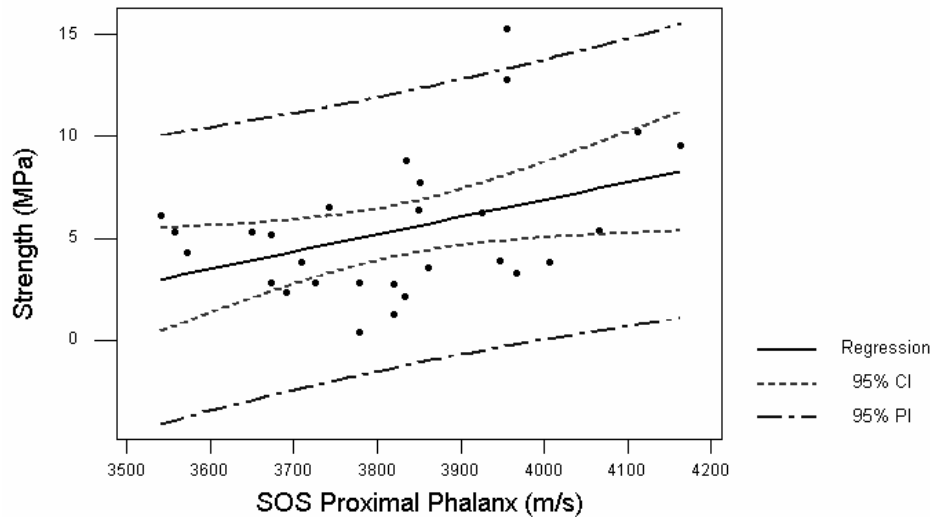


Figure 6. Comparison of strength with speed of sound measurements from the proximal phalanx.

	<i>Age</i>	<i>Distal Radius</i>	<i>Proximal Phalanx</i>	<i>Mid-shaft Tibia</i>	<i>BUA* Calcaneus</i>	<i>SOS Calcaneus</i>
Ultimate Strength	-0.387 (0.038)	0.362 (0.054)	0.403 (0.033)	0.221 (0.259)	0.307 (0.105)	0.372 (0.047)
Young's Modulus	-0.016 (0.933)	0.178 (0.357)	0.349 (0.068)	0.183 (0.351)	0.152 (0.431)	0.221 (0.249)
Yield Strength	-0.395 (0.034)	0.311 (0.1)	0.414 (0.029)	0.209 (0.287)	0.357 (0.058)	0.444 (0.016)

* BUA – Broadband Ultrasound Attenuation, a measure of the attenuation an ultrasound signal undergoes as it passes through the bone. The quality of the bone affects the level of attenuation.

Table 1. Pearson's correlation coefficients (p-value) between age, clinical ultrasound measurement values and biomechanical parameters (grey cells, $p < 0.05$).

Similar results (Table 1) were observed for the other clinical measurements versus the ultimate and yield strength, and modulus of elasticity values, however only the proximal phalanx and SOS of the calcaneus achieved any level of statistical significance. The results show that ultrasound assessment of the phalanx has the potential ability to predict the mechanical properties of the axial skeleton.

REAL-WORLD INJURY ASSESSMENTS

REAL WORLD in-depth crash injury data was used to identify the types of crashes and occupants who would most benefit from the BOSCOS system and to determine the injury/cost reduction benefits of such a system. The accident data provided a basis for the modelling of the current injury situation. This baseline was the starting point from which to assess the potential effectiveness of modified restraint systems. The real-world data was collected by the UK Co-Operative Crash Injury Study (CCIS), which samples accidents based on vehicle age and injury outcome (Mackay et al, 1985). To enter the sample, an accident must include at least one towed car less than seven years old in which an occupant was injured. The data are also collected within a stratified sample which is biased towards 'fatal' and 'serious' injury outcome. Of all crashes occurring in the geographical sampling regions, approximately 80% of all fatal and serious accidents, and 10-15% of slight injury crashes are investigated.

Because the CCIS sampling is biased toward serious and fatal injury outcomes, it was necessary to weight the data so that it was representative of the whole population of injury, tow-away accidents. To

do this, weighting factors were calculated which correct the under-representation of slight injury accidents. Accidents which occurred between 1995 and 2005 were examined.

IMPACT TYPE: Initially, it was intended to examine as many different impact types as possible. 73% of belted front seat occupants who sustained an AIS 2+ injury were involved in either frontal or side impacts. Impacts such as rollovers and under-runs were not considered, since not only is occurrence of these impact types low, but mathematical modelling of such impacts is difficult due to their inherent variability. Although side impacts make up around 23% of occupants with MAIS 2+ injury, it was decided not to attempt to apply the BOSCOS system to side impacts at this stage and to restrict the investigation to frontal crashes only, which still covered 57% of the MAIS 2+ occupants in the database. However, it was anticipated that the application of BOSCOS to side impacts could provide the basis for further development work in the future.

BODY REGIONS AND TYPES OF INJURY: The next stage of problem definition was to identify the body regions and types of injury that were most likely to be mitigated with the introduction of a BOSCOS system. Since the basis of such a device was to adapt the restraint system according to the skeletal strength of the occupant, it follows that skeletal injuries are those most likely to be reduced. Obviously a reduction in skeletal injury resulting from “softer” restraints is also likely to be accompanied by a reduction on the occurrence of soft tissue injuries, although the exact influence on these types of injuries will be harder to determine.

Figure 7 shows the location of skeletal injuries for belted drivers with airbags (Lenard et al, 1998a). It is clear that the body regions of concern in this context were the chest and extremities. Since injuries to the chest are likely to pose a higher threat to life than those to the extremities, AIS 2+ chest injuries provided the focus for the initial development of BOSCOS.

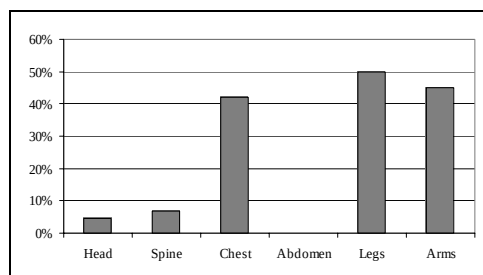


Figure 7. Location of skeletal injury for belted drivers with airbags

The BOSCOS sample consisted of 4821 belted drivers in cars equipped with airbags and pretensioners involved in frontal crashes. Table 2 shows the distribution of maximum chest injury severity for those drivers.

Chest AIS	N	%
0	2927	60
1	1590	33
2+	304	7
Total	4821	100

Table 2. Maximum Chest Injury Severity for Belted Drivers (weighted data)

304 drivers sustained AIS 2+ chest injury. 214 (70%) had sustained their injuries from the seat belt. Injury causation for the remaining 30% was unclear and likely due to a combination of mechanisms. The BOSCOS system would benefit these drivers as well but to a more limited extent. 71% of all serious (AIS 2+) chest injuries were fractures to the ribs or sternum. In crashes where the crash severity is known, as determined by an ETS calculation, 75% of injuries occurred at speeds lower than 56km/h, the current basis for legislative testing. ETS is the vehicle delta v, calculated on

the assumption that deformation was caused by impact with a fixed rigid barrier (Lenard et al, 1998b). Since 96% of these cases below 56km/h sustained little or no facia intrusion (<4cm) it is clear that there is the potential for an adaptive restraint system to provide significant benefit to chest injury risk.

OCCUPANT TYPES: It is widely accepted that human bone strength decreases with age, and as such it is expected that the benefits of a BOSCOS system will be of greater magnitude to the elderly. With the ageing population of the UK, the societal benefit as a whole will increase as more and more older drivers and passengers become exposed to the increased risk of injury attributable to a decrease in bone strength. It is expected however that a BOSCOS system will also be of benefit to younger occupants with weaker bone structures. The ability of the BOSCOS system to measure bone strength means that sufferers of conditions such as osteoporosis will be detected and the restraint system tailored to them as much as is practicable.

ACCIDENT MATRIX

The BOSCOS target group consisted of 214 drivers with AIS 2+ chest injury from the seat belt. This group was used as the basis for the next stage of the work – development of a matrix of accident scenarios to be replicated with mathematical models.

One of the limitations of mathematical modelling is that models have to be validated by full-scale crash tests to ensure that the results produced are valid. Since the motor industry has a need to optimise performance for legislative and consumer tests, there is no guarantee that extrapolating the models outside these types of impact will produce valid results. For this reason, the BOSCOS target group was categorised into the following impact types (scenarios) to represent the crash conditions associated with AIS 2+ seat belt injury. The percentages in brackets show how much of the target group was covered by each scenario.

- Full overlap – Greater than 85% overlap. ETS between 25 km/h and 45 km/h (40%)
- Offset – Less than 55% overlap. ETS of 28 km/h (31%)
- One chassis rail plus engine - An overlap of 75% and ETS of 40 km/h (24%)

BASELINE MATHEMATICAL MODELLING

A series of mathematical modelling studies were conducted to investigate the four accident scenarios. Madymo models were developed for two vehicle sizes to represent typical driver configurations - vehicles A (small size) and B (large size).

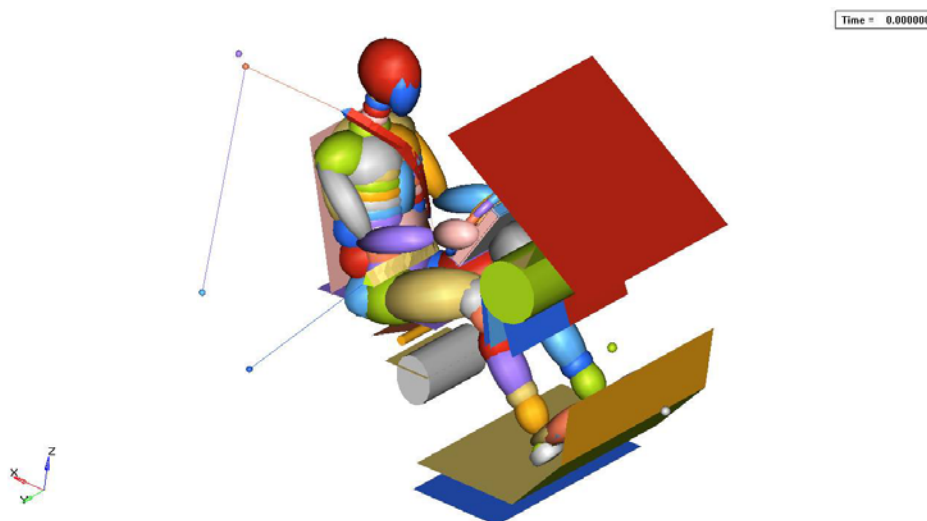


Figure 8. Madymo Model Set-Up

A Hybrid III dummy model was used with a seating and interior design unique to each vehicle together with the standard airbag and three-point seatbelt systems. For vehicle A, a seat belt load limiter value of 6kN was selected for the baseline simulations (Figure 8).

The models were able to predict the levels of acceleration, belt loads and trajectories of body parts. For each different configuration these criteria provided an indication of the severity of the crash pulses.

The base line simulation results for the four scenarios are shown in Table 3. The 45kph scenario gives the highest HIC and CTI calculation, whereas the 28kph 55% offset gives the lowest injury indices.

Base	45kph	25kph	40kph	28kph
	100%	100%	75%	55%
HIC	392	66	271	65
Head Accel.	565	246	494	222
Upper Torso Accel.	377	241	365	206
Lower Torso Accel.	523	275	493	252
Sternum Deflection	29.1	22.1	28.4	22.1
CTI calculation	0.73	0.50	0.71	0.46

Table 3. Baseline Results

ASSESSMENT AND VALIDATION OF CHEST INJURY RISK

It was necessary to provide a method of read across from simulation output to a real injury value using injury risk curves in order to give an estimate of real-world benefit for the BOSCOS system. For chest injuries the simulations provided dummy chest deflection, acceleration and the Combined Thoracic Index (CTI). The CTI is a measure of chest injury severity based on a combination of chest compression and acceleration. Injury risk curves for each parameter were derived from data provided by NHTSA (Eppinger et al, 1999). Table 3 shows the predicted injury risk from each of these parameters compared to the risk from accident data. The accident data was focussed into groups which very closely matched the simulated scenarios both in terms of front overlap and crash severity.

Impact Type	Vehicle A			Vehicle B			Real Crashes	
	2+ risk acceleration	2+ risk chest deflection	2+ risk CTI	2+ risk acceleration	2+ risk chest deflection	2+ risk CTI	2+ risk accident data	ETS range km/h (N)
45 km/h 100%	68%	35%	33%	66%	37%	30%	24%	40-50 (63)
25 km/h 100%	52%	27%	11%	46%	28%	9%	6%	20-30 (184)
40 km/h 75%	68%	34%	33%	54%	37%	19%	20%	35-45 (59)
28 km/h 55%	45%	26%	9%	43%	32%	9%	10%	23-33 (188)

Table 4. Predicted versus Real Risk Of AIS 2+ Chest Injury

Table 4 shows the CTI giving a much better approximation to real world injury risk than either acceleration or deflection alone. For both vehicle simulations, acceleration and deflection appear to overestimate the risk of AIS 2+ chest injury. CTI was therefore the chest injury measure of choice for assessing the benefits of BOSCOS.

PARAMETRIC MATHEMATICAL MODELLING

Using the vehicle A baseline mathematical model a number of different simulations were executed to evaluate different seatbelt load limiter settings, different airbags and pre-tensioner settings. One of the changes was made to the load limiter value to reduce the load level to 2kN. By reducing the load limit the chest was not expected to experience a severe loading from the seatbelt and it would allow the seatbelt to pay-out more webbing when compared to the baseline simulations.

For the higher speed scenarios the extra pay-out of the seatbelt did not improved the indices with the CTI increasing to 0.97 for the 45kph scenario (Table 5). However at the lower speed scenarios the CTI has decreased from 0.46 to 0.35.

2kN	45kph	25kph	40kph	28kph
	100%	100%	75%	55%
HIC	336	68	357	61
Head Accel.	571	248	536	231
Upper Torso Accel.	569	207	450	159
Lower Torso Accel.	534	359	502	253
Sternum Deflection	30.8	19.2	30.8	16.7
CTI calculation	0.97	0.43	0.83	0.35

Table 5. 2kN Load Limiter Results

The load limiting value could be modified for different crash pulses, although as has been shown by these simulations it would be of most benefit at the lower crash speeds. With information regarding the skeletal strength of the occupant the restraint system could make a decision to change the load limiting value at an appropriate time through the crash cycle, not necessarily at the start of the impact. The drop in CTI value is an example of how a BOSCOS type system can reduce the injury indices for a specific crash pulse by selecting a 2kN load limiter in preference to the standard 6kN value. The example of the 2kN load limiter change in dummy indices has been developed later on in this paper to show how the change of CTI level influences a change in AIS level over a number of real world accidents.

BOSCOS BENEFIT STUDY

INJURY RISKS: The benefits of the BOSCOS system were measured in terms of both a reduction in injury risk and a corresponding reduction in injury costs. Seat belt performance parameters were changed in the simulations of crash conditions causing AIS 2+ chest injury to real drivers. The belt system giving the lowest risk of AIS 2+ injury for older drivers was then chosen and fed into the accident data to give an indication of optimum benefit. The NHTSA risk curves (Eppinger et al, 1999) for CTI are based on the 50% probability of risk for cadavers adjusted down to a 25% probability for the driving population. For BOSCOS, the chest injury risk curves were adjusted back to the injury probability for cadavers to give an indication of risk for people with weaker bones (Figure 9).

