

CRANFIELD UNIVERSITY

CHRISTOPHER MALBON

FEMALE POLICE BODY ARMOUR: IMPROVING COMFORT,
PROTECTION, AND TESTING

CENTRE FOR DEFENCE ENGINEERING
CRANFIELD DEFENCE AND SECURITY

PhD

Academic Year: 2020 - 2021

Supervisor: Dr Debra Carr (2016 – 2017)

Dr Clare Knock (2017 – 2021)

Associate Supervisor: Dr Richard Critchley

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ABSTRACT

There is a paucity of published research into female body armour resulting in a lack of evolution in design and testing solutions.

A series of surveys and experiments were designed to extend the knowledge relating to female body armour, focusing on comfort, protection, and testing. Comfort was shown to be improved through professional fitting and sizing of new bras, with a sports bra being reported as most comfortable after refitting by 77% of participants. Statistically significant differences in key anthropometric measurements around the breast area were identified between bra types, including bust to bust length, bust circumference, and bust prominence. Exposure of the anterior lateral region of the body was greater compared to the posterior lateral region for female police officers, particularly around the breast area, (exposed anterior lateral breast area – underwired bra: mean 55%, max 72%; sports bra: mean 57%, max 75%).

A comparison of three backing materials used for the assessment of back face signature (BFS): Roma Plastilina No1 (RP1); 10% ballistic gelatine; SEBS gel; showed that there were statistically significant differences between the three materials. 10% ballistic gelatine had the greatest variation in measured BFS with both projectiles (9mm; BFS 21.5 – 42.3mm: 0.357”; BFS 31.5 – 67.3mm). RP1 had the smallest variance in measured BFS with both projectiles (9mm; BFS 17.6 – 30.9 mm: 0.357”; BFS 18.9 – 32.5 mm), however, there were statistically significant differences in the spread of results for RP1.

The knowledge gained is enabling the development of new guidance for female police officers on improvement in comfort when wearing body armour by the Police Federation. Designers of body armour have information on the effects of bra type on breast shape enabling future designs of body armour to be more tailored to shape, enable a better fit, and reduce the risk of air gaps under the armour. Understanding of the differences in three backing materials will enhance the development of future testing methods for female body armour, which will deliver improvements in the safety of body armour.

Keywords:

Breasts, Sports bra, Underwired bra, Female body armour (armor), Roma
Plastillina No1, Ballistic gelatine, SEBS

*Dedicated to all police officers who have lost their lives in the line of duty to
protect us, thank you*

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LIST OF ABBREVIATIONS

AIS	Abbreviated Injury Scale
BABT	Behind Armour Blunt Trauma
BFS	Back Face Signature
CI	Confidence Interval
CREL	Centre de Recherche et d'Expertise de la Logistique
CT	Computer Tomography
FMJ	Full Metal Jacket
HOCAS	Home Office Centre for Applied Science and Technology (formally HOSDB)
HOSDB	Home Office Scientific Development Branch
JSP	Jacketed Soft Point
KE	Kinetic Energy
NATO	North Atlantic Treaty Organization
NIJ	National Institute of Justice
PC	Police Constable
PFEW	Police Federation of England and Wales
PMHS	Post-Mortem Human Subject
PPE	Personal Protective Equipment
RP1	Roma Plastilina No1
SD	Standard Deviation
Surg Lt Cdr (RN)	Surgeon Lieutenant Commander (Royal Navy)

UHMWPE Ultra-High Molecular Weight Polyethylene

GLOSSARY OF TERMS

Abbreviated Injury Scale	“developed in the mid-1960s for tracking injury in automotive and aircraft crashes, it has grown to become an internationally recognized traumatic injury scoring system.” (Loftis, Price and Gillich, 2018)
Anterior	The front facing half of the body
Anthropometric measurements	Physical measurements taken of the human body (see anthropometry)
Anthropometry	“the scientific study of the measurements and proportions of the human body” (Carr, Wilson and Laing, 2012)
Back Face Signature	“The maximum depth of indentation made by body armour into ballistic backing material after impact, measured perpendicular from the surface of the backing material.”(Payne, O’Rourke and Malbon, 2017)
Ballistic gelatine	“A specific technical gelatine, which when mixed to a specific density creates an analogue for human tissue.” (Defensible Ballistics Ltd., 2020)
Behind Armour Blunt Trauma	“spectrum of non-penetrating injuries to the torso resulting from the impact of projectiles on personal armours.”(Cannon, 2001)
Biofidelic	Exhibiting biofidelity; faithfully modelling a biological system. (Wordsense dictionary, 2021)
Lateral plane	Also known as the Sagittal plane. A vertical plane that divides the left- and right-hand side of the body, when viewed as a side profile of the body.

One-way Anova	“Analysis of variance between one independent variable (referred to as a factor) which has a number of different levels. These levels correspond to the different groups or conditions” (Pallant, 2016)
Posterior	The rear facing half of the body
Roma Plastilina No1 (RP1)	An oil-based modelling clay used as a method of measuring back face signature in ballistic testing of body armour.
SEBS	“Commercial thermoplastic elastomers consisting of triblock (styrene–ethylene / butylene-styrene) copolymers. When mixed with mineral oil, SEBS forms (non-chemically) crosslinked, thermally reversible gels that exhibit very good transparency.” (Mauzac et al., 2012)
Sports Bra	A bra that is designed to hold the breasts more firmly in place during physical activity
Two-way Anova	“Analysis of variance between two independent variables which have a number of different levels with different people in each group. Enables the investigation of individual and joint effect of two independent variables on one dependant variable.” (Pallant, 2016)
Underwired bra	A bra that contains a wire under the cup section of the bra used for support and shape of the breast

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1 INTRODUCTION

1.1 Identification of the need for the research

In 2014 whilst working for the Home Office Centre for Applied Science and Technology as the lead for body armour, I was contacted by a female front line police officer who was about to undergo an elective double mastectomy due to a high risk of breast cancer. As part of the surgery, she was due to have breast reconstruction using silicone implants. Her police force had raised concerns over the safety of her continuing as a front-line officer and being able to wear body armour. This was the first time this question had been raised and I was unaware of any previous research in this area.

I reached out to body armour experts in partner government organisation in the USA, Germany, and France, as well as the Impact and Armour Group at Cranfield University, who were the established UK centre of academic excellence in this field. No prior research was identified by these bodies on this topic, and more broadly only limited research regarding female body armour issues was identified.

A rapid initial research project was established with Cranfield University investigating the potential consequences of a ballistic impact on a body armour over a breast containing a silicone implant (Carr et al., 2016). This work showed that out of seven tests, five implants ruptured even though the round was stopped successfully by the body armour. Whilst this research did not include any breast-tissue or skin simulant, it did highlight the risk of the breast implant rupturing because of the ballistic impact over the breast area. Although the health risk associated with ruptured breast implants was identified as low, it would still require surgery to replace the damaged implant.

As a result of this initial work and the paucity of previous published research in the open literature, the need for further research into impacts over the female breast was identified. This led to development of the focus for this thesis, ensuring both male and female wearers of body armour are appropriately protected in the future.

1.2 Design bias

Throughout history there are many examples where design has been orientated around male anthropometric data, such as

1. Crash test dummies, typically used in the safety testing of vehicles, have been around since the 1950s and originally typically based on the fiftieth percentile male of the time (typically 76 kg and 1.77 m tall) (Mertz and Irwin, 2015)
2. In the USA, structural firefighters' turnout suits had predominantly been based on male anthropometric data, resulting in an increased risk to female firefighters of sustaining injury (McQuerry, 2020)
3. The US military did not introduce combat uniforms designed for and specifically based on female anthropometric data until 2011, some 35 years after females were allowed to enlist (Admas, 2011)

The main identified reason for this bias to male anthropometric dimension has been the availability of data. Criado-Perez, in her book on this topic, identifies many examples where purely because of the historical bias in data sets to males, female orientated design has been left behind (Criado-Perez, 2019).

More recently, in 2017, the Trade Union Congress (TUC) released a guidance document on personal protective equipment (PPE) for women (TUC, 2017). This work was based on a survey conducted in 2016 which identified only 29% of PPE issued was specifically designed for females, with 57% of respondents reporting that their issued PPE caused them issues when working. Whilst this survey was across a broad range of occupations, the survey did include responses from wearers of body armour who identified significant problems from rubbing against the skin, and it not being designed for various sized breasts and hips.

Whilst it will never be possible to cover every variation of body size and shape in the human population, the fact that gender bias is evident in design, especially for PPE, emphasises the requirement for research in this field to ensure that the appropriate PPE can be supplied to those who need it.

1.3 Anatomy of the female breast

The mammary gland, or breast, is present in both sexes, however it typically only develops in females where its primary function is in the production of milk for nursing mothers. The mammary gland is effectively a modified sweat gland and is encapsulated in skin in front of the pectoral muscles of the thorax, Figure 1-1

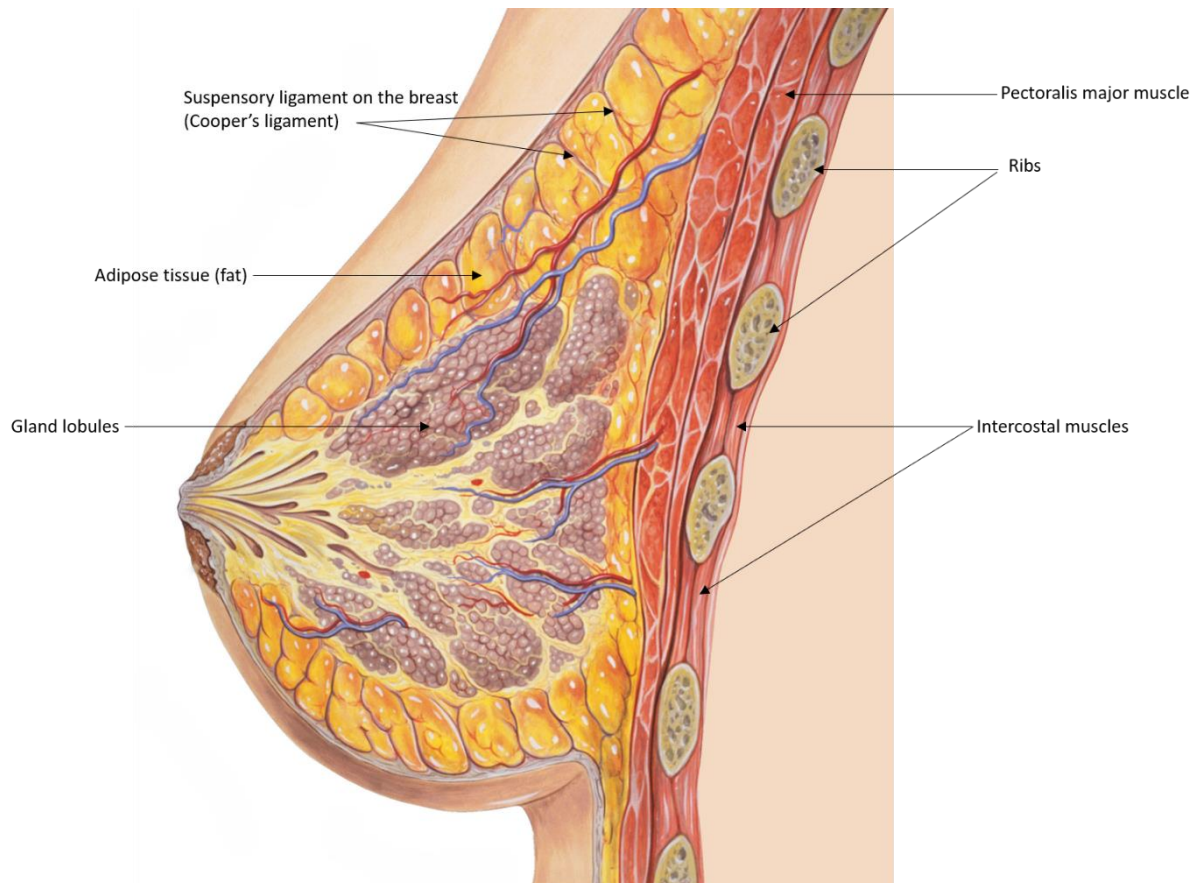


Figure 1-1 Cross sectional image of the female breast (Meyerson, 2016)

The breast contains suspensory ligaments which provide natural breast support, and these ligaments attach the breast to the skin and underlying muscle. Within the breast are the gland lobules, which increase in size and produce milk for nursing mothers. For non-nursing mothers, the glandular structure is less developed, and the breast is predominantly made up of adipose tissue which dictates the size of the breast.

The female breast can be affected by cyclic changes during the menstrual cycle, which can cause swelling, tenderness or pain in the breast which could influence the comfort of bras, clothing and PPE being worn (Bruinvels et al., 2021).

1.4 Injuries to the breast

Three main areas were identified where traumatic injuries to the breast may occur which are relevant to this research presented in this thesis: ballistic injuries, motor vehicle accident injuries and sports/activity related injuries. These are discussed below.

1.4.1 Ballistic injuries

There is very limited research in the open literature on ballistic injuries to a breast. The research that has been published relates to the medical care of ballistic trauma to the chest rather than research into wound ballistics (e.g. Chung and Leung, 2020; Onder et al., 2013; Polcz and Sweeting, 2018; Sampson, 1975). Polcz and Sweeting identified in their research that out of 22 reported gunshot injuries to the breast over a three-year period, only three affected the breast alone. The 19 other cases had extensive injuries to the intra-thoracic and intra-abdominal areas, with an overall mortality rate of 71%. This high mortality rate and high proportion of significant life-threatening injuries may be disguising the amount of post-operative care required to repair the breasts. Of note, in one reported case, debris from bullet fragments and clothing caused an infection that needed additional operative care as well as antibiotics to resolve. The research presented by Chung and Leung, Onder et al and Sampson, also focused on the issues with infection from gunshot wounds to the breast. The risk of infection in the breast, highlights the additional potential complications to recovery as well as the longer-term requirements for potential reconstructive and cosmetic surgery to restore the shape and form of the breast.

Within the open literature, no cases of non-perforating ballistic injury to the breasts were identified.

1.4.2 Motor vehicle accident injuries

A systematic literature review by Song et al, identified 43 cases with varying levels of injury to the female breast during motor vehicle accidents (Song, Teo and Song, 2015). These were predominantly caused by the seat belt tightening over a single breast during an impact resulting in it being compressed. Injuries identified ranged from bruising and swelling, the formation of diagonal cleft in the breast or detachment of the breast from the pectoral muscles. They identified 17 patients who originally presented only with minor injuries, but then presented with palpable masses in the breast one month to four years later. Whilst there is no evidence showing that blunt trauma increases the risk of the development of a carcinoma, the formation of these palpable masses post impact would be a cause of concern for the patient (Carr, 1998). In a separate report, a woman with a silicone breast implant was involved in a motor vehicle accident suffering a seat belt injury to her left breast (Akan et al., 2003). At the time of the incident the potential for a ruptured implant was not considered and it was five years until it was diagnosed, after she had been reporting pain in her breast for a period of time. This highlights the significance of considering implants if the breasts are subjected to a severe trauma.

1.4.3 Sport/activity related injuries

Within the open literature, research has been published on breast support and motion, and bra design connected with sporting activity, primarily involving running (e.g. Brown et al., 2014; Burbage and Cameron, 2016; McGhee et al., 2013; Milligan, Mills and Scurr, 2014; White and Scurr, 2012; Zhou, Yu and Ng, 2013). However, there is a paucity of research on blunt trauma breast injuries sustained by female sports participants. In professional sports, breast injuries are not commonly reported, either by the athlete, the coach or team medic (Brisbine, 2019). The research did identify that the injuries sustained did cause the athletes to be more hesitant about performing activities, such as diving or tackling, that might exaggerate or repeat the injury. While Brisbine was able to identify that injuries do occur, including bruising, swelling, and rubbing, his research did not investigate the injury mechanism further.

A study of non-ballistic impact torso injuries in UK military personnel identified only a small number of cases over a 13 year period (Carr, 1998). Of the cases identified the majority were from transport related injuries, although no further details of the cause of the injury were presented. They did estimate that within the female military population at the time, post traumatic fat necrosis incidents would be 1 in 84000 per year. The work highlighted the issue with palpable lumps forming post impact, which could be misdiagnosed through mammography as potential carcinomas.

1.4.4 Additional data

One additional case reported, outside of ballistic, motor vehicle accident, and sports injuries, relates to an injury sustained by a woman who fell forward onto a pavement (Lee, Ko and Han, 2009). She presented to hospital two months after the incident with a lump in her breast, which was eventually diagnosed as a thrombosed pseudoaneurysm (false aneurysm) because of the blunt trauma.

The identification of palpable masses, a period of time post a traumatic incident to the breast can be misdiagnosed as malignancy (Gatta et al., 2006). This potential misdiagnosis could cause additional stress and procedures to a person if the link to traumatic injury is not known.

The potential for impact trauma to cause a similar type of injury to those seen in both motor vehicle accident data and sports/activity related data must be considered. Understanding the breast response to a ballistic impact is essential for further developing body armour and the immediate and longer-term care of females post any incidents.

1.5 Body armour usage by police officers in England and Wales

Within England and Wales, the wearing of body armour when on duty away from a police station is commonplace. The body armour worn by police officers in England and Wales is normally certified to the Home Office body armour standard, most recently updated in 2017 (Payne, O'Rourke and Malbon, 2017). The level of threat resistance afforded by these armours varies depending upon role, but for a routine patrol officer it is typically designed to protect against a

knife or low-velocity ballistic projectile. Whilst the level of threat a body armour is designed to resist is the same for both male and female officers, the design, fit, comfort, and certification testing differs.

Across England and Wales, there has been a steady increase in the percentage of female police officers since 2007. Data from the Home Office shows that the number of male officers has decreased but the number of female officers has slowly increased. In 2020 females made up 32% of all police officers, Figure 1-2 (Home Office National Statistics, 2020).

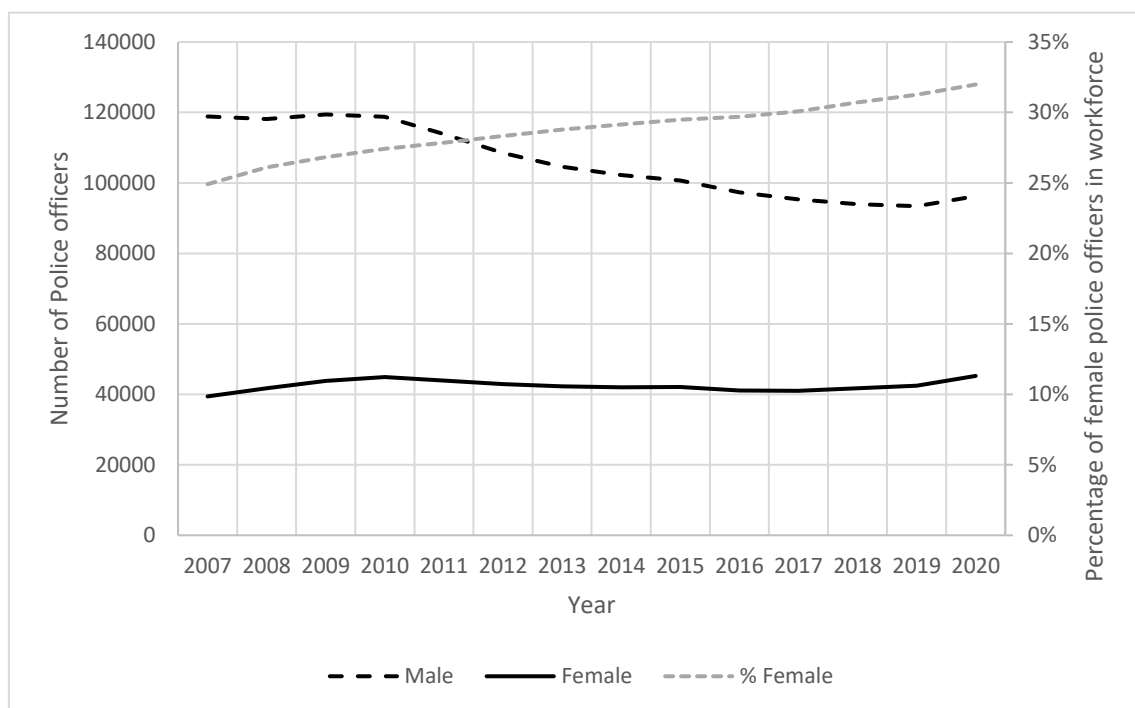


Figure 1-2 Number of male and female police officers in England and Wales from 2007 to 2020

1.6 Body armour design

The materials used in body armour designed for the police are typically para-aramids, ultra-high molecular weight polyethylene (UHMWPE), laminated para-aramids and chain mail (Lewis et al., 2017). Armours typically have multiple layers of materials and may be used in combinations depending on the type of protective resistance provided. For example, multiple layers of para-aramids and chain mail could be combined to provide ballistic (para-aramid) and stab

(chain mail) resistance. Female armours typically have bust cups formed into the design. These bust cups can be formed by various methods such as darting-and-stitching, folding, or cut-and-stitch. The forming of multiple layers of material used in a typical body armour can lead to non-ideal shapes being formed which may result in a poor or uncomfortable fit. The range of sizes of body armour that is available is dependent upon the manufacturer and is not mandated in standards.

The fit of a body armour is critical, not only to ensure it covers the vital organs of the heart, great vessels, liver, and spleen, but also to ensure it is close fitting to the body (Breeze, Lewis and Fryer, 2016; Tilsley et al., 2018). Whilst the work by Breeze et al was focused on military personnel, the protection of any organs that could lead to a potential death if not treated within 60 minutes is also applicable for police officers. The work by Tilsley et al, is more critical, especially for the design of female body armour, as it identified that there is an increased risk of perforation of a body armour from a ballistic threat when a 10 mm air gap is introduced. It is possible that an air gap of this size could be present around or between the breasts, depending upon the design or fit of the body armour.

1.7 Testing of body armour for ballistic resistance

Ballistic protective body armours are tested against two primary criteria, firstly the capability to resist the perforation of the body armour by a bullet and secondly, limitation of the energy transferred through the body armour to the body. It is this transfer of energy that is considered responsible for Behind Armour Blunt Trauma (BABT) injuries. Cannon defined BABT as "...spectrum of non-penetrating injuries to the torso resulting from the impact of projectiles on personal body armours." (Cannon, 2001). The measurement of this energy transfer is typically achieved by recording the permanent deformation in a backing material, commonly Roma Plastilina No 1 (RP1). The measurement of this deformation in the backing material is called the back face signature (BFS).

In the UK, when police body armour is tested in accordance with the Home Office standard, it is mounted on a flat tray of RP1 and the BFS recorded for

each test shot. However, in the testing of the breast area of female body armour, no measurement of BFS is taken and the only criterion is that the test round does not perforate the body armour. Until 2017 in the UK, female body armour was tested by mounting it on the same flat tray as previously described, but with two 'mounds' created to represent the female bust. These were made by hand to fit the body armour panel provided. In the 2017 Home Office body armour standard, a new anthropometrically correct female torso was introduced to improve the consistency of testing. There is still no measurement of BFS taken in this process, so the potential BAPT risk to the female breast is not quantified in any way. Whether or not the body armour is perforated in the breast area is considered.

1.8 Previous female body armour research

Body armour research has been heavily focused on protecting the thorax, with the original identified research in the open literature by Montanarelli et al, which conducted experiments using goats (Montanarelli et al., 1973). The reasons goats were used is explained in a later report by Goldfarb et al (Goldfarb et al., 1975).

1. A 40 to 50 kg goat is a "model" for a typical 70 kg man.
2. Damage levels of various organs will be similar in goat and man.
3. Goat experiences the same natural course of disease as a human after injury.
4. A 70 kg human with thicker and more resistant abdominal and chest walls would suffer no greater damage.

In 2018, the mean weight for adults aged 16 to 64 years old in England for a male was 84.6 kg and for a female was 72.5 kg (NHS Digital, 2018). Although the more recent data shows that females now match the originally assumed 70 kg male, it still does not consider the fact that female physiology and muscle tone is potentially different, and significantly does not take account of developed breast tissue. At the time of the work by Goldfarb et al body armour would have been almost exclusively worn by men, which may account for no reference to females or breast tissue.

In work presented by Anderson et al on a NATO task group investigating BABT, they proposed an animal model using 60 kg pigs, as the thorax size mimics human anatomy and enables ease of instrumentation (Anderson et al., 2002). The paper does not expand on how this assessment was achieved and makes no mention of whether this was applicable to male and female anatomy either.

Research published by Prat et al investigated the correlation between pig thorax and post mortem human subject (PMHS) to establish if the results were comparable (Prat et al., 2012). Their research involved 12 PMHS of which seven were female, and the use of 40 kg large white pigs, sex undefined. They identified that there was a correlation between results obtained on PMHS and pigs, however in the analysis of their results they did not separate by human gender, so it is not known if there were significant differences in gender response.

Research by Wilhelm et al did focus on female body armour (Bir and Wilhelm, 2004; Wilhelm, 2003). The research was based on case reports from the United States of America involving both male and female police officers who had been shot. There were four female case studies reviewed, two of which were on the back or side of the torso, with the other two cases on the front torso. In the first front torso case, the officer sustained a ballistic impact on her body armour resulting in an open wound located centrally on the front torso, just below the breasts. In the second incident, the officer's body armour was struck on the left side, resulting in a laceration below her left breast, fractured ribs and bruising to the side of her breast. They assigned Abbreviated Injury Scale (AIS)¹ scores ranging from 'minor' (1) to 'maximal' (6) to these frontal injuries, and to a further set of ten case studies of male officers who had received frontal injuries. Of the 12 cases reviewed, the highest score assigned was for the two females and one male each being assessed as 'serious' (AIS 3). One other case was assessed as 'moderate' (AIS 2) whilst the remaining eight cases were all assessed as

¹ ".....initially developed in the mid-1960s for tracking injury in automotive and aircraft crashes, it has grown to become an internationally recognized traumatic injury scoring system." (Loftis, Price and Gillich, 2018)

‘minor’ (AIS 1). A second part of their research involved impacting cadavers with a blunt impactor (0.14 kg wooden baton at 40 ms⁻¹) to determine the response of both males and females to a behind body armour style of impact on the sternum. Distinct differences between the two sexes were reported for both force and displacement, with higher forces seen in males but greater displacement for females. Additional impacts on the breast transition area, the slope from the chest wall to the point of the breast, did not show a difference to the sternum impacts on females, however, the area that was tested has very little additional breast tissue compared to a direct impact to the tip of the breast. In addition, the breast size and condition of the PMHS tissue was unknown.

This data is significant for researching potential injury criteria for female body armour testing as it shows that females do not align to males in response to impact. However, Wilhelm et al did not investigate impacts directly on the tip of the breast, therefore the effect that the soft tissue structure of the breast would have on potential injury or how the materials of the body armour would react, is unknown.

The only work found in the open literature that used a simulated female torso for assessing injury behind body armour, investigated the effect of an impact on the wire in an underwire bra (Burrell et al., 2014). The work presented used a female shop mannequin as a mould to form a PermaGel™ torso with a 34D bra size. PermaGel™² was selected by the authors as it provided a non-temperature sensitive material which had been shown to be similar to 10% ballistic gelatine. This work was able to show that the wires in the bras did not increase the risk of injury behind the body armour, however, all the shots were under the bust and did not include any investigation into the response of the breast itself.

Within the open literature two papers were identified that investigated the effect of a ballistic impact on a breast implant (Carr et al., 2016; Pannucci et al., 2018). The work by Carr et al investigated the effect on a breast implant

² It is understood that PermaGel™ is no longer commercially available.

mounted behind a body armour subjected to a non-perforating ballistic impact. They were able to show that in five out of seven cases the implant ruptured. Whilst the work did not consider breast tissue or skin, it did highlight an issue for female officers who have breast implants. The work by Pannucci et al was based on a case study where a female with implants was shot in the breast at close range and the projectile was stopped by the implant. Ballistic trials were conducted to understand the effect a breast implant has on penetration depth. The work showed that there was a statistically significant decrease in penetration distance when the projectile passed through the implant first. This work highlights that silicone implants do change the properties of the breast tissue, which may also have an implication on how the breast responds to a non-perforating impact on a body armour.

1.9 PhD thesis structure

This thesis is structured around a series of distinct chapters covering the work underpinning it, which are described below and presented in Figure 1-3. The thesis is presented in accordance with Cranfield University PhD by paper format, with chapters 2 to 5 presented as journal papers.

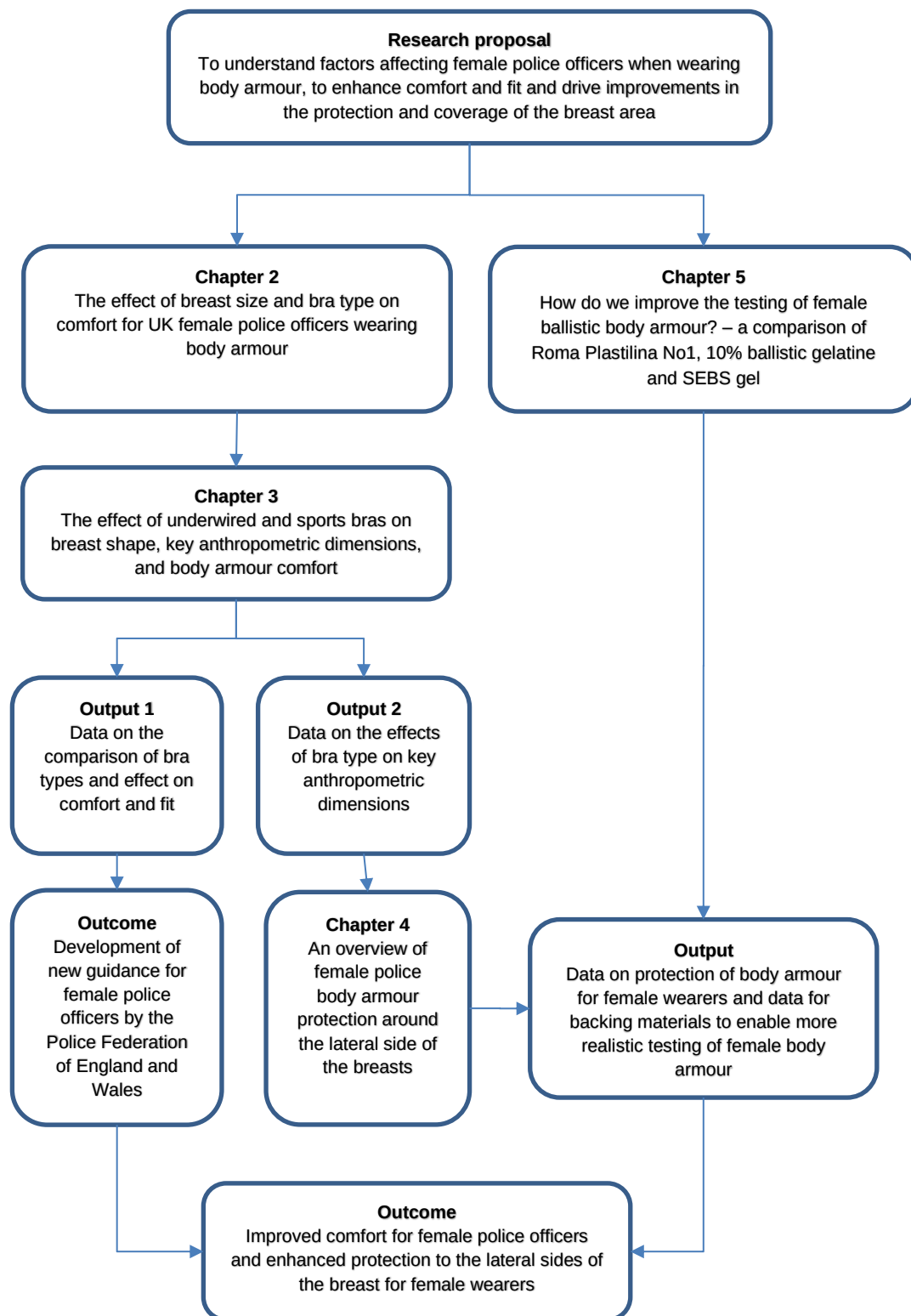


Figure 1-3 Diagram showing the structure of the thesis and how the individual chapters link together to deliver the aim of the thesis

Chapter 1 introduces the thesis and provides the background to the research, and the aims and objectives of the thesis

Chapter 2 is a published paper that investigates issues with current female police body armour. Data was collected using a questionnaire supported by the Police Federation of England and Wales and issued to all female police officers. The work is published in *Applied Ergonomics*.

Publication: Malbon, C., Knock, C., Critchley, R. and Carr, D. (2020) 'The effect of breast size and bra type on comfort for UK female police officers wearing body armour', *Applied Ergonomics*, 84, p. 103012 doi: 10.1016/j.apergo.2019.103012.

The aim of this work was to build an initial dataset from female police officers in England and Wales to

- Understand the factors that affect comfort when wearing body armour.
- Understand the range of bra types and sizes worn under body armour.
- Set the direction for the following stages of the research presented in this thesis.

Chapter 3 is a published paper that investigates the effect of underwired and sport bras on comfort, and key anthropometric data for female police officers when wearing body armour. Data was collected using 3D body scanning and questionnaires. The work is published in the *Police Journal: Theory, practice, and principles*.

Publication: Malbon, C., Knock, C., Critchley, R. and Carr, D.J. (2021) 'The effect of underwired and sports bras on breast shape, key anthropometric dimensions, and body armour comfort', *The Police Journal: Theory, Practice and Principles*, doi: 10.1177/0032258X211011619.

The aims of this work were to

- Determine if a professionally fitted underwired or sports bra has any effect on the comfort of a female police officer whilst wearing body armour.

- Determine what effect different bra types have on key anthropometric data and how this may affect the sizing of body armour for female officers.

Chapter 4 investigates the protection afforded by the body armour to the lateral sides of the breast when wearing an underwired or sports bra.

Publication: Malbon, C., Knock, C., Critchley, R. and Carr, D.J. (2021) 'An overview of female police body armour protection around the lateral sides of the breasts' *pending publication*.

The aim of this work was to

- Investigate the protection provided by the body armour to the lateral sides of the female breast in serving police officers.
- Investigate if an underwired, sports bra or breast size affects the protection provided by the body armour in this area.

Chapter 5 compares three different materials which are already used in ballistic research and investigates their repeatability and response characteristics to two ballistic test rounds. It also considers their applicability to the future testing of female body armour to allow for a more dynamic test to be developed, considering not only perforation of the body armour but also the potential risk from BABT.

Publication: Malbon, C., Knock, C., Critchley, R. and Carr, D.J. (2021) "How do we improve the testing of female ballistic body armour? – a comparison of Roma Plastilina #1, 10% Ballistic Gelatine and SEBS gel" *pending publication*

The aim of this work was to

Compare potential materials for the testing of female body armour with respect to ballistic resistance of body armour and BABT. including

- Roma Plastilina No 1
- SEBS gel at 30/70%
- 10% (by mass) ballistic gelatine.

Chapter 6 presents an overall discussion of the research presented and conclusions drawn from it and suggested further work to follow on from the research presented.

Appendix A provides copies of the questionnaires used in this research.

Appendix B provides instruction on the image analysis process used in chapter 4

1.10 Data associated with research

The data that was collected and used in this research is available at

<https://doi.org/10.17862/cranfield.rd.15052197>

1.11 Aims and objectives

1.11.1 Research Question

To understand factors affecting female police officers when wearing body armour to enhance comfort and fit and drive improvements in the protection and coverage of the breast area.

1.11.2 Aims

The aims of this research are to

1. Understand the factors that affect the comfort and fit of female police body armour in the UK.
2. Investigate backing materials for use in future testing of female body armour.

1.11.3 Objectives

The objectives of the research are to

1. Build a dataset from female police officers on the comfort of their body armour, and the types and size range of bras that are worn.
2. Evaluate the benefits of the most common bra types used when correctly fitted on comfort when wearing body armour and assess the effects on

anthropometric measurements to understand how this affects body armour design.

3. Identify potential issues with coverage on female body armour to understand potential risks and design issues.
4. Compare backing materials used in ballistic testing to understand the consistency and potential applicability to testing female body armour.

1.11.4 Outcome

Generate a greater understanding of the issues facing female wearers of body armour, to provide knowledge and information to support the rapid development of better fitting and safer body armour systems.

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2 THE EFFECT OF BREAST SIZE AND BRA TYPE ON COMFORT FOR UK FEMALE POLICE OFFICERS WEARING BODY ARMOUR

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2.1 Abstract

Within the Police service of England and Wales the wearing of ballistic and stab resistant body armour is common, with most police forces mandating its usage when away from the police station. Of all the serving police officers in England and Wales 29.1% are female (Hargreaves et al., 2017). A survey was developed and then distributed by the Police Federation of England and Wales to all serving female police officers up to the rank of Inspector. The survey returned 2633 responses after cleaning of the data. From the responses it was seen that the predominant bra type worn is underwired (71%) and the predominant UK bra size is 34B (9%). It was also determined that the predominant areas where the body armour either rubbed or caused discomfort were the left and right anterior mammary regions and the posterior lateral sacral region. By understanding the distribution of bra size, type of bra worn and areas of discomfort or rubbing it helps further understand the issues faced by female police officers and how body armour design could be improved.

Keywords UK bra size, Sports bra, Underwired bra, Activity

2.2 Introduction

Within England and Wales there are 43 separate police forces (39 England, 4 Wales) with a total of 123,142 serving police officers, of which 29.1% (35,834) are female (Hargreaves et al., 2017). All these officers will have been issued with a body armour suitable for their role. Each individual police force is responsible for the supply of body armour to their officers, therefore the style, manufacturer and materials used may be different between police forces.

Typically the body armour issued will provide resistance to low velocity ballistic and stab threats (Lewis et al., 2017). These factors can affect the form and fit of the body armour to the wearer.

The wearing of body armour is mandated in most police forces within England and Wales when officers are away from the police station, typically being worn for between 8 to 12 hours without being removed. This includes wearing in police vehicles, while patrolling or dealing with incidents.

In designing body armour for ballistic and stab resistance for any wearer, a designer has to take into account conflicting requirements, including but not limited to: coverage; protection levels; flexibility; comfort; and fitting to body form.

The design of body armour intended for female wearers has improved over recent years, however, these improvements are limited and generally involve the folding, stitching, tapering, or layering of the materials to form breast-like shapes. The use of anthropometric measurements for the design of clothing and PPE for both male and female forms has been reviewed (Carr et al., 2012). This review of literature at that time (2012) highlighted that the use of anthropometric measurements would become crucial in the correct sizing of clothing and PPE. A much earlier study analysed clothing size measurements that had been collected from 1217 female US military personnel in 1977 (Salusso-Deonier et al., 1985). This study showed that the measurement systems used when the data was collected did not take into account overall body proportions, resulting in poorly fitted clothing. A study of 139 female American soldiers was conducted which investigated the fit of body armour on females and the effects on performance (Mithchell et al., 2010). They were able to show that the correct fitting of body armour to the person was crucial to minimising effects on human performance, which relates to the optimisation of user centred design of body armour.

More recent studies have investigated the use of 3D scanning techniques and 3D weaving to create better formed and shaped body armours (Abtew et al., 2018; Abtew, Bruniaux and Boussu, 2017; Boussu and Bruniaux, 2012;

Cichocka, Bruniaux and Frydrych, 2014; Mahbub, Wang and Arnold, 2014). However, this research has not significantly influenced the design and development of female body armour since it was introduced into the UK in the late 1990s. Additionally, the range of sizes available is limited depending upon the number of sizes of body armour a manufacturer wishes to make and does not necessarily compare to standard UK bra sizing.

The certification testing of police body armour for both male and female officers in the UK is conducted in accordance with the 2017 Home Office Body Armour Standard (Payne et al., 2017). For body armours designed for the female form, the standard stipulates the requirements for ballistic and stab testing using standardised female forms of two sizes. Whilst the use of these standardised female forms has improved the assurance in testing of body armour, it has not driven the development of the design and comfort of body armour.

Activity and the effect this can have on the female breast, in terms of movement and discomfort, has been extensively studied in the literature. Several studies have investigated the effects of running on breast pain and how bra type, design and fit are all influencing factors on individual perceived comfort e.g. (Brown et al., 2014; Milligan, Mills and Scurr, 2014). These studies showed that the type of bra used influenced the level of perceived discomfort for the wearer. Research focused on the effects of larger breasts (UK D cup and above) during exercise has considered both support and the kinematics of running (White et al., 2015). Breast support was a factor in pain levels, with greater support reducing perceived pain. However, the level of support provided by the bra played no factor on the kinematics of running. Although this research did not consider the wearing of body armour, police officers are routinely required to perform strenuous physical activities, including running and self-defence techniques. As such the research is important when considering factors that may affect the comfort of female police officers when wearing body armour.

A number of studies have been reported that looked at the effect of body armour and equipment carried by male police officers and its effect on mobility e.g. (Dempsey, Handcock and Rehrer, 2013; Lewinski et al., 2015). Two studies

reported on similar work also included a female cohort (Filtiness, Mitsopoulos-Rubens and Rudin-Brown, 2014; Ramstrand et al., 2016). All the studies reported that equipment and body armour affected the officer's mobility, such as flexion and extension of the trunk, and as such affected the officer's ability to perform tasks efficiently.

Therefore, wearing body armour affects perceived comfort, and limits or reduces the ability to perform actions which may be amplified for female officers if the design of the body armour is poor, or if the wrong style or size of bra is being used.

Although behind armour blunt trauma³ (BABT) is not the focus of this paper, it is important to discuss it briefly to provide an overall picture of the issues. The effects of BABT on the human body have been well reported in the literature (Carr et al., 2013). Most of the studies on BABT focused on a flat torso shape and mainly considered the effects of a non-perforating ballistic impact over the ribs or abdomen. There have been two preliminary studies on the effects of BABT over the spine looking at both soft and hard body armour impacts (Jennings et al., 2018a, 2018b). This work showed that impacts over the spine resulted in different injury mechanisms than had been seen on anterior torso impacts. There has been a limited study done on the effects of non-perforating ballistic impacts on the female torso (Bir and Wilhelm, 2004). This study reviewed injuries sustained by four female police officers and compared them to injuries sustained by ten male police officers. Of the four female case studies, only two were on the anterior of the torso, one over the heart and one defined as 'left chest'. The authors noted that this study was limited, and further data collection was needed to gain a further understanding of the differences between male and females. They did recommend that a separate criterion be developed for testing of female body armour which considered the size and

³ "....spectrum of non-penetrating injuries to the torso resulting from the impact of projectiles on personal armours." (Cannon, 2001)

stature of the wearer. The low number of impacts directly over the breast limits the usefulness of the study for this work.

Due to the nature of the materials typically used in body armour (e.g., multiple layers of woven fabric, laminated materials, chain mail), they do not allow for a fit that easily conforms to the contours of the body. Other factors also complicate the design of female body armours including the shape of the bust, the type of bra being worn under the body armour or the correct shaping of the body armour to the female form. One of the main areas of concern with relation to body armour design for females is the correct fit. Tilsley et al, demonstrated that a 10 mm airgap under the body armour can increase the risk of a ballistic projectile perforating the body armour when compared to a body armour that is close fitting to the body (Tilsley et al., 2018). Air gaps can form above, between and below the breast depending on how the body armour is designed which could potentially result in a ballistic perforation. Understanding more about the factors that may affect the fit of female body armour are important in developing the design of body armour in the future.

The profile of the female body is dependent on breast size, body shape and type of bra worn, which the design of the body armour has to conform to. The aim of this paper was to develop an insight of preliminary data of factors that may affect the comfort, fit and usage of body armour by female police officers in England and Wales by understanding

- the type of bra that is normally worn by a female police officer in combination with body armour
- the range of bra sizes worn by female police officers in England and Wales
- which areas on the body are uncomfortable for female officers
- other factors that may influence the comfort of the body armour

2.3 Method

2.3.1 Survey development and delivery

To deliver on the aims of this work a survey was developed to collate relevant information from female police officers in England and Wales (Appendix A.1). The survey was designed to ensure anonymity of the participants to aid response rate. Bra size was determined by asking the respondent to declare their current UK bra size they routinely wear in combination with their body armour in inches and cup designation (International Organization for Standardization (ISO), 2017; Pechter, 1998; Zheng, Yu and Fan, 2006). In addition, the respondents were requested to define the type of bra they would normally wear under their body armour, such as underwired, sports bra, padded etc. Further details were added to the survey to provide a more comprehensive understanding of issues for female police officers when wearing body armour. These included

- the number of years body armour has been worn for
- role
- comfort when wearing body armour and performing defined actions
- where, if any, the body armour was uncomfortable and / or it rubbed

To identify areas of discomfort and / or rubbing of the body armour, an image was created showing the anterior, posterior, and sides of a generic female torso. This enabled officers to identify any area they experienced rubbing and / or discomfort, not just the breast area. Participants could select up to ten locations of rubbing and / or discomfort on this image, which was the limit of the survey software used. Each point identified by the respondent was counted, therefore if a respondent clicked multiple times in one area each click counted for the analysis.

This image was sub divided into 14 distinct zones to aid in data analysis (Figure 2-1 and Table 2-1). These zones were selected to divide the anterior of the body into left and right areas at the shoulder and breast areas and were then carried around to the posterior of the body.

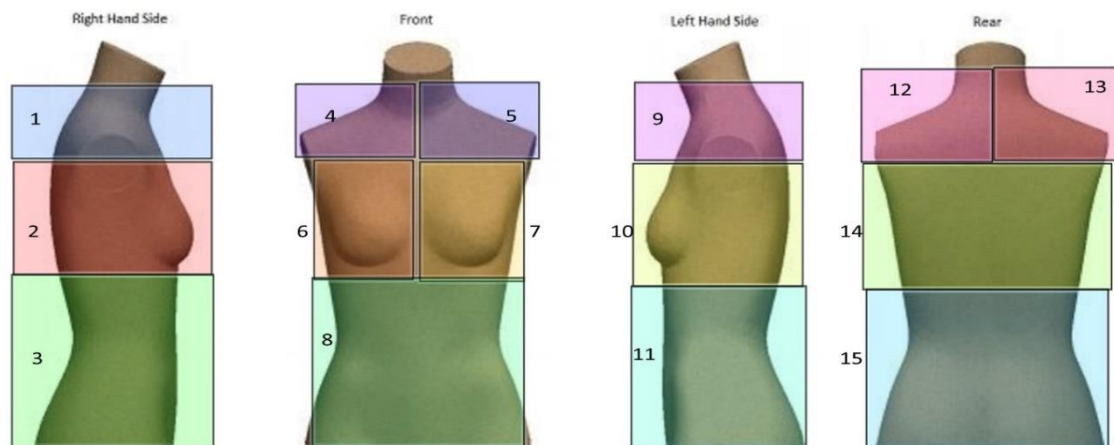


Figure 2-1 Torso image with zones and identifiers

Table 2-1 Descriptive terminology for body area zones

Zone on image	Descriptor	Zone on image	Descriptor
1	Right shoulder region (deltoid)	9	Left shoulder region (deltoid)
2	Right lateral mammary region	10	Left lateral mammary region
3	Right loin / flank	11	Left loin / flank
4	Right anterior shoulder region (deltoid)	12	Left posterior shoulder region
5	Left anterior shoulder region (deltoid)	13	Right posterior shoulder region
6	Right anterior mammary region	14	Posterior thoracic region
7	Left anterior mammary region	15	Posterior lumbar-sacral region
8	Abdominal region		

Ethical approval of the research was obtained from Cranfield University Ethics committee (Reference: CURES/1609/2016).

The survey was prepared for on-line distribution using Qualtrics® survey software⁴, which enabled the responses to questions to be coded for simpler data analysis. In addition, the use of Qualtrics® enabled the survey to be distributed via a web link to increase the target population pool. Internal testing of the survey was conducted to ensure functionality prior to it being distributed. The survey was distributed by the Police Federation of England and Wales, which represents police officers up to and including the rank of inspector, to its female members at the beginning of July 2016. The survey was kept open until

⁴ www.qualtrics.com

October 2016 when the response rate had dropped to zero for the previous two weeks.

2.3.2 Data cleaning

After closing the survey there were 3213 responses. The data was downloaded from Qualtrics to Microsoft Excel to enable the data to be reviewed and filtered to remove any inaccurate or incomplete data.

The following criteria were used to remove records:

- survey not completed 0.6% (n = 19)
- insufficient data submitted, for example entering bra size as 34 or just D rather than 34D 17% (n = 558)
- where stated 'body armour not worn' 0.4% (n = 4)

Post cleaning of the survey data, 2633 responses remained which was a reduction of 18%.

For the category 'Role type', where a participant had selected 'other' and specified their own role designation, they were reviewed and grouped to standardised categories with the assistance of a serving police officer⁵. This was required due to the diverse nature of roles within the Police of England and Wales and resulted in a total of nine categories being used for 'role'; Routine patrol, Specially trained firearms officer, Specially trained public order officer, Traffic officer, Detective, Custody/offender management, Police Community support officer, Civilian staff, Other. Certain roles were collated together under the term 'other' as the number of respondents was two or less.

For the type of bra worn, where 'other' was specified, these were reviewed to ensure that a significant style of bra was not prominent in this category. In addition, where a participant stated something similar to 'mainly underwired, occasional sports bra' it was re-classified as underwired in the response.

⁵ Chief Inspector with 25 years' service

For the determination of areas of rubbing, any indications that fell outside of torso images were discounted from the survey to ensure the analysis of the response only counted valid indications.

For the comfort while wearing body armour and performing actions, no additional cleaning of the data was required as these were fixed responses.

2.3.3 Data analysis

All data analysis was conducted using IBM® SPSS Statistics v24. Data was presented as frequency plots or tabulated as percentages of respondents to the question.

The full data set is available at DOI: [10.17862/cranfield.rd.10059434](https://doi.org/10.17862/cranfield.rd.10059434)

2.4 Results

The initial response to the survey was 8.9% (n = 3213) of female police officers in England and Wales. Once the data cleaning, as described in section 2.3.2, had been completed, the number of responses remaining was 7.3% of female police officers in England and Wales (n = 2633).

2.4.1 Summary of respondents' answers

The range of years that body armour had been worn for is shown in Figure 2-2. The largest group of respondents had worn body armour for six to ten years (34.76%). Overall, 78.65% of respondents had been wearing body armour for more than five years. This demonstrated that the largest proportion of respondents were experienced of working in body armour having worn it for more than five years. The number of years that the respondent had worn body armour does not necessarily relate to the number of years' service or the age of the respondent.

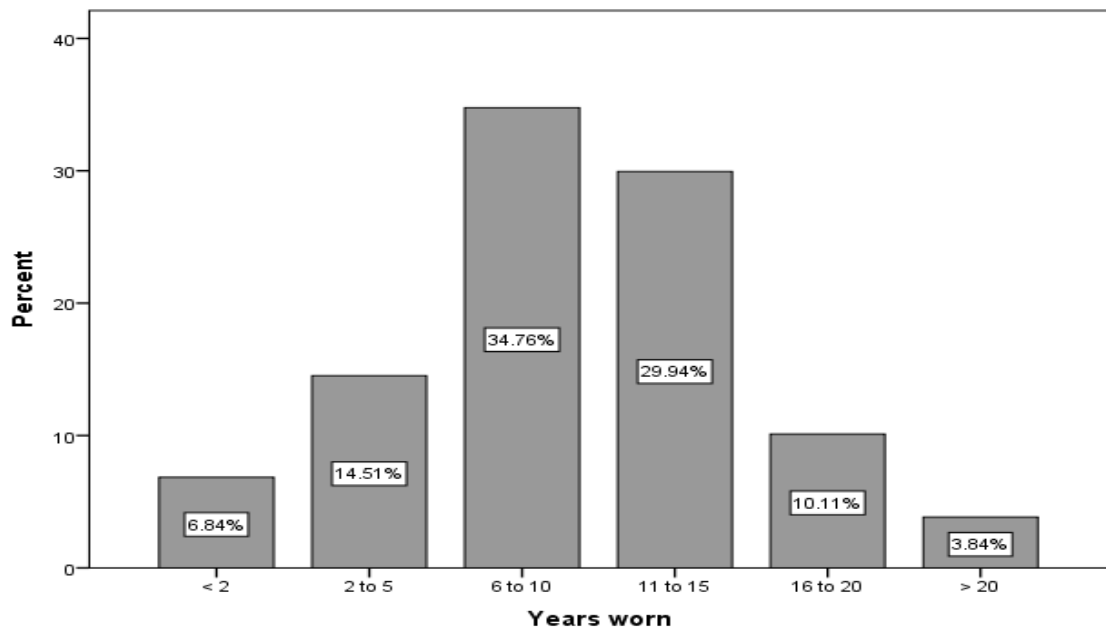


Figure 2-2 Years that body armour had been worn for by percentage

The most common type of bra worn was underwired (70.83%) with the second most common being sports bras (16.97%) as shown in Figure 2-3. Very few officers did not wear a bra (0.46%).

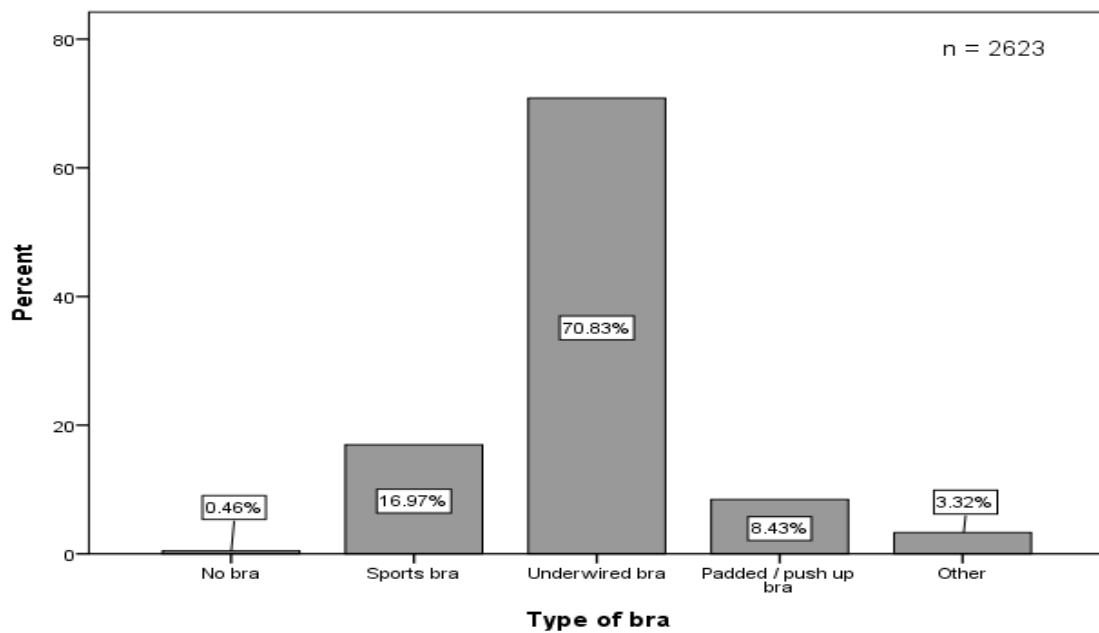


Figure 2-3 Type of bra normally worn under body armour

The distribution of bra sizes (i.e., the UK bra size the respondent is currently wearing) is shown in Figure 2-4. The most common UK bra size was 34B (9%) followed closely by 36C and 34C (8%). The smallest bra size was 23B and the largest bra size was 80C, each with 1 respondent. The top 10 UK bra sizes worn by the respondents are shown in Table 2-2.