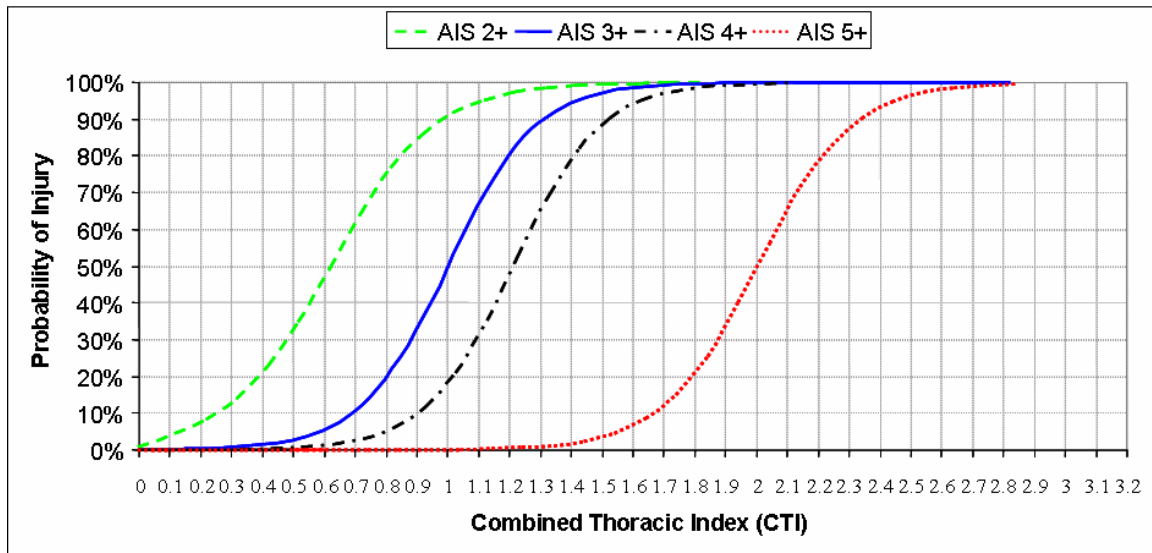


Figure 9. Chest Injury Risk Curves for Weaker Bones

Simulation results showed that employing a 2kN load limiter in low speed crashes gave the greatest risk reduction in AIS 2+ chest injuries for persons with weaker bones. Figure 10 and Figure 11 show the injury risks for a 2kN load limiter compared to those for other seatbelt types in low speed crashes. It can also be seen that head and thigh injury risks are predicted as negligible in the low speed crashes, irrespective of the belt system used.

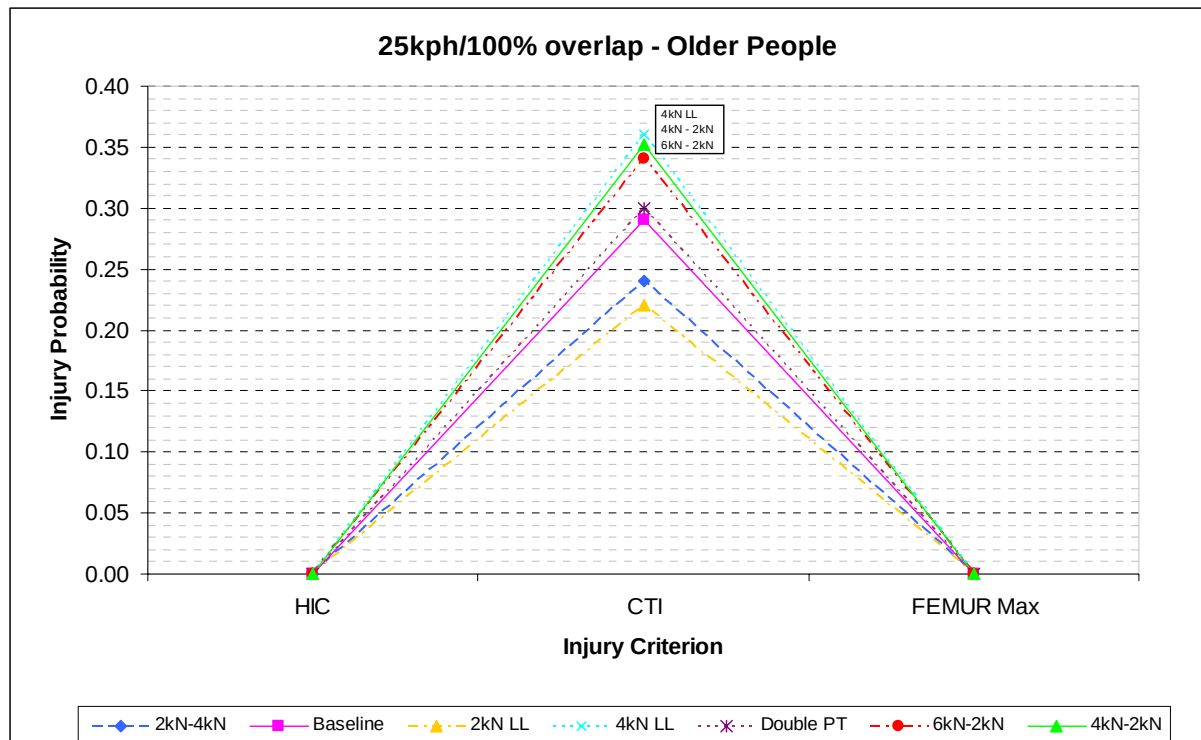


Figure 10. Injury Risk for Weaker Boned Persons in 25 km/h Full Overlap

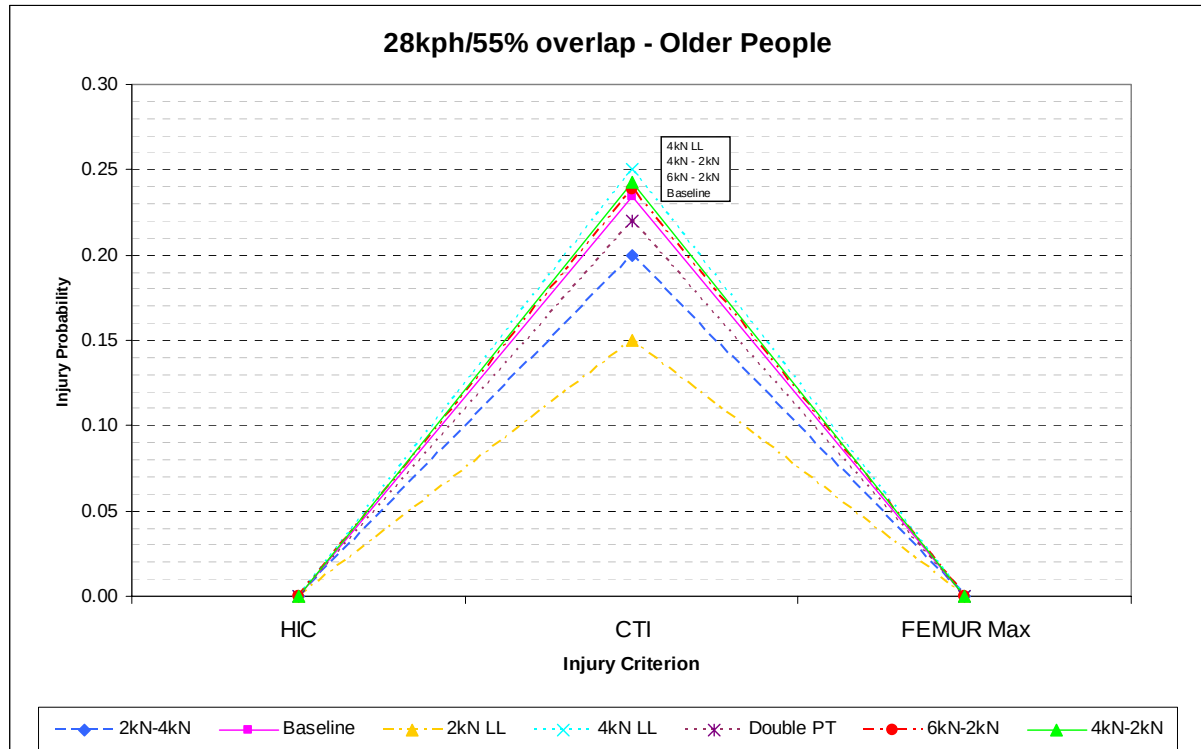


Figure 11. Injury Risk for Weaker Boned Persons in 28 km/h Offset

Although the AIS 2+ chest injury risk was lowest using the 2KN load limiter, the benefits calculation required the most probable injury outcome in terms of a discrete AIS level injury. A technique developed in the European Commission VC Compat project (VC-COMPAT, 2003) was used to determine the chest AIS for weaker boned people in the simulated low speed crashes. The calculation is shown in Figure 12.

Expected AIS level

$$E(X_{CTI}) = \sum_{i=1}^6 w_i P_{w_i}(X_{CTI})$$

$E(X_{CTI})$ = Expected AIS score for injury X_{CTI}
 X_{CTI} = Injury criterion value X_{CTI}
 w_i = Discrete value of AIS level (e.g. $w_2 = w_{2+} - w_{3+}$)
 $P(X_{CTI}, w_i)$ = Probability of injury criterion value X_{CTI} at given AIS level w_i , e.g. $P(1, w_2) = P(1, w_{2+}) - P(1, w_{3+})$

Figure 12. Calculation of Discrete AIS level

CTI values for the low speed simulations suggest that weaker boned persons would likely receive only AIS 1 chest injury with a 2KN load limiter. Therefore, it was assumed that, in the real crashes represented by the low speed simulations, AIS 2+ chest injuries for men over 60 and women over 50 could be reduced to AIS 1, if bone strength was known and a 2KN load limiter deployed. This change in injury outcome was used to show the potential benefits of BOSCOS for the whole population of drivers with AIS 2+ chest injury from the belt.

The benefits of changing the restraint system parameters were not as apparent in the higher speed simulations. To give a predicted chest injury outcome of AIS 1 in those impacts, the necessary reduction in CTI for the best performing restraints was calculated. Changing CTI from 0.67 to 0.55 in the 40 km/h model and from 0.71 to 0.53 in the 45 km/h model would show an enhancement of the system by benefiting higher severity crashes in the accident population. This change was used to show

the benefits of an Enhanced BOSCOS system for the whole population of drivers with AIS 2+ chest injury from the belt.

Figure 13 shows the potential real-world benefits of BOSCOS and an Enhanced BOSCOS system compared to the current baseline risk of AIS 2+ chest injury from the seat belt.

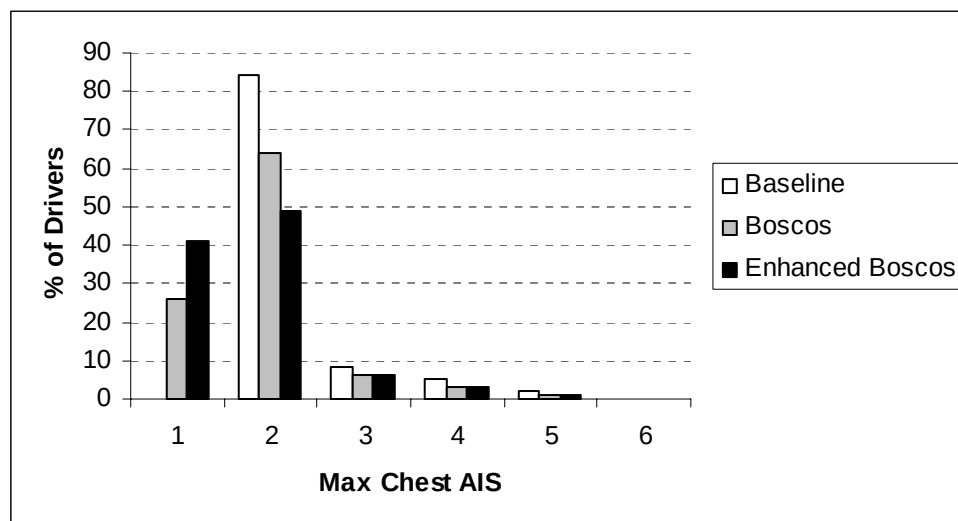


Figure 13. Injury Reduction Benefits for Drivers with AIS 2+ Chest Injury from the Seat Belt (N=214)

There is a clear indication that tailoring belt performance to bone strength could give injury reduction benefits. Figure 13 shows that a sizeable number of AIS 2 chest injuries could be downgraded to AIS 1 utilizing BOSCOS in low speed impacts. Additionally, there would also be some benefit for the small number of drivers with more serious chest injury. Reductions to chest loads in higher speed impacts gives additional benefit. Under those circumstances however, care would be needed to ensure head injury protection was not compromised.

INJURY COSTS: Evaluating changes in injury costs gives a measure which can be used to offset costs incurred by proposed BOSCOS systems. Several cost benefit scales were considered including HARM (Malliaris et al, 1985, Miller et al, 1991). HARM was not considered because injury costs in Europe do not exist in an appropriate usable form. Instead, the ‘Willingness to Pay’ approach was used (Hopkirk and Simpson, 1995). This approach enables the calculation of the human cost of serious and slight injuries. A Standard Gamble questionnaire was used to carry out a survey, asking people how much they would be willing to pay to reduce the risk of injury, relative to the cost of a fatality (Road Casualties Great Britain, 2002). The respondents were also asked to specify the level of risk at which they would opt for treatment of an injury. It was then possible to convert the survey results into values relative to the cost of death and as a percentage value of death. Therefore the human cost of each injury state can be expressed as a percentage of the human cost of a fatality. Human costs do not include medical and support costs, lost output of the individual, or accident damage, although these can also be calculated. ‘Human costs reflect the non-resource element of the cost of road accident casualties; the pain and distress suffered by accident victims, their family and friends, and in the case of fatalities, the intrinsic loss of enjoyment of life, beyond the consumption of goods and services.’ (Hopkirk and Simpson, 1995.)

The serious and slight injury states considered are shown in Table 6.

Injury State	% of death	(2002 prices)
Recover 3-4 months (Out-patient): F	2.0	£24,998
Recover 3-4 months (In patient): W	2.0	£24,998
Recover 1-3 years (in-patient): X	5.5	£68,744
Mild permanent disability (Out patient): V	5.5	£68,744
Mild permanent disability (In patient): S	15.1	£188,733
Some permanent disability with scarring: R	23.3	£291,224
Paraplegia/quadruplegia: N	100	£1,249,890
Severe head injuries L	100	£1,249,890
Cost of UK road accident fatality		£1,249,890
Whiplash		£43,944
Other Slight injury		£8,966

Table 6. Injury State Costs

It was possible to map the individual chest injuries in the BOSCOS sample onto the costing scale (VSRC Injury Costings, 2005). All except two of the database chest injuries can be attributed to the AIS level costs shown in Table 7. This enables the calculation of the cost of a chest injury, based on its AIS level. Multiplying the cost of the maximum chest injury severity by its occurrence allows the chest injury cost comparison shown in Table 8.

Example	AIS Level	2002 Cost
Rib Fracture	1	£8,966
Sternum Fracture	2	£24,998
Unilateral Lung Contusion	3	£24,998
Flail Chest	4	£68,744
Tension Pneumothorax	5	£68,744

Table 7. Cost of Thoracic Injuries in BOSCOS Dataset by AIS Level

AIS level	Baseline	BOSCOS	Enhanced BOSCOS
1	£0	+ £502,096	+ £780,042
2	£4,524,638	- £1,124,910	- £1,899,848
3	£449,964	- £99,992	- £99,992
4	£756,184	- £343,720	- £343,720
5	£274,976	- £137,488	- £137,488
Total (£)	6,005,762	4,801,748	4,304,756
Total (€)	8,708,355	6,962,535	6,241,896

Table 8. Cost Benefits of BOSCOS System & Enhanced BOSCOS System

Table 8 shows that had a BOSCOS system been implemented in the data sample areas, over the time frame studied and for the types of crash and vehicles considered then around 1.7 million Euro would have been saved due to chest injury costs. BOSCOS implementation in higher speed crashes would have improved the cost saving by a further 0.7 million Euro.

DISCUSSION

The BOSCOS project was an initial investigation into the possibility of in-car scanning to deliver more optimally adjusted restraint systems for individual occupants' biomechanical limits. The prototype scanner is just that, a prototype and further development will be needed to improve signal resolution and achieve a miniaturised version that can be successfully integrated into a vehicle at each occupant seating position. The development of a larger database would improve read across from the phalangeal scan to the skeletal capabilities of the ribs. In addition, the number of computer simulations conducted was lower than the number a restraint system manufacture would conduct to fully optimise a product for a particular vehicle.

Nevertheless, the estimate of BOSCOS benefits show a 20% reduction in injury costs if the system were to be implemented for women over 50 and men over 60 in low speed crashes. That in itself is a substantial benefit for a restraint system. In addition, were the system to be implemented in higher speed crashes, then the benefits would rise to 28%.

These savings however are quite probably an under-estimate of BOSCOS benefits because they were calculated only for the CCIS sample of crashes. If we were able to take account of the whole of the UK and the rest of Europe and include benefits for younger, weak boned drivers, then add a factor for the increase in numbers of elderly car drivers over the next two decades the BOSCOS potential could be very substantial indeed. The Organisation for Economic Co-operation and Development estimate that, in western countries by the year 2030, one in every four persons will be aged 65 or over (Morris et al, 2002). It is estimated that, over the next three decades private car travel by this sector of the population is likely to increase at a rate consistent with growth in the number of older adults in the population as a whole.

CONCLUSIONS

The BOSCOS project has set out to identify the best means of calculating the bone strengths of vehicle occupants. The ultrasound technology has been selected as the most effective and safe tool to use and highlighted its benefits through scans of human subjects. Different ultrasound devices have been evaluated and a new prototype device has been built which could be adapted for in-car use. Real world vehicle accident data has been assessed to determine which accidents are causing chest injuries. A number of accident scenarios have been selected and they have been used in the mathematical modelling. New restraint technologies have been identified which could be enhanced with the addition of BOSCOS type technology and demonstrated to have lower injury risk potential. A method has been established to map dummy indices to real-world injury risk by AIS levels. Furthermore, the risk levels have been associated with costs which showed that a BOSCOS system can provide a saving in chest injury costs.

CCIS – acknowledgment.

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REFERENCES

- Ekman, A., et al., Dual X-ray Absorptiometry of Hip, Heel Ultrasound, and Densitometry of Fingers Can Discriminate Male Patients with Hip Fractures from Control Subjects, *Journal of Clinical Densitometry* 2002 5(1): p. 79-85.
- Eppinger, R., Sun, E., Bandak, F., et al. Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II. National Highway Traffic Safety Administration, November, 1999.
- Hopkin J. M. & Simpson H., Valuation of Road Accidents, TRL Research Report 163, Transport Research Laboratory, Crowthorne, 1995.
- Improvement of Vehicle Crash Compatibility through the Development of Crash test Procedures (VC Compat). <http://vc-compat.rtdproject.net/>, 2003.
- Kent, R. and Patrie, J. (2004), *Forensic Science International*, Article in Press.
- Lenard, J., Frampton, R. J., Thomas, P. The Influence of European Airbags on Crash Injury Outcomes, *Proceedings 16th ESV Conf*, Windsor, 1998a, p. 972-982.
- Lenard, J., Hurley, B., Thomas, P. The Accuracy of CRASH3 for Calculating Collision Severity in Modern European Cars, *Procs 16th ESV Conf*, Windsor, 1998b, p. 1242-1249.
- Mackay, G. M., Galer. M. D., Ashton, S. J., et al. The Methodology of In-depth Studies of Car Crashes in Britain. SAE Technical Paper Number 850556, Society of Automotive Engineers, Warrendale, PA, 1985.
- Malliaris A. C. et al., Harm Causation and Ranking in Car Crashes. SAE 850090, Society of Automotive Engineers, Warrendale, PA, 1985.
- Miller T. R. et al., Motor Vehicle Injury Costs by Body Region and Severity, *Proceedings of the Annual Conference of the Advancement of Automotive Medicine*, 34, Scottsdale, AZ, 1990, pp. 97-110.
- Morris A. P. et al., An Overview of the Requirements for the Crash Protection of Older Drivers, *Proceedings of the Annual Conference of the Advancement of Automotive Medicine*, 46, Tempe, AZ, 2002, pp. 141-156.
- Road Casualties Great Britain 2003: Annual Report, Department for Transport, National Statistics, 2004.
- Schmidt, G., Kallieris, D., Barz, J. and Mattern, R. (1994a), Biomechanics of impact injury and injury tolerances of the thorax-shoulder complex, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 311-316.
- Schmidt, G., Kallieris, D., Barz, J., Mattern, R. and Klaiber, J. (1994b), Biomechanics of impact injury and injury tolerances of the thorax-shoulder complex, Vol. PT-45 (Ed, Backaitis, S. H.) Society of Automotive Engineers, Inc., pp. 371-399.
- VSRC Injury Costings, developed by Vehicle Safety Research Centre for use in the UK Department For Transport Secondary Safety Priorities (SSP) Project – research currently in progress.
- Yamada, H. (1970), *Strength of Biological Materials* (Ed, Evan, F. G.) Williams and Wilkins Company, Baltimore, pp. 2.

● *Original Contribution*

THE ABILITY OF PERIPHERAL QUANTITATIVE ULTRASOUND TO IDENTIFY PATIENTS WITH LOW BONE MINERAL DENSITY IN THE HIP OR SPINE

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Abstract—This study aims to assess the sensitivity and specificity of two commercially available quantitative ultrasound (QUS) scanners (CUBA ClinicalTM, Sunlight OmnisenseTM), to differentiate patients with osteoporosis (OP) or osteopenia at the spine and hip confirmed by dual-energy x-ray absorptiometry (DXA) and to investigate the optimum cut-off values to maximize the effectiveness of the screening technique. Participants ($n = 268$) received DXA scans on their lumbar spine (L1–L4) and hip, with paired QUS scans on their distal radius, proximal phalanx, midshaft tibia and calcaneus. Scanners were evaluated by using receiver-operating characteristics curves and their area under the curve (AUC) values. Measurement of the calcaneus by the CUBA ClinicalTM showed a superior ability to predict DXA, with AUC values between 0.75 to 0.83 in comparison with AUC values of 0.60 to 0.70 for the Sunlight OmnisenseTM. Cut-off values varied according to the technique used and the accuracy of the screening required. Assessment of the calcaneus was the best QUS technique for the prediction of low bone density at the axial skeleton as diagnosed by DXA. (E-mail: p.zioupou@cranfield.ac.uk)
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Key Words: Osteoporosis, Screening, Specificity, Sensitivity, DXA, Ultrasound scanners.

INTRODUCTION

Dual energy x-ray absorptiometry (DXA) is widely seen as the “gold standard” for bone densitometry, supplying results of bone mineral density (BMD) (g/cm^2) for various axial or peripheral sites on the skeleton, but it has certain limitations in its clinical or widespread use in comparison with ultrasound (US). Quantitative US (QUS) measurement of bone is increasingly now becoming a recognized method of determining bone quality, with review papers written discussing the technique’s abilities and usefulness (Hans et al. 1993; Kaufman and Einhorn 1993; Glüer 1997; Gregg et al. 1997; Njeh et al. 1997). QUS scanners, in particular, have advantages in that they are portable, less expensive than X-ray-based technologies, do not use ionizing radiation and do not require a skilled radiographer to perform the measurements.

The Sunlight OmnisenseTM (Sunlight Medical, Rehovot, Israel) and the CUBA ClinicalTM (McCue plc., Winchester, UK) are two such portable QUS machines.

The Sunlight OmnisenseTM has the capability to scan the distal radius, the proximal phalanx and the midshaft tibia and supplies results as speed of sound (SOS) (m/s) transmitted through the cortical bone at the measurement site. The CUBA ClinicalTM works on the status and properties of the mostly cancellous bone material of the calcaneus, by supplying either or both broadband US attenuation (BUA) in dB/MHz and velocity of sound (VOS) (m/s). Both DXA scanners and QUS scanners show results in T-score values, which can be calculated simply as: $T\text{-score} = (\text{subject measurement} - \text{peak young adult mean})/(\text{SD peak young adult mean})$. This method allows for a quantitative definition of osteopenia and osteoporosis, the levels for which (at least for DXA) have been set by the World Health Organization (WHO) (Kanis et al. 1994), and also allows for direct comparison of bone status at different measurement sites by using the same analytical approach.

Although work has been performed comparing different calcaneal assessment devices on the market for their abilities (Njeh et al. 1997, 2000), the authors are unaware of any studies comparing the Sunlight OmnisenseTM with the CUBA ClinicalTM and for a section of

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the population similar to the one we have reviewed here. Given the different physical principles employed by these two scanners, the different parts of bone matrix and the different skeletal sites, such comparisons would be very interesting. The aim of this study, therefore, was to assess the ability of these two US scanners, either in isolation or in combined modes, to differentiate patients with osteoporosis (OP) or osteopenia at the spine and hip confirmed by DXA, and to relate this to the performance for the various measurement sites. From the clinical management point of view, our interests were both to establish what percentage of OP patients would be missed if simply US were used and, also, what percentage of normals would have to be scanned unnecessarily, who otherwise have good bone mineral density.

MATERIALS AND METHODS

Subjects and experimental design

The study was approved by the ethical research committee of Swindon and Marlborough NHS Trust. Informed consent was given by 268 Caucasian females, of pre-, peri- and postmenopausal status, who were attending the DXA scanning sessions at the Great Western Hospital, Swindon, UK. A total of 22 patients were excluded from the analysis because of incomplete sets of investigations. No other exclusion criterion was imposed on the group because we wished to view the QUS technique's ability to predict the DXA result, not to view the specific effect of osteoporotic risk factors.

Table 1 shows the anthropometric data for the study group. The patients received a DXA scan of their lumbar spine L1–L4 and four sites around the proximal femur, using a Hologic QDR-4500C, (Hologic Inc. Bedford, MA, USA). The patients received paired measurements on both the Sunlight Omnisense™ and the CUBA Clinical™, then completed a questionnaire designed to give relevant medical history and various lifestyle factors that might affect the patients' bones. In total, the patients were scanned at 12 sites, although, for the purpose of this study, the combined results supplied by the DXA scans for total hip BMD and L1–L4 BMD were used. All scans were performed on the nondominant side of the individual, with dominance being determined by asking the patient or, in cases of confusion, the use of simple questions that allowed for its identification.

Quality assurance checks were performed before each scanning session using the manufacturers' guidelines and phantoms. The short-term precision of the Sunlight Omnisense™ was previously reported to be 0.29% (0.24 to 0.37 95% CI) for the distal radius, 0.55% (0.46 to 0.7 95% CI) for the proximal phalanx and, for the CUBA Clinical™, 2.88% (2.39 to 3.62 95% CI) for the BUA and 0.31% (0.26 to 0.4 95% CI) for the VOS (Cook et al. 2003).

The method by which the Sunlight Omnisense™ performs its measurements is outlined in a number of papers (Njeh et al. 1999, 2001; Weiss et al. 2000; Knapp et al. 2001, 2002). The region-of-interest (ROI) for the distal radius was selected by measuring the distance from the point of the elbow (olecranon) to the tip of the middle finger, with the forearm in the supine position, the wrist straight and the fingers extended and fully adducted. This measurement is then divided in half, to give the point of measurement at approximately one third the length of the distal radius. The ROI for the proximal phalanx is selected by the measurement of the middle phalanx. The length of the middle phalanx is then measured from the interphalangeal joint back along the proximal phalanx toward the metacarpophalangeal joint. The operator takes a measurement by passing the probe repeatedly over the skin, above the ROI, in a 140° arc at the distal radius and a 180° arc at the proximal phalanx. Each arc should take approximately 5 s for the distal radius and 4 s for the proximal phalanx.

The measurement method for the CUBA Clinical™ was outlined by Langton et al. (1984, 1990). Positioning of the foot is important to ensure that the ROI of the calcaneus is positioned correctly between the transducers. The importance of the correct ROI selection has been discussed previously by Cheng et al. (2002). The CUBA Clinical™ requires the patient's foot to be assessed for size; the assessment is performed by using lines marked in the foot well and by assessment of the position of the tip of the big toe in relation to the lines, which indicates which of the inserts is required. The inserts are designed to raise the foot by a set distance from the floor of the foot well, so that the patient's calcaneus is positioned between the transducers.

The foot is then removed from the machine, the insert is put into place if required and the US gel is applied both to the transducers and to the patient's heel. The foot is replaced and the leg is supported with velcro straps that pass around the calf and prevent excessive movement of the heel during the measurement. The transducers are then closed so that they apply light pressure to either side of the calcaneus.

The measurement is taken by using the CUBA^{PLUS+™} software version 4. This takes about 1 min, including an initial 30 s settling period to allow for

Table 1. Anthropometric data for the study group

	Range	Mean	SD
Age	28–84	57.4	12.1
BMI (kg/m ²)	15.7–44.6	25	4.4
Height (cm)	137.2–182.9	161.6	7.1
Weight (kg)	41.3–114.3	64.9	12

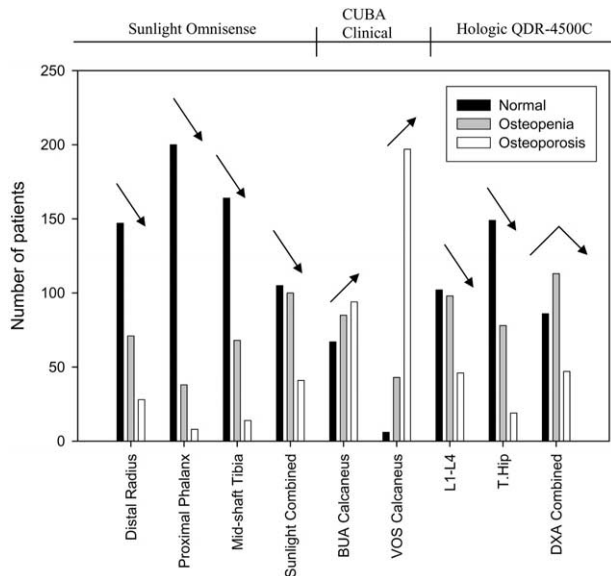


Fig. 1. Classification of the sample group, according to their T-score results.

any air bubbles in the gel to be removed and for some compression of the surrounding soft tissue. The measurement is then taken and the transducers are opened, releasing the heel.