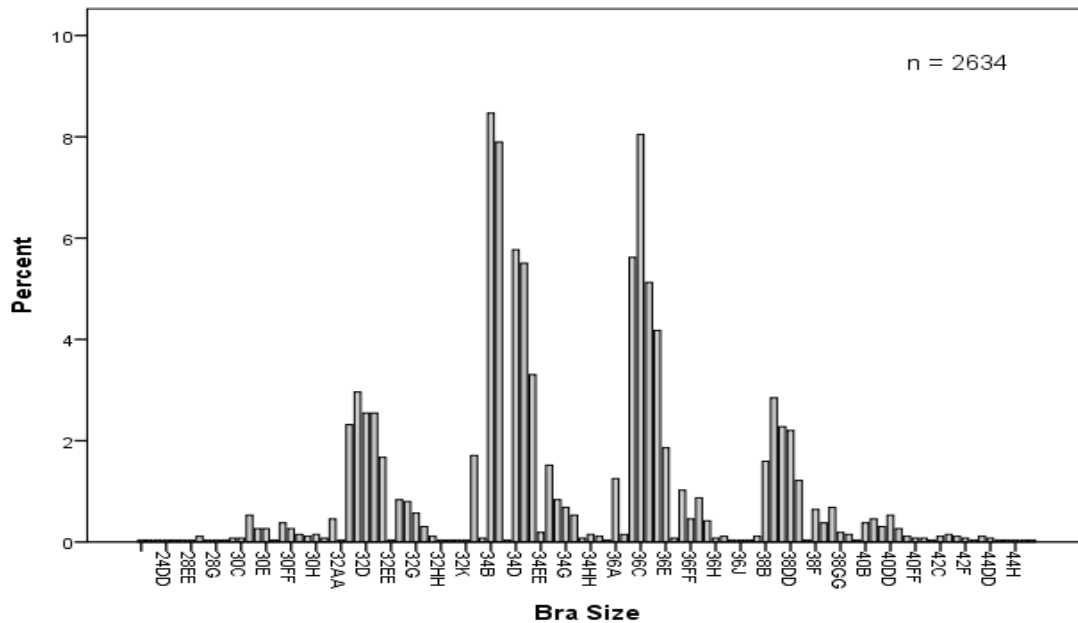


Figure 2-4 distribution of respondent specified UK bra size

Table 2-2 Ten most common UK bra sizes as specified by respondent

Bra size	Count	% of all responses
34B	223	9
36C	212	8
34C	208	8
34D	152	6
36B	148	6
34DD	145	6
36D	135	5
36DD	110	4
32C	78	3
38C	75	3

The relationship between bra size and bra type for the top 10 bra sizes is shown in Table 2-3. As chest size increases the ratio between wearing sports bra to

underwired bra increases (32C 13 : 68 %, 38C 27 : 65 %) as can be seen in Figure 2-5.

Table 2-3 Bra type worn in relation to most common bra size declared

Bra size (n)	Bra type				
	None	Sports	Underwired	Padded/Push up	Other
32C (78)	0%	13%	68%	15%	4%
34B (220)	1%	14%	64%	17%	4%
34C (207)	0%	12%	73%	12%	3%
34D (151)	0%	15%	76%	8%	1%
34DD (145)	1%	12%	79%	6%	1%
36B (148)	1%	16%	69%	10%	4%
36C (212)	0%	19%	67%	8%	5%
36D (135)	0%	18%	75%	4%	4%
36DD (110)	0%	25%	68%	5%	3%
38C (74)	0%	27%	65%	3%	5%

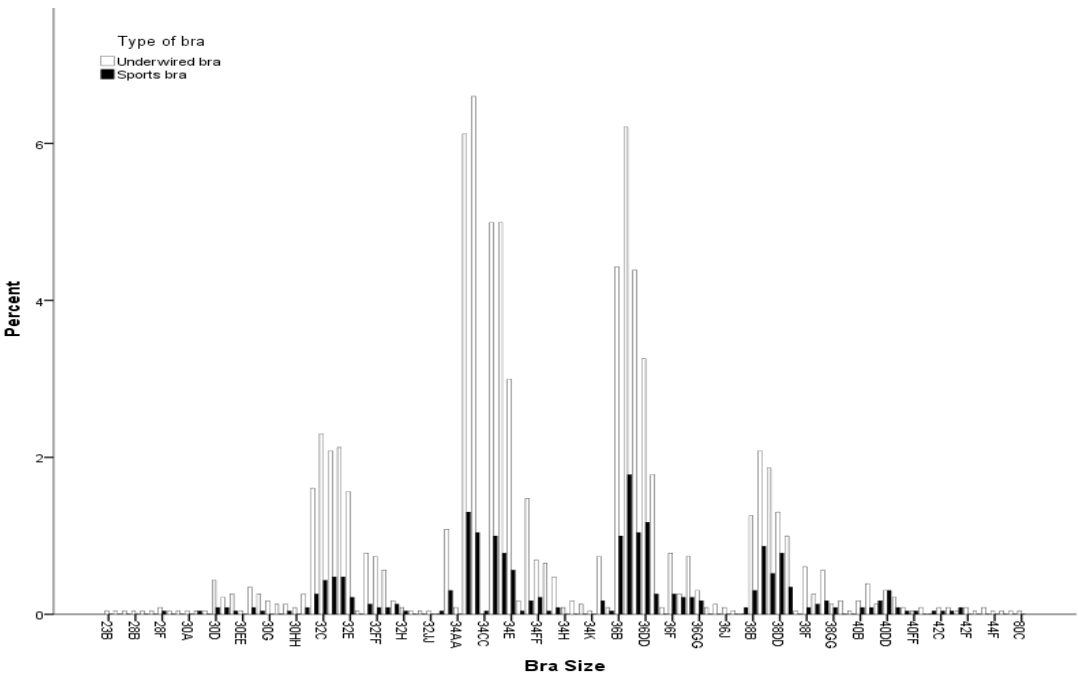


Figure 2-5 Comparison of underwired and sports bra to declared UK bra size

The primary role of the respondents was reviewed in relation to the type of bra worn (Table 2-4). In all roles the main bra type worn is underwired, however in roles which are more active, such as public order, the percentage of officers wearing a sports bra increases compared to other roles such as routine patrol.

Table 2-4 Bra type worn by primary role within the police

Primary role (n)	Type of bra (% by primary role)				
	No bra	Sports bra	Underwired bra	Padded / push up bra	Other
Routine Patrol (2008)	0	17	71	9	3
Specially trained firearms officer (19)	0	16	74	5	5
Specially trained public disorder officer (16)	0	25	63	6	6
Traffic officer (66)	2	23	65	6	5
Detective (311)	0	14	74	9	4
Custody / Offender management (58)	0	19	74	3	3
Police community support officer (14)	0	20	73	0	7
Civilian staff (49)	0	18	63	6	12
Other (81)	1	17	70	9	2
Total across all roles (2622)	0	17	71	8	3

The level of female officer perceived comfort when standing wearing body armour in relation to the type of bra worn is shown in Table 2-5. Overall, 67% of female officers found the wearing of body armour either uncomfortable or very uncomfortable regardless of bra type. The most comfortable bra identified was the padded/push up bra.

Table 2-5 Comfort when standing in body armour with normal bra type worn

Bra type (n)	Very Comfortable	Comfortable	Uncomfortable	Very uncomfortable
Underwired (1849)	1%	31%	53%	14%
Sports (445)	1%	25%	56%	18%
Padded/push up (219)	2%	42%	45%	11%
Other (87)	0%	38%	52%	10%
None (12)	8%	17%	67%	8%

The effect of different bra type whilst wearing body armour was considered in Table 2-6 for a range of normal activities a police officer may perform. Walking was the easiest task performed compared to running which was considered the most difficult. The use of a firearm or TASER was balanced between easy and difficult, although the lower response rate should be noted as less officers will be involved in these duties.

Table 2-6 Ability to performing defined actions when wearing body armour and normal bra type worn

Activity	Bra type (n)	Very Easy	Easy	Difficult	Very difficult
Sitting in a car	Underwired (1775)	2%	37%	48%	13%
	Sports (424)	1%	34%	49%	15%
	Padded/push up (212)	3%	41%	46%	11%
	Other (82)	0%	35%	52%	12%
	No bra (8)	0%	25%	50%	25%
Driving a car	Underwired (1754)	1%	25%	52%	20%
	Sports (420)	1%	23%	51%	23%
	Padded/push up (212)	2%	30%	52%	15%
	Other (80)	0%	33%	46%	18%
	No bra (7)	0%	0%	75%	13%
Walking	Underwired (1764)	3%	71%	23%	3%
	Sports (423)	3%	72%	22%	3%
	Padded/push up (211)	4%	73%	21%	2%
	Other (81)	2%	72%	25%	1%
	No bra (7)	14%	71%	14%	0%
Running	Underwired (1776)	1%	8%	45%	47%
	Sports (425)	0%	6%	44%	50%
	Padded/push up (210)	0%	7%	48%	44%
	Other (82)	0%	11%	42%	46%
	No bra (8)	0%	0%	50%	50%
Self defence	Underwired (1714)	1%	22%	57%	18%
	Sports (408)	0%	21%	57%	20%
	Padded/push up (202)	1%	29%	53%	15%
	Other (79)	0%	27%	47%	22%
	No bra (8)	0%	25%	63%	13%
Using a firearm / TASER	Underwired (191)	3%	45%	36%	16%
	Sports (62)	5%	47%	34%	15%
	Padded/push up (23)	0	57%	39%	4%
	Other (6)	0	50%	33%	17%
	No bra (0)	0	0	0	0

The areas on the torso (Figure 2-1, Table 2-1) that were identified as either rubbed and / or caused discomfort are compared by type of bra worn in Table 2-7.

The predominate regions identified by most respondents as the areas of greatest discomfort and / or rubbing were the left and right anterior mammary

regions. This was except for the respondents who normally wore a padded / push up bra who had a lower percentage response in these areas.

Table 2-7 Areas of rubbing / discomfort identified as percentage of respondent for each bra type worn

Zone	Bra type (n)					Overall (9809)
	Underwired (6870)	Sports (1784)	Padded/push up (810)	Other (306)	None (39)	
Right lateral mammary region	9%	10%	7%	7%	5%	9%
Right anterior mammary region	11%	12%	9%	14%	13%	11%
Left anterior mammary region	12%	12%	9%	13%	10%	12%
Left lateral mammary region	10%	10%	7%	9%	8%	10%
Posterior thoracic region	5%	5%	5%	5%	8%	5%
Right loin / flank	4%	4%	5%	4%	0%	4%
Abdominal region	6%	6%	8%	9%	13%	6%
Left loin / flank	3%	3%	5%	3%	5%	4%
Posterior lumbar-sacral region	8%	8%	9%	8%	8%	8%
Right shoulder region (deltoid)	3%	3%	3%	3%	0%	3%
Left anterior shoulder region	7%	6%	9%	6%	8%	7%
Right anterior shoulder region	6%	6%	8%	6%	8%	6%
Left shoulder region (deltoid)	3%	3%	3%	3%	0%	3%
Right posterior shoulder region	6%	6%	7%	5%	8%	6%
Left posterior shoulder region	6%	6%	6%	5%	8%	6%

The areas identified by the respondents that were uncomfortable and / or rubbed were compared to the 10 most common bra sizes as shown in Table 2-8. The predominate regions identified as the areas of greatest discomfort and / or rubbing were the left and right anterior mammary regions. There is a tendency that as bra size increases the percentage of responses in these two areas increases.

Table 2-8 Areas of rubbing / discomfort identified as percentage of respondent for each bra type for 10 most common bra sizes

Zone	Bra size (n)									
	32C (258)	34B (780)	34C (728)	34D (544)	34DD (580)	36B (493)	36C (781)	36D (506)	36DD (457)	38C (269)
Right lateral mammary region (2)	6%	8%	9%	8%	12%	8%	8%	10%	9%	8%
Right anterior mammary region (6)	11%	8%	10%	11%	12%	11%	10%	13%	13%	10%
Left anterior mammary region (7)	10%	10%	11%	12%	12%	11%	12%	15%	12%	11%
Left lateral mammary region (10)	7%	8%	9%	9%	12%	8%	9%	11%	9%	9%
Posterior thoracic region (15)	7%	5%	5%	5%	5%	7%	4%	6%	4%	4%
Right loin / flank (3)	5%	4%	5%	5%	3%	3%	5%	4%	5%	3%
Abdominal region (8)	9%	8%	5%	8%	7%	7%	8%	6%	6%	6%
Left loin / flank (11)	4%	4%	4%	4%	3%	4%	5%	3%	5%	3%
Posterior lumbar-sacral region (15)	8%	9%	9%	8%	8%	9%	11%	6%	9%	9%
Right shoulder region (deltoid) (1)	3%	3%	2%	2%	2%	3%	3%	3%	4%	3%
Left anterior shoulder region (5)	7%	7%	7%	5%	6%	7%	6%	6%	5%	10%
Right anterior shoulder region (4)	8%	8%	8%	6%	6%	6%	6%	6%	5%	9%
Left shoulder region (deltoid) (9)	3%	3%	2%	3%	1%	4%	2%	3%	3%	3%
Left posterior shoulder region (12)	6%	8%	7%	6%	5%	6%	6%	4%	7%	7%
Right posterior shoulder region (13)	6%	8%	6%	6%	5%	5%	5%	5%	6%	6%

2.5 Discussion

The purpose of this study was to understand the distribution of bra size and bra type within the female police population in England and Wales and the effect this had on comfort of wearing body armour. In addition, data gathered on comfort and physical activity enabled the development of an understanding of issues for female police officers to be developed.

The key findings from this study were

- the most common bra type currently worn by female police officers in England and Wales is underwired (71%) followed by sports bra (17%),

- the most common officer declared UK bra size is 34B (9%) with a range of 23B to 80C
- the most reported areas of rubbing and / or discomfort were around the anterior mammary regions and posterior lumbar-sacral region

The sample size of the survey (2633 respondents) enabled a comprehensive picture to be formed to support the key findings in this study. The largest percentage of respondents were routine patrol officers (76%), with smaller numbers from more specialised roles. This bias was expected due to the primary role of most police officers being routine patrol. However, all these officers would be wearing their issued body armour for much of their shift.

The bra size data was the size declared by the respondent at the time they completed the survey. It should be noted that it is possible that officers may not be wearing the correct sized bra or that between bra manufacturers there may be a discrepancy in sizing. This survey does demonstrate that within the respondents there were four main clusters of bra size declared. By understanding the spread of bra sizes, it may support the development of improved size ranges of body armour for female wearers.

The primary type of bra across all roles that an officer chooses to wear under their body armour was underwired (63% to 74%), although the exact type and style was not ascertained. In some of the more physically demanding roles, including public order officers, more officers declared that they used sports bras (25%) compared to routine patrol (17%), although the majority still specified underwired (63%). This may be due to the more physical nature of the duties and training conducted by public order officers. The data did show one occurrence that was unexpected; traffic officers, which may be perceived as a less physical role potentially, had a higher than expected percentage of respondents wearing sports bras (23%) compared to the average across all roles (17%). The wearing of seatbelts, manoeuvring in and out of vehicles and the requirement to go from sitting to running may explain this.

It is expected that a certain amount of the rubbing and / or discomfort for all users of body armour will be directly related to the wearing of body armour and the burden that places on the person. For female officers this may be exaggerated or in different areas due to the physiological differences (e.g. breasts, waist size, shoulder width).

The type of bra made little difference to the areas identified as either rubbing and / or discomfort for the respondents, except for the padded bra which showed less rubbing and / or discomfort on the anterior mammary regions, than all other types of bras. When size of the bra is considered, the main areas identified as rubbing and / or discomfort were the same as for bra type, however as the bra size increased there was an increase in respondents identifying the breast as areas of discomfort or rubbing. This could be related to lack of support for larger breasts or poor fitting of the body armour.

The data collected concerning comfort when standing and activities when wearing body armour indicates that the wearing of body armour causes a level of discomfort and restriction in capability to perform actions. Some of this may be due to the body armour itself and the restriction that it places on movement as identified from the literature. However, the most difficult task identified for all bra types was running, followed closely by self-defence. These are the two most physical activities surveyed and may be an indication that bra type and support may be critical in comfort when wearing body armour.

Some of the factors that affect the comfort of the body armour may be due to the design, fit and shape of body armour itself, especially where discomfort occurs at the side of the breast. This paper has not considered the effect of carriage of equipment on comfort and ease of activity. The style and correct sizing of the bra has also not been considered, as although generic descriptors were used for the bra type, details of the bra, materials used in the bra and age of the bra were not considered.

The survey has provided a data set from which it is possible to hypothesise that comfort of body armour relates to the interaction between bust size, bra type and precise shape of the contours of the female body compared to the design of

body armour, although further work building on this survey is needed to develop a greater understanding.

2.6 Conclusions

This study has developed a comprehensive data set for UK female police officers for size range and type of bra worn, both of which will influence the form and shape of the breast under body armour. The two most commonly worn bra types were underwired (71%) and sports bra (17%) with nine percent of respondents wearing size 34B bra. The data does not conclude that one bra type is better than another when comfort whilst wearing body armour is considered, although potentially padding can improve comfort in certain circumstances.

By understanding the effects body armour has on female officers it may be possible to focus design efforts into improving the comfort, fit and protection afforded in an area that has had less research compared to male users since body armour was first developed.

2.7 Acknowledgements

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3 THE EFFECT OF UNDERWIRED AND SPORTS BRAS ON BREAST SHAPE, KEY ANTHROPOMETRIC DIMENSIONS, AND BODY ARMOUR COMFORT.

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3.1 Abstract

This study follows on previous research which investigated the comfort and types of bras worn by UK female police officers when wearing body armour and performing typical activities. This controlled study involved a cohort of 31 female police officers and investigated three main areas. Firstly, the effect of professional bra fitting on size and comfort, secondly the effect of wearing an underwired bra or a sports bra on comfort and ability to perform certain actions, and thirdly the effect of an underwired bra and sports bra on key anthropometric data in relation to the fitting of body armour.

3.2 Highlights

- 77% of participants were resized for an underwired bra and 87% for a sports bra
- Cup size or under bust measurement does not influence where participants identified areas of rubbing and / or discomfort when wearing body armour
- Bust to bust length, chest circumference and bust prominence are all statistically significantly greater for an underwired bra than a sports bra
- 71% of participants identified that when wearing a body armour, they will now be wearing a sports bra

3.3 Keywords

Underwired bra, Sports bra, Anthropometric chest measurements, Professional bra fitting.

3.4 Introduction

A previous study identified that within the Police service of England and Wales, female police officers wore a range of bras under body armour, with the predominant types being underwired and sports bras (Malbon et al., 2020). This paper further investigates the effects of both underwired and sports bra on comfort and fit of body armour for female police officers within a controlled group.

3.4.1 Literature review

Within the Police service of England and Wales, female police officers make up 33% of the work force and are routinely issued with ballistic and / or knife resistant body armour suitable for their role (Home Office, 2019a). This body armour can be from a variety of suppliers and designs dependent upon individual police forces. However, all body armours supplied have been tested against and comply to the minimum performance specification defined in the UK Home Office standard for body armour (Payne, O'Rourke and Malbon, 2017). This standard includes several tests specific to body armour designed for a female form (known as formed armour).

Previous work has demonstrated that female police officers found body armour uncomfortable to wear, particularly around the breast area, and some actions such as self-defence techniques and driving a car were difficult to perform (Malbon et al., 2020). An investigation into female British soldiers wearing the OSPREY armour system, reported similar findings (Davis, Lewis and Ellett, 2020). That study identified that female soldiers experienced challenges in carrying out basic movements and being able to access personnel equipment worn on the person. However, they identified that OSPREY armour was originally sized based on male anthropometric data and was therefore not idealised for female anthropometric dimensions. Whilst military and police body armour are designed to protect against different threats, the reported issues are similar in both studies, providing additional evidence that body armour for female wearers is not optimised.

The issues with personal protective equipment (PPE) not being designed or optimised for females is not unique to body armour. Research by McQuerry et al identified issues with apparel and PPE for female firefighters (McQuerry, Kwon and Johnson, 2019). They clearly identified that most of the personal protective clothing had been designed around male anthropometric data, which results in a lack of protection and a decrease in mobility for female wearers. Within the construction industry, research has shown that PPE is similarly focused on male anthropometric data, resulting in badly fitting PPE, exposing female workers to additional safety hazards (Onyebeke et al., 2016).

This highlights further the issue that for previously male dominated roles, PPE must develop to cover a wider perspective of users, not only for variances due to gender, but also ethnicity.

The wearing of body armour and the limitations and discomfort this can cause to the wearer may be compounded for female users by additional factors, such as correct sizing and type of bra, bust size and changes to the natural properties of the body associated with aging and physical condition (Coltman, Steele and McGhee, 2017). Within the police service, body armour tailored and certified for female police officers has been available in the UK since 1995 (Pettit, 1995).

Although female body armour testing has been around since 1995 in the UK, the development of body armour designs for the female form has not progressed. Limited research has been published in the open literature into understanding factors which may affect the comfort and wearability of body armour.

The size and type of bra an officer wears are outside the control of the designer of a body armour. However, it may influence the key anthropometric dimensions of the bust depending on style and type of bra (Daanen, 2006). Within the open literature there is little evidence regarding the effect of bra size on comfort under body armour. However, research into the effects of ill-fitting bras leading to the development of musculoskeletal pain inhibiting women from participating in physical activity does provide an insight into one potential issue (McGhee and

Steele, 2010). The research determined that 85% of the participants in the study were deemed to be wearing the wrong size bra, causing pain during physical activity. However, they did not determine if correct fitting bras decreased the incidence of musculoskeletal pain.

Traditionally, in the UK, bra size has been determined by the relationship between the under bust and chest circumference measurements, giving a band size measurement and a cup size denoted by a letter. This cup size is determined through the difference between the under bust and chest circumference measurements (BS EN 13402-3, 2017). The more common method for determining bra size by professional fitters involves the assessment of the bra when worn to determine best fit for an individual.

Professional fitting and guidance for females when selecting and adjusting bras has been shown to improve comfort (McGhee, Steele and Munro, 2010). A further study compared the use of professional bra fitters to the standard method of measuring described above to determine the best method to provide optimal comfort and fit in an underwired bra (White and Scurr, 2012). That study determined that there were significant differences between the traditional and professional 'best-fit' bra sizes for a cohort of 45 participants, especially for larger bra sizes. However, the study did not identify if the professional 'best-fit' bra fitting gave an improvement in comfort or support for the participants.

Whilst there is some evidence in the academic literature to suggest a large proportion of women are wearing the wrong size bra, more has been reported through the general press with reports stating that 70 to 100% of women are in the wrong sized bra (e.g. Davis, 2018; Moss, 2016; Perling and Colizza, 2019). Whilst this does not necessarily have a scientific grounding, it does indicate that bra size may need to be considered as part of the approach to improving the comfort and fit of body armour for female police officers.

The design of individual parts of a bra may also affect fit, particularly for females with medium to hypertrophic (large) breasts (Coltman, Steele and McGhee, 2018). They determined that the design and sizing of the underwire and front band of bras was poor, which may affect comfort and fit. This work did not

consider the professional fitting of bras and how shape and form may influence the design of the bra that is best suited to an individual.

Breast pain has been associated with age, larger bra cup size and lower levels of physical activity (Scurr et al., 2014). Although this work was based on data collected from the general population and not by occupation. A significant correlation was reported with reduction in skin thickness from the age of 45 years and a decrease in breast skin elasticity from the mid 20's years of age, reducing natural breast support (Coltman, Steele and McGhee, 2017). Whilst no data is available in the open sources related directly to the age range of female police officers, general data shows that over 44% of police officers in England and Wales are over 41 years old (Home Office, 2019b). It can be assumed that a percentage of these will be female and may be a factor associated with comfort of police body armour.

Physical activity without appropriate breast support has been linked to increased levels of breast pain particularly for larger breasted females (White et al., 2015). This work focused on upper kinematics during running and did not consider body armour or other clothing. It did establish a link between breast movement during activity and the need for greater breast support. This is of significance for female police officers when involved in physical activities such as self-defence.

The review of the literature highlights that there is not one factor that influences breast pain, but several factors that need to be considered to improve the comfort of female police officers when wearing body armour. The effect of different bra types also needs to be considered and how this may affect how the body armour fits the female form by understanding the key anthropometric dimensions.

The aims of this research are

1. To determine if a professionally fitted underwired or sports bra has any effect on the comfort of a female police officer whilst wearing body armour

2. To determine what affect different bra types have on key anthropometric data, and how this may affect the sizing of body armour for female officers.

3.5 Method

A study was developed consisting of four parts

1. Recruitment of female police officers to participate in the study
2. A professional bra fitting session and the supply of an underwired and sports bra that were both best fit and style for the participant
3. A 3D body measurement scan of each participant in the underwired and sports bra
4. The completion of a three-part survey, pre-fitting and then post-fitting wearing each of the bras for a minimum of 10 shifts.

Ethical approval for the study was gained from Cranfield University (ref CURES/2560/2017). Participants were provided with a briefing and provided informed consent for the study and were able to withdraw at any stage.

3.5.1 Recruitment of participants

Working with the local area representative from the Police Federation of England and Wales (PFEW) for Bedfordshire, Cambridgeshire and Hertfordshire Constabularies, female police officers were asked to volunteer to participate in this study. The study was supported by the Chief Constables of each police force involved, enabling the officers to attend bra fitting and scanning during work time.

The following criteria were used in the selection of the participants for the trial

- willing and able to attend a professional bra fitting at either the Peterborough or Cambridge branches of John Lewis and Partners department store⁶ during a specified one-month period

⁶ <https://www.johnlewis.com/>

- willing and able to attend Cambridgeshire Constabulary Police Headquarters on one of two days for 3D body scan wearing only the bras supplied on their torso and
- willing to wear each bra for ten shifts under their normal uniform and body armour and complete a questionnaire.

The officers were not paid for participating in the study, but they were able to keep the bras supplied at the completion of the study.

The final selection of officers was completed by the PFEW representative resulting in a cohort of 31 participants.

3.5.2 Bra fitting

A previous study identified the most common styles of bras worn by police officers under body armour were underwired (71%) and sports (17%) bras (Malbon et al., 2020). For this study, each participant attended a professional bra fitting session and fitted for a new underwired and sports bra. The participants did not necessarily see the same fitter; however, each fitter had been trained to the same standard by John Lewis and Partners and the following guidance was provided

- fit for an underwired and sports bra that is the best fit regardless of manufacturer
- ensure the participant is comfortable and aware of how to adjust the bras for best fit.

At each bra fitting session, the fitter recorded the bra size, type, and stock number for both the underwired and sports bra selected. The participant was not issued with the bras at this time.

3.5.3 3D Body measurement scan

All participants were scanned in the near nude state using a Sizestream 3D scanning system⁷ to provide a full body scan.

On arrival for scanning the participants were issued with their two bras and assigned a unique ID. The bras were in new condition with sales tags still attached and had not been laundered.

The participant was provided with the following instructions on how to place themselves in the 3D scanner, shown in Figure 3-1, when they were ready to be scanned

- Stand upright facing forwards
- Feet, shoulders width apart centred on the reference line running perpendicular across the scanner floor
- Arms running parallel to the torso with the hands holding sliding adjustable grips, ensuring the arms remained straight throughout the scan

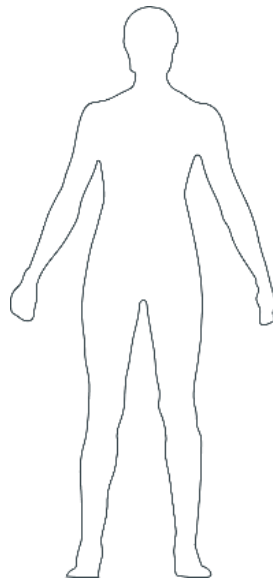


Figure 3-1 Posture adopted within 3D scanner

⁷ SizeStream® Body Scanner 2014 v12.0, set to collect 10000 data points from across the body

For this study, participants were requested to remove their torso clothing and tie their hair up (if long). If the participant was wearing a skirt, they were asked to remove this for the scan to enable the system to acquire reference points from the crotch area, otherwise lower garments remained on during the scan.

On entering the scanner, the participant changed into one of the bras, placed themselves in the correction location and standing posture, confirmed which bra they were wearing, and they were ready to be scanned. On completion of the first scan, the officer changed into the second bra and the process was repeated. Each scan lasted approximately 3 seconds.

The measurements shown in Figure 3-2 and listed in Table 3-1 were recorded for each scan taken. Circumference measurements followed the contours of the body, height measurements were straight line distances.