Discriminatory ability

The results from the 246 patients were separated into three groups according to the T-score value that was supplied by the different machines. The three groups were classified as normal, osteopenic and osteoporotic; the levels used to differentiate the groups differed between machines, depending on the manufacturers' recommendations. The Sunlight Omnisense™ and the Hologic QDR-4500C adhere to the levels set out by the WHO (Kanis *et al.* 1994), normal (T-score > -1), osteopenic ($-1 \leq \text{T-score} < -2.5$) and osteoporotic (T-score ≤ -2.5). For the CUBA Clinical™, the manufacturer recommends a cut-off level of normal (T-score > -1), osteopenic ($-1 \leq \text{T-score} < -2$) and osteopo-

rotic (T-score ≤ -2), but had no formal cut-off level for VOS, so that, for VOS, the WHO definition was applied. The three groups were then plotted to show any trends (Fig. 1) and the discriminatory ability of the different techniques. The kappa scores were calculated as a formal comparison of the technique's discriminatory ability in comparison with DXA (Table 2).

Diagnostic ability of ultrasound

The standards for reporting of diagnostic accuracy (STARD) initiative has produced reports on the methods for the complete and accurate reporting of studies of diagnostic accuracy (Bossuyt *et al.* 2003). Further papers (Greenhalgh 1997; Biggerstaff 2000; Grimes and Schulz 2002; Glas *et al.* 2003) report the correct method for calculation of factors that allow for the comparison of the diagnostic ability of different techniques.

Sensitivity is a measure of how good a test is at picking up people who have the condition. Specificity is a measure of how a test can correctly exclude people without the condition. The accuracy of a technique is calculated as the proportion of all tests giving the correct result.

The receiver-operating characteristic (ROC) curves (Greenhalgh 1997; Biggerstaff 2000; Grimes and Schulz 2002; Glas *et al.* 2003) were plotted by calculating values for sensitivity ranging from 100% to 0%, with the corresponding specificity values. The sensitivity was then plotted against the (1-specificity) to give a curve. The area under the curve (AUC) was subsequently calculated to provide a single value comparison between the different techniques.

Statistical analysis

The Pearson correlation between the measurement sites of the 246 patients was calculated using Minitab™ version 13 statistical software. The ROC curves and AUC values were performed using Sigma Plot™ version 8.06 graphic software.

Table 2. Kappa scores for comparison of the discriminatory abilities of the different techniques

	Distal radius	Proximal phalanx	Mid-shaft tibia	Sunlight™ combined	BUA calcaneus	VOS calcaneus
Proximal phalanx	0.19					
Mid-shaft tibia	0.12	0.14				
Sunlight™ combined	0.68	0.24	0.5			
BUA calcaneus	0.12	0.03	0.08	0.16		
VOS calcaneus	0.0	0.0	0.0	0.02	0.18	
L1-L4 BMD	0.14	0.09	0.02	0.15	0.20	0.07
T. Hip BMD	0.14	0.18	0.08	0.11	0.14	0.0
DXA combined	0.14	0.07	0.11	0.14	0.22	0.07

Table 3. Pearson correlation coefficients between the measurement techniques

		Sunlight Omnisense™			CUBA Clinical™		Hologic QDR-4500C
		Distal radius	Proximal phalanx	Mid-shaft tibia	BUA calcaneus	VOS calcaneus	L1–L4 BMD
Sunlight Omnisense™	Proximal phalanx	0.488 (0.000)					
	Mid-shaft tibia	0.309 (0.000)	0.206 (0.001)				
CUBA Clinical™	BUA calcaneus	0.376 (0.000)	0.371 (0.000)	0.270 (0.000)			
	VOS calcaneus	0.343 (0.000)	0.341 (0.000)	0.307 (0.000)	0.805 (0.000)		
Hologic QDR-4500C	L1–L4 BMD	0.306 (0.000)	0.308 (0.000)	0.251 (0.000)	0.588 (0.000)	0.516 (0.000)	
	T.hip BMD	0.249 (0.000)	0.315 (0.000)	0.171 (0.007)	0.661 (0.000)	0.537 (0.000)	0.731 (0.000)

Pearson correlation coefficients (*p* values).

RESULTS

The discriminatory ability of the US machines is shown graphically in Fig. 1. The arrows show the trends of the data (subclassification within the three categories) as performed by the three instruments. The Sunlight Omnisense™ trend mirrored that of the individual DXA sites, but in an “overoptimistic” way, by classifying a greater number as normal in comparison with the DXA results. However, when used in a combined mode, the Sunlight Omnisense™ showed a very similar trend and numerical relation to the individual DXA results. The BUA results from the CUBA Clinical™ showed a trend not in accordance with the individual DXA results and classified proportionally more individuals as osteopenic or osteoporotic; however, when the DXA results were used in combination, both the trend and numerical relationship were closely matched. The VOS results show a poor relationship with regard to the DXA results, in both trend and numbers, and showed an “overpessimistic” relationship. Table 2 shows the kappa scores for the individual technique’s discriminatory abilities in comparison with DXA. The values all show a poor level of agreement between the different techniques.

Table 3 shows the Pearson’s correlations between the different measurement sites; all the correlations were statistically significant, with most showing a high level of statistical significance. The results show a poor correlation between the peripheral skeleton, as measured by the Sunlight Omnisense™, and the axial skeleton, with correlations ranging from 0.309 to 0.161. Improved correlations, ranging from 0.637 to 0.481, were obtained between the calcaneus, measured with the CUBA Clinical™, and the axial skeleton.

Table 4 shows the different potential cut-off points, based on the best balance between sensitivity and specificity, and the cut-off points that ensure the highest number of correct diagnoses, using the accuracy calculation. The “optimum” T-score cut-off level, as judged by using sensitivity and specificity as criteria, varied very

little between the different levels, changing by a maximum of 0.5 SD. In comparison, the “optimum” T-score cut-off levels by using “accuracy” as the criterion varied by as much as 6 SD, depending on the measurement site and instrument. The number and percentage of incorrect investigation results were also higher when best performance was assessed by using “accuracy” rather than when using either sensitivity or specificity.

Figure 2 shows the ROC curves for the different screening techniques at a DXA level of −2.5. The curves give an indication of the diagnostic abilities of the different techniques. Table 5 shows the AUC with 95% confidence intervals for the different techniques at differing DXA T-score levels ranging from −2.5, which denotes osteoporosis, to −1, which denotes osteopenia and osteoporosis. According to suggestions in the literature, AUC values higher than 0.9 indicate “high” diagnostic ability (some computerized tomography scanning applications achieve AUC = 0.96) (Swets 1988); AUC in the range of 0.7 to 0.9 shows good diagnostic ability; the range 0.6 to 0.7 shows moderate ability and 0.5 to 0.6 should be deemed as having very poor performance. The present results consistently showed that measurement of the calcaneus had the greatest diagnostic ability of the screening tests. The different sites and combination of the Sunlight™ varied in their abilities depending on the DXA T-score level, but with the midshaft tibia coming last at every level.

DISCUSSION

Within this study, we have not tried to supply a replacement to DXA; we have aimed to investigate the ability of QUS to predict the result supplied by a DXA scanner. The purpose of performing the study was to investigate the potential of screening individuals with QUS to predict the DXA result, so as to alleviate some of the demand placed upon DXA scanning clinics. The T-score system, although not suitable for osteoporosis diagnosis *via* QUS, was used because it allowed for a

Table 4. Potential cut-off values for prediction of DXA and their associated numbers of false-positive and false-negative results

Site	DXA	Best sensitivity + specificity cut-off value	False-negatives	False-positives	Total pts misdiagnosed (% of group)	Best accuracy cut-off value	False-negatives	False-positives	Total pts misdiagnosed (% of group)
Distal radius	-2.5	-0.5	8	94	102 (41.5)	-4.5	46	0	46 (18.7)
Proximal phalanx	-2.5	-0.5	20	45	65 (26.4)	-3	44	1	45 (18.3)
Mid-shaft tibia	-2.5	-1	25	60	85 (34.6)	-3	44	1	45 (18.3)
Sun combined	-2.5	-1	8	102	110 (44.7)	-3	37	8	45 (18.3)
BUA calcaneus	-2.5	-2	11	58	69 (28.0)	-3.5	40	2	42 (17.1)
VOS calcaneus	-2.5	-3.25	13	55	68 (27.6)	-4	34	11	45 (18.3)
Distal radius	-2	-0.5	22	71	93 (37.8)	-2	58	21	79 (32.1)
Proximal phalanx	-2	-0.5	45	33	78 (31.7)	-1	55	17	72 (29.3)
Mid-shaft tibia	-2	-0.5	35	71	106 (43.1)	-2.5	76	6	82 (33.3)
Sun combined	-2	-1	20	77	97 (39.4)	-2	48	34	82 (33.3)
BUA calcaneus	-2	-2	22	32	54 (22.0)	-2	22	32	54 (22.0)
VOS calcaneus	-2	-3.25	27	32	59 (24.0)	-3.5	38	20	58 (23.6)
Distal radius	-1.5	-0.5	35	49	84 (34.1)	-0.5	35	49	84 (34.1)
Proximal phalanx	-1.5	0	52	35	87 (35.4)	0	52	35	87 (35.4)
Mid-shaft tibia	-1.5	-0.5	49	50	99 (40.2)	-0.5	49	50	99 (40.2)
Sun combined	-1.5	-1	32	54	86 (35.0)	-1	32	54	86 (35.0)
BUA calcaneus	-1.5	-2	45	20	65 (26.4)	-2	45	20	65 (26.4)
VOS calcaneus	-1.5	-3.25	51	21	71 (28.9)	-3.25	51	21	72 (29.3)
Distal radius	-1	-0.5	58	31	89 (36.2)	0.5	17	63	80 (32.5)
Proximal phalanx	-1	0	78	20	98 (39.8)	3	5	75	80 (32.5)
Mid-shaft tibia	-1	-0.5	70	30	100 (40.7)	3	0	85	85 (34.6)
Sun combined	-1	-1.5	83	18	101 (41.1)	-0.5	29	50	79 (32.1)
BUA calcaneus	-1	-2	71	5	76 (30.9)	-1.5	44	20	64 (26.0)
VOS calcaneus	-1	-3.25	79	8	87 (35.4)	-2.75	48	28	76 (30.9)

direct comparison between measurement techniques. This study has limitations; the study population was collected from a DXA scanning clinic to which the individuals had been referred due to the presence of one or more clinical risk factors. This meant that the population was biased toward having low bone quality, rather than being a random sample selected from the general population. The study population is small and specific to

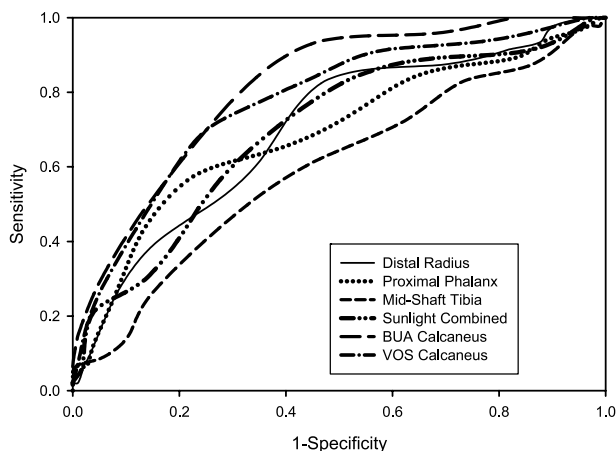


Fig. 2. ROC curves for the various US techniques for the prediction of DXA at a T-score of -2.5.

the Swindon and Marlborough NHS Trust and should be used with caution when considering other population groups.

The discriminatory ability of the QUS machines to separate people into three distinct groups, according to their diagnoses, showed a poor association between the different techniques, despite showing similar trends in Fig. 1. The numbers in each category varied between investigation sites and the kappa scores provided a formal demonstration of the poor agreement between the techniques. Three previous studies presented their discriminatory abilities; [Damilakis et al. \(2003a\)](#) used the Sunlight Omnisense™ on a larger study group than in this study and, despite a larger percentage of osteopenic and osteoporotic participants in that study, the Sunlight Omnisense™ showed the same “overoptimistic” trend as found in the present study. The two studies using the CUBA Clinical™ ([Naganathan et al. 1999](#); [Stewart and Reid 2000](#)) both had study groups different from this study, with more osteopenic and osteoporotic participants. The trends for the BUA were similar to those shown here, but with the VOS showing the opposite of the “overpessimistic” trend found in this study.

The lack of association shown in the discriminatory ability results is reflected in the poor correlations obtained between the sites. In previous studies ([Herd et al.](#)

Table 5. Values for the area under the ROC curves (AUC)

Measurement site	DXA -2.5	DXA -2	DXA -1.5	DXA -1
BUA calcaneus	0.809 (0.8468–0.7868)	0.828 (0.8511–0.8168)	0.798 (0.8057–0.8017)	0.821 (0.8308–0.8242)
VOS calcaneus	0.773 (0.8262–0.7312)	0.791 (0.8215–0.7708)	0.762 (0.7700–0.7638)	0.754 (0.7618–0.7552)
Sunlight™ combined	0.696 (0.7547–0.6454)	0.682 (0.7037–0.6630)	0.693 (0.6967–0.6948)	0.676 (0.6982–0.6597)
Proximal phalanx	0.688 (0.7548–0.6284)	0.654 (0.6897–0.6231)	0.665 (0.6836–0.6515)	0.663 (0.6784–0.6553)
Distal radius	0.696 (0.7513–0.6493)	0.668 (0.6920–0.6505)	0.666 (0.6691–0.6682)	0.655 (0.6768–0.6378)
Mid-shaft tibia	0.595 (0.6591–0.5355)	0.603 (0.6324–0.5763)	0.627 (0.6370–0.6206)	0.631 (0.6414–0.6242)

1994; Brooke-Wavell et al. 1995; Graafmans et al. 1996; Greenspan et al. 1997; Johansen et al. 1999; Njeh et al. 2000), the correlation coefficients between the CUBA Clinical™ BUA, total hip DXA and lumbar spine DXA have ranged from 0.39 to 0.64. The VOS from the CUBA Clinical™ shows a lower correlation of between 0.20 to 0.48. Gregg et al. (1997) reviewed numerous studies between BUA and VOS of the calcaneus and DXA of the axial skeleton, all with correlations ranging from 0.32 to 0.87 for BUA and 0.33 to 0.77 for VOS. The correlations found in this study using the CUBA Clinical™ were at the top range of the previously published ranges. Two previous studies (Knapp et al. 2001; Damilakis et al. 2003b) have correlated the Sunlight Omnisense™ to the axial skeleton and obtained correlations in the region of 0.21 to 0.47, depending on the measurement site. These results were consistently higher than the correlations achieved in this study. The reasons for the differences both between studies and measurement sites could be due to the demographics of the scanned population, the physical principle of the US application and the kind of bone matrix (cortical or cancellous) that was scanned.

The results in Table 4 show that, by using the variable cut-offs set by the accuracy calculations, the incorrect diagnoses can be kept to a minimum. However, the balance between the false-negative and false-positive results is uneven, with the number of false-negatives being unacceptably high. For example, at a DXA T-score of -2.5, there are 47 patients who are genuinely osteoporotic according to DXA; using the accuracy cut-off levels for the distal radius, 46 of the 47 patients would be classified as nonosteoporotic. By using the sensitivity- and specificity-based cut-offs, a greater percentage of the overall population would receive inaccurate measurement results, but a balance would be obtained between the false-positive and false-negative rates. The National Osteoporosis Society states that the "... low QUS is an independent risk factor for the future osteoporotic fracture in postmenopausal women." This shows that the false-positives, despite having no agreement with the DXA scan, should not be ignored, because the QUS result is supplying information independently of the DXA result that it is important for the clinician to consider.

The authors are unaware of any previous work showing the recommended cut-off levels for use with the Sunlight Omnisense™ for the prediction of DXA. Three previous studies (Frost et al. 2000; Damilakis et al. 2001; Dargent-Molina et al. 2003) have utilized QUS of the calcaneus as an investigation to differentiate between those people requiring further investigation using BUA and those classified as normal. The first study recommends a T-score cut-off of -2 for BUA, in agreement with this study and the manufacturers' recommendation. The second recommends a T-score threshold of -1.80 for both BUA and VOS. The third study looked at using BUA measurement values both alone and in combination with the weight of the patient and BMD assessment. The cut-off level for the BUA assessment was based on the BUA measurement values from the Lunar Achilles QUS system, rather than the supplied T-score from the CUBA Clinical™ system. In addition, the results were for the determination of fracture risk instead of DXA-determined BMD status. The study does, however, show that BUA has the ability to be used to select individuals with low bone quality. Another study (Langton et al. 1999) using the CUBA Clinical™ recommended a cut-off of 63 dB MHz⁻¹, which equates to a T-score of between -1.58 and -1.64, slightly lower than the levels in this study. The variation in the threshold levels can be partly explained by the studies having used different calcaneal assessment tools, because each system will have its own database from which the T-score is calculated and the variation in the point of the peak young adult mean can lead to this disparity in threshold value.

The AUC results show that the CUBA Clinical™, measuring both BUA and VOS, demonstrates a greater diagnostic ability than the Sunlight Omnisense™. Previous studies (Herd et al. 1994; Stewart and Reid 2000) looking at the AUC for the CUBA Clinical™ prediction of osteoporosis at the hip and spine achieved AUCs of 0.720 to 0.856 and 0.750 to 0.816 for BUA and 0.68 to 0.871 and 0.72 to 0.820 for VOS, respectively. The results from the present study are in agreement with these previous results for the CUBA Clinical™ and also with other calcaneal devices, which ranged from 0.64 to 0.888 for BUA and 0.68 to 0.871 for VOS (Stewart and

Reid 2000; Adler *et al.* 2001; Sørensen *et al.* 2001; Ekman *et al.* 2002; Falgarone *et al.* 2004), depending on measurement site and device.

Damilakis *et al.* (2003a) achieved an AUC for the phalanx of 0.709, slightly higher than that achieved here, and 0.659 for the radius, which was slightly lower than that in the present study. However, both results were within the same range.

CONCLUSIONS

The AUC results show that the CUBA Clinical™ is a better system for the screening of patients with regard to identifying correctly those patients in need of further investigation with DXA.

Each technique has its own cut-off point, which should be used when screening patients for osteoporosis. Caution should be used when assessing QUS results because there is potential for false-negative results and, therefore, negative results should not be taken as the definitive answer (Damilakis *et al.* 2003b; Knapp *et al.* 2002; Langton *et al.* 1990; Njeh *et al.* 2001).

Positive QUS results should be further investigated with measurement of the axial skeleton and results shown to be false-positives after further investigation should not be ignored, due to the well-proven QUS ability independently to predict fracture risk.

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REFERENCES

- Adler RA, Funkhouser HL, Holt CM. Utility of heel ultrasound bone density in men. *J Clin Densitom* 2001;4:225–230.
- Biggerstaff BJ. Comparing diagnostic tests: A simple graphic using likelihood ratios. *Stat Med* 2000;19:649–663.
- Bossuyt PM, Reitsma JB, Bruns DE, *et al.* Towards complete and accurate reporting of studies of diagnostic accuracy: The STARD initiative. *Clin Biochem* 2003;36:1–7.
- Brooke-Wavell K, Jones PR, Pye DW. Ultrasound and dual x-ray absorptiometry measurement of the calcaneus: Influence of region of interest location. *Calcif Tissue Int* 1995;57:20–24.
- Cheng S, Njeh CF, Fan B, *et al.* Influence of region of interest and bone size on calcaneal BMD: Implications for the accuracy of quantitative ultrasound assessments at the calcaneus. *Br J Radiol* 2002;75:59–68.
- Cook, RB, Collins, D, Curwen, C, Zioupos P. Comparison of inter-site bone densitometry measurements, and the short-term precision of two bone quantitative ultrasound scanners. York: Institute of Physics and Engineering in Medicine. Annual Scientific Meeting, 2003. pp. 94–95.
- Damilakis JE, Papadokostakis G, Perisnakis K, Hadjipavlou A, Gourtsoyannis N. Can radial bone mineral density and quantitative ultrasound measurements reduce the number of women who need axial density skeletal assessment? *Osteoporos Int* 2003a;14:688–693.
- Damilakis JE, Papadokostakis G, Vrahoriti H, *et al.* Ultrasound velocity through the cortex of phalanges, radius, and tibia in normal and osteoporotic postmenopausal women using a new multisite quantitative ultrasound device. *Invest Radiol* 2003b;38:207–211.
- Damilakis JE, Perisnakis K, Gourtsoyannis C. Imaging ultrasonometry of the calcaneus: Optimum t-score thresholds for the identification of osteoporotic subjects. *Calcif Tissue Int* 2001;68:219–224.
- Dargent-Molina P, Pault S, Bréart G. A comparison of different screening strategies to identify elderly women at high risk of hip fracture: Results from the EPIDOS prospective study. *Osteoporos Int* 2003;14:969–977.
- Ekman A, Michaëlsson K, Petré-Mallmin M, Ljunghall S, Mallmin H. Dual x-ray absorptiometry of hip, heel ultrasound, and densitometry of fingers can discriminate male patients with hip fractures from control subjects. *J Clin Densitom* 2002;5:79–85.
- Falgarone G, Porcher R, Duché, A, *et al.* Discrimination of osteoporotic patients with quantitative ultrasound using imaging or non-imaging device. *Joint Bone Spine* 2004;71:419–423.
- Frost ML, Blake GM, Fogelman I. Can the WHO criteria for diagnosing osteoporosis be applied to calcaneal quantitative ultrasound? *Osteoporos Int* 2000;11:321–330.
- Glas AS, Lijmer JG, Prins MH, Bonsel GJ, Bossuyt PM. The diagnostic odd ratios: A single indicator of test performance. *J Clin Epidemiol* 2003;56:1129–1135.
- Glüer C-C. Quantitative ultrasound techniques for the assessment of osteoporosis: Expert agreement on current status. *J Bone Miner Res* 1997;12:1280–1288.
- Graafmans WC, Lingen AV, Ooms ME, Bezemer PD, Lips P. Ultrasound measurements in the calcaneus: Precision and its relation with bone mineral density of the heel and the lumbar spine. *Bone* 1996;19:97–100.
- Greenhalgh T. How to read a paper: Papers that report diagnostic or screening tests. *BMJ* 1997;315:540–543.
- Greenspan SL, Bouxsein ML, Melton ME, *et al.* Precision and discriminatory ability of calcaneal bone assessment technologies. *J Bone Miner Res* 1997;12:1303–1313.
- Gregg EW, Kriska AM, Salamone LM, *et al.* The epidemiology of quantitative ultrasound: A review of the relationships with bone mass, osteoporosis and fracture risk. *Osteoporos Int* 1997;7:89–99.
- Grimes DA, Schulz KF. Uses and abuses of screening tests. *Lancet* 2002;359:881–884.
- Hans D, Schott A-M, Meunier P-J. Ultrasonic assessment of bone: A review. *Eur J Med* 1993;2:157–163.
- Herd RJM, Blake GM, Miller CG, Parker JC, Fogelman I. The ultrasonic assessment of osteopenia as defined by dual x-ray absorptiometry. *Br J Radiol* 1994;67:631–635.
- Johansen A, Evans W, Stone M. Bone assessment in elderly women: What does a low bone ultrasound result tell us about bone mineral density? *Arch Gerontol Geriatr* 1999;28:239–246.
- Kanis JA, Melton LJ, Christiansen C, Johnston CC, Khaltaev N. The diagnosis of osteoporosis. *J Bone Miner Res* 1994;9:1137–1141.
- Kaufman JM, Einhorn TA. Perspectives: Ultrasound assessment of bone. *J Bone Miner Res* 1993;8:517–525.
- Knapp KM, Blake GM, Fogelman I, Doyle DV, Spector TD. Multisite quantitative ultrasound: Colles' fracture discrimination in postmenopausal women. *Osteoporos Int* 2002;13:474–479.
- Knapp KM, Blake GM, Spector TD, Fogelman I. Multisite quantitative ultrasound: Precision, age- and menopause-related changes, fracture discrimination, and t-score equivalence with dual-energy x-ray absorptiometry. *Osteoporos Int* 2001;12:456–464.
- Langton CM, Ali AV, Riggs CM, Evans GP, Bonfield W. A contact method for the assessment of ultrasonic velocity and broadband attenuation in cortical and cancellous bone. *Clin Phys Physiol Med* 1990;11:243–249.
- Langton CM, Langton DK, Beardsworth SA. Comparison of accuracy and cost effectiveness of clinical criteria and BUA for referral for BMD assessment by DXA in osteoporotic and osteopenic perimenopausal subjects. *Technol Health Care* 1999;7:319–330.
- Langton CM, Palmer SB, Porter RW. The measurement of broadband ultrasonic attenuation in cancellous bone. *Eng Med* 1984;13:89–91.
- Naganathan V, March L, Hunter D, *et al.* Quantitative heel ultrasound as a predictor for osteoporosis. *Med J Aust* 1999;171:297–300.

- Njeh CF, Boivin CM, Langton CM. The role of ultrasound assessment of osteoporosis: A review. *Osteoporos Int* 1997;7:7–22.
- Njeh CF, Hans D, Li J, et al. Comparison of six calcaneal quantitative ultrasound devices: Precision and hip fracture discrimination. *Osteoporos Int* 2000;11:1051–1062.
- Njeh CF, Hans D, Wu C, et al. An in vitro investigation of the dependence on sample thickness of the speed of sound along the specimen. *Med Eng Phys* 1999;21:651–659.
- Njeh CF, Saeed I, Grigorian M, et al. Assessment of bone status using speed of sound at multiple anatomical sites. *Ultrasound Med Biol* 2001;27:1337–1345.
- Sørensen HA, Jørgensen NR, Jensen J-EB, et al. Comparison of quantitative ultrasound and dual x-ray absorptiometry in estrogen-treated early postmenopausal women. *J Clin Densitom* 2001;4:97–104.
- Stewart A, Reid DM. Quantitative ultrasound or clinical risk factors—which best identifies women at risk of osteoporosis? *Br J Radiol* 2000;73:165–171.
- Swets JA. Measuring the accuracy of diagnostic systems. *Science* 1988;240:1285–1293.
- Weiss M, Ben-Shlomo AB, Hagag P, Rapoport M. Reference database for bone speed of sound measurement by a novel quantitative multi-site ultrasound device. *Osteoporos Int* 2000;11:688–696.

Original Article

Comparison of questionnaire and quantitative ultrasound techniques as screening tools for DXA

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Abstract The aim of the study is to assess the sensitivity and specificity of different techniques and their ability to act as screening tools in relation to dual energy X-ray absorptiometry (DXA) in a group of 208 postmenopausal women. In this study we examined eight screening systems for the diagnosis of osteoporosis, the osteoporosis self-assessment tool (OST), the osteoporosis risk assessment instrument (ORAI), the osteoporosis index of risk (OSIRIS), a risk index derived using data from the study of osteoporotic fractures (SOF SURF), the simple calculated osteoporosis risk estimation (SCORE), patient body weight (pBW), along with two ultrasound based systems, the Sunlight Omnisense (Sunlight Medical, Rehovot, Israel) and the CUBA Clinical (McCue plc, Winchester, UK). The sensitivity and specificity of the different techniques in relation to DXA were plotted as receiver-operating characteristic (ROC) curves at three different levels (DXA T-score -2.5 osteoporosis, -2 and -1 osteopenia). The areas under the curves (AUC) were calculated and showed broadband ultrasound attenuation (BUA) at the calcaneus to provide consistently the

highest AUC (0.77–0.81). The velocity of sound (VOS) of the calcaneus (AUC =0.72–0.76) was equally good, but was out-performed by some of the questionnaire systems (AUC =0.66–0.79). Both the questionnaire systems and the CUBA Clinical out-perform the Sunlight Omnisense (AUC =0.58–0.7), which showed comparable performance with body weight (AUC =0.66–0.69). The results show that QUS is capable of selecting patients with low bone density as measured by DXA. A patient displaying a low QUS value should be followed up with a DXA scan to confirm the diagnosis.

Keywords DXA · Osteoporosis · Screening · Sensitivity · Specificity · Ultrasound scanners

Introduction

With 1 in 3 women and 1 in 12 men over the age of 50 suffering from osteoporosis, and the resultant estimated cost to the NHS and the government being £1.7 billion/annum (UK figures), the diagnosis and management of osteoporosis is a very important issue. The ‘gold-standard’ method for osteoporosis diagnosis is by dual-energy X-ray absorptiometry (DXA), which relies on the measurement of bone mineral density (BMD) at various sites, notably the lumbar spine, hip or distal radius. DXA, however, is expensive, it uses ionizing radiation (albeit at safe levels), requires the supervision of a qualified radiographer and is, therefore, best suited for the precise/accurate diagnosis of osteoporosis, rather than for the screening of large populations. Large numbers of potential patients can be reached by questionnaire-based methods or the use of portable quantitative ultrasound (QUS) scanners.

A number of questionnaire-based systems have been devised in an attempt to produce a cost-effective method of screening for osteoporosis. Questionnaires focus on clinical risk factors for osteoporosis and use a varying number of them to produce quantitative scores. The scores are designed to give information on those patients at risk of having low bone mineral density, who need to undergo a full assessment of their bone status. Examples of previously examined questionnaires are the Osteoporosis Self-assessment Tool (OST, OSTA) [1, 2, 3, 4, 5, 6, 7], Osteoporosis Risk Assessment Instrument (ORAI) [3, 8], Simple Calculated Osteoporosis Risk Estimation (SCORE) [3, 9, 10, 11, 12, 13], Osteoporosis Index of Risk (OSIRIS) [14, 15], the risk index derived using data from the study of osteoporotic fractures (SOF SURF) [3, 16], the Osteoporosis Assessment Questionnaire (OPAQ) [17] and three further systems, one based around

nutritional assessment [18], another based on life-style factors [19] and the third based purely on the patients' body weight (pBW) [20].

Alternative approaches for mass screening advocate the use of quantitative ultrasound (QUS) systems. QUS has been utilized for the measurement of bone and provides information that is not only comparable to, but also independent of DXA. QUS has the benefits of reduced costs in comparison to DXA, is a portable and radiation-free system with shorter investigation times than DXA and is, therefore, a better proposition for performing screening of large populations.

In this study we intend to examine comparatively and assess six questionnaire-based screening systems (OST, ORAI, OSIRIS, SOFSURF, SCORE and pBW) and two ultrasound-based systems, the Sunlight Omnisense (Sunlight Medical, Rehovot, Israel) and the CUBA Clinical (McCue plc, Winchester, UK). The aim of the study is to assess the abilities of these alternative methods/systems as screening tools for DXA and to investigate the cut-off levels for the various techniques.