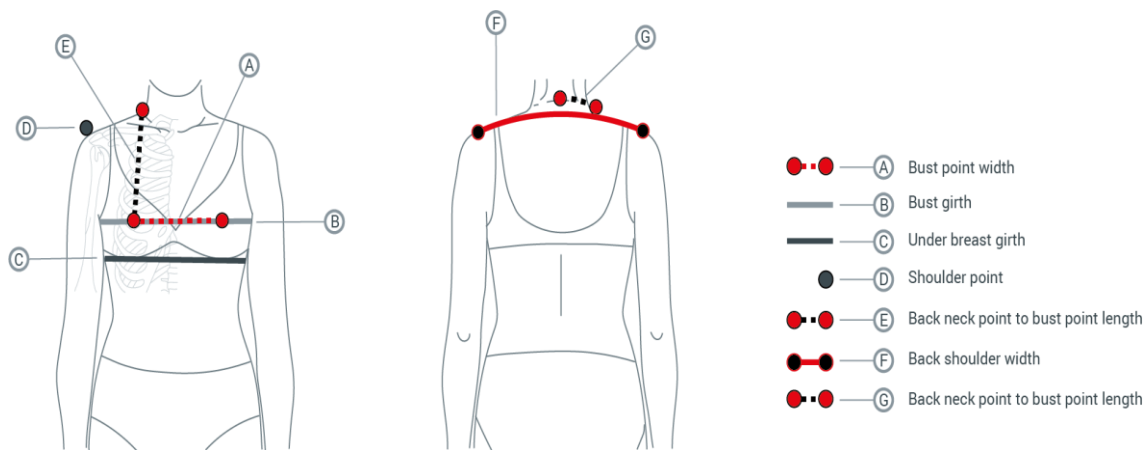


Figure 3-2 Anthropometric measurements

Table 3-1 Anthropometric data terms and descriptions

Measurement	Description	Equivalent BS ISO 8559-1 2017 reference
Subject height	Height from the floor to the top of the subject head (hair is included)	Stature
Waist circumference	Circumference taken at a 15-degree angle starting at the back point that is 80% of the distance from the crotch level to the small of the back point	Waist girth
Back shoulder width	Distance between the right and left shoulder points ⁸	Back shoulder width
Bust-to-bust length	Distance between the bust points ⁹	Bust point width
Chest circumference	Horizontal circumference measured across the bust points, under the arm pits and around the back	Bust girth
Under bust circumference	Horizontal circumference taken below the bust	Under bust girth
Cervical-to-bust length	Distance from the back-neck point ¹⁰ along the neck base line to side neck point ¹¹ , then to bust point (left and right)	Back neck point to bust point
Bust prominence	Distance from the sternum across the bust to the frontal plane ¹²	No equivalent

3.5.4 Survey

A three-part survey was developed to capture relevant information at the following points in the study

1. pre-fitting of new bras to establish a baseline for each participant involved in the study, Appendix A.2.
2. post-fitting first bra after ten shifts, Appendix A.3.
3. post-fitting second bra after ten shifts, Appendix A.3.

⁸ “most lateral point of the lateral edge of the spine of the scapula, projected vertically to the surface of the skin” (BSI ISO 8559-1:2017, 2017)

⁹ “most anterior point of the bust when wearing a bra” (BSI ISO 8559-1:2017, 2017)

¹⁰ “tip of the prominent bone at the base of the back of the neck in the mid-sagittal plane, and projected posteriorly to the surface of the skin” (BSI ISO 8559-1:2017, 2017)

¹¹ “crossing point of the neck base line and the anterior border of the trapezius muscle” (BSI ISO 8559-1:2017, 2017)

¹² The frontal plane is a linear vertical plane splitting the front and rear of the body at the 50% body mass point.

The survey was conducted using a web-based survey tool¹³. After completing the wearing of both bras, the participants were asked to answer two further questions

- What bra did you personally find most comfortable?
- What type of bra will you use from now on?

3.5.5 Data analysis

All data from the 3D body scans and post analysis were recorded in millimetres and rounded to the nearest integer. Where left and right hand side measurements were taken, a visual check was conducted to ensure the results were similar, differences greater than 50 mm were investigated and where they could not be accounted for all data for that participant was removed from the analysis.

All statistical analysis was conducted using SPSS¹⁴. For the paired sample t-test, checks for normality of data were conducted prior to analysis, ensuring no outliers, and the data was normally distributed using Shapiro Wilks test for normality ($p > 0.05$)

All data collated for this paper can be accessed here
10.17862/cranfield.rd.14381141

3.6 Results

Of the initial 31 participants who attend bra fittings, 29 attended a 3D measurement scan and completed the pre-fitting questionnaire. Of these, after post scanning extraction of measurements, nine contained erroneous data where the body scanner was unable to determine the correct anatomical landmarks. The measurements for these participants were removed prior to analysis. Of the participants who completed the initial questionnaire, 15 completed the survey

¹³ Qualtrics©

¹⁴ IBM® SPSS® Statistics V24.0.0.1

post-fitting of the underwired bra and 19 post-fitting of the sports bra. Of these 12 participants completed both surveys.

3.6.1 Bra fitting

The largest number of participants, 38% (n = 11) stated they had been fitted for a bra in the last two years. The second largest was 24% (n = 7) who said they had been fitted for a bra sometime in the last 5 years. However, 14% said they could not remember when they were last fitted.

The distribution of UK bra sizes for pre-fitting and post-fitting for underwired and sports bra is shown in Figure 3-3 (n = 31). The distribution of UK bra cup size is shown in Figure 3-4. A summary of the data is provided in Table 3-2.

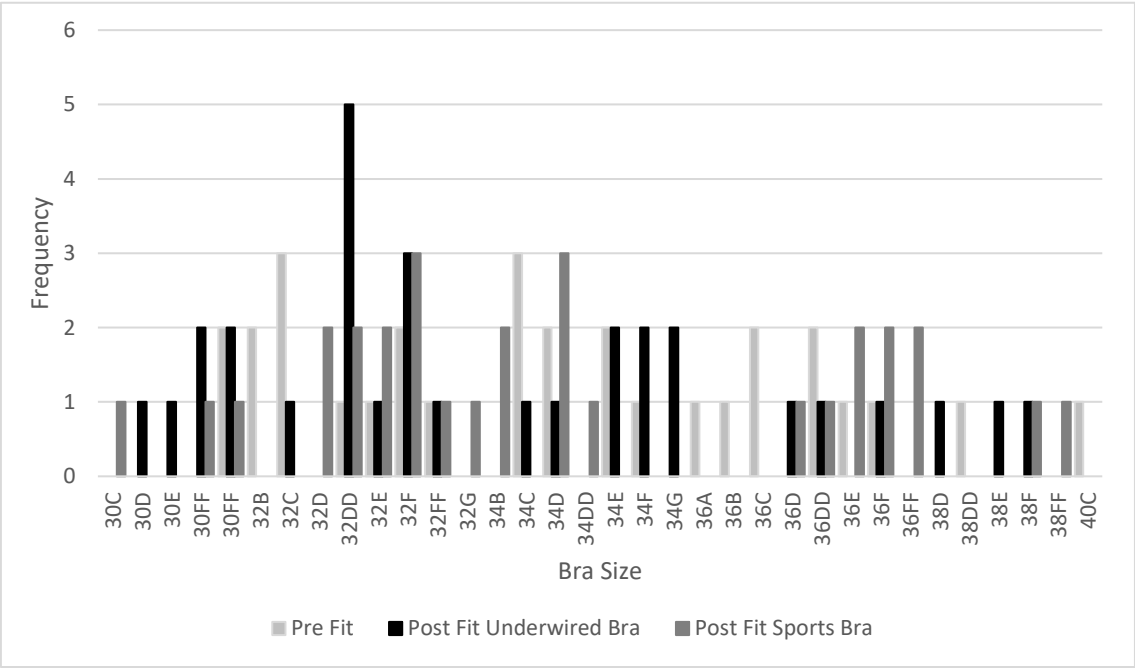


Figure 3-3 Pre and post-fitting UK bra size distribution

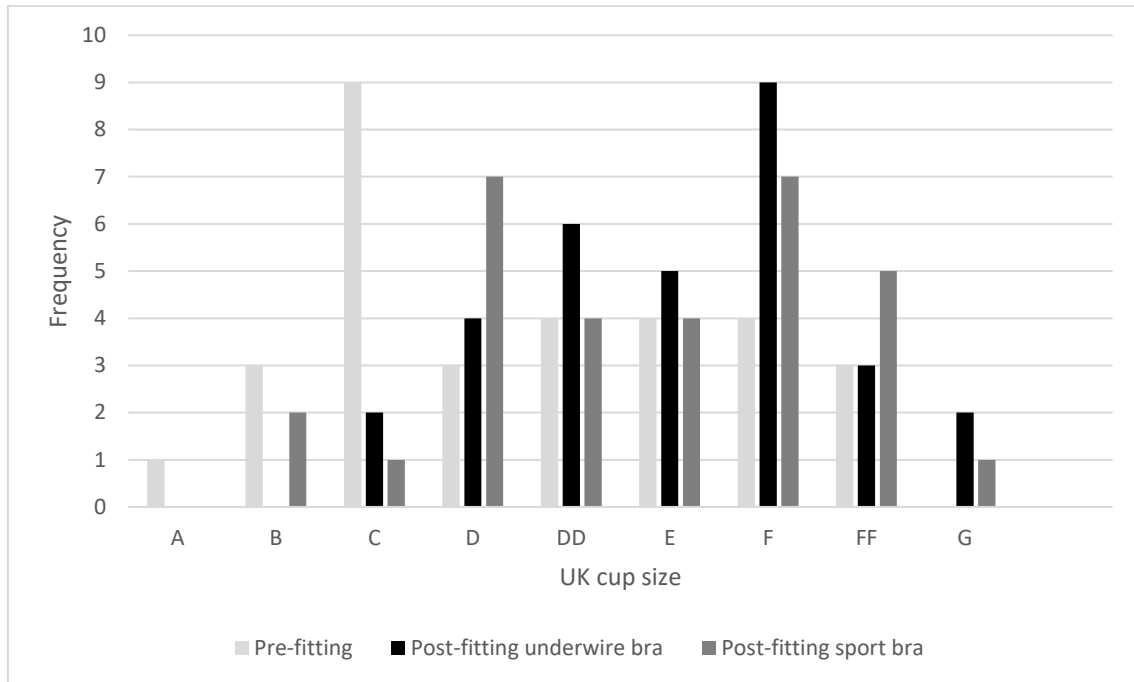


Figure 3-4 Pre and post-fitting UK Bra cup size distribution

Table 3-2 Summary of data of bra fitting outcomes

	Pre-fitting	Post-fitting Underwired bra	Post-fitting Sports bra
Number of bra sizes	19	20	20
Range of bra sizes	30FF to 40C	30D to 38F	30C to 38FF
Most common bra size(s)	32C, 34C, 34D (n=3)	32DD (n=5)	32F, 34D (n=3)
Number of cup sizes	8	7	8
Range of cup sizes	A to FF	C to G	B to G
Most common cup size(s)	C (n=9)	F (n=9)	D, F (n=7)
Percentage resized	n/a	77%	87%
Resized for under bust measurement	n/a	42%	39%
Resized for cup	n/a	74%	87%
Resized for both underbust and cup	n/a	42%	39%
Price range	n/a	£22 to £48 (mean £35)	£16 to £42 (mean £34)

After professional fitting, 77% of participants were resized for an underwired bra and 87% for a sports bra, with the majority being resized for cup rather than under bust measurement. The resizing of the participants predominantly moved

the range of cup sizes upwards, with no A cups or lower being supplied. There was a slight increase in the number of different bra sizes issued with a downward shift in the larger sizes.

Across the two bra types the mean price was similar, however price was not used in this study as a factor and is supplied for reference only.

3.6.2 3D Body scan measurements

The measurements listed in Table 3-1 were obtained for both bra types from the 3D measurement scans using the scanner system software¹⁵.

3.6.3 Participant baseline anthropometric data

For each participant, their height, waist circumference and shoulder width was recorded (Table 3-3).

Table 3-3 Summary anthropometric data

	Height (mm)	Waist circumference (mm)	Back Shoulder width (mm)
Mean	1682	971	455
Min	1582	849	397
Max	1899	1178	556
SD	70	115	37
CV (%)	4	12	12

The baseline data demonstrated that the participants represented a range of body size and shape.

3.6.4 Bust to bust length

For each participant the bust to bust length was measured when wearing the underwired and sports bra, Table 3-4. A paired sample t-test was conducted to determine if there was a statistically significant difference between bust to bust length between the underwired and sports bra.

¹⁵ Size Stream Studio V3.0 (2014)

Table 3-4 Summary data – Bust to bust measurement for underwired and sports bra

	Underwired bra	Sports bra
Mean (mm)	163	151
Min (mm)	142	121
Max (mm)	200	193
SD	17	19
CV (%)	11	12

The paired sample t-test identified that when wearing an underwired bra there is statistically greater distance between the bust points than in a sports bra, $t(19) = 2.729$, $p < 0.05$. This means that the breasts are held further apart when wearing an underwired bra compared to a sports bra. This difference may impact on how the body armour sits across the breasts and on any airgaps that may form under the body armour between the left and right breast.

3.6.5 Chest circumference

For each participant the chest circumference was measured when wearing the underwired and sports bra, Table 3-5. A paired sample t-test was conducted to determine if there was a statistically significant difference between chest circumference between the underwired and sports bra.

Table 3-5 Summary data - Chest circumference measurement for underwired and sports bra

	Underwired bra	Sports bra
Mean (mm)	1057	1030
Min (mm)	941	938
Max (mm)	1249	1230
SD	91	78
CV (%)	9	8

The paired sample t-test confirmed that the chest circumference in the underwired bra was statistically significantly greater than in the sports bra, $t(19) = 3.303$, $p < 0.005$. The mean difference between underwired and sports bra chest circumference was 25mm.

3.6.6 Under bust circumference

A paired sample t-test was conducted and identified that there was no significant difference between the underwired and sports bra. This was expected as it is not affected by bust volume in the same way as chest circumference is.

3.6.7 Cervical to bust point length

The cervical to bust point data is summarised in Table 3-6. When testing for normality, two data points were identified as erroneous. On further investigation of the original data, it was identified that the measurement software had been unable to correctly identify the cervical point from the 3D body scan due to the participants hair obscuring part of the neck on the right-hand side. These data points were removed and the test for normality repeated which confirmed the data was normally distributed.

A paired sample t-test was conducted to compare cervical to bust point measurements on the left and right side within bra type and between bra type. The cervical to bust point measurements, both within bra type and between bra types were not statistically significantly different.

Table 3-6 Summary data – Cervical to bust point measurement for underwired and sports bra

	Underwire bra (mm)		Sports bra (mm)	
	Left	Right	Left	Right
Mean (mm)	381	384	386	393
Min (mm)	331	334	337	345
Max (mm)	455	446	459	458
SD	33	31	36	33
CV (%)	9	8	9	8

3.6.8 Bust Prominence

Bust prominence data is summarised in Table 3-7. A paired sample t-test was conducted to compare left and right breast prominence within bra type and between bra type.

Table 3-7 Summary data – Left and right bust prominence measurement for underwired and sports bra

	Underwire bra (mm)		Sports bra (mm)	
	Left	Right	Left	Right
Mean (mm)	253	257	233	241
Min (mm)	209	221	200	196
Max (mm)	286	297	255	274
SD	21	22	15	19
CV (%)	8	8	7	8

There was no significant difference identified between the left and right breast prominence when wearing an underwired bra. However, when wearing a sports bra, there was a statistically significant difference in breast prominence between the left and right breast, $t(19) = 2.75$, $p < 0.05$. There was also a significant difference in breast prominence when the left and right breast were compared between bra types, with breast prominence greater for both breasts when wearing the underwired bra: left breast, $t(19) = 6.65$, $p < 0.0005$; right breast, $t(19) = 6.83$, $p < 0.0005$.

The difference between the left and right breast prominence when wearing the sports bra may be due to the way the sports bra compresses the breasts to hold them more in place compared to the underwired bra, which tends to provide more uplift support.

3.6.9 Survey Data

As part of the survey, participants were asked to state how often they had laundered their new bra and how many early, late, or night shifts¹⁶ they had conducted during the trial. The summary data for this is shown in Table 3-8.

¹⁶ Early – Typically 0600 to 1500, Late – Typically 1400 to 2300, Night – Typically 2200 to 0700

Table 3-8 Summary data - number of times bras were washed and shifts worn during trial

	Bra type	Washes	Early shift	Late shift	Night shift
Mode	Underwired	3	3	4	4
	Sports	3	4	3	4
Minimum	Underwired	2	1	1	1
	Sports	2	1	0	3
Maximum	Underwired	15	10	10	10
	Sports	15	10	10	6

The most common number of each shift worked was evenly spread for both bra types and time of shift. Whilst at least one officer conducted no late shifts the variation in shift pattern ensured that most participants trialled the bras at different times of day. The most common number of times the bras were washed was consistent between bras, this is important as it is known that fabric materials can be affected by machine washing in terms of the physical and mechanical properties of the materials used in the bra which could affect comfort (Gore et al., 2006). All participants washed their bras at least twice during the trial.

3.6.10 Areas of discomfort or rubbing

The areas identified by the participants as either rubbing and / or discomfort were compared for each stage of the trial. Not all participants completed all three surveys, therefore the data is presented as percentages of total respondents for each stage of the trial: Pre-fitting (n=29), post-fitting underwired bra (n=15) and post-fitting sports bra (n=18). Only areas that had a recorded response were reviewed, shown in Figure 3-5

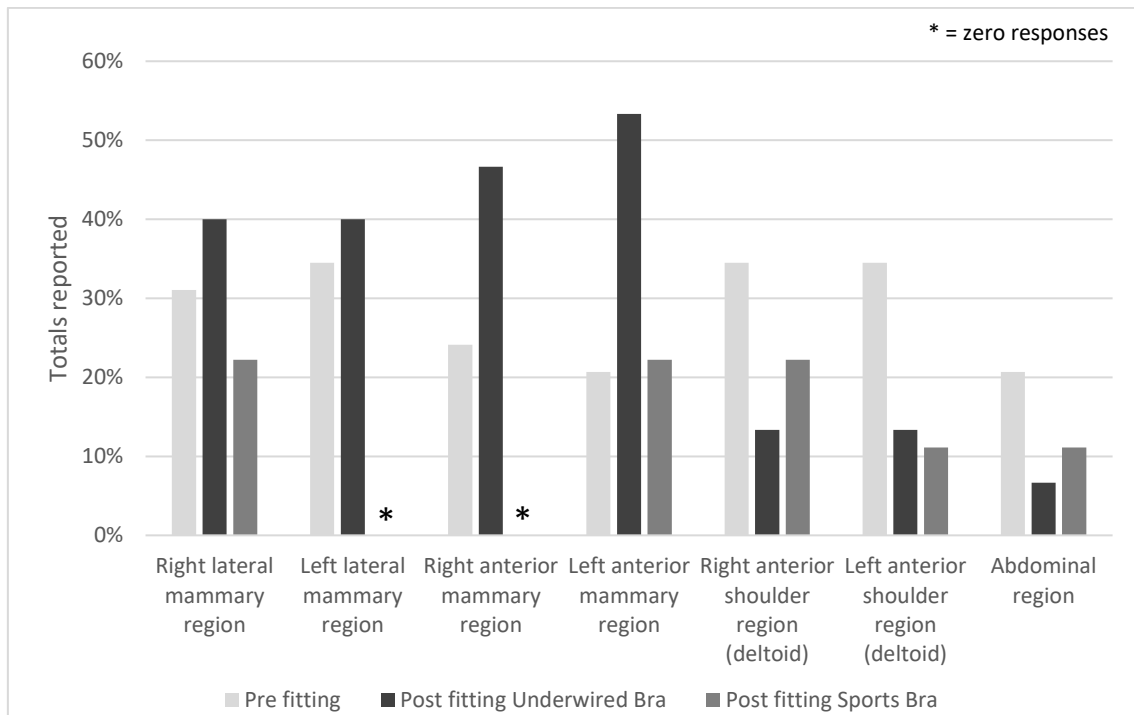


Figure 3-5 Total identified areas of rubbing or discomfort pre- and post-fitting

Further analysis was conducted on the data from participants who completed all three stages of the trial (n=12) to investigate the effects of professional bra fitting on rubbing and / or discomfort, Figure 3-6. This data was then broken down by under bust size, Figure 3-7, and cup size, Figure 3-8, focusing on the right and left lateral mammary regions and the right and left anterior shoulder regions to investigate if either of these factors had more of an effect. A further effect was investigated comparing bust prominence determined by the 3D measurement scans with rubbing and / or discomfort on the lateral mammary and anterior shoulder regions. For the purpose of this, the mean value for left and right bust prominence was calculated for each bra type, Table 3-9.

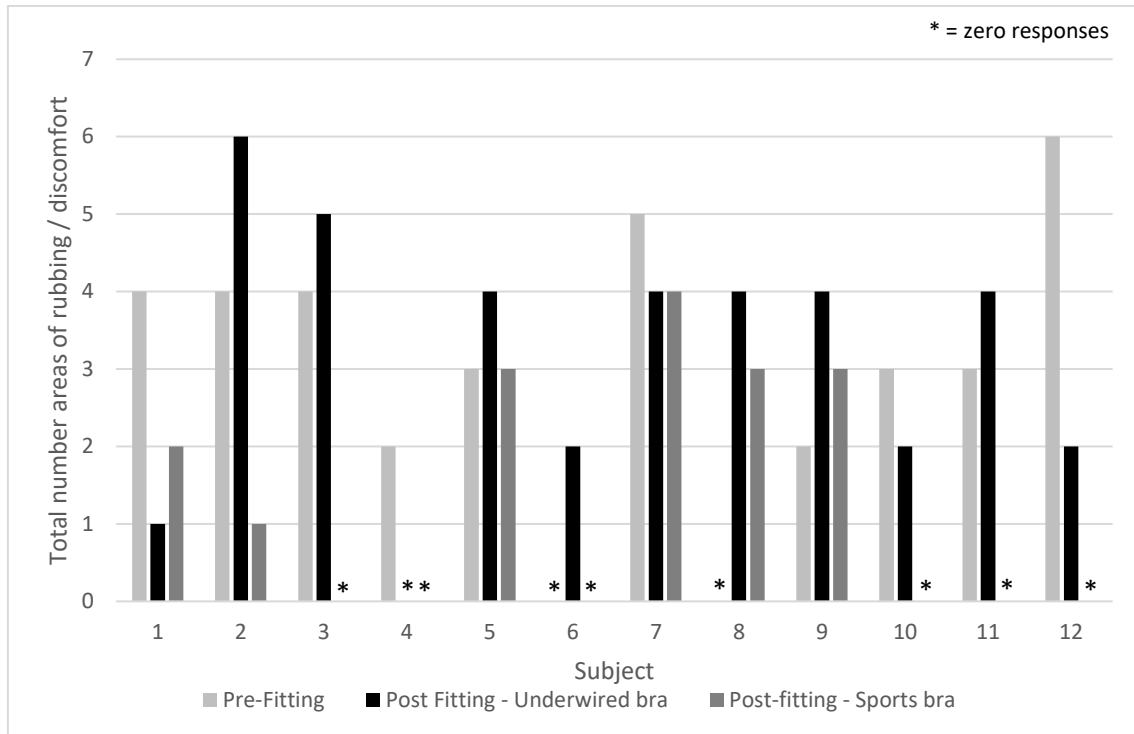


Figure 3-6 Comparison of pre and post-fitting effects on perceived discomfort and / or rubbing

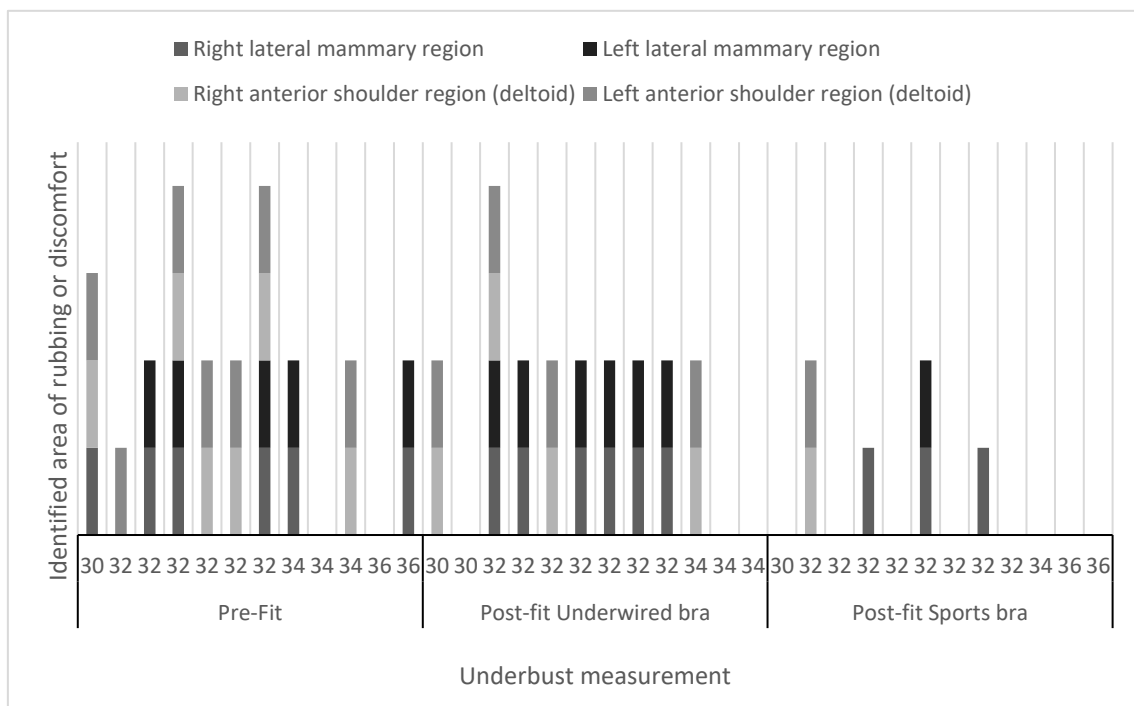


Figure 3-7 Under bust measurement effect on perceived discomfort and / or rubbing

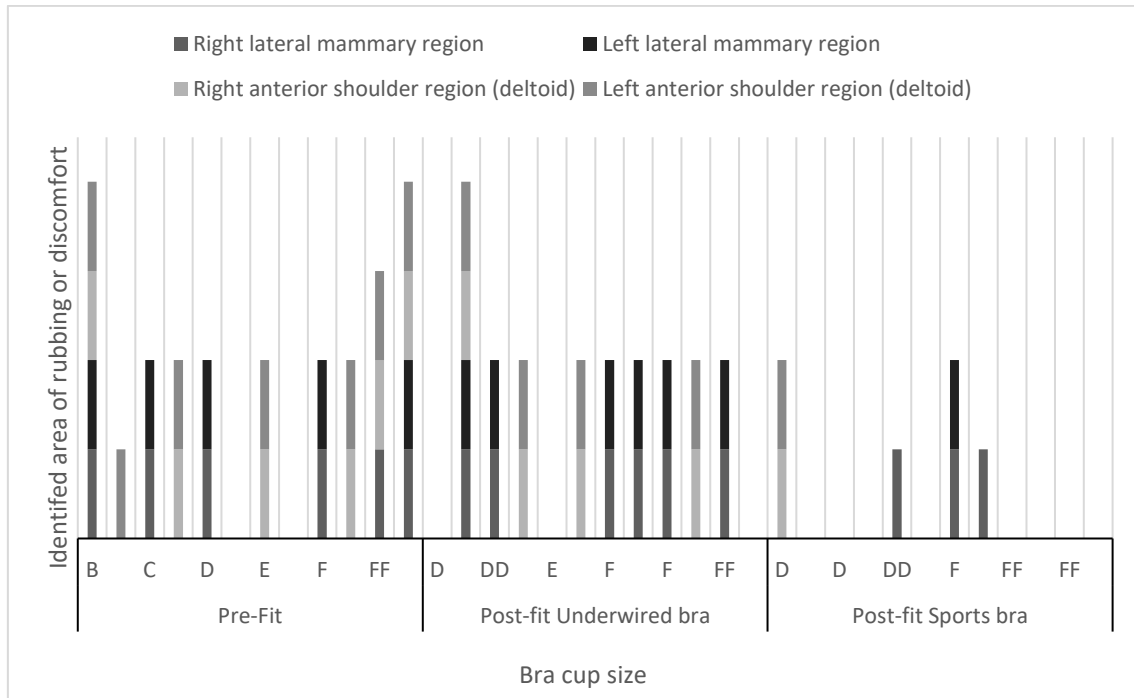


Figure 3-8 Bra cup size effect on perceived rubbing and / or discomfort

Table 3-9 Correlation of bust prominence to perceived rubbing and / or discomfort

Bra type	Lateral mammary region		Anterior shoulder region	
	Strength (r)	Significance (p)	Strength (r)	Significance (p)
Underwired (n=24)	-0.202 (small)	0.344	0.230 (small)	0.280
Sports (n=28)	-0.408 (medium)	< 0.05	-0.209 (small)	0.287

For all areas compared, Figure 3-5, all participants who responded identified that the sports bra had the same as or lower rates of rubbing and / or discomfort. However, with the underwired bra, for both the anterior and lateral mammary regions the levels of rubbing and / or discomfort increased. This may be due to the newness of the bras and wire moving the natural breast position, as identified by changes in the bust to bust length, and any changes in cup size being unfamiliar to the participant. However, this was not investigated further during this study.