Materials and methods

The study group consisted of 208 women, considered to be postmenopausal through natural or unnatural causes, recruited with consent from the DXA scanning clinics at the Great Western Hospital, Swindon, UK. All subjects attended the clinic because of referral from GPs or hospital-based clinics as a consequence of the presence of one or more clinical risk factors for osteoporosis. There were no general exclusion criteria for the study. Table 1 shows the anthropometrical data for the study group.

[Table 1 will appear here. See end of document.]

Each patient received a DXA scan of their lumbar spine L1–L4, and four sites around the proximal femur using a Hologic QDR-4500C (Hologic Inc., Bedford, Mass.), answered a questionnaire designed to give information on the patient's nutritional, life-style and historical risk factors for osteoporosis, received paired scans on their distal radius, the proximal phalanx of the middle finger, and mid-shaft tibia using the Sunlight Omnisense and paired measurements of the calcaneus using the CUBA Clinical. The QUS machines underwent system quality verification tests each day prior to any measurements being performed using the phantoms supplied by the manufacturers. All ultrasound scans were performed on the patient's non-dominant side, using Parker ultrasound gel (Parker Laboratories Inc., Fairfield, N.J.) to provide the coupling between the ultrasound probes and skin surface.

The precision of the QUS machines was previously examined in a group of 16 normals (aged 25–58). Four repeated measurements were performed on each individual, with repositioning between scans, and gave a RMSCV of 0.29% for the distal radius, 0.55% for the proximal phalanx, 2.88% for BUA of the calcaneus and 0.31% for VOS of the calcaneus.

Calculation of risk indices

The questionnaire systems were calculated as follows: OST [1, 2, 3, 4, 5, 6, 7] is based on only two variables, body weight and age. Two very similar methods have been suggested for its calculation, both giving virtually identical results. The first method is calculated as: $0.2 [\text{weight (kg)}] - 0.2 [\text{age (years)}]$; the last digit is dropped from each to give an integer, and the resulting values added together. The second method is calculated as $(\text{weight in kilograms} - \text{age in years}) \times 0.2$ and truncated to give an integer. The risk index for OST varies between populations and the site being assessed. For a Caucasian population [1], values >2 signify low risk, <2 to >-3 indicate moderate risk and <-3 denote high risk of low BMD.

ORAI [3, 8] is based on three variables, age, weight and estrogen usage. The ORAI index is calculated using the following scoring system: +2 points for non-current usage of estrogen; +9 points for a body weight of less than 60 kg or +3 points for a body weight between 60 and 70 kg and 0 points for weight above 70 kg; +15 points for ages 75 years or more; +9 points for ages between 65–74 years; +5 points for ages between 55 and 64; 0 points for 45–54. The risk index for ORAI stipulates that results <9 are low risk of low BMD, between >9 and <17 is moderate risk and >17 denotes high risk of low BMD.

OSIRIS [14, 15] is based on four variables, age, weight, HRT usage and history of low trauma fracture. The index is calculated as current age times -2 and truncated to an integer, weight in kg times 2 and truncated to an integer, +2 points if a current HRT user and -2 points for a history of prior low impact fracture. The risk index for OSIRIS shows that values $>+1$ indicate low risk of low BMD, $<+1$ and >-3 are the intermediate risk category, and values <-3 indicate a high risk of low BMD.

SOFSURF [3, 16] is also based on four variables, age, weight, smoking and history of postmenopausal fracture. The index is calculated as +0.2 points for every year over 65 years of age and -0.2 points for every year under 65 years of age; +3 points for weight below 130 lb (59 kg) and +1 point for weight between 130 lb (59 kg) and 150 lb (68 kg); +1 point for a current smoker and +1 point for a history of post-menopausal fracture. The risk index for SOFSURF shows that

values <0 indicate a low risk of low BMD; >0 and <4 indicate an intermediate risk of low BMD, with values >4 denoting those at high risk of low BMD.

SCORE [3, 9, 10, 11, 12, 13] uses six variables, race, rheumatoid arthritis, history of non-traumatic fracture, HRT usage, age and weight. The index is calculated as +5 points for a race other than Black, +4 points for rheumatoid arthritis sufferers, +4 points for non-traumatic fractures (wrist, hip and rib) over the age of 45, up to a total of 12 points; +1 if never used HRT, 3 times the first digit of the patients age, and -1 times the patients weight in pounds divided by ten and truncated to an integer. The risk index for SCORE based on a Caucasian population uses values <7 to indicate low risk, >7 and <15 to show moderate risk and >15 to denote high risk of low BMD.

pBW [20] relies on one variable, weight (kg). The recommended cut-off value is 70 kg, with women below 70 kg in weight being considered to be at risk of osteoporosis. The risk index states that pBW >70 kg indicates a low risk, between 57 kg and 70 kg a moderate risk and below 57 kg a high risk of the patient having low BMD.

Correlations

The correlations between the measurement sites were calculated using Minitab Statistical Software Release v.13.31.

Sensitivity and specificity calculation

Previous papers [21, 22, 23, 24] have reported the correct method for calculation of factors that allow for the comparison of the diagnostic ability of different techniques, in particular the sensitivity and specificity of a technique. The calculations are based around a 2×2 table as shown in Table 2. The sensitivity is a measure of how good a test is at picking up people who have the condition. The specificity is a measure of how well a test correctly excludes people without the condition. The positive and negative predictive values are measures of probability, with the positive referring to the probability of the individual having the condition if they test positive, and the negative to the probability of an individual not having a condition, should they test negative.

[Table 2 will appear here. See end of document.]

Three levels were assessed using the DXA T-scores: a T-score of -2.5 , which denotes confirmed osteoporosis, a T-score of -2 and a T-score of -1 , below which patients are considered to be osteopenic, but including the osteoporotic patients. The DXA results for the lumbar spine and the total hip were combined, so that a patient showing a T-score of -2.5 or below at only one of the

two sites was classified osteoporotic, even if the other site was diagnosed as normal. A population-specific database was not used for calculation of the T-scores; all T-scores were computed using the databases supplied with the systems.

Different levels were then assessed using the diagnostic tools (questionnaires and QUS) to gain a range of sensitivity values with a corresponding specificity value. Using SigmaPlot version 8.0, the results were plotted as sensitivity vs. 1-specificity. This supplied a range of receiver operator characteristic curves (ROC), from which the area under the curve (AUC) could then be calculated.

Cut-off points

The purpose of a screening tool is to select correctly those patients that have, or are at risk of having, low BMD and to exclude those patients who are subsequently found to have normal BMD levels. The optimum screening tool would provide a cut-off point that could be used to provide the correct diagnosis of every individual's bone status and provide no false positives or false negatives. It is therefore important that a point be selected above which patients are considered to be normal, and below which they are deemed to need a further investigation. Previous studies performing validation [2, 8] of screening tools have used cut-offs, which supply a sensitivity of 90%, regardless of the specificity, to ensure that the percentage of patients with low BMD correctly selected is high. In addition to this method of cut-off selection, the best balance between the sensitivity and specificity was investigated. By combining the sensitivity and specificity scores, a value was supplied that varied between cut-off levels, and the highest combined value was used as the cut-off level.

Results

Of the 208 women included in this study, the T-scores from DXA scans classified 21.6% (45) of the patients as being osteoporotic at the lumbar spine or hip, 47.6% (99) as being osteopenic and 30.8% (64) of the patients as being of normal bone density.

Table 3 shows the correlations between the different questionnaires, QUS techniques and DXA. The CUBA Clinical displayed the best correlation, in relation to DXA at the lumbar spine ($r = 0.568$), with OSIRIS correlating best with the total hip ($r = 0.658$). The Sunlight Omnisense correlated poorly with the DXA results ($r = 0.127-0.340$), having correlations below those for the two questionnaire systems ($r = -0.417-0.658$), also below the two CUBA Clinical measures: BUA and VOS ($r = 0.473-0.650$) and only comparable to pBW ($r = 0.33-0.492$). The mid-shaft tibia

result was non-significant in five out of nine cases and marginal in one of the rest. This is neither surprising nor disappointing as this index/measurement method has not yet obtained FDA approval and is not recommended for clinical use. In all but a few cases the correlations showed a high level of statistical significance, with P -values generally ≤ 0.001 .

[Table 3 will appear here. See end of document.]

Analysis of the AUC for the ROC curves as shown in Fig. 1 allows for comparisons between techniques, with the larger AUC value indicating a greater clinical utility. The results in Table 4 show BUA at the calcaneus to provide consistently the highest AUC (0.77–0.81), although the VOS of the calcaneus (AUC =0.72–0.76) is outperformed by some of the questionnaire systems (AUC =0.66–0.79). Both questionnaire systems and the CUBA Clinical outperform the Sunlight Omnisense (AUC =0.58–0.7), which only showed comparable performance with pBW (AUC =0.65–0.69).

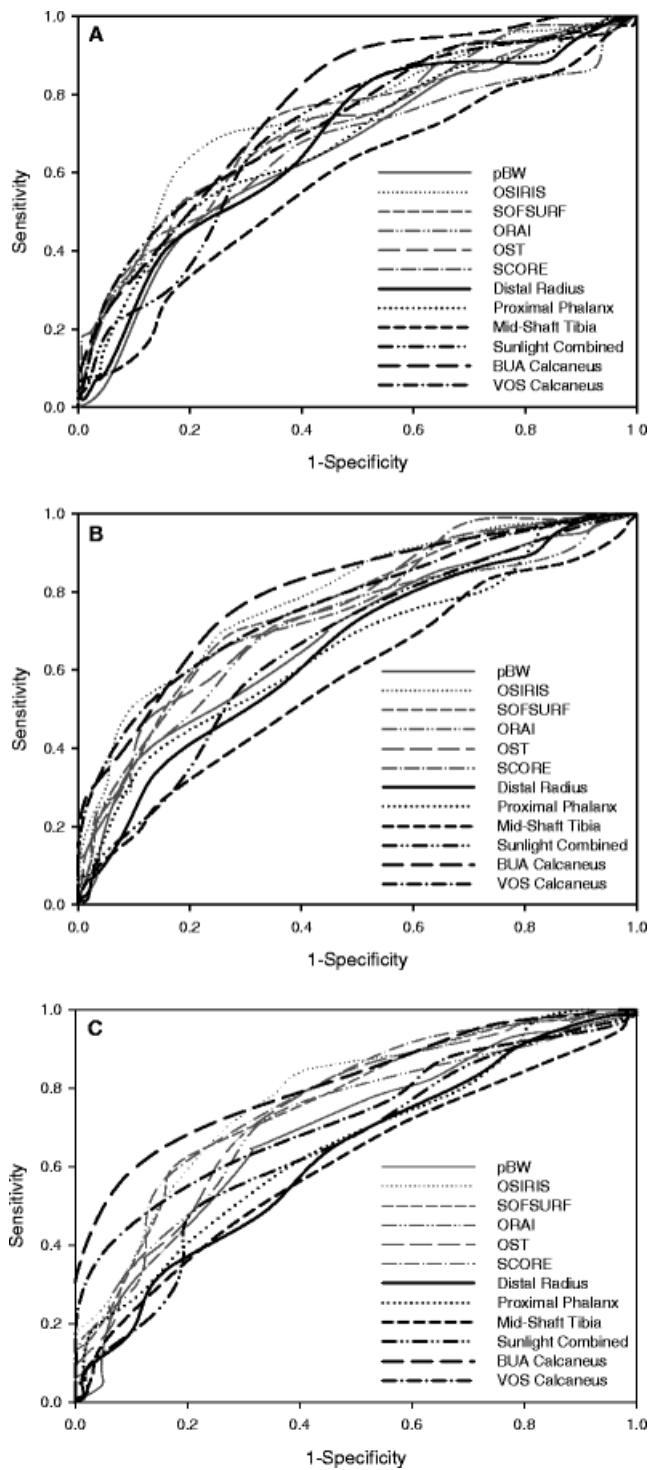


Fig. 1 ROC curves for the questionnaire and QUS systems in comparison to combined T hip and L1-L4 spine DXA. **A** Prediction of combined DXA T-score -2.5 . **B** Prediction of combined DXA T-score -2 . **C** Prediction of combined DXA T-score -1

[Table 4 will appear here. See end of document.]

Tables 5 and 6 show the potential cut-off values for the different techniques and their associated sensitivity, specificity, positive and negative predictive values, and percentage of incorrectly diagnosed patients. The sensitivity and specificity method incorrectly diagnoses a smaller percentage

of the overall group in comparison to the 90% sensitivity method. The positive and negative predictive values provide important information on the techniques abilities, with techniques providing probabilities of over 0.9 for both exclusion of patients because of negative test results and correct diagnosis of sufferers because of positive test results, depending on the DXA cut-off level assessed.

[Table 5 will appear here. See end of document.]

[Table 6 will appear here. See end of document.]

An effort was also made to explore the potential of using these QUS systems and questionnaires in combination. We performed stepwise regression analysis to predict the minimum of the two T-scores for hip and spine (worst case scenario) by using the raw data output of the QUS systems and questionnaires. We considered three likely situations: (1) clinicians who possess no instruments and would be able to only apply questionnaires (with knowledge of weight and age of course), (2) a case where one possesses the instruments, but chooses not to use the questionnaires and (3) the case where both QUS scanners and questionnaires are available for full use by the clinician. The results of the best stepwise regression are shown in Table 7. In this analysis, the use of scanners was shown to be more effective than the use of questionnaires. Taking account of questionnaire values in addition to QUS scanner values only improved the R^2 of the relationship marginally from $R^2=44.6$ to 46.8. Fig. 2 depicts graphically the result for the cases of predictive equations 1 and 10 (Table 7).

[Table 7 will appear here. See end of document.]

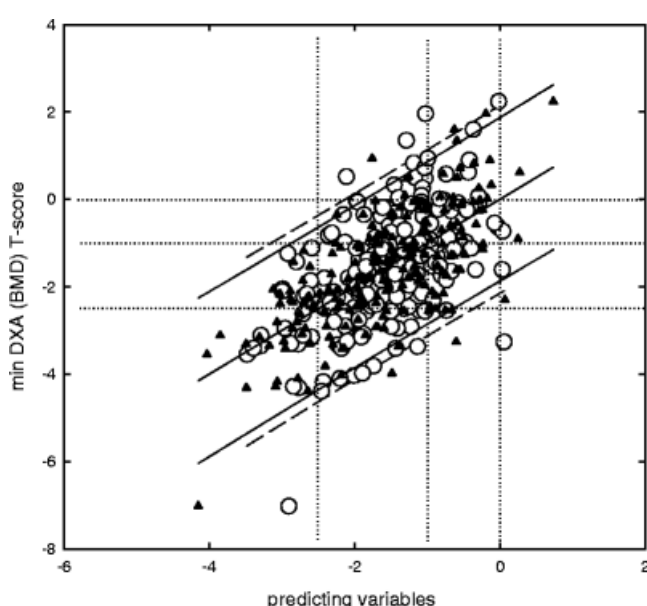


Fig. 2 Predictions of the minimum hip or spine DXA T-score by using equation 1 (*open symbols and dotted lines*) and equation 10 (*solid symbols and lines*) of Table 7. The regression lines with their 95% prediction intervals are shown in both cases. The 0, -1, and -2.5 score levels are also highlighted

Discussion

This study comparatively examined and assessed six questionnaire-based screening systems (OST, ORAI, OSIRIS, SOFSURF, SCORE and pBW) and two ultrasound based systems (Sunlight Omnisense, CUBA Clinical) as potential screening tools for DXA. The study assessed the abilities of these alternative methods/systems and investigated the cut-off levels for the various techniques. The aim is not necessarily to replace DXA, but to explore various strategies and approaches by which the demand on DXA services can be reduced by, for instance, screening large sections of the population for the exclusion of individuals who upon DXA examination would have shown themselves as normal.