In Figure 3-6, seven of the participants reported that the underwired bra was more uncomfortable than the bra they were wearing pre-fitting. For the sports bra this was only for two of the participants, As previously highlighted this could

be due to the newness and unfamiliarity of the underwired bra compared to the participants original bra.

When comparing rubbing and / or discomfort to under bust measurement and cup size, Figure 3-7 and Figure 3-8, no visible indication was identified that larger sizes have any relationship to greater reported levels of rubbing and / or discomfort. Of note is the reduction in reported discomfort and / or rubbing when trialling the sports bra against both the underbust and cup size measurements. The number reduced from 24 areas identified pre-fit to only six post-fit for the sports bra. The same affect was not seen for the underwired bra where the reduction was only reduced in four reported areas.

The relation between bust prominence and perceived rubbing and / or discomfort was investigated using the Pearson Product-moment Correlation, Table 3-9. For the sports bra, there was a statistically significant, medium strength, negative correlation between increasing bust prominence and discomfort and / or rubbing for the lateral mammary region. There was a small strength, negative correlation for anterior shoulder region, however this was not significant. For the underwired bra, there was a small strength negative correlation for the lateral mammary region, and a small strength, positive correlation for the anterior shoulder region, neither of which was statistically significant.

The lack of significance of these results could be due to the sample size being $n < 30$. Of interest is the positive correlation between the bust prominence and rubbing and /or discomfort in the anterior shoulder region for the underwired bra, indicating an increase in the identified areas of discomfort and / or rubbing. Although the data is not statistically significant, a further investigation was conducted. On review of the comments from the participants, several did identify that the straps of the underwire bra did 'dig in' around the shoulder and sides. This may be due to the design of the bras and width of the shoulder straps applying additional pressure to the shoulders.

The pre-fitting data does show a higher indication of rubbing and / or discomfort for FF cup size, but it also shows the same for a B cup with consistent levels for

all cup sizes between. The data does support a visible reduction in reported rubbing and / or discomfort when the participants were wearing the sports bra.

3.6.11 Comfort when standing

The participants were asked to rank, on a scale of very comfortable to very uncomfortable, how they found standing when wearing body armour for both pre-fitting and then post-fitting in each of the bra types. Not all participants completed each survey, and the data is presented as percentages based on the number of responses per survey, Table 3-10.

Table 3-10 Summary data - perceived comfort when standing in body armour by bra type as percentage of responses per stage of trial

Stated comfort level	Pre-fitting % (n)	Post-fitting Underwired Bra % (n)	Post-fitting Sports Bra % (n)
Very comfortable	4 (1)	20 (3)	50 (9)
Comfortable	48 (14)	53 (8)	22 (4)
Uncomfortable	48 (14)	20 (3)	22 (4)
Very uncomfortable	0	7 (1)	6 (1)

The percentage of participants who reported they were comfortable or very comfortable increased from 52% pre-fitting to post-fitting 73% for underwired and 72% for sports bra. Less participants reported that the bra was uncomfortable post-fitting, however for both the post-fitting underwired and sports bra, a single response identified the bra was very uncomfortable. On further investigation, these two cases were not from the same participant. For the underwired bra, the participant pre-fitting was 32C and post-fitting was a 32D. For the sports bra, the participants size did not change pre to post-fitting from a 32F. For both participants, the bras had been washed three times and they had both done a similar range of shifts. In reviewing the comments, the participant who had been wearing the underwired bra identified that she did not normally wear an underwired bra for work and found it very uncomfortable. For the participant wearing the sports bra she identified she found it very tight in general which made it uncomfortable to wear and work in.

3.6.12 Level of difficulty to perform certain tasks

The participants were asked to rate from very easy to very difficult several different activities that they may perform during their normal working day. No guidance was given on what was defined as easy or difficult and was left to the opinion of the participant. Activities involving use of a TASER or firearm were excluded from the analysis as only one participant responded to this activity, Table 3-11.

Table 3-11 Summary data - perceived difficulty in performing task in bra type as percentage of response per stage of trial

Activity	Activity rating	Pre-fitting % (n)	Post-fitting Underwired bra % (n)	Post-fitting Sports bra % (n)
Driving a car	Very easy	7 (2)	20 (3)	44 (8)
	Easy	38 (11)	47 (7)	33 (6)
	Difficult	52 (15)	33 (5)	23 (4)
	Very difficult	3 (1)	0	0
Passenger in a car	Very easy	11 (3)	27 (4)	39 (7)
	Easy	48 (14)	53 (8)	39 (7)
	Difficult	41 (12)	20 (3)	22 (4)
	Very difficult	0	0	0
Walking	Very easy	10 (3)	27 (4)	44 (8)
	Easy	76 (22)	67 (10)	44 (8)
	Difficult	14 (4)	7 (1)	12 (2)
	Very difficult	0	0	0
Running	Very easy	3 (1)	14 (2)	24 (4)
	Easy	14 (4)	36 (5)	59 (10)
	Difficult	55 (16)	50 (7)	17 (3)
	Very difficult	28 (8)	0	0
Self-defence techniques	Very easy	4 (1)	17 (2)	25 (4)
	Easy	50 (14)	42 (5)	56 (9)
	Difficult	42 (12)	33 (4)	13 (2)
	Very Difficult	4 (1)	8 (1)	6 (1)

For all the activities there was improvement in positive responses (easy and very easy) when wearing the professionally fitted bras. The most notable change was for running, where pre-fitting 28% of the participants rated the

activity as very difficult compared to 0% of participants post-fitting. Additionally, 59% now rated this as easy in the sports bra compared to 14% pre-fitting. This was not unexpected due to the nature of sports bras providing support during physical exertion. For self-defence techniques two separate participants identified this as being very difficult, these were not the same who identified standing as being uncomfortable. The participant who identified it as very difficult for post-fitting underwired bra also identified the same level for the pre-fitting stage of the trial. However, the same participant found this activity very easy in the post-fitting sports bra. Both participants were larger cup sizes when compared to the under bust measurement, underwired being 32FF and sports bra being 30F.

3.6.13 Free text questions

The participants were asked three free text questions once they had completed wearing of both bras

- Any general comments
- Which bra was most comfortable?
- Which style of bra will you wear going forward?

A summary of typical comments is shown in Table 3-12

Table 3-12 Summary of free text comments post wearing of underwired and sports bra

Underwired bra	
Positive comments (n = 5)	Negative comments (n = 5)
<p>Bra was very comfy compared to what I used to wear, showing the new bra fits a lot better</p> <p>The bra feels fine, however the weight of the armour is the real issue</p>	<p>The underwired bra provided no support when performing more physical activities</p> <p>The pressure of the body armour has caused indentations in my skin under my breasts, and it was very uncomfortable when performing physical activities.</p>
Sports bra	
Positive comments (n = 9)	Negative comments (n = 6)
<p>Very supportive and the design of the straps (Halter neck) has taken a lot of pressure of my shoulders</p> <p>Never having a worn a sports bra under armour I was very surprised at how good it was and will always wear a sports bra from now on</p>	<p>Whilst I appreciate the sports bra is more supportive than a normal bra when not active, I found it too snug</p> <p>The cups of the sports bra were comfortable, however the straps cut into my skin when wearing body armour</p>

The comments summarised in Table 3-12 indicate that a sports bra is more supportive and comfortable performing physical activities however it can be a bit 'snug'. There are several comments relating to the underwired bra marking the skin after wearing it, potentially due to the body armour applying pressure to the straps and structure of the bra.

When asked which bra they found most comfortable, 71% (n = 15) of the participants stated the sports bra was. When asked which bra they would routinely wear under body armour in the future, 71% (n = 15) stated they would be wearing a sports bra, whereas 14.5% (n = 3) would use the underwired bra. Of the participants, 14.5% (n = 3) stated they would be wearing alternative bras but did not specify the type.

3.7 Discussion

The purpose of this study was to understand the effect of two bra types on key anthropometric data relating to the breast and the effect that a professionally fitted underwired, or sports bra has on comfort for female police officers while wearing body armour.

The key findings from this study were

- bra type has a statistically significant effect on the shape and dimensions of the breast, which will affect how the body armour fits the body
- 77% of participants were resized for an underwired bra and 87% for a sports bra, and an individual does not necessarily wear the same size underwired bra and sports bra
- the wearing of a sports bra was reported as more comfortable compared to an underwired bra for most activities
- cup size, under bust measurement or bust prominence have no direct effect on level of reported rubbing and / or discomfort when wearing either an underwired or sports bra.

When considering the anthropometric data for the two bra types, there were three areas that showed a significant difference in measurements; bust to bust, chest circumference and bust prominence. In all of these, the underwired bra had the largest measurements. The significance of this is relevant during the design of body armour by a manufacturer. If a design is based on anthropometric data only considering underwired bras, a wearer who uses a sports bra may find that the forming of the body armour does not sit comfortably. Secondly, body armour is designed to sit close to the body to aid the dissipation of energy during a ballistic impact. It has been shown in previous work that even small air gaps of 10 mm can increase the probability of a round perforating the body armour (Tilsley et al., 2018).

The data collected in the research provides evidence that a large percentage of women, after attending a professional bra fitting, were identified as having been wearing the wrong size bra. This could be due to the participants just buying the same size bra without being refitted or using the traditional bra fitting system of the under bust and over bust measurements. The time since the participants were last fitted is also a factor in the change in bra size, with 62% not having been refitted in the last two years. With natural changes in body shape over time due to lifestyle choices, the effect of aging on breast tissue and skin thickness it was anticipated that a percentage of participants would be

resized as part of this study. Considering the percentage of participants who had been fitted in the previous two years to the number who were resized during this study, raises questions over how they were fitted and potential variations in fitting processes by different suppliers. It was also identified that it cannot be assumed that the same size sports bra and underwired bra will correctly fit. This is potentially due to variation in design and cutting of the bras between manufacturers and the data they are basing their designs on.

When considering the comfort of the bras and the ability to perform various actions, it is clear from the data that most participants found the sports bra most comfortable. There was a visible decrease in rubbing and / or discomfort identified when the sports bra was worn compared to the underwired bra. There was also an increase in participants reporting that various actions were easier to perform when wearing the sports bra. This is most likely due in part to participants having been refitted and wearing bras that provided more support overall.

There was no visible connection between larger cup sizes, under bust measurements or bust prominence and identified areas of rubbing and / or discomfort. This was an unexpected outcome of the study, as it was believed prior to the start that larger breasts would be a factor. Whilst there was a positive trend with regards to rubbing and / or discomfort on the shoulders when wearing the post-fitting underwired bra in relation to bust prominence, no other trends could be clearly seen. Some of the participants did identify that the underwired bra straps dig into their shoulders. This positive trend could be associated to an increase in breast volume, and hence weight, placing additional loading on the shoulders which is then exaggerated by the weight of the body armour on the shoulders.

3.8 Conclusions

This study has clearly identified that for female police officers, when wearing body armour, sports bras can improve the comfort. Going forward, 71% of the participants said they will be using a sports bra due to the overall improved comfort and support it provides them. Encouraging female police officers to be

professionally fitted for new bras and trying different styles of bras has been clearly shown to improve comfort. Over time and with age, breast shape and tissue strength changes, which can lead to the need for different support. Alongside this, natural changes in body shape due to lifestyle choices can also have a significant effect on cup size and under bust measurements.

When considering the design of body armour, it has been shown that key anthropometric data is different depending on the type of bra that is worn. This has effects on how the body armour is designed to account for the shape of the female form, as well as the number of different breast sizes there are. Guidance must be given that when measuring for body armour, a female ensures they are wearing the style of bra that they would normally use underneath the body armour as well as any additional clothing layers e.g. uniform top.

Whilst standards for body armour have not been discussed in this paper, there will also be a need for these to potentially adapt, to support improvements in body armour design for female wearers, whilst seeking a balance between risk and protection and enabling designers of body armour to be creative.

This research has focused on female police officers, however this work may be applicable to all designers, specifiers, and wearers of body armour for females.

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4 AN OVERVIEW OF FEMALE POLICE BODY ARMOUR PROTECTION AROUND THE LATERAL SIDE OF THE BREASTS

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Pending publication

4.1 Abstract

Body armour designed for female police officers in England and Wales typically has shaping and forming to enable it to form to the contours of the body, particularly the breast. However, the protection provided to the lateral sides of the breasts and the effect of underwired and sports bras on this has not been investigated. Using photographic images of 17 female police officers and two male police officers, the research in this paper investigated if this was an issue. The research compared the anterior and posterior lateral exposed area under the arm. It showed that the mean anterior exposed area for females was 56% for underwired bras and 52% for sports bras, for the male officers the anterior exposed area was only 33%. Additionally, the peak distance from the medial line of the body to the boundary between the body armour and bra is statistically significantly greater for the underwired bra than the sports bra (means 9.45 cm, 7.8 cm respectively). This exposed area may result in a greater risk to female police officers for a stab or ballistic injury and warrants further investigation.

4.2 Keywords

Sports bra, Underwired bra, Coverage, Female body armour, protection

4.3 Introduction

All police officers in England and Wales routinely wear protective body armour on their torso when on duty away from a police station. These body armour systems are typically designed to provide resistance from low level ballistic threats and stab attacks. For female police officers, to aid with the fit of the body armour, it typically has shaping and forming to fit the contours of the female

form, such as the breasts. Previous research has highlighted issues with comfort for female officers particularly around the breasts (Malbon et al., 2020). However, protection of the breasts, particularly the lateral sides, has not been previously investigated.

Issues with body armour for female police officers is not unique to the UK; the National Institute of Justice (NIJ) in the United States of America (USA) have begun a project to investigate the topic (Stoe and Otterson, 2016). Whilst their work has initially focused on investigating potential airgaps under the body armour around the breast area, they did highlight issues with coverage and protection that needed further investigation. The US military have also identified issues with comfort and protection for female personnel, where often the design strategies for female protective equipment has been to down scale male versions (Bass, Schmidt and Pierce, 2016). Their work identified that it is important to consider the biophysical and biomechanical differences between the sexes, and not just scale male equipment to suit females.

With the selection of body armour, and by association its design, there are several primary factors that have to be taken into consideration; threats and risk, performance standards, ergonomics and fit (Payne and O'Rourke, 2017)

4.3.1 Threats and risk

The two primary threats that are faced by a police officer in England and Wales are a stab or a ballistic attack.

Between September 2019 and September 2020 there were a total of 55201 police recorded incidents of gun and knife crime in England and Wales (Office for National Statistics, 2021). Of these, 85% were knife or sharp weapon related, of which 47% were recorded as assault with injury and assault with intent to cause serious harm. During the same period (September 2019 and September 2020) the police recorded 6242 cases of gun crime. Whilst these cases of gun and knife crime are not always directed at the police, the attendance by the police at an incident where knives, sharp weapons or firearms may be present is always possible.

The threat from a ballistic attack is easier to categorise, as bullet types and velocity can be quantified. However, for a stab attack, differences in weapon type, sharpness, shape, angle of attack and force at which the weapon contacts the body armour can be more variable. It has been shown that the typical kinetic energy density on the tip of a knife blade (e.g. bowie knife 160Jmm^{-2}) is greater than that on the tip of a bullet (e.g. 0.357" JSP, 16Jmm^{-2}) (Horsfall, 2012).

The resistance to a threat afforded by a body armour has a direct impact on the weight of the body armour panels. As a rule, the greater the threat the more protective materials that are needed to provide resistance (Lewis et al., 2017).

Most cases of knife crime are due to untrained individuals using knives not designed for stabbing, such as kitchen knives. However, the potential for a police officer to face someone who has been trained, and a sharp weapon designed or modified for stabbing and slashing is present (Carr, Godhania and Mahoney, 2019). Research by Carr et al showed that a victims posture and protective clothing could influence the approach a person trained in knife attacks took (Carr et al., 2017). One of the areas they identified was the under-arm, which when wearing a body armour, particularly with a high visibility covering, framed these areas.

4.3.2 Performance standards

Historically the standards for body armour worn by the Police in England and Wales have been developed by the Home Office in conjunction with the National Police Chiefs Council and Police Federation of England and Wales. The Home Office started its work on ballistic resistant body armour in 1979 with work conducted by E C Brown (Brown, 1979). This primarily was a review of body armours and standards already available and how they performed against the threat in the UK. They did note that the threat in the UK from firearms was different to that in the USA at that time, and as such body armours developed for the US market may not provide the correct resistance to the threat in the UK. At the time they did not consider female body armour as it was not available.

The first known stab resistant standard in the UK was produced by the Home Office in 1993 (Home Office, 1993). This was introduced in response to research conducted into stab resistant body armour after the killing of PC Blakelock in the Broadwater farm riots of 1985 (Police Memorial Trust, 2019; Tan and Parker, 1992). They determined the threat level based on a range of human trials and then recreating this using a controlled system and commercially available knives. This standard was further developed and updated in 1999, including an improved stab test mechanism and increased human trials data, based on work by Horsfall (Horsfall, 2000).

Whilst the primary purpose of body armour is to resist the perforation of a ballistic or stab attack, it also needs to provide protection from potential secondary injuries. For a ballistic threat this relates to the risk of Behind Armour Blunt Trauma (BABT). This was described by Cannon as "...spectrum of non-penetrating injuries to the torso resulting from the impact of projectiles on personal armours." (Cannon, 2001). This BABT injury is a result of the energy transferred from the bullet impacting the body armour into the body which can cause bruising, contusions, lacerations, or potential more serious injuries to the organs including internal haemorrhage. Within body armour standards there are limits set for the measurable back face signature behind the body armour panel. These levels are set to reduce the risk of a BABT injury to a police officer from a ballistic trauma. The topic around BABT has been extensively discussed in the open literature and as such is not discussed here (Carr, Horsfall and Malbon, 2016; Hanlon and Gillich, 2012).

For stab resistance, within England and Wales, the current 2017 Home Office body armour standard allows the tip of the knife to penetrate through the body armour by up to 8mm (Payne, O'Rourke and Malbon, 2017). This allowance was based on work by Bleetman and Dyer who investigated if a level of injury could be sustained which would not lead to a serious or critical injury (Bleetman and Dyer, 2000). Their work focused on determining the depth of various organs to the skin surface using Computer Tomography (CT) and ultrasound scans. However, this work was based on patients in hospital receiving

treatment and is not representative of the police population. Based on this research, Mr Bleetman made the following statement “I would accept that a blade could ‘safely’ be pushed to a depth of 9mm into the human trunk. Armour made to this specification would protect against a serious injury and death after stabbing.” More recently a review of the work by Bleetman and analysis of CT scans of military personnel has proposed that this limit could be raised to 17mm (Breeze, Lewis and Mahoney, 2020). However, this was based on a male military population set and a limited range of attack angles and locations which may limit its applicability to the UK police population.

The Home Office body armour standard does not specify the design of a body armour, only that it must protect the vital organs (heart, great valves, liver and spleen) (Breeze et al., 2016). Additional guidance on coverage, comfort and fit is provided in a Home Office guidance document, published at the same time as the standard, to support manufacturers and end users (Payne and O’Rourke, 2017). Within the standard and guidance document, there are no specific details on coverage specifically for female wearers, such as the lateral sides of the breast.

4.3.3 Ergonomics and fit

In the design of a body armour the ergonomics of the wearer when performing work related activities must be considered. The ergonomics not only applies to the ability to be able to perform actions but also the comfort of the body armour when standing, walking, or sitting for example.

The wearing of body armour can have impacts on the individual beyond restricting their ability to perform tasks. In a systematic review by Tomes et al, they determined that the wearing of body armour can lead to increased exertion, decreased work capability, decreased balance and stability and increased ground reaction forces (Tomes, Orr and Pope, 2017).

The assessment of the ergonomics of a body armour for use by police is challenging due to the varied activities they may undertake. Work by Watson et al, using a number of trials and questionnaires, were able to develop a process

to assess the comfort and fit of a body armour (Watson, Horsfall and Fenne, 2010). The research identified several movements including twisting, bending and arm movements which identified ergonomic difficulties with the body armour. Whilst in the reported trials there were female participants, the results published do not separate by gender.

The fitment of a body armour to the wearer is as important as its design, as a badly fitted body armour will not only be less comfortable but could also result in inadequate protection. For example, in research by Tilsley et al they determined that there is an increase in risk of penetration of a body armour from a ballistic round with a 10mm airgap compared to no airgap under the body armour (Tilsley et al., 2018). This is of relevance for female police officers as badly fitting body armour over the breast may leave additional air gaps.

There are many published research papers on anthropometric measurements for the design and fit of clothing. Of particular relevance is work by Carr et al that focused on the design of military clothing and equipment (Carr, Wilson and Laing, 2012). They identified the data reviewed applied to a military population not a general population, however, the theories transpose to police clothing and personal protective equipment. It highlights the importance of accurate measurement of the body to ensure an appropriate fit.

4.3.4 Aim

The aim of this paper was to investigate the protection of the lateral sides of the female breast in serving female police officers and to understand if bra type and breast size affects the protection provided by the body armour in this area.

The work in this paper is based on a subjective review of female police officers who were photographed wearing body armour over two different bra types (underwired and sports bra) and includes two male police officers in body armour for comparison.

The selection of the underwired and sports bra was based on previous work by Malbon et al that identified these were the most common bras worn by police officers in England and Wales when wearing body armour (Malbon et al., 2020).

This paper does not consider body armour designed for the military and is focused on female police officers in England and Wales. The work presented in this paper follows on from previous research into the comfort of female body armour and the effect of bra type on body armour fit and comfort (Malbon et al., 2020, 2021).

4.4 Method

A cohort of 30 female police officers and two male police officers volunteered for the research and provided informed consent prior to participating. The work was approved by Cranfield University Ethics Committee (ref CURES/25602017).

Each female participant was asked to change into either the sports or underwired bra without any other clothing on their torso and then don their personal issue body armour and adjust to fit. Once they were prepared, they were asked to raise their left arm parallel to the body, horizontal to the shoulder and with the other arm hold a photographic scale against the left side of their body armour. An image was then taken encompassing the side of the body armour from the shoulder straps to the waist of the individual, Figure 4-1. The process was then repeated for the other bra type.

The two male participants were asked to put their body armour on over the naked torso. The same left side lateral view image was then taken, Figure 4-2.

All participants were routine patrol officers and used their personally issued body armour. The body armours all provided the same level of protection to ballistic and stab threats, although they were not necessarily from the same supplier.

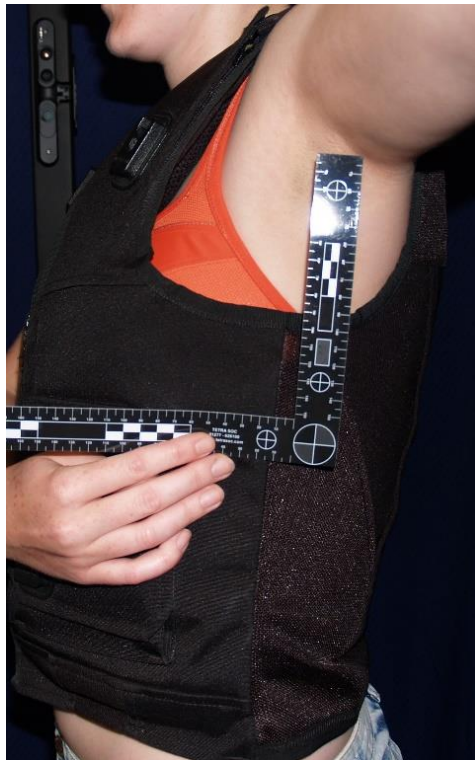


Figure 4-1 Example of image showing female lateral view of body armour and bra



Figure 4-2 Example of image showing male lateral view of body armour

4.4.1 Post image processing

Each image was cropped to remove any identifying features of the participants. No other image processing was performed.

4.4.2 Image analysis

All image analysis was conducted using ImageJ¹⁷. For each image, the exposed torso area was divided into the anterior and posterior lateral areas, Figure 4-3, by setting boundaries described below.

1. The vertical boundary identified as the most anterior visible point at which the front of the arm joined the torso.

¹⁷ Rasband, W., *ImageJ V1.53a* Available at: <https://imagej.nih.gov/ij/> (Accessed: 14 May 2021).

2. The horizontal boundary identified as the lowest visible point at which the underneath of the arm joined the torso at the armpit.
3. The body armour boundary identified as the edge of the body armour with either the body or bra.

Once the horizontal and vertical boundaries had been established, the anterior and posterior areas were identified and the area within the boundaries recorded, Figure 4-4 and Figure 4-5. The longest length from the vertical boundary to the anterior body armour boundary was measured using a straight line, Figure 4-6.

The full process is detailed in Image analysis process, Appendix B.

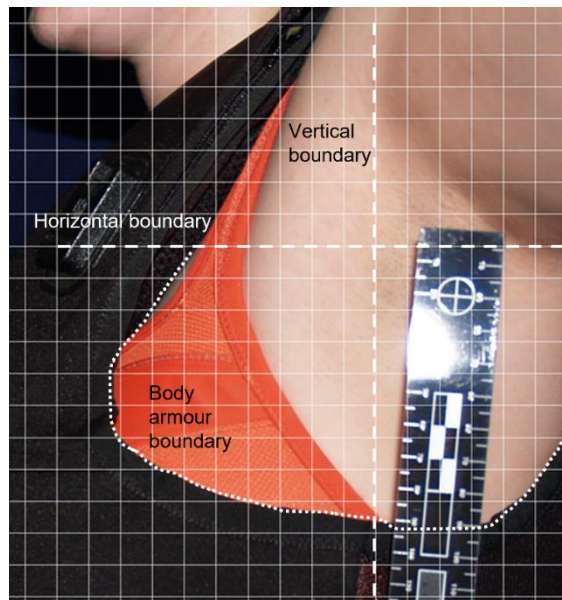


Figure 4-3 Vertical, horizontal and body armour boundaries

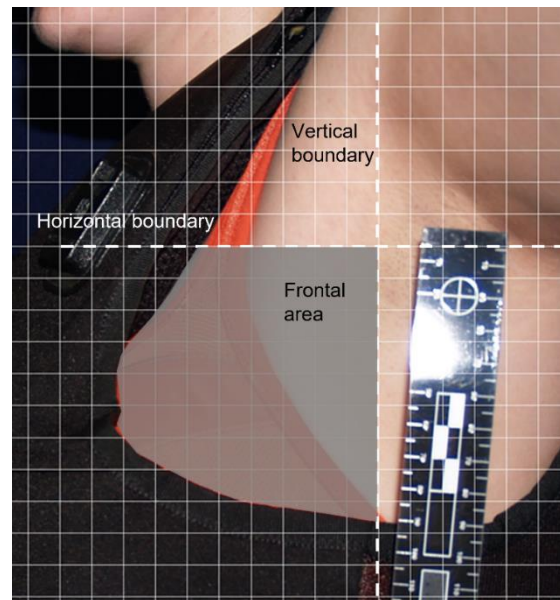


Figure 4-4 Anterior area

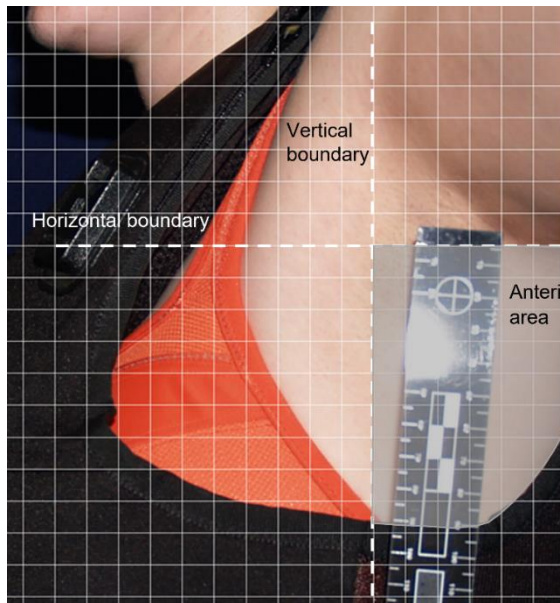


Figure 4-5 Posterior area

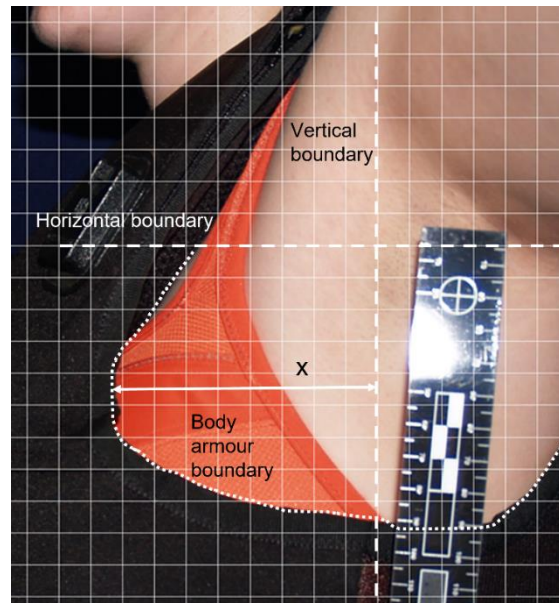


Figure 4-6 Longest length between vertical boundary and border of body armour and bra (identified x on the diagram)

4.4.3 Limitations on data

The following limitations on the accuracy of the data are defined

- The angle that the image was taken from was not controlled due to limitation on space. Where possible, the same position was maintained
- The marking up of images, including dividing of image and tracking of edge of body armour was done by eye and is therefore subject to error

The results for area are presented as a percentage of total area identified below the horizontal boundary.

4.5 Results

Of the original 30 pairs of images for female participants, only 17 pairs were used due to either one or both images being unusable for image analysis.

A comparison by bra type of the percentage of exposed anterior area is shown in Figure 4-7. A paired sample t-test was conducted on the data, no statistically

significant difference between exposed area for underwired and sports bra was proven, $t(16) = 1.197$, $p > 0.05$. The mean anterior area for underwired bras was 55% and for the sports bra 57%. For the two male participants, the mean anterior area was 33%.

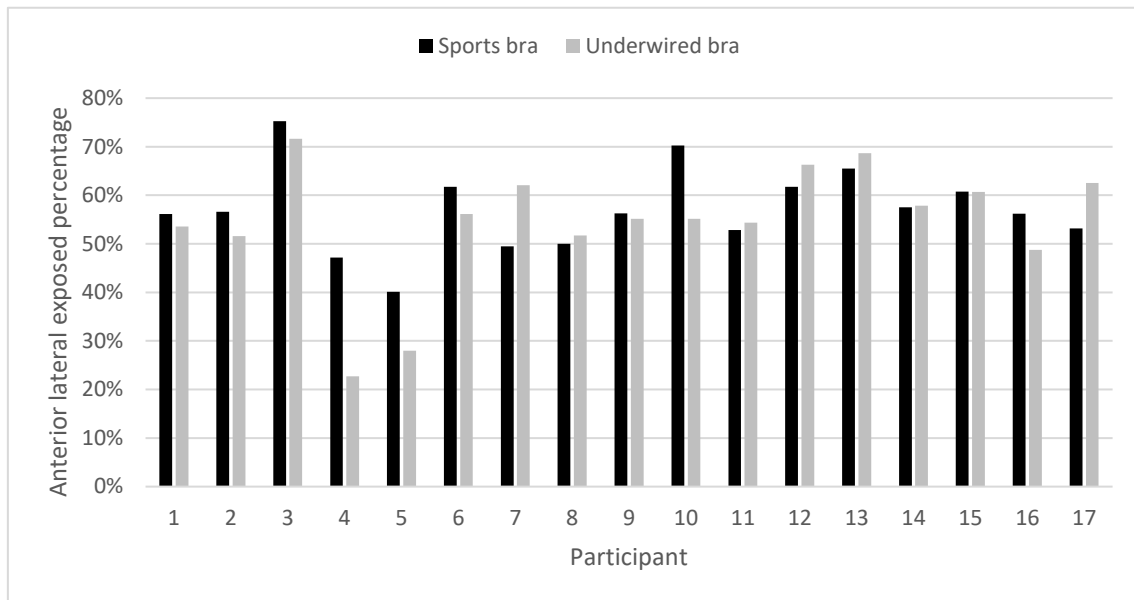


Figure 4-7 Comparison between underwired and sports bra for exposed anterior lateral area

In six circumstances, the underwired bra had a larger exposed anterior area than the sports bra.

A further comparison was conducted within bra type to understand if there was a relationship between bra size and exposed area, Figure 4-8 and Figure 4-9. Where more than one participant had the same bra size, a mean percentage was calculated and used.

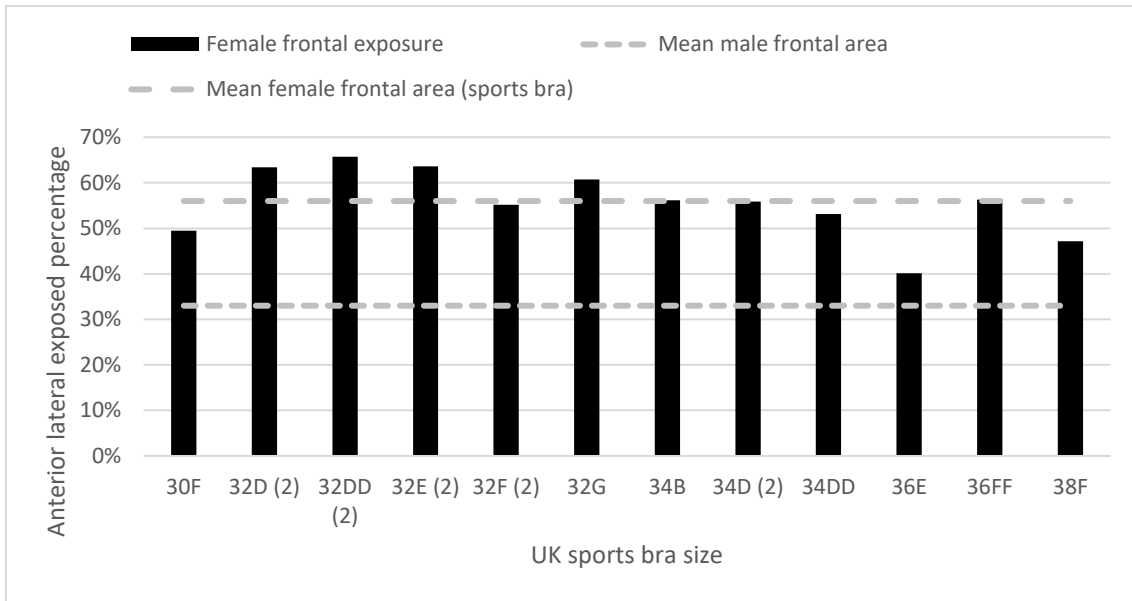


Figure 4-8 Sports bra anterior area by bra size ((number) denotes multiple participants of same size bra)

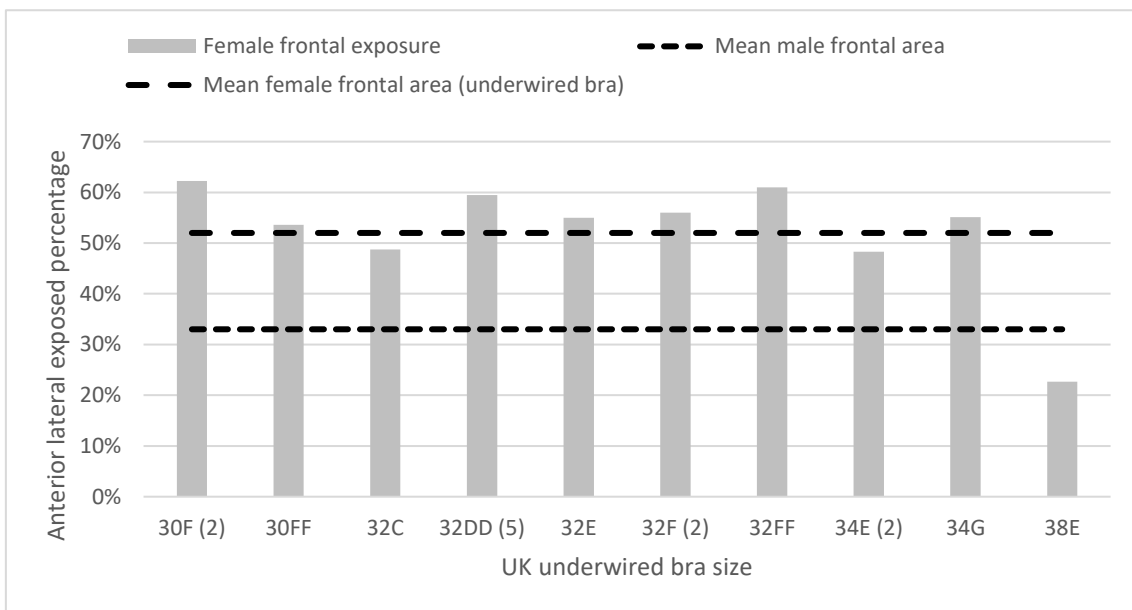


Figure 4-9 Underwired bra anterior area by bra size, ((number) denotes multiple participants of same size bra)

From the data presented, there was no visible relationship between bra size and exposed area for both types of bras. For both bra types and sizes, in all but one case, the percentage exposed anterior area is greater for females than

males. For the sports bra, 15 out of 17 participants had an anterior area of greater than 50%, for the underwired bra this was 14 out of 17 participants.

The longest length from vertical boundary to edge of body armour, as shown in Figure 4-6, was compared between bra types, Figure 4-10. A paired sample t-test determined there was a statistically significant difference between the bra types. There was a statistically significant reduction in distance for the underwired bra (mean 9.5 cm SD 1.1) compared to the sports bra (mean 7.8 cm SD 1.8), $t(16) = 2.894$, $p < 0.05$ (two-tailed).

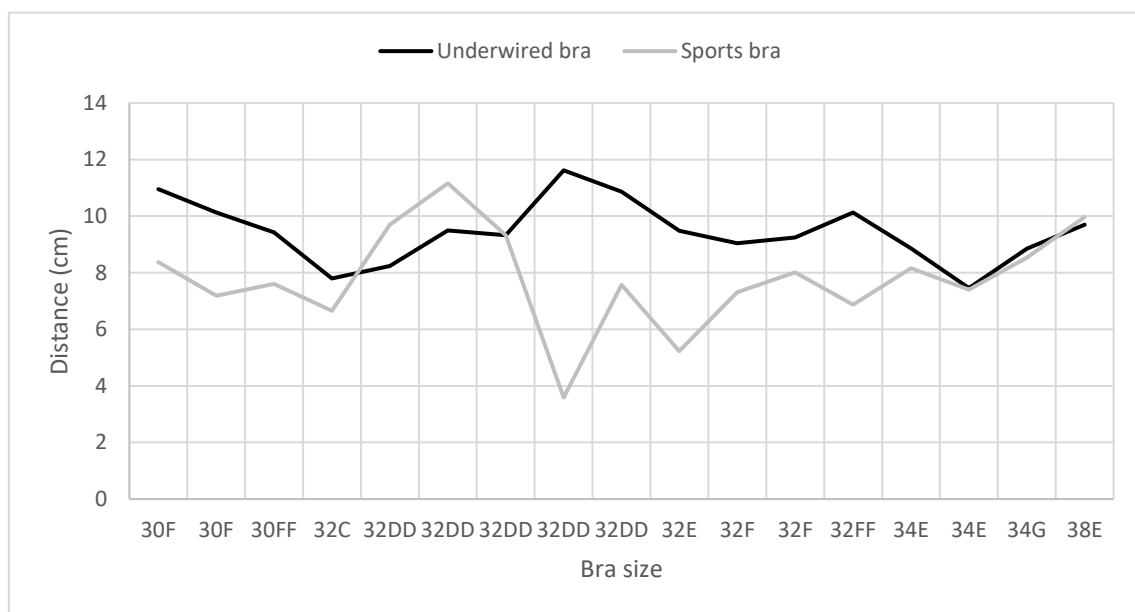


Figure 4-10 Comparison of bra type and distance from edge of vertical boundary to edge of body armour (maximum)

From the data shown in Figure 4-10 there is no visible correlation between increase in bra size relating to an increase in measured distance between the vertical boundary and the body armour boundary.

The statistically significant difference in prominence of the breast in underwired bras identified in this data concurs with previous research by Malbon et al which showed, using 3D anthropometric scan data, that bust prominence is greater when wearing an underwired bra (Malbon et al., 2021)

During the trial it was identified that potentially for some of the participants their body armour was no longer the correct size for them. For example, the overlap

at the sides around the stomach area was insufficient, or the length of the body armour did not appear to provide coverage as far down as expected, Figure 4-11 and Figure 4-12. They were advised to request a resizing of their armour at their earliest convenience.



Figure 4-11 Example 1 – lack of overlap at side and short on body



Figure 4-12 Example 2 – lack of overlap at side of body

4.6 Discussion

The purpose of this research was to understand the protection provided by the body armour to the lateral side of female breasts. The key findings from this study are

1. The mean percentage of lateral anterior area that is exposed is greater for females than males, with sports bras having marginally greater percentage of exposed anterior area compared to underwired bras (Means, Females 56% and 52% respectively, males 33%)
2. The type of bra worn has a statistically significant effect on the distance from the vertical boundary to the body armour / bra boundary at the front of the body

This research has shown that protective coverage to the lateral side of the female breast is lacking due to the shape of the female body. The difference in anterior area between females and males has the potential to increase the risk of a stab or ballistic attack occurring outside of the body armour. As shown in the work by Carr et al on trained knife attacks, potentially the body armour edge may provide an indication of a vulnerable location for a knife attack (Carr et al., 2017).

Whilst no statistically significant difference in anterior area between an underwired and sports bra was identified, there was a statistically significant difference in the longest length from the vertical boundary to the edge of the body armour between bra types (means; underwired bra 9.45cm, sports bra 7.8cm). This difference was expected as it had previously been identified by Malbon et al who investigated the effects of bra type on key anthropometric data (Malbon et al., 2021). This difference highlights the need to ensure bra type is taken into consideration when measuring for a body armour.

The addition of more armour materials, increased folding, stitching, or shaping may enable greater coverage to be achieved. However, this may be at the expense of comfort and the ability for an officer to be able to easily move and perform activities, such as self-defence.

At the edge of a body armour, the ballistic protective properties can decrease (Rice et al., 2014). However, there was no literature found on the edge effects in relation to stab protections. Within the 2017 Home Office standard the minimum distance to the edge of the body armour for any stab test is 50mm. However, this appears to be a historic value carried forward from previous iterations of the standard and no evidence could be found as to the rationale behind this. Whilst it is potentially possible to increase the protection provided by a body armour to a female wearer, the benefits may be negated by the edge effects of the material. In addition, the number of times an officer may face a risk within any one shift, compared to the physical burden of any additional protection may make any changes unusable. Further research is required to understand the protection provided by any additional coverage.

The capability for a manufacturer to develop new body armour is intrinsically linked to the requirements in a standard. Being able to have a standard that is adaptable and flexible enough to enable novel designs to improve protection would be required.

With comfort and ergonomics, reduction in an officer's ability to be able to function effectively is significant.

4.7 Conclusions

This study has clearly identified that body armour for female officers provides less coverage to the lateral sides of the body than their male equivalents (anterior mean exposed area; female 56%, male 33%). This is an area where more research is required to develop solutions for female police officers.

However, as identified, it is not as simple as just adding additional protective material and shaping to a female body armour due to the effect this may have on comfort, fit and ergonomics. Novel weaving and forming techniques may in the future enable approaches to be developed that naturally drapes the material around the shape of a breast rather than having to be manipulated.

If there is an increase in trained, or even semi trained knife attackers in the UK as described in the work by Carr et al, then providing additional protection may be more essential. However, by adding this protection, a decrease in the ability to defend and counter an attack happens, therefore, an increase in protection could be negative to officer safety.

To achieve enhanced protection for female officers in the future will require end users, manufacturers, researchers, and standard setters to work collaboratively to understand the risk and develop novel practical solutions.

4.8 Acknowledgements

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5 HOW DO WE IMPROVE THE TESTING OF FEMALE BALLISTIC BODY ARMOUR? – A COMPARISON OF ROMA PLASTILINA #1, 10% BALLISTIC GELATINE AND SEBS GEL

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Pending publication

5.1 Abstract

Body armour designed for use by police officers in England and Wales is currently tested using Roma Plastilina No1 (RP1) as the witness material for the measurement of back face signature (BFS). However, this material has limitations when testing body armour designed for females, as it is not possible to measure the BFS. To enable measurement of BFS for females over the breast, an alternative backing material is required to form surrogate breasts and torso which would enable BFS to be measured. A comparison was conducted between RP1, 10% ballistic gelatine and a 30/70% SEBS gel, using standardise ballistic test packs and two projectiles: DM11A1B2 9mm FMJ $365 \pm 10 \text{ ms}^{-1}$; Remington R357M3 0.357" JSP $390 \pm 10 \text{ ms}^{-1}$. The results showed that there was a statistically significant difference identified in measured BFS between the three backing materials with both projectile types (9mm $F_{(2,66)} = 142.123$, $p < 0.001$; 0.357" $F_{(2,93)} = 171.766$, $p < 0.001$). With 10% ballistic gelatine, when testing with the 0.357" projectile, a greater variance in measured BFS was shown compared to the other materials. The SEBS gel was consistent for the 0.357" projectile, but with the 9mm projectile there was greater variance in results. Both 10% ballistic gelatine and SEBS gel would enable a moulded female test form to be created, however SEBS gel has a much longer shelf life and showed resistance to damage, although neither of these materials could be considered as a biofidelic substitute for breast tissue, and further work is required to define limits for testing.

5.2 Keywords

Back Face Signature (BFS); Behind armour blunt trauma; Breasts;

5.3 Introduction

Body armour is commonly used by military and law enforcement personnel when there is a risk of a ballistic or stab attack. The level of resistance to threats provided by a body armour can vary between users and roles (Lewis et al., 2017). Body armour can be designed to fit male or female torsos, commonly referred to as unformed and formed armours, although currently not all body armour is available in both unformed and formed versions. Ballistic protective body armour is not only designed to resist perforation by projectiles, but also to reduce the risk of an injury or lethality from behind armour blunt trauma (BABT), defined by Cannon as "...spectrum of non-penetrating injuries to the torso resulting from the impact of projectiles on personal armours." (Cannon, 2001).

Research into BABT has already been extensively discussed in the open literature (Carr, Horsfall and Malbon, 2016; Hanlon and Gillich, 2012). However, very little of this research has consider BABT over the female breast, or the potential injuries that may occur to the breast structure. Whilst these injuries in themselves may not be life threatening, they could be potentially life changing for a female. The way in which the armour materials react to impact may also be affected by the dynamic response of breast tissue to an impact. This reaction of the armour materials is critical in the dissipation of energy from the impact and the prevention of the round penetrating through the body armour.

The commonly used material used in standards for the assessment of body armour, Roma Plastina No 1, does not enable any true assessment of potential injury over the breasts.

This paper considers various backing materials that can be used in the assessment of BABT with reference to the testing of body armour designed for female users.

5.3.1 Roma Plastilina No1

Since the 1970s, the traditional material used for assessing BABT has been various forms of modelling clay, such as Roma Plastilina No1 (RP1) used in civilian standards in the United States of America and the United Kingdom (National Institute of Justice, 2008; Payne, O'Rourke and Malbon, 2017). The clay provides a witness material that enables the measurement of any deformation of the body armour panel post testing, commonly referred to as back face signature (BFS). The current limits, specified in the UK standard, for the maximum depth of BFS for low velocity bullets, such as those from handguns, is 44 mm. For armour designed to protect against high velocity projectiles, such as rifle bullets, the limit is currently 25 mm. Unformed body armours, such as those typically used by males, are tested on flat blocks of modelling clay prepared in accordance with a relevant standard e.g. ASTM International, 2020. However, formed body armours, such as those typically worn by females, have traditionally been tested on modified modelling clay blocks. Shapes approximating a bust, made by free hand to fit the supplied test body armour, are stuck to the flat surface of the block used for testing unformed body armour, Figure 5-1 (Croft and Longhurst, 2007). More recently, in the UK the Home Office 2017 body armour standard defined two female forms made from Plastiline® 40¹⁸, which, unlike RP1, can be melted to enable pouring into moulds, to improve consistency in testing, Figure 5-2 (Payne, O'Rourke and Malbon, 2017).

Whilst the testing of unformed body armours enables the measurement of the resultant BFS in the modelling clay, when testing formed body armours, this is not possible due to the collapsing of the backing shapes after impact. This results in only a pass or fail based on whether or not the projectile perforates the body armour being used.

Modelling clays currently used are not biofidelic and the BFS recorded has no real known correlation to BABT (Dorn, Tam and Gotts, 2000). The limits set in

¹⁸ G.Lalo, Herbin Sueur SA, France

the standards for maximum BFS recorded in RP1 were based on work by Goldfarb et al and Prather et al, on torso shots over ribs on goats (Goldfarb et al., 1975; Prather, Swann and Hawkins, 1977). The shots over goats were recreated on 20% ballistic gelatine, which at the time was commonly used in the United States of America for wound ballistic research, and several clay-based materials. The selection of RP1 at the time was based on it having a similar performance to 20% ballistic gelatine and being low cost, convenient, and not requiring the use of expensive high-speed filming. When RP1 was selected, formed body armour was not tested and breast tissue was not considered. However, RP1 is manufactured as a modelling clay for use by artists, rather than a consistent backing material for testing of body armour. The formulation of RP1 is not tightly controlled and its properties have varied since 1975 changing its performance as a backing material for testing body armour (Seppala et al., 2014). To manage this variance in material properties, calibration methods were defined in body armour standards. By the use of temperature preconditioning, the response of RP1 can be controlled to meet the requirements of a standard.



Figure 5-1 Example female formed shape made from RP1 on a flat backing tray (image produced by author)



Figure 5-2 Example female test form as specified in Home Office Body Armour standard 2017 (image produced by author)

Very little work was found in the open literature concerning backing materials used for assessing ballistic impacts on body armour for female users. Research on underwired bras and potential injury from a non-perforating ballistic impact on a body armour was considered using a female torso made from PermaGel™ and RP1 (Burrell, 2013). The research identified small indentations in the RP1, however they only conducted two shots. Overall, the research did not identify an obvious risk of additional injury due to an underwired bra after impact by the test projectile, however, they did not consider BFS in the PermaGel™. It has also been shown that PermaGel™ is not a good tissue simulant for wound ballistics studies compared to ballistic gelatine (Mabbott et al., 2013). In trials they identified that the depth of penetration of a 5.5mm ball bearing into PermaGel™ was shorter at lower velocities ($v = 250 \text{ ms}^{-1}$, mean difference = -32.77) and greater at higher velocities ($v = 500 \text{ ms}^{-1}$, mean difference = 33.5 mm) compared to 10% ballistic gelatine.

Work by Forster et al did investigate creating bust surrogates for use in stab testing of body armour (Forster et al., 2015). A stack of neoprene circles of decreasing sizes was used to create bust shapes, but limited testing was reported. The concept was simple to implement, however human breasts are not perfect circles, and they were placed on a flat backing surface which would not enable the body armour to form to a natural shape. The limited stab testing conducted did show one failure when testing on the foam breast surrogate compared to no failures on the RP1 breast surrogate. In addition, between the busts they reported two out of three failures for the foam. They also noted that careful positioning of the body armour was required to ensure best fit on the surrogates. Whilst the approach is simple, testing of a body armour on a non-natural shape may affect the results.

The aim of the research presented in this paper was to investigate the use of alternatives to RP1 for assessment of BFS which could be easily moulded to form a suitable surrogate bust shape. Of initial consideration were SEBS gel and 10% ballistic gelatine.

5.3.2 SEBS gel

SEBS gel was first discussed in the open literature in 2010 as an alternative to ballistic gelatine in the assessment of dynamic BFS (Mauzac et al., 2010). SEBS gels are made from commercial thermoplastic elastomers consisting of triblock co polymers; styrene-ethylene / butylene-styrene which forms a transparent block when mixed with mineral oil (Bracq et al., 2017). A comparison of 30/70% by weight SEBS gel to 20% gelatine showed comparative results for impacts on body armour between 600ms^{-1} to 800ms^{-1} (Bracq et al., 2021). The main advantage of the SEBS gel over ballistic gelatine was shown to be its reusability and stability over extended time periods, with over 100 shots fired at the same SEBS gel block over a five-day period with no apparent change in results, compared to a very limited usable life span for ballistic gelatine of a couple of days.

More recent work has started to compare impacts on SEBS gel to human response to injury, particularly to less lethal kinetic impacts (Bracq et al., 2017, 2019, 2021; Shen, Taddei and Roth, 2020). Although there is not yet sufficient data to form the basis for injury assessment to be achieved using SEBS gel. As SEBS gel can be melted and reformed in various moulds, as well being able to measure the BFS directly behind the body armour panel it was included in this work.

5.3.3 10% Ballistic gelatine

Ballistic gelatine has been used extensively to represent human tissue. It is commonly used in two different formulations, 10% and 20%, which refers to the mass of gelatine powder to water.

Gelatine is produced by the extraction of collagen from swine tissue and its use as a tissue surrogate for wounds ballistics research has been well reported in the open literature. A comprehensive overview of its usage of ballistic gelatine in wound ballistics is available (Carr, Stevenson and Mahoney, 2018). Work by Mabbott et al compared 10 and 20% gelatine to porcine thorax for wound ballistics (Mabbott et al., 2016). 10% ballistic gelatine provided a more

representative depth of penetration (DoP) than 20% ballistic gelatine when considering higher velocity projectiles (5.56 x 45 62 grain; 10%, $V_{\text{mean}} = 847 \text{ ms}^{-1}$, $\text{DoP}_{\text{mean}} = 426 \text{ mm}$; 20%, $V_{\text{mean}} = 845 \text{ ms}^{-1}$, $\text{DoP}_{\text{mean}} = 296 \text{ mm}$; thorax model, $V_{\text{mean}} = 846 \text{ ms}^{-1}$, $\text{DoP}_{\text{mean}} = 460 \text{ mm}$). They also conducted the same experiment using a lower velocity handgun projectile (9 x 19 FMJ, 124grain, $V_{\text{mean}} = 427 \text{ ms}^{-1}$), however, the projectile passed through both the simulated thorax and gelatine block, so no data was available.

When using ballistic gelatine, it has shown sensitivity to both temperature and aging (Cronin and Falzon, 2011). The research showed that temperature had a significant effect on the mechanical properties of ballistic gelatine with respect to penetration resistance and needs to be carefully controlled.

Within the open literature, the use of ballistic gelatine for assessment of BABT was first discussed by Metker et al who used 20% gelatine in their work developing a method for measuring BFS on body armour (Metker, Prather and Johnson, 1975). The selection of gelatine was to enable the visualisation and measurement of BFS, although no details of the exact gelatine used or why 20% gelatine was selected were included in the report. Work published in 1977 compared the BFS in 20% gelatine to the results seen in goats thorax (Prather, Swann and Hawkins, 1977). Their work showed that 20% gelatine had a deeper depth of measured BFS over time than that seen in goat thorax; interestingly in the data presented, RP1 had a very similar response to the gelatine at the time. In the same way that SEBS gel can be moulded it is possible to mould a ballistic gelatine female torso form and measure BFS behind the body armour, which was included in this research.

5.3.4 Aim

The aim of this comparison was to inform on potential materials for the testing of female body armour with respect to ballistic resistance of body armour and BABT.

In this paper the commonly used testing material RP1 was compared against:

- SEBS gel at 30/70%

- 10% (by mass) ballistic gelatine. This concentration was selected based on the work by Mabbott et al who showed that 10% ballistic gelatine matched the thorax model for wound ballistics.

5.4 Methods

An experimental method was developed to build a dataset enabling a comparison of the three different backing materials, RP1, 10% ballistic gelatine, and SEBS gel, to be conducted.

5.4.1 Test panels

All ballistic testing was conducted using a single batch of test panels manufactured by DuPont®, specified to have an average BFS on RP1 of 25mm, and each measuring 300 x 300mm. The panels consisted of 10 layers of Kevlar® XP102 with a single layer of 3mm foam on the non-strike face. Each test panel was marked with the same ten shot pattern, Figure 5-3. Each shot location was a minimum of 50mm from the edge of the panel and at least 100mm from any other shot location, all shot locations were on a different horizontal and vertical axis.