The decision to investigate the systems in comparison to low DXA, rather than fracture risk, was due to the nature of the DXA clinics from which the subjects were recruited. The DXA clinic aimed to supply a T-score value that will enable a clinician to assess potential courses of medical treatment or the cessation of currently undertaken treatments. Our approach reflected current recommendation standards for clinical practice as outlined in the official positions of the International Society of Clinical Densitometry [25]. The alternative method would be to supply a parameter related to risk of fracture or the probability of fracture. The outputs are essentially only numerically different, the basic essence of the course of action or the implications for having, or being likely to have, a future fracture are basically very similar.

One factor that may influence the robustness of the conclusions and results is the make up of the cohort of subjects that participates in a study. Our volunteers showed that they were either osteoporotic or osteopenic (judged by DXA) at 69% of the total. This percentage is higher than what would be found if a database like cross section of the population had been recruited. Our intention, however, was not to seek specifically normals, but to apply our methodology and approach to the most relevant cross section of subjects. Hence, volunteers were recruited from a DXA scanning clinic, where all patients were referred because of the presence of at least one risk factor.

Only one previous study [5] has provided any correlation between a questionnaire system and DXA, and this showed moderate correlation coefficients between OST and BMD of the femoral neck and lumbar spine of 0.62 and 0.49, respectively ($P < 0.0001$). In the present study the

correlation between OST and BMD were closely comparable to this with 0.633 and 0.451 for total hip and lumbar spine, respectively.

Overall, there were excellent ($r=0.95$) to moderate ($r=0.46$) correlations seen between the various questionnaires. The variability may, to a certain degree, be due to the method of questionnaire data collection whereby questionnaires rely on patient's self-reported data. Bearing in mind that the various questionnaire systems follow different designs and philosophies of approach (focusing on different risk factors) and that their implementation also differs considerably may explain the variability of performance between them. In correlation to DXA questionnaires performed less effectively ($r=0.417$ – 0.658), but this is to no extent disappointing, and if anything considering that the population had a bias to the lower BMD end of the population and that the questionnaires were not designed to be replacement measurements for BMD but an indicator of a patient's bone status, it is very encouraging.

The results for the CUBA Clinical and Sunlight Omnisense within this study showed close comparison with those of the previous studies. Correlations between measurement sites using the ultrasound are affected by the physical principle of the ultrasound application and the kind of bone matrix that is scanned (cortical or cancellous). Hence the CUBA Clinical, which assesses a load-bearing cancellous bone site that matches the make up and loading of the hip and spine, correlates better with the axial skeleton. The correlations from this study of ($r=0.473$ – 0.650) for BUA and VOS were in close agreement with previous studies ($r=0.20$ – 0.64) [26, 27, 28, 29, 30, 31], being higher than the correlations for the Sunlight Omnisense in both this study ($r=0.127$ – 0.340) and previous studies [32, 33] ($r=0.21$ – 0.48). The moderate correlations for the CUBA Clinical can be further explained; the attenuation and velocity of an ultrasound pulse will be affected by the structure of the material it is passing through [34], with strong and complex trabecular structure affecting the ultrasound in different ways in fragile and broken trabeculae, a factor not taken into consideration by the measurement of density alone.

Calculation of the AUC showed BUA of the calcaneus to have the highest value for each DXA cut-off level. The questionnaire systems and VOS of the calcaneus obtained the next highest values with the Sunlight Omnisense, and pBW had the lowest values. The AUC values for the questionnaire systems ranged from 0.66–0.75 for osteoporosis (T-score -2.5), within the range (0.594–0.87) of previous studies [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. At a DXA T-score of -2 , the results from this study were lower than previous studies.

The AUC results show that the CUBA Clinical, measuring both BUA and VOS, demonstrates a better diagnostic ability in comparison to the Sunlight Omnisense. Previous studies [30, 35]

looking at the AUC for the CUBA Clinical prediction of osteoporosis at the hip and spine achieved AUC of 0.72–0.856 and 0.75–0.816 for BUA, and 0.68–0.871 and 0.72–0.820 for VOS, respectively. The results from the present study are in agreement with these previous results for the CUBA Clinical, and also with other calcaneal devices, which ranged from 0.64–0.888 for BUA and 0.68–0.871 for VOS [35, 36, 37, 38, 39], depending on the measurement site and device.

J. Damilakis et al. [40] reported AUC for the phalanx of 0.709, which was slightly higher than achieved here, and for the radius 0.659, which was slightly lower than in the present study. However, both results were within the same range.

The AUC for the different techniques also supplies information on the diagnostic accuracy of the different technique. J. Swets [24] supplied different areas in terms of their diagnostic accuracy with AUC between 0.50–0.70 representing low accuracy, between 0.70–0.90 showing moderate diagnostic accuracy and any technique showing an AUC of greater the 0.90 considered to be of high accuracy. The AUC results for the different techniques in this study show the majority of the methods being considered to have moderate diagnostic accuracy, with the measurements from the Sunlight Omnisense, ORAI and pBW showing low diagnostic accuracy.

The two different methods for the selection of cut-off values both have utility within the clinical environment, but depend on the chosen DXA cut-off level that is deemed to be desirable for predictions. For the prediction of osteoporosis, neither the 90% sensitivity, nor the sensitivity and specificity cut-off levels, will provide a high probability of a positive test result, meaning the individual has the condition. However, by using the suggested cut-offs, a clinician could confidently exclude an individual with a negative test result from any further diagnosis. Should the clinician wish to ensure the correct inclusion of individuals with osteoporosis or osteopenia ($DXA < -1$) for further investigation, the sensitivity and specificity cut-off values can offer high post-test probabilities of an individual having the condition when a positive test result is achieved. It is important to note that certain techniques will provide a greater post-test probability than others, but we have provided the full range to enable comparison.

The cut off values for the different questionnaire systems vary from those previously published for the techniques [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 20]; the variation in the cut-off values can be explained by the different demographics of the study populations and the methods of selection for the cut-off values.

To the best of our knowledge only one previous paper has offered potential cut-off values for the Sunlight Omnisense [41] for the prediction of both osteoporosis and osteopenia. The cut-off values were much lower than those used within this study and not suitable for use as screening

cut-offs, as only 10 patients out of 45 would be correctly diagnosed as osteoporotic using the distal radius with only 3 out of 45 correctly diagnosed at the proximal phalanx and the mid-shaft tibia. The same problem is demonstrated using the cut-off levels for osteopenia with only 57, 21 and 14 out of 144 patients being correctly diagnosed at the distal radius, proximal phalanx and mid-shaft tibia, respectively.

There are five previous studies [42] using QUS of the calcaneus as an investigation. Two studies recommend a T-score cut-off of -2 , lower than found in the present study. The third recommends -1.3 for BUA and -1.5 for VOS, while the fourth using the CUBA Clinical recommends a cut-off of 63 dB MHz^{-1} , which equates to a T-score of between -1.58 and -1.64 ; these values show a close agreement with the cut-off of -1.5 recommended in this study. The final study by D. Hans et al. [43] sets out a full screening strategy based on the use of clinical risk factors and QUS of the calcaneus. There were discernable differences between the studies in terms of study population, QUS systems, the prediction of BMD of the femoral neck and not a combination of total hip and spine, and additional risk factors not considered within the previously devised questionnaire systems. Despite this the resultant cut-off values supplied by the study for the QUS were similar to those within this study.

There are limitations of the present study that one may wish to consider before using the cut-off values suggested. The population was relatively small in numbers in comparison to the validation cohorts used for the development of these systems. The population was also somewhat biased to the lower bone density due to the collection of data from a DXA scanning clinic, where clinical referral criteria have already been applied to the participants to ensure they all display at least one risk factor for osteoporosis. For the purposes of this study, this was intentional and constitutes a strong positive factor, but in a more general situation researchers are reminded of these simple facts of our study.

With these considerations in mind, we believe that the analysis of the present study, especially based on ROC curves, allowed for a robust comparison of the different scanning techniques and an assessment of their clinical utility. The CUBA Clinical through the measurement of BUA appears to provide a useful tool in the screening of this population, with the various questionnaire systems proving that they have good diagnostic accuracy. The Sunlight Omnisense on the other hand showed overall less promise as a screening tool for DXA.

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References

1. Geusens P, Hochberg MC, van der Voort DJM, et al (2002) Performance of risk indices for identifying low bone density in postmenopausal women. *Mayo Clin Proc* 77:629–637
2. Koh LKH, Sedrine WB, Torralba TP, et al (2001) A simple tool to identify asian women at increased risk of osteoporosis. *Osteoporos Int* 12:699–705
3. Fujiwara S, Masunari N, Suzuki G, et al (2001) Performance of osteoporosis risk indices in a Japanese population. 62:586–594
4. Adler RA, Tran MT, Petkov VI (2003) Performance of the Osteoporosis Self-assessment Screening Tool for osteoporosis in American men. *Mayo Clin Proc* 78:723–727
5. Kung AWC, Ho AYY, Sedrine WB, et al (2003) Comparison of a simple clinical risk index and quantitative bone ultrasound for identifying women at increased risk of osteoporosis. *Osteoporos Int* 14:716–721
6. Richy F, Gourlay M, Ross PD, et al (2004) Validation and comparative evaluation of the Osteoporosis Self-Assessment Tool (OST) in a Caucasian population from Belgium. *Q J Med* 97:39–46
7. Park HM, Sedrine WB, Reginster JY, et al (2003) Korean experience with the OSTA Risk Index for Osteoporosis. *J Clin Densitom* 6:247–250
8. Cadarette SM, Jaglal SB, Kreiger N, et al (2000) Development and validation of the Osteoporosis Risk Assessment Instrument to facilitate selection of women for bone densitometry. *Can Med Assoc J* 162:1289–1294
9. Von Mühlen D, Lunde AV, Barrett-Connor E, et al (1999) Evaluation of the Simple Calculated Osteoporosis Risk Estimation (SCORE) in older Caucasian women: The Rancho Bernardo Study. *Osteoporos Int* 10:79–84
10. Sedrine WB, Devogelaer JP, Kaufman JM, et al (2001) Evaluation of the Simple Calculated Osteoporosis Risk Estimation (SCORE) in a sample of White women from Belgium. *Bone* 29:374–380
11. Cadarette SM, Jaglal SB, Murray TM (1999) Validation of the Simple Calculated Osteoporosis Risk Estimation (SCORE) for patient selection for bone densitometry. *Osteoporos Int* 10:85–90
12. Falasca GF, Dunston C, Banglawala YA (2003) Further validation of a questionnaire to identify women likely to have low bone density. *J Clin Densitom* 6:231–236
13. Ungar WJ, Josse R, Lee S, et al (2000) The Canadian Score Questionnaire. *J Clin Densitom* 3:269–280
14. Sedrine WB, Chevallier T, Zegels B, et al (2002) Development and assessment of the Osteoporosis Index of Risk (OSIRIS) to facilitate selection of women for bone densitometry. *Gynecol Endocrinol* 16:245–250
15. Reginster JY, Sedrine WB, Viethel P, et al (2004) Validation of OSIRIS, a prescreening tool for the identification of women with an increased risk of osteoporosis. *Gynecol Endocrinol* 18:3–8
16. Black DM, Steinbuch M, Palermo L, et al (2001) An assessment tool for predicting fracture risk in postmenopausal women. *Osteoporos Int* 12:519–528
17. Randell AG, Bhalerao N, Nguyen TV, et al (1998) Quality of life in osteoporosis: reliability, consistency, and validity of the Osteoporosis Assessment Questionnaire. *J Rheumatol* 25:1171–1179
18. Gerber V, Krieg MA, Cornuz J, et al (2003) Nutritional status using the Mini Nutritional Assessment Questionnaire and its relationship with bone quality in a population of institutionalized elderly women. *J Nutr Health Aging* 7:140–145
19. Goemaere S, Zegels B, Toye K, et al (1999) Limited clinical utility of a self-evaluating risk assessment scale for postmenopausal osteoporosis: lack of predictive value of lifestyle-related factors. *Calcif Tissue Int* 65:354–358

20. Michaëlsson K, Bergström R, Mallmin H, et al (1996) Screening for osteopenia and osteoporosis: selection by body composition. *Osteoporos Int* 6:120–126
21. Greenhalgh T (1997) How to read a paper: papers that report diagnostic or screening tests. *BMJ* 315:540–543
22. Glas AS, Lijmer JG, Prins MH, et al (2003) The diagnostic odd ratios: a single indicator of test performance. *J Clin Epidemiol* 56:1129–1135
23. Grimes DA, Schulz KF (2002) Uses and abuses of screening tests. *Lancet* 359:881–884
24. Swets JA (1988) Measuring the accuracy of diagnostic systems. *Science* 240:1285–1293
25. Leib ES, Lewiecki EM, Binkley N, et al (2004) Official positions of the international society for clinical densitometry. *J Clin Densitom* 7:1–6
26. Greenspan SL, Bouxsein ML, Melton ME, et al (1997) Precision and discriminatory ability of calcaneal bone assessment technologies. *J Bone Miner Res* 12:1303–1313
27. Brooke-Wavell K, Jones PR, Pye DW (1995) Ultrasound and dual X-ray absorptiometry measurement of the calcaneus: influence of region of interest location. *Calcif Tissue Int* 57:20–24
28. Johansen A, Evans W, Stone M (1999) Bone assessment in elderly women: what does a low bone ultrasound result tell us about bone mineral density? *Arch Gerontol Geriatr* 28:239–246
29. Njeh CF, Hans D, Li J, et al (2000) Comparison of six calcaneal quantitative ultrasound devices: precision and hip fracture discrimination. *Osteoporos Int* 11:1051–1062
30. Herd RJM, Blake GM, Miller CG, et al (1994) The ultrasonic assessment of osteopenia as defined by dual X-ray absorptiometry. *Br J Radiol* 67:631–635
31. Graafmans WC, Lingen AV, Ooms ME, et al (1996) Ultrasound measurements in the calcaneus: precision and its relation with bone mineral density of the heel and the lumbar spine. *Bone* 19:97–100
32. Knapp KM, Blake GM, Spector TD, et al (2001) Multisite quantitative ultrasound: precision, age- and menopause-related changes, fracture discrimination, and *t*-score equivalence with dual-energy X-ray absorptiometry. *Osteoporos Int* 12:456–464
33. Damilakis JE, Papadokostakis G, Vrahoriti H, et al (2003) Ultrasound velocity through the cortex of phalanges, radius, and tibia in normal and osteoporotic postmenopausal women using a new multisite quantitative ultrasound device. *Invest Radiol* 38:207–211
34. Nicholson PHF, Strelitzki R, Cleveland RO, et al (2000) Scattering of ultrasound in cancellous bone: predictions from a theoretical model. *J Biomech* 33:503–506
35. Stewart A, Reid DM (2000) Quantitative ultrasound or clinical risk factors—which best identifies women at risk of osteoporosis? *Br J Radiol* 73:165–171
36. Adler RA, Funkhouser HL, Holt CM (2001) Utility of heel ultrasound bone density in men. *J Clin Densitom* 4:225–230
37. Ekman A, Michaëlsson K, Petré-Mallmin M, et al (2002) Dual X-ray absorptiometry of hip, heel ultrasound, and densitometry of fingers can discriminate male patients with hip fractures from control subjects. *J Clin Densitom* 5:79–85
38. Sørensen HA, Jørgensen NR, Jensen J-EB, et al (2001) Comparison of quantitative ultrasound and dual X-ray absorptiometry in estrogen-treated early postmenopausal women. *J Clin Densitom* 4:97–104
39. Falgarone G, Porcher R, Duché A, et al (2004) Discrimination of osteoporotic patients with quantitative ultrasound using imaging or non-imaging device. *Joint Bone Spine* (corrected proof)
40. Damilakis JE, Papadokostakis G, Perisinakis K, et al (2003) Can Radial bone mineral density and quantitative ultrasound measurements reduce the number of women who need axial density skeletal assessment? *Osteoporos Int* 14:688–693
41. Knapp KM, Blake GM, Spector TD, et al (2004) Can the WHO definition of osteoporosis be applied to the multi-site axial transmission quantitative ultrasound? *Osteoporos Int* 15:367–374
42. Gambacciani M, de Aloysio D, Elia D, et al (2003) Quantitative ultrasound (qus) of bone in the management of postmenopausal women. *Maturitas* 47:139–149
43. Hans D, Hartl F, Krieg MA (2003) Device-specific weighted T-score for two quantitative ultrasounds: operational proportions for the management of osteoporosis for 65 years and older women in Switzerland. *Osteoporos Int* 14:251–258