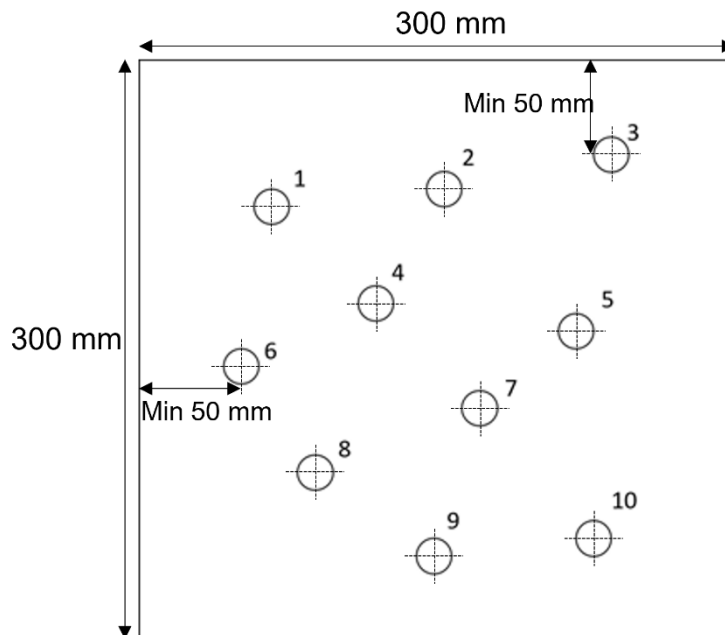


Figure 5-3 Shot location template

5.4.2 Projectiles

Testing was conducted using the test projectiles and velocities specified in the HOSDB Body Armour Standard 2007, part 2, at the HG1a protection level, Table 5-1 (Croft and Longhurst, 2007).

Table 5-1 Test round details and velocities (Croft and Longhurst, 2007)

Calibre	Description	Projectile mass	Range (m)	Velocity (ms ⁻¹)
9mm	9mm Full Metal Jacket (FMJ) Dynamite Nobel DM11A1B2	8.0 g (124 grain)	5	365 ± 10
0.357"	0.357 Magnum Jacketed Soft Point (JSP) Remington R357M3	10.2 g (158 grain)	5	390 ± 10

5.4.3 Backing material – Roma Plastilina No 1

Two steel trays, measuring 420 mm x 350 mm x 100 mm were filled and prepared from a single batch of new RP1 material and conditioned in accordance with HOSDB body armour standard 2007 (Croft and Longhurst, 2007). The trays were rotated throughout testing, each being refilled and smoothed with preconditioned material from the same initial batch of material before being placed back into the conditioning chamber as described in the test standard. Each tray was tested for compliance with calibration checks before each batch of testing, Table 5-2. If a tray was outside calibration, it was refilled, smoothed and place back in the conditioning chamber for a minimum of 30 minutes before being rechecked.

Table 5-2 Calibration check of RP1 tray

Test object	Drop height (m)	Spacing	Requirement
Steel sphere Diameter 63.5 ± 0.05 mm Mass 1.043 ± 0.005 kg	1.5 ± 0.02 m	75 mm from the edge of the tray to any indent centre 100 mm between indent centres	Mean depth of indent 15 ± 1.5 mm

During testing, no test shot was conducted closer than 50mm to the edge of the tray or 100mm from a previous impact point in the RP1.

The depth of the indent in the RP1 was measured at its deepest point using a calibrated digital calliper to determine the BFS.

5.4.4 Backing material – 10% Ballistic gelatine

Type 3 (265 bloom) ballistic photographic grade gelatine from the same batch was used to make ten blocks of 10% ballistic gelatine. Blocks were manufactured in accordance with the instructions in Mabbott PhD thesis (Mabbott, 2015, p262).

Once set, each block was cut in half lengthways to create blocks of size 250mm x 300mm x 250mm. Calibration of the blocks was performed in accordance with the method proposed by Jussila using 4.5 mm ball bearings fired at velocities between 120 to 190 ms⁻¹ (Jussila, 2004).

During testing no two impacts occurred on the same location and the block was rotated to an alternative side if any damage was identified.

Each shot was recorded using a Phantom high-speed camera at 21000 frames per second, mounted perpendicular to the side of the block. Post-test analysis of the recordings was conducted using Phantom CineView (CV) software¹⁹. Calibration was achieved through a photographic scale and set for each high-speed video. Measurements were taken on each frame using the inbuilt cursor and measurement tool in the software, identifying points by eye.

5.4.5 Backing material – SEBS gel

A SEBS gel block of size 250mm cubed, composition 30% mass polymer (Kraton G1652) and 70% mass mineral oil (Primol 352) was used. The block was manufactured and consistency checked in accordance with the process detailed by Bracq et al (Bracq et al., 2017). SEBS gel did not require preconditioning before use and all test shots were conducted on the same location.

Each shot was recorded using a high-speed camera at 10,000 frames per second, mounted perpendicular to the side of the block with a photographic scale visible. Data was processed using an automated algorithm developed by

¹⁹ Version 3.5.792.0

Centre de Recherche et d'Expertise de la Logistique (CREL). This algorithm provided the measurements for the entire impact duration of BFS recorded in an Excel spreadsheet.

5.4.6 Test method

Testing was conducted as described in the HOSDB body armour standard 2007 for ballistic testing at three separate test facilities (Croft and Longhurst, 2007).

RP1 testing was conducted at the firing range by the Home Office Centre for Applied Science and Technology (CAST), St Albans (UK), 10% ballistic gelatine was conducted by the Impact and Armour Group at Cranfield University, Shrivenham (UK) and SEBS gel was conducted by CREL in Paris (France).

5.4.7 Data analysis

The data was validated to ensure that shot velocities were within specification, those outside of specification were not included in further analysis. The number of usable test shots per projectile and backing material type is shown in Table 5-3.

Table 5-3 Number of samples available post validation checks

Material	Projectile type	Number of test packs used	Total Number of valid shots
Roma Plastilina No 1	9mm	5	30
	0.357"	5	43
10% Ballistic gelatine	9mm	5	46
	0.357"	5	47
SEBS Gel	9mm	4	29
	0.357"	5	33

For 10% ballistic gelatine and SEBS gel, the depth and diameter of the BFS were collected at each frame of video until the maximum depth was identified. From this data the rate of change (acceleration) for depth was calculated using

Equation 5-1. An estimate of volume of BFS was calculated based on the assumption the shape could be considered a spherical cap²⁰, Equation 5-2.

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

a = acceleration

$$v = \frac{\Delta d}{\Delta t} \text{ (velocity)}$$

t = time

d = distance

Equation 5-1

$$V = \frac{\pi h}{6} (3a^2 + h^2)$$


Equation 5-2

5.4.8 Statistical tests

All statistical analysis was conducted using SPSS²¹. Only statistically significant results are discussed in the results section.

A two-way analysis of variance was conducted to explore the impact of backing material and shot location of maximum BFS for both projectile types.

Tests for homogeneity were conducted before each test to ensure assumptions for test were not violated. Where a statistically significant variance was identified ($p < 0.05$) a Post-Hoc comparison was conducted using Tukey Honestly Significant Difference test (Tukey HSD).

5.5 Results²²

For all backing materials the data was analysed for variance within and between test packs as well as between backing materials. For both SEBS gel and 10% ballistic gelatine, further analysis was conducted looking at the dynamic response of the materials to impact.

²⁰ "A portion of a ball cut from it by a horizontal plane is called a spherical cap" (Polyanin and Manzhirrov, 2007)

²¹ IBM® SPSS® Statistics V26.0.0.0

²² The raw data discussed in this paper was previously partially presented as a poster at the 30th International Symposium on Ballistics 2017 in Long Beach, CA. (Malbon and Carr, 2017)

5.5.1 Relationship of energy to BFS

A scatter graph and descriptive statistics for all shots within velocity tolerance was created comparing kinetic energy of the test projectile to maximum depth of BFS, Figure 5-4 and Table 5-4.

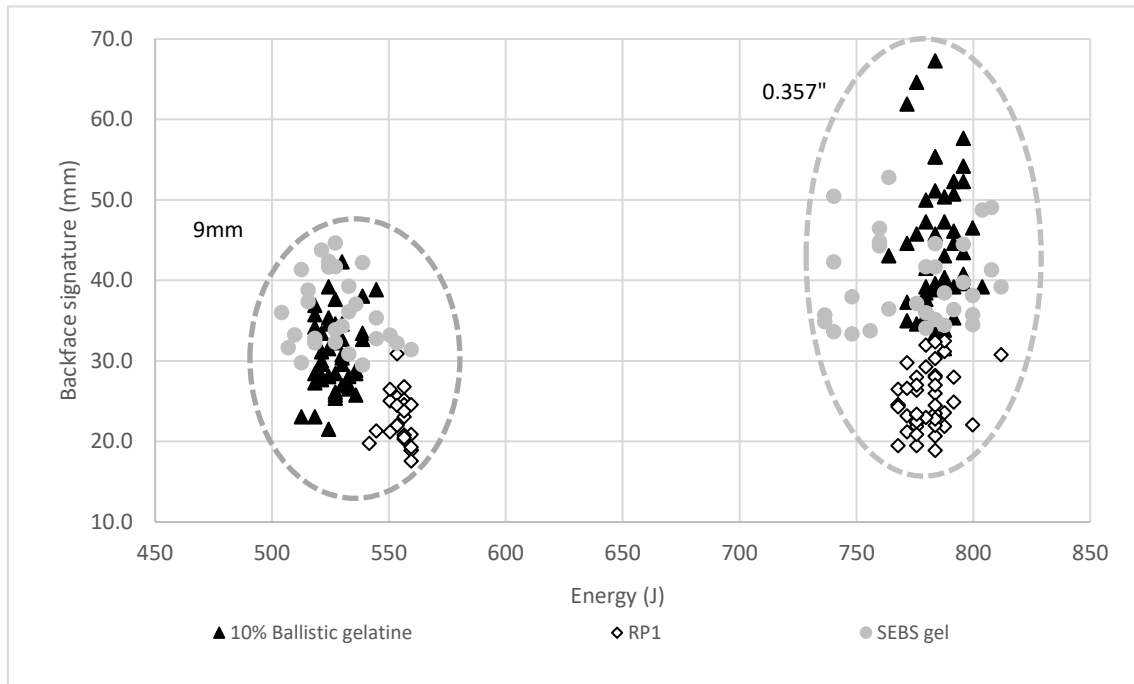


Figure 5-4 Kinetic energy against Maximum BFS for RP1, 10% Ballistic gelatine and SEBS gel

Table 5-4 Descriptive statistics for depth of BFS

Projectile type	Descriptive	RP1	10% ballistic gelatine	SEBS gel
9mm	Mean BFS (mm)	22.8	30.8	36.2
	Standard deviation	3.1	4.6	4.6
	Max BFS (mm)	30.9	42.3	44.7
	Min BFS (mm)	17.6	21.5	29.5
	n	30	46	29
0.357"	Mean BFS (mm)	25.2	44.4	39.9
	Standard deviation	3.7	8.38	5.3
	Max BFS (mm)	32.5	67.3	52.8
	Min BFS (mm)	18.9	31.5	33.4
	n	43	47	33

At lower energies, the spread of results for all three materials was minimal (Means – Energy 543 J; BFS - RP1 22.8 mm, 10% 30.8 mm, SEBS gel 36.2 mm) when compared to higher energies (Means – Energy 780 J; BFS-RP1 25.2 mm, 10% 44.4 mm, SEBS 39.9 mm). 10% ballistic gelatine had the greatest spread of results, especially at the higher energies (BFS 31.5 to 67.3 mm). The spread of results for RP1 was the smallest at both energy levels (543 J – 17.6 to 30.9 mm; 780J - 18.9 to 32.5 mm).

5.5.2 Effect of backing material and shot location on maximum BFS depth

A two-way anova within each projectile type was conducted to determine the individual and joint effect of backing material and shot location on maximum BFS depth.

5.5.2.1 9mm projectile

Residual analysis was conducted to test for assumptions of the two-way anova. Outliers were assessed by inspection of box plots. This highlighted that for pack 56, there were three shot location outliers. Further investigation identified that for test shot location no. 3, it had a pyramidal shaped BFS, commonly referred to as pencing²³, which resulted in a large measurement of BFS. The further two outliers did not demonstrate this response, however they had higher measurement of BFS.

As no other test pack showed the same variance for BFS in relation to shot location for both projectile types on the SEBS gel backing material and the 0.357" projectile type on 10% ballistic gelatine, the data for the entire test pack was excluded from further analysis. It is possible that the lighting used for the high speed camera had increased the ambient temperature around the block, resulting in a change in the properties of the ballistic gelatine (Cronin and Falzon, 2011). Although temperature of the ballistic gelatine was not recorded so this cannot be confirmed.

²³ ".....a tapered and more concentrated back-face deformation than the conventional hemispherical deformation..." (Lewis et al., 2004)

Residual analysis was repeated and showed no further outliers and normality was assessed using Shapiro Wilk normality test, all residuals were normally distributed.

Homogeneity of variances was tested using Levene's test of equality of error variances which identified that there was significant result ($p < 0.01$). A more stringent significance level of 0.01 was therefore applied to the output of the two-way anova.

There was no statistically significant interaction effect between backing material and shot location on maximum back face signature, $F(18, 66) = 2.155$, $p = 0.013$. There were statistically significant main effects for both backing material, $F(2, 66) = 142.123$, $p < 0.001$, and for shot location, $F(9, 66) = 7.526$, $p < 0.001$. The effect size for the backing material, (partial eta squared = 0.812), was greater than for shot location, (partial eta squared = 0.506).

Post-Hoc comparison conducted using Tukey HSD for the effect of backing material type on maximum BFS for RP1 ($M = 22.7$, $SD = 3.1$), Gelatine ($M = 29.3$, $SD = 3.6$), and SEBS ($M = 36.2$, $SD = 4.6$) were all statistically significantly different from each other.

For shot location, Tukey HSD post-hoc comparison indicated that the maximum BFS for all shot locations apart from 2 and 8 had a significant difference to at least two other shot locations, Table 5-5.

Table 5-5 Comparison of effect of shot location on BFS for 9mm, all backing materials

Shot location (Mean and SD)	Significant difference to (Mean and SD)
1 (M = 31.2, SD = 5.4)	4 (M = 26.3, SD = 5.6)
	7 (M = 26.6, SD = 6.3)
3 (M = 34.7, SD = 6.8)	4 (M = 26.3, SD = 5.6)
	5 (M = 28.3, SD = 7.4)
	6 (M = 27.6, SD = 4.5)
	7 (M = 26.6, SD = 6.3)
	9 (M = 28.0, SD = 6.6)
4 (M = 26.3, SD = 5.6)	1 (M = 31.2, SD = 5.4)
	3 (M = 34.7, SD = 6.8)
	10 (M = 34.1, SD = 7.1)
5 (M = 28.3, SD = 7.4)	3 (M = 34.7, SD = 6.8)
	10 (M = 34.1, SD = 7.1)
6 (M = 27.6, SD = 4.5)	3 (M = 34.7, SD = 6.8)
	10 (M = 34.1, SD = 7.1)
7 (M = 26.6, SD = 6.3)	1 (M = 31.2, SD = 5.4)
	3 (M = 34.7, SD = 6.8)
	10 (M = 34.1, SD = 7.1)
9 (M = 28.0, SD = 6.6)	3 (M = 34.7, SD = 6.8)
	10 (M = 34.1, SD = 7.1)
10 (M = 34.1, SD = 7.1)	4 (M = 26.3, SD = 5.6)
	5 (M = 28.3, SD = 7.4)
	6 (M = 27.6, SD = 4.5)
	7 (M = 26.6, SD = 6.3)
	9 (M = 28.0, SD = 6.6)

5.5.2.2 0.357” projectile

Residual analysis was conducted to test for assumptions of the two-way anova. Outliers were assessed by inspection of box plots. This highlighted that for pack 26 tested on ballistic gelatine, that shot location 4 was an outlier. No further outliers were identified for pack 26 or any other pack, and it was decided to proceed including this data point. Normality was assessed using Shapiro Wilk normality test, all residuals were normally distributed.

Homogeneity of variances was tested using Levene's test of equality of error variances which identified that there was a significant result ($p < 0.01$). A more stringent significance level of 0.01 was therefore applied to the output of the two-way anova.

There was no statistically significant interaction effect between backing material and shot location on maximum back face signature, $F(18, 93) = 1.186$, $p = 0.289$. There were statistically significant main effects for both backing material, $F(2, 93) = 171.766$, $p < 0.001$, and for shot location, $F(9, 93) = 8.691$, $p < 0.001$. The effect size for the backing material, (partial eta squared = 0.787), was greater than for shot location, (partial eta squared = 0.457).

Post-Hoc comparison conducted using Tukey HSD for the effect of backing material type on maximum BFS for RP1 ($M = 25.2$, $SD = 3.7$), Gelatine ($M = 44.4$, $SD = 8.5$), and SEBS ($M = 39.9$, $SD = 5.4$) were all statistically significantly different from each other.

For shot location, Tukey HSD post-hoc comparison indicated that the maximum BFS for all shot locations apart from 2 and 8 had a significant difference to at least one other shot locations, Table 5-6.

Table 5-6 Comparison of effect of shot location on BFS for 0.357", all backing materials

Shot location (Mean and SD)	Significant difference to (Mean and SD)
1 (M = 42.3, SD = 11.5)	4 (M = 33.6, SD = 10.6)
	5 (M = 30.7, SD = 7.1)
	6 (M = 32.6, SD = 7.9)
	7 (M = 32.8, SD = 9.6)
3 (M = 43.9, SD = 12.2)	4 (M = 33.6, SD = 10.6)
	5 (M = 30.7, SD = 7.1)
	6 (M = 32.6, SD = 7.9)
	7 (M = 32.8, SD = 9.6)
	9 (M = 34.7, SD = 9.5)
4 (M = 33.6, SD = 10.6)	1 (M = 42.3, SD = 11.5)
	3 (M = 43.9, SD = 12.2)
5 (M = 30.7, SD = 7.1)	1 (M = 42.3, SD = 11.5)
	3 (M = 43.9, SD = 12.2)
	10 (M = 41.5, SD = 14.5)
6 (M = 32.6, SD = 7.9)	1 (M = 42.3, SD = 11.5)
	3 (M = 43.9, SD = 12.2)
	10 (M = 41.5, SD = 14.5)
7 (M = 32.8, SD = 9.6)	1 (M = 42.3, SD = 11.5)
	3 (M = 43.9, SD = 12.2)
	10 (M = 41.5, SD = 14.5)
9 (M = 34.7, SD = 9.5)	3 (M = 43.9, SD = 12.2)
10 (M = 34.1, SD = 7.1)	5 (M = 30.7, SD = 7.1)
	6 (M = 32.6, SD = 7.9)
	7 (M = 32.8, SD = 9.6)

5.5.2.3 Summary

The initial analysis of variance showed the following

- Between materials there was statistically significant difference in results
- Between shot locations, for both projectiles across all materials, there was a significant difference in results apart from shot locations 2 and 8
- Backing material had a greater effect size for both projectile types compared to shot location

5.5.3 Assessment of dynamic BFS between 10% ballistic gelatine and SEBS gel

The following rules were applied when reviewing dynamic BFS data for 10% ballistic gelatine and SEBS gel

- Data for only one test pack for each projectile per backing material type was selected
- Test packs which had outliers identified through residual analysis were excluded.

The following analysis of dynamic material behaviour was conducted

- Within material comparison of dynamic BFS depth and response rate
- Between projectile type comparison of dynamic BFS depth and response rate
- Between projectile type comparison of dynamic BFS surface diameter
- Between projectile type comparison of dynamic BFS volume
- Rate of change in BFS depth

5.5.4 Within material comparison of dynamic BFS depth and response rate

A comparison of dynamic mean peak BFS and response curve for 10% ballistic gelatine and SEBS gel to 9mm and 0.357 projectile types was conducted, Figure 5-5 and Figure 5-6 respectfully and Table 5-7. 95% confidence intervals (95% CI) were calculated for each plot and included on the graphs.

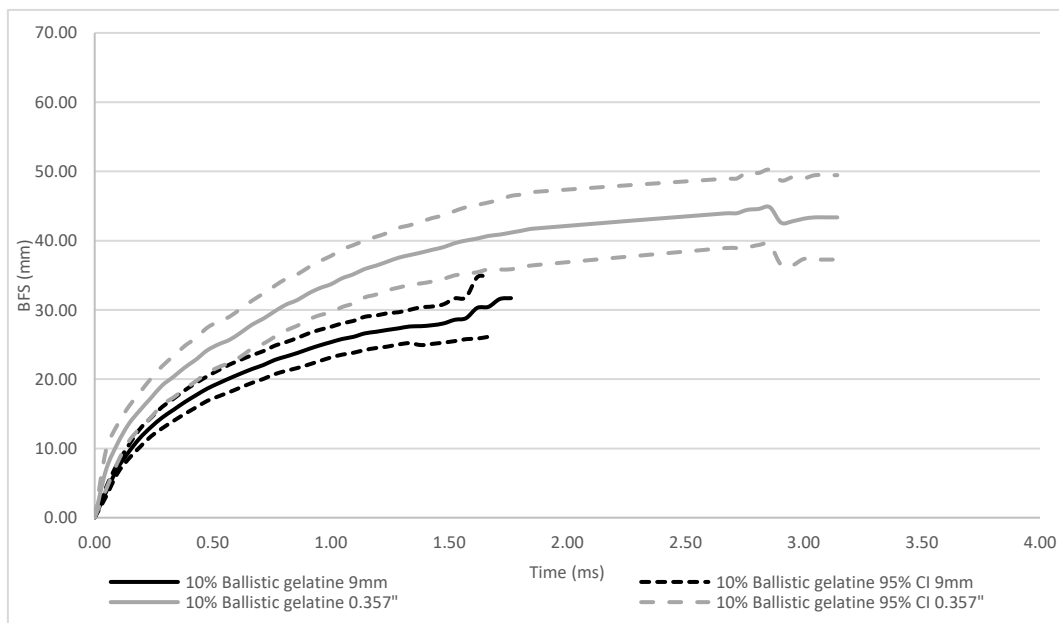


Figure 5-5 Comparison of 9mm and 0.357\"/>

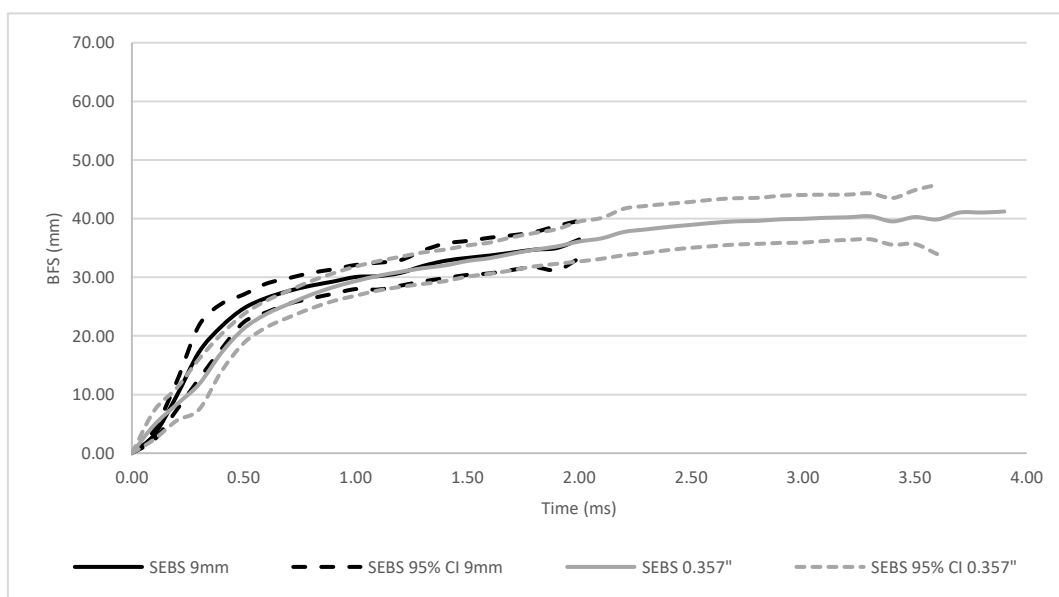


Figure 5-6 Comparison of 9mm and 0.357\"/>

Table 5-7 maximum depth BFS data for SEBS gel and 10% ballistic gelatine

Material	Projectile (KE) (n)	Peak BFS (mm) (95% CI)	Time to peak BFS (ms)
10% ballistic gelatine	9mm (533J) (n = 10)	35 (± 4.3)	1.86
	0.357" (776J) (n = 10)	49 (± 4.8)	3.38
SEBS gel	9mm (533J) (n = 5)	39 (± 1.54)	2.4
	0.357" (776J) (n = 10)	41 (± 5.9)	3.9

The 10% ballistic gelatine for both projectiles achieved peak BFS in the shortest times (1.86 ms, 3.38 ms) when compared to SEBS gel (2.4 ms, 3.9 ms).

However, Figure 5-5 shows that 10% ballistic gelatine had a different response rate for the two projectiles, whereas Figure 5-6 shows that SEBS gel had a very similar response to both projectiles. The difference was anticipated due to the higher kinetic energy of the 0.357" projectile, however with no noticeable difference in the SEBS gel it indicates that SEBS gel was stiffer than the 10% ballistic gelatine, supporting the initial analysis on the distribution of results, Figure 5-4.

5.5.5 Between projectile type comparison of dynamic BFS mean depth and response rate

A comparison of dynamic BFS mean depth response rate for 10% ballistic gelatine and SEBS gel within projectile type was conducted, Figure 5-7 and Figure 5-8. 95% confidence intervals (95% CI) were calculated for each plot and included on the graphs.