Table 1 Anthropometric data for the subjects ($n = 208$) of the present study

	Range	Average
Age	29–87 years	59.7 years
Height	137–182 cm	161.1 cm
Weight	41.3–104.8 kg	65.6 kg
BMI	15.7–43	25.4
Years since menopause	0–54 years	15.4 years

Table 2 Combination table of outcomes of alternative diagnostic test results with respect to the DXA outcome

Diagnostic tool test result	DXA test result	
	Positive	Negative
Positive	True positive (TP)	False positive (FP)
Negative	False negative (FN)	True negative (TN)
	TP + FN	FP + TN
		TP + FN + FP + TN

Sensitivity: $TP/(TP + FN)$. Specificity: $TN/(FP + FN)$; +ve predictive value: $TP/(TP + FP)$; -ve predictive value: $TN/(FN + TN)$

Table 3 Correlation coefficients of the various T-score results of the various physical (DXA, QUS) and empirical (questionnaire) methods

	Weight	SOFSURF	SCORE	OST	OSIRIS	ORAI	Distal radius	Proximal phalanx	Mid-shaft tibia	BUA calcaneus	VOS calcaneus	BMD L1-L4
Questionnaires	SOFSURF	-0.460, 0.000										
	SCORE	-0.536, 0.000	0.897, 0.000									
	OST	0.774, 0.000	-0.883, 0.000	-0.878, 0.000								
	OSIRIS	0.666, 0.000	-0.904, 0.000	-0.927, 0.000	0.945, 0.000							
	ORAI	-0.469, 0.000	0.880, 0.000	0.778, 0.000	-0.839, 0.000							
Sunlight omniscense	Distal radius	0.112, 0.113	-0.474, 0.000	-0.453, 0.000	0.400, 0.000	-0.402, 0.000						
	Proximal phalanx	0.220, 0.001	-0.574, 0.000	-0.558, 0.000	0.512, 0.000	-0.479, 0.000	0.485, 0.000					
	Mid-shaft tibia	-0.087, 0.219	-0.143, 0.042	-0.157, 0.025	0.092, 0.191	-0.132, 0.060	0.262, 0.000	0.183, 0.009				
	BUA calcaneus	0.233, 0.001	-0.590, 0.000	-0.560, 0.000	0.515, 0.000	-0.507, 0.000	0.362, 0.000	0.383, 0.000	0.244, 0.000			
CUBA Clinical	VOS calcaneus	-0.028, 0.689	-0.438, 0.000	-0.391, 0.000	0.299, 0.000	-0.367, 0.000	0.312, 0.000	0.323, 0.000	0.294, 0.000	0.792, 0.000		
	BMD L1-L4	0.330, 0.000	-0.463, 0.000	-0.460, 0.000	0.451, 0.000	-0.417, 0.000	0.295, 0.000	0.318, 0.000	0.225, 0.001	0.568, 0.000	0.473, 0.000	
Hologic QDR-4500C	BMD total	0.492, 0.000	-0.599, 0.000	-0.598, 0.000	0.633, 0.000	-0.558, 0.000	0.275, 0.000	0.340, 0.000	0.127, 0.070	0.650, 0.000	0.519, 0.000	0.717, 0.000
	hip											

Table 4 Area under the curve values (*AUC*) of the various diagnostic methods in order to predict the DXA outcome at *t* -score levels between -2.5 to -1. The *AUC* allows for a direct single value comparison of the different techniques' clinical accuracy for the prediction of DXA. The provided 95% CI also allow for a fast visual inspection for statistical differences

Investigation	AUC	95% CI	AUC	95% CI	AUC	95% CI
	DXA T-score -2.5		DXA T-score -2		DXA T-score -1	
OSIRIS	0.747	0.805-0.702	0.788	0.813-0.788	0.773	0.758-0.800
SOFSURF	0.717	0.777-0.670	0.754	0.773-0.746	0.756	0.739-0.785
ORAI	0.664	0.739-0.595	0.703	0.733-0.679	0.718	0.704-0.742
OST	0.716	0.775-0.669	0.746	0.767-0.737	0.740	0.717-0.775
SCORE	0.720	0.779-0.674	0.751	0.772-0.743	0.764	0.741-0.796
Distal radius	0.676	0.731-0.628	0.651	0.670-0.640	0.624	0.593-0.659
Proximal phalanx	0.678	0.737-0.629	0.657	0.685-0.639	0.652	0.630-0.685
Mid-shaft tibia	0.582	0.645-0.521	0.578	0.606-0.553	0.600	0.580-0.622
Sunlight combined	0.698	0.751-0.654	0.661	0.679-0.650	0.643	0.614-0.678
BUA calcaneus	0.766	0.805-0.743	0.794	0.825-0.776	0.808	0.814-0.817
VOS calcaneus	0.723	0.781-0.676	0.760	0.793-0.739	0.717	0.720-0.724
pBW	0.655	0.708-0.607	0.684	0.707-0.667	0.687	0.660-0.717

Table 5 The suggested cut-off points that allow for the best sensitivity and specificity balance

Site	Combined DXA cut-off level	Sensitivity + specificity cut-off value	Sensitivity	Specificity	+ve predictive value	-ve predictive value	% of group (total FN + FP)
OSIRIS	-2.5	0	0.7	0.73	0.42	0.89	27.9% (58)
SOFSURF	-2.5	1	0.72	0.67	0.38	0.89	32.2% (67)
ORAI	-2.5	14	0.43	0.86	0.48	0.84	23.1% (48)
OST	-2.5	-1	0.52	0.82	0.44	0.56	25% (52)
SCORE	-2.5	12	0.5	0.83	0.46	0.85	24% (50)
Distal radius	-2.5	-0.5	0.84	0.47	0.30	0.91	43.3% (90)
Proximal phalanx	-2.5	-0.5	0.56	0.75	0.38	0.86	29.3% (61)
Mid-shaft tibia	-2.5	-0.5	0.64	0.51	0.26	0.84	45.2% (94)
Sun combined	-2.5	-1.5	0.69	0.66	0.35	0.89	32.2% (67)
BUA calcaneus	-2.5	-1.5	0.91	0.51	0.34	0.95	40.4% (84)
VOS calcaneus	-2.5	-3.5	0.53	0.8	0.42	0.86	26% (54)
Weight	-2.5	60kg	0.56	0.7	0.34	0.85	33.2% (69)
OSIRIS	-2	1	0.7	0.74	0.63	0.80	27.4% (57)
SOFSURF	-2	1	0.68	0.74	0.62	0.79	28.4% (59)
ORAI	-2	10	0.68	0.68	0.57	0.77	32.2% (67)
OST	-2	1	0.71	0.65	0.56	0.79	32.7% (68)
SCORE	-2	8	0.68	0.71	0.59	0.78	30.3% (63)
Distal radius	-2	-0.5	0.73	0.5	0.48	0.74	39.9% (83)
Proximal phalanx	-2	-1	0.37	0.88	0.64	0.70	31.3% (65)
Mid-shaft tibia	-2	-1.5	0.27	0.85	0.53	0.65	36.5% (76)
Sun combined	-2	-1.5	0.59	0.68	0.53	0.73	33.2% (69)
BUA calcaneus	-2	-2	0.71	0.76	0.61	0.83	26% (54)
VOS calcaneus	-2	-3.5	0.51	0.88	0.72	0.74	26.4% (55)
Weight	-2	55kg	0.36	0.9	0.69	0.69	30.8% (64)
OSIRIS	-1	2	0.7	0.73	0.86	0.52	28.8% (60)
SOFSURF	-1	0	0.63	0.8	0.87	0.49	32.2% (67)
ORAI	-1	8	0.71	0.67	0.83	0.51	30.3% (63)

Site	Combined DXA cut-off level	Sensitivity + specificity cut-off value	Sensitivity	Specificity	+ve predictive value	-ve predictive value	% of group (total FN + FP)
OST	-1	2	0.72	0.67	0.83	0.51	29.8% (62)
SCORE	-1	8	0.56	0.84	0.98	0.46	35.1% (73)
Distal radius	-1	-0.5	0.65	0.54	0.77	0.39	37% (77)
Proximal phalanx	-1	0	0.51	0.7	0.79	0.39	42.3% (88)
Mid-shaft tibia	-1	-1.5	0.25	0.93	0.90	0.35	52.9% (110)
Sun combined	-1	-1.5	0.51	0.77	0.84	0.39	38.9% (81)
BUA calcaneus	-1	-2	0.56	0.92	0.94	0.48	33.2% (69)
VOS calcaneus	-1	-3	0.61	0.72	0.85	0.45	35.6% (74)
Weight	-1	65 kg	0.71	0.55	0.82	0.46	34.1% (71)

Table 6 The suggested cut-off points that allow for a guaranteed 90% sensitivity level

Site	Combined DXA cut-off level	90% sensitivity cut-off	Sensitivity	Specificity	+ve predictive value	-ve predictive value	% of group (total FN + FP)
OSIRIS	-2.5	5	0.96	0.22	0.26	0.95	61.5% (128)
SOFSURF	-2.5	-2	0.91	0.22	0.25	0.9	63% (131)
ORAI	-2.5	0	0.96	0.056	0.22	0.82	74.5% (155)
OST	-2.5	3	0.91	0.33	0.28	0.93	53.8% (112)
SCORE	-2.5	4	0.93	0.26	0.26	0.93	59.1% (123)
Distal radius	-2.5	1	0.93	0.12	0.22	0.86	68.3% (142)
Proximal phalanx	-2.5	2	0.91	0.15	0.23	0.86	67.8% (141)
Mid-shaft tibia	-2.5	1.25	0.93	0.1	0.22	0.84	70.2% (146)
Sun combined	-2.5	-0.5	0.93	0.24	0.25	0.92	57.7% (120)
BUA calcaneus	-2.5	-1.5	0.91	0.51	0.34	0.95	40.4% (84)
VOS calcaneus	-2.5	-2.5	0.91	0.35	0.28	0.93	52.9% (110)
Weight	-2.5	80kg	0.96	0.15	0.24	0.92	67.8% (141)
OSIRIS	-2	4	0.91	0.41	0.49	0.88	39.9% (83)
SOFSURF	-2	-2	0.95	0.27	0.46	0.9	46.6% (97)
ORAI	-2	2	0.925	0.1	0.39	0.68	58.2% (121)
OST	-2	3	0.9	0.39	0.48	0.86	41.3% (86)
SCORE	-2	4	0.96	0.33	0.47	0.93	42.8% (89)
Distal radius	-2	0.5	0.9	0.19	0.41	0.74	51.9% (108)
Proximal phalanx	-2	2	0.94	0.18	0.41	0.82	52.9% (110)
Mid-shaft tibia	-2	1.25	0.92	0.1	0.39	0.68	56.7% (118)
Sun combined	-2	0	0.97	0.091	0.4	0.85	53.8% (112)
BUA calcaneus	-2	-1	0.93	0.33	0.43	0.90	33.2% (96)
VOS calcaneus	-2	-2	0.94	0.26	0.44	0.87	48.1% (100)
Weight	-2	80kg	0.94	0.16	0.41	0.81	53.8% (112)
OSIRIS	-1	5	0.9	0.36	0.76	0.61	26.9% (56)
SOFSURF	-1	-2	0.9	0.38	0.76	0.62	26.4% (55)
ORAI	-1	2	0.93	0.14	0.71	0.47	31.3% (65)

Site	Combined DXA cut-off level	90% sensitivity cut-off	Sensitivity	Specificity	+ve predictive value	-ve predictive value	% of group (total FN + FP)
OST	-1	5	0.94	0.25	0.74	0.64	27.4% (57)
SCORE	-1	3	0.91	0.36	0.76	0.64	26% (54)
Distal radius	-1	1	0.92	0.19	0.73	0.5	28.4% (59)
Proximal phalanx	-1	2	0.9	0.22	0.72	0.5	30.8% (64)
Mid-shaft tibia	-1	1.5	0.94	0.033	0.69	0.2	31.7% (66)
Sun combined	-1	0	0.95	0.11	0.72	0.46	27.9% (58)
BUA calcaneus	-1	-0.5	0.96	0.27	0.75	0.74	25.5% (53)
VOS calcaneus	-1	-1.5	0.95	0.063	0.695	0.36	32.2% (67)
Weight	-1	80 kg	0.92	0.23	0.73	0.58	28.8% (60)

Table 7 Stepwise regression equations for three scenarios, where the introduced parameters are shown in column 1, the best equations produced in sequence are in column 2 and the r^2 values in column 3. Note that equations 5–7 are identical to equations 2–4 even in the presence of the questionnaires as additional factors

Parameters	Equation	r^2	Eq. no.
Weight, OSIRIS, OST, SOFSURF, SCORE, ORAI	Min DXA T-score = 0.178 OSIRIS – 1.915	31.0	1
Weight, age, distal radius, proximal phalanx, BUA	Min DXA T-score = 0.0472 BUA – 4.471	37.7	2
Calcanus, VOS calcanus	Min DXA T-score = 0.0431 BUA + 0.0249 weight (kg) – 5.841	43.0	3
	Min DXA T-score = 0.0259 BUA + 0.0308 weight (kg) + 0.0085 VOS – 18.505	44.6	4
Weight, OSIRIS, OST, SOFSURF, SCORE, ORAI, distal radius, proximal phalanx, BUA calcanus, VOS calcanus	Min DXA T-score = 0.0472 BUA – 4.471	37.7	5
	Min DXA T-score = 0.0431 BUA + 0.0249 weight (kg) – 5.841	43.0	6
	Min DXA T-score = 0.0259 BUA + 0.0308 weight (kg) + 0.0085 VOS – 18.505	44.5	7
	Min DXA T-score = 0.0215 BUA + 0.0220 weight (kg) + 0.0080 VOS + 0.047 OSIRIS – 17.001	45.3	8
	Min DXA T-score = 0.0208 BUA + 0.0304 weight (kg) + 0.0085 VOS + 0.120 OSIRIS – 0.112 OST – 18.287	46.0	9
	Min DXA T-score = 0.0198 BUA + 0.0460 weight (kg) + 0.0087 VOS + 0.088 OSIRIS – 0.220 OST – 0.144 SOFSURF – 19.289	46.8	10