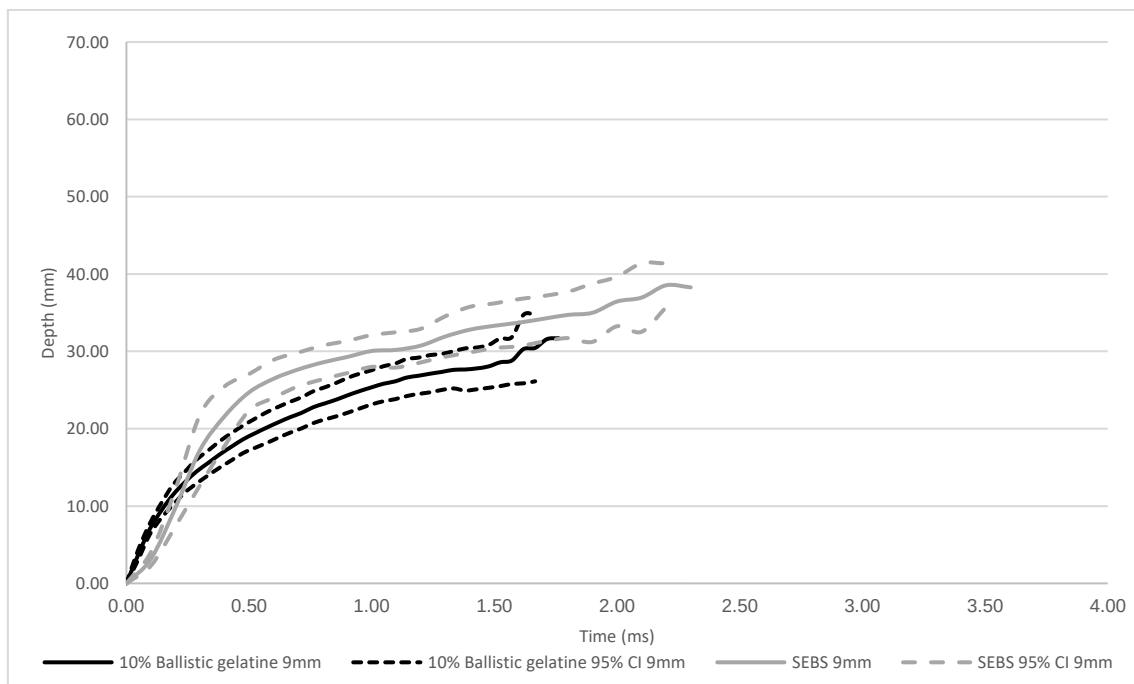


Figure 5-7 Comparison of dynamic BFS mean depth on SEBS gel and 10% ballistic gelatine – 9mm projectile

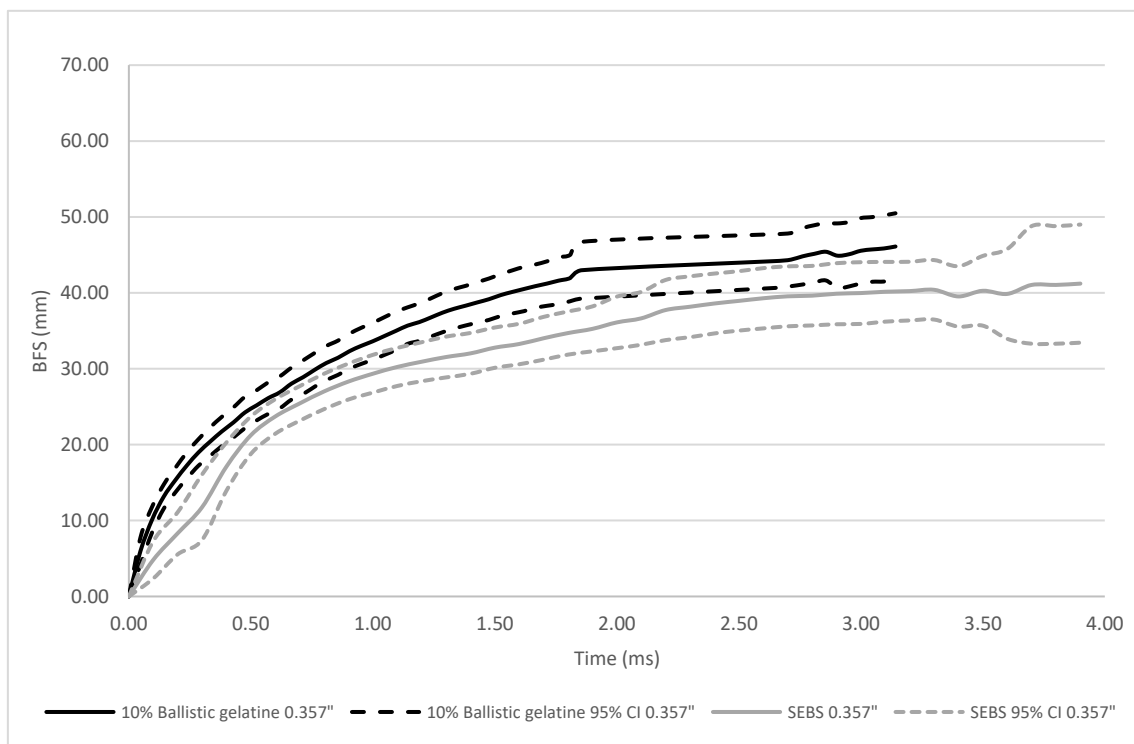


Figure 5-8 Comparison of dynamic BFS mean depth on SEBS gel and 10% ballistic gelatine – 0.357\"/>

For the 9mm projectile, 10% ballistic gelatine responded quicker for the first 0.2 ms than the SEBS gel, however, at that point the reaction of the 10% ballistic gelatine slowed compared to SEBS gel, Figure 5-7. The SEBS gel took longer to reach the mean peak BFS when compared to the 10% ballistic gelatine (2.0 ms, 1.86 ms respectively). For the 0.357" projectile, the 10% ballistic gelatine had a more rapid response throughout the duration of the response compared to SEBS gel. However, SEBS gel had a longer overall response time compared to 10% ballistic gelatine (3.9 ms, 3.29 ms respectively)

5.5.6 Between projectile type comparison of dynamic BFS mean surface diameter

A comparison of dynamic BFS mean diameter at the surface of the backing material for 10% ballistic gelatine and SEBS gel within projectile type was conducted, Figure 5-9 and Figure 5-10. 95% confidence intervals (95% CI) were calculated for each plot and included on the graphs.

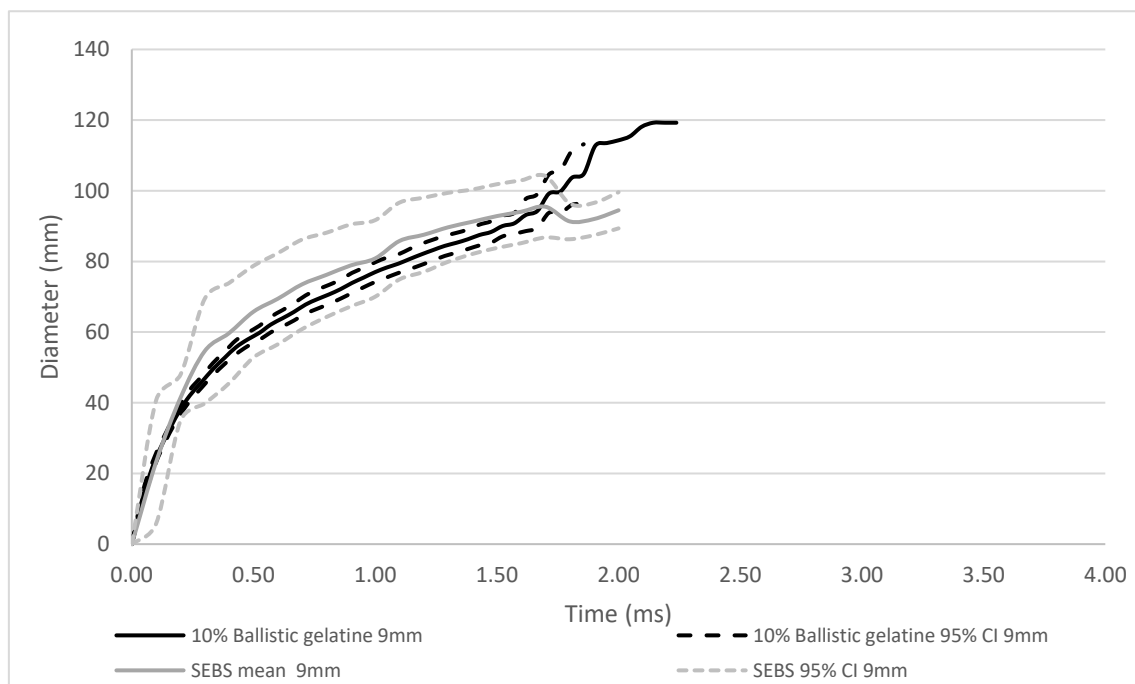


Figure 5-9 Comparison of dynamic BFS mean diameter on SEBS gel and 10% ballistic gelatine – 9mm projectile

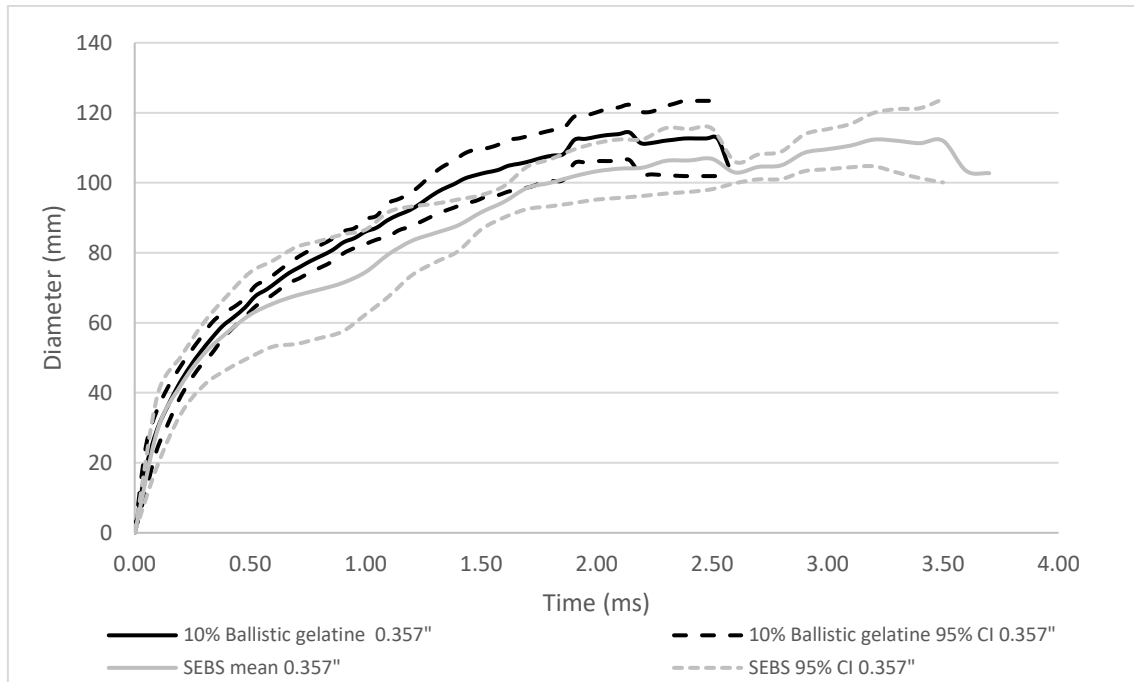


Figure 5-10 Comparison of dynamic BFS mean diameter on SEBS gel and 10% ballistic gelatine – 0.357” projectile

For the 9mm projectile, both 10% ballistic gelatine and SEBS gel had very similar mean diameters throughout the impact duration, Figure 5-9. However, the final mean peak diameter for ballistic gelatine was greater than for the SEBS gel (mean 105mm, 94mm respectively). For the 0.357” projectile, the mean peak diameters for both 10% ballistic gelatine and SEBS gel were very similar (113 mm, 112 mm respectively). However, as the duration of the impact for the SEBS gel was longer than for the 10% ballistic gelatine, the increase in diameter over time was slower than for the 9mm projectile.

For both BFS depth and diameter, the 0.357” projectile had higher mean peak values in both the 10% ballistic gelatine and the SEBS gel compared to the 9mm projectile. The time to peak BFS depth was longer for SEBS gel for both projectile types compared to the 10% ballistic gelatine, which generally also showed a slower mean response rate in the curves.

A further investigation was conducted to understand if there was a relationship between the maximum depth and diameter of BFS, Figure 5-11. A Pearson

product-moment correlation coefficient test was conducted to assess the relationship and if it was significant, Table 5-8.

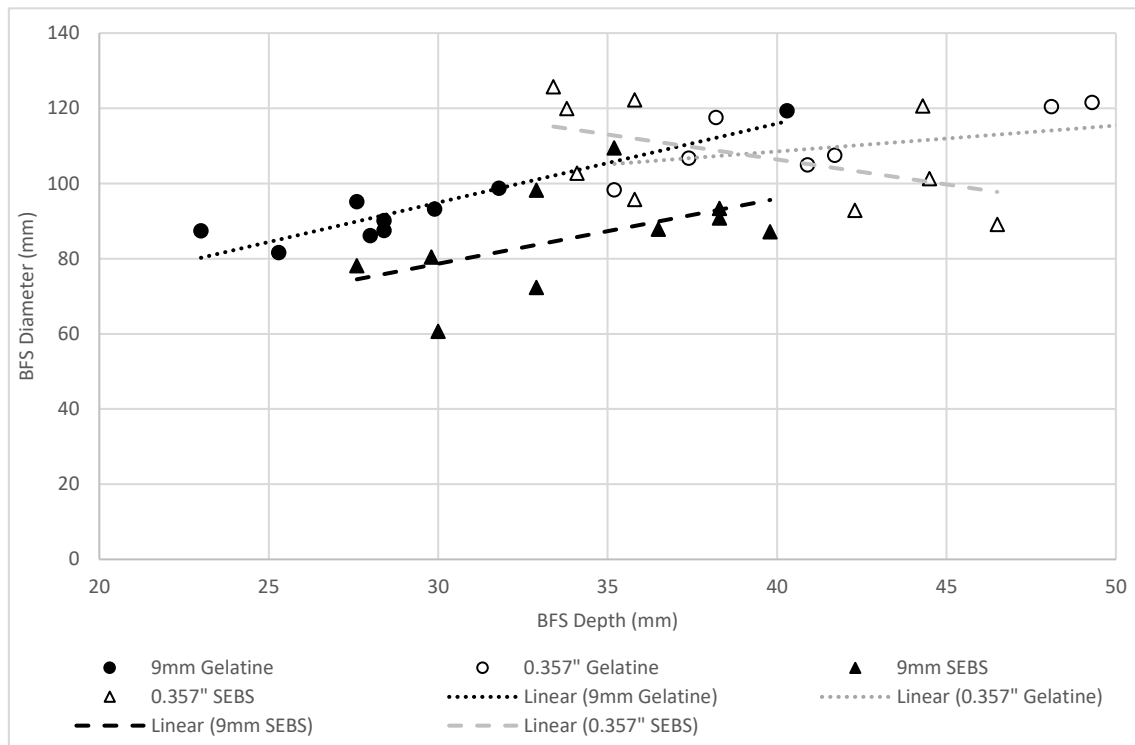


Figure 5-11 Relationship between depth and diameter of BFS in 10% ballistic gelatine and SEBS gel for both projectile types

Table 5-8 Pearsons product-moment correlation coefficient test - depth vs diameter

Backing material	Projectile	Pearsons product-moment correlation
10% Ballistic gelatine	9mm	$r = 0.925, n=9, p < 0.001$
	0.357"	$r = 0.513, n = 10, p > 0.05$
SEBS	9mm	$r = 0.522, n = 10, p > 0.05$
	0.357"	$r = -0.497, n = 9, p > 0.05$

There was a statistically significant, strong positive correlation between depth of BFS and diameter for the 9mm projectile on the 10% ballistic gelatine. However, for the 0.357" projectile on 10% ballistic gelatine, and both projectiles on SEBS, no statistically significant correlation was identified.

5.5.7 Between projectile type comparison of dynamic BFS mean volume

The mean volume of the BFS signature was estimated from the data obtained for both depth and diameter, using the assumption that the shape of the witnessed BFS is a spherical cap. This enabled a comparison of the mean volume to be conducted using Equation 5-2.

A comparison of dynamic BFS mean volume, within projectile type on 10% ballistic gelatine and SEBS gel was conducted, Figure 5-12 and Figure 5-13. 95% confidence intervals (95% CI) were calculated for each plot and included on the graphs.

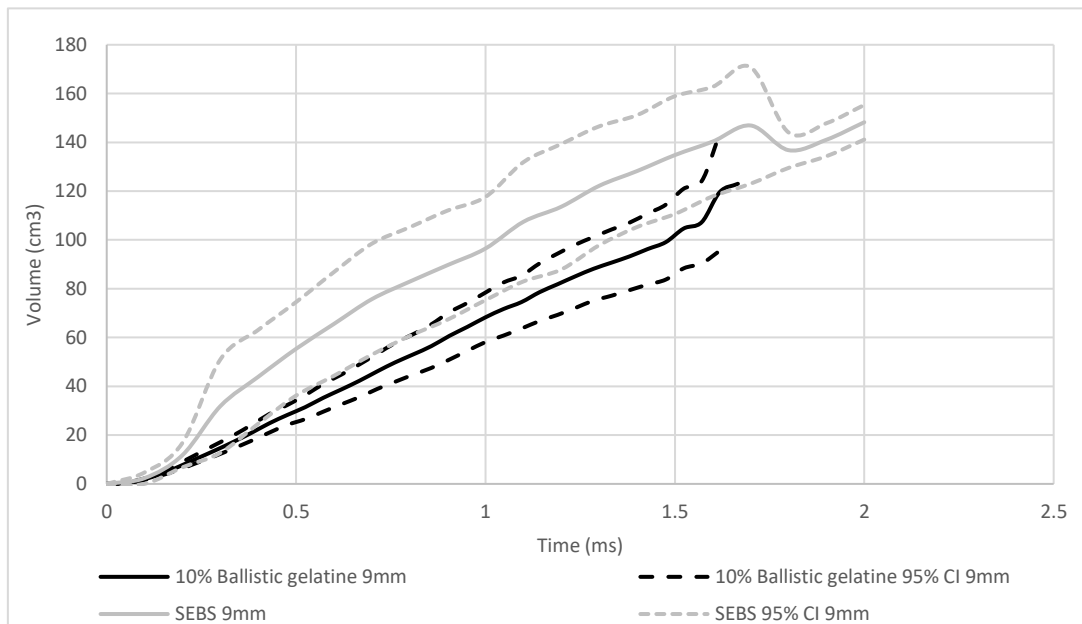


Figure 5-12 Comparison between SEBS gel and 10% ballistic gelatine of dynamic BFS mean estimated volume of BFS from 9mm

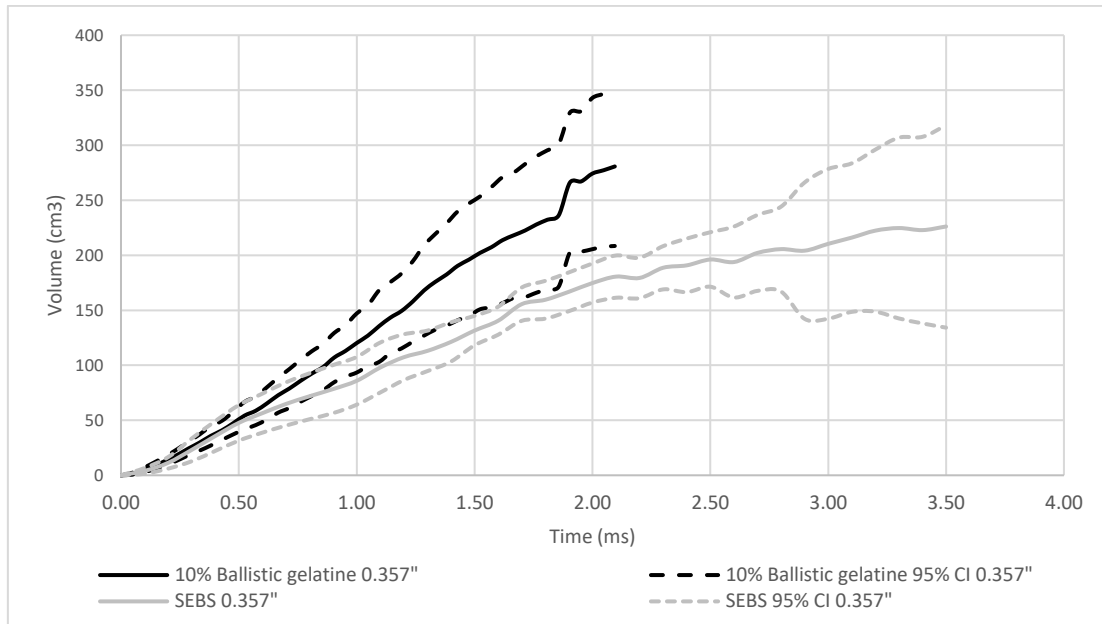


Figure 5-13 Comparison between SEBS gel and 10% ballistic gelatine of dynamic BFS mean estimated volume of BFS from 0.357"

The volume of the mean peak BFS for the 9mm projectile was greater for SEBS gel compared to 10% ballistic gelatine, Figure 5-12 (148 cm³, 120 cm³ respectively). For the 0.357" projectile the volume of the mean peak BFS was greater for the 10% ballistic gelatine than the SEBS gel, Figure 5-13 (281 cm³, 226 cm³).

5.5.8 Rate of change in BFS mean depth

To investigate further the difference in response of the two materials, the rate of change (acceleration) of the BFS depth for each projectile type was calculated using Equation 5-1 and is shown in Figure 5-14.

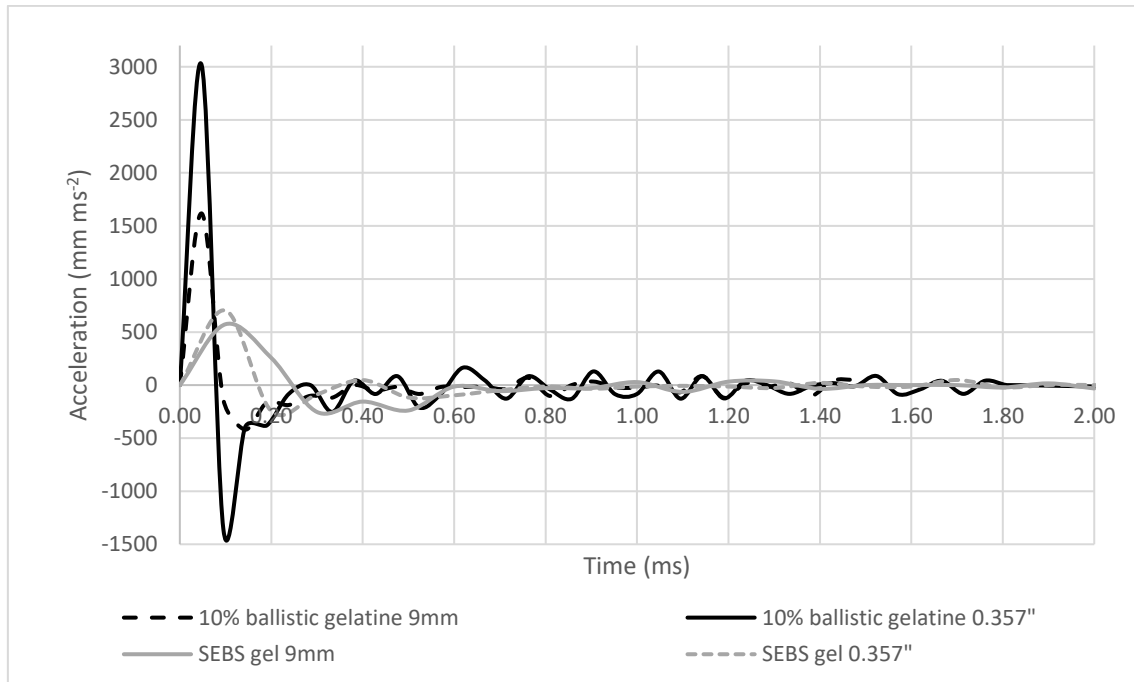


Figure 5-14 Acceleration of BFS mean depth in 10% ballistic gelatine and SEBS gel in response to impacts on armour panels from 9mm and 0.357\" projectiles

The 10% ballistic gelatine had a far greater initial response to impact for both the 9mm and 0.357\" projectile when compared to SEBS gel. In both materials for the 9mm projectile, the initial response lasted approximately 0.3 ms before reducing to a 'steady' state. For the 0.357\" projectile on SEBS gel it also settled to a 'steady' state in 0.3 ms, but for 10% ballistic gelatine, it showed evidence of 'oscillations' in its response to over 1 ms.

5.6 Discussion

The purpose of this study was to identify variances between three different backing materials for assessment of BFS, and the consideration for their use in the testing of formed body armour designed for female wearers.

The key findings from this study were

- There was statistically significant variance between RP1, 10% ballistic gelatine and SEBS gel in the measurement of BFS
- For both projectiles, 10% ballistic gelatine exhibited more variation in BFS

- RP1 had the smallest distribution of results of the three materials
- The mean depth of BFS was greater for SEBS gel at lower energies and greater for 10% ballistic gelatine at higher energies
- The mean diameter of the BFS signature was similar in both SEBS gel and 10% ballistic gelatine
- The mean volume of BFS followed the same pattern as for depth of BFS
- 10% ballistic gelatine was more energy sensitive and responsive to change than SEBS gel

The data presented in this paper is based on a total of 228 test shots (9mm, n=105, 0.357" n=123) which has enabled a comprehensive comparison to be conducted.

The statistically significant variance in results among the BFS measured in the three backing materials assessed was expected. This means it is not possible to simply swap one material for another when it comes to the assessment of BFS utilising the limits in current testing standards.

Ballistic gelatine has been the material of choice for a long time as a tissue surrogate for wound ballistics. However, when used as a medium for assessment of BFS, 10% ballistic gelatine appeared to be rate sensitive to the energy of impact, Figure 5-5 and Figure 5-14. Within wound ballistic research, evidence has also been presented that the properties of ballistic gelatine are affected by the energy of the impact (Mabbott et al., 2013; Stevenson, Carr and Stapley, 2019). The work by Mabbott et al, used 5.5mm ball bearings with increasing velocities and recorded increases in depth of penetration in the ballistic gelatine. They identified that when compared to previous work that had used 4.5mm ball bearings, using energy rather than velocity, the results were similar. In the work by Stevenson et al, although they used two different projectiles (7.62 x 39mm, 5.56 x 39mm), at typical muzzle velocities for those projectiles (648ms⁻¹, 883ms⁻¹) when the resultant temporary cavities were reviewed in 10% ballistic gelatine, the results were very similar. Again, the energy of impact for the two projectiles were similar (1658J, 1337J)

respectively). This evidence supports the theory that the response of 10% ballistic gelatine is energy sensitive.

This research only considered lower velocity rounds typically used in handguns. At higher velocities and hence higher energies, it is unknown how 10% ballistic gelatine would perform in measuring BFS. The data presented in Figure 5-4 shows that at higher energies there was an increase in the spread and depth of the measured BFS, and from the research by Mabbott et al and Stevenson et al, it can be assumed that the spread and depth of BFS for higher velocity projectiles would increase.

Comparing this to SEBS gel, which had a smaller spread of results at higher energies, it could be assumed that SEBS gel would give more consistent results at these higher energies. However, at lower energies, SEBS gel was less consistent with a greater spread of results.

This variance in response was suspected to be due to the stiffness of the SEBS gel as it has been shown to be strain rate sensitive, Figure 5-4. The impact energy of the 9mm projectile may have been at the border of the strain rate sensitivity, resulting in the increased variability in BFS. This was further seen when considering the acceleration of SEBS gel, Figure 5-14. The acceleration of SEBS gel to the 9mm projectile was the slowest of all the results presented (574 mmms^{-2}) and peak acceleration was not reached until 0.2 ms, which when compared to the 0.357" projectile on SEBS gel was slower (703 mmms^{-2} , peak 0.1 ms). When these were compared to the result on 10% ballistic gelatine, both the 9mm and 0.357" projectiles reached peak acceleration at 0.05ms (1618 mmms^{-2} , 3018 mmms^{-2} respectively). It may be possible to adjust the formulation of the SEBS gel to make a slightly less stiff variant that could have reduced variability at these lower impact energies, however this may adversely affect its behaviour at higher energies. The original work on SEBS gel did have a lower stiffness version, however in the initial testing by Mauzac et al the lowest ballistic impact energy was $\approx 690 \text{ J}$ compared to a mean energy during this study of $\approx 530 \text{ J}$ (Mauzac et al., 2012). Whilst this testing at the time

demonstrated similar results to those seen on 20% ballistic gelatine, it did not consider lower ballistic impact energies.

The results for RP1 had the smallest distribution of results compared to the other materials for both the 9mm and 0.357" projectile even with changes in energy of impact. On closer examination of the results, it was suspected that this was due to the cooling of the RP1 during testing. Work by Seppala et al has demonstrated that as RP1 cools it becomes stiffer, which relates to a smaller indent being formed from the same energy impact (Seppala et al., 2014). This demonstrates that when working with RP1 time is critical to the completion of testing while the material is still showing similar levels of strain rate sensitivity.

Of interest is that the mean diameter of the BFS in both 10% ballistic gelatine and SEBS gel within each projectile type were closely matched, Figure 5-9 and Figure 5-10. Considering this in relation to testing for formed body armour, particularly for female breast forms, the diameter of the BFS may be significant. A large diameter BFS may be greater than the diameter of the test form, which could potentially affect the resultant depth of BFS measured. There was a statistically significantly strong correlation between depth and diameter of BFS for 10% ballistic gelatine, however for SEBS gel, no statistically significant correlation was established, Figure 5-11. This lack of correlation would need to be further investigated to ensure that if used for testing of breast forms, the diameter does not vary to a point where it exceeds the diameter of any future female test form breast, as this could potentially affect the results.

Whilst the diameter was relatively consistent between SEBS gel and 10% ballistic gelatine, the depth of the BFS varied, which when calculating the estimated volume produced distinct differences between the materials. As previously mentioned, the relationship for SEBS gel was non-linear, and as such was repeated in the volume calculations. If energy transfer as a potential mechanism for assessing BAPT related injury potential was to be considered as a method, an understanding of why this non-linear relationship has occurred would be needed.

5.7 Conclusions

This work has presented a comparative data set on three different materials: RP1; 10% ballistic gelatine; SEBS gel, which have been used for the assessment of BFS. It has highlighted that whilst RP1 is the established medium for most current test standards, there is variation in the measured BFS between test shots on the same armour panel. This variation in measured BFS (9mm min = 17.6 mm, max = 30.9 mm; 0.357" min = 18.9 mm, max = 32.5 mm) could be enough to wrongly pass or fail a body armour²⁴. It does provide a low cost, simple method for the testing of body armour that can be conducted without the need for specialist equipment such as high-speed cameras. However, it is not ideal for the testing of formed body armours designed for the female form, due to the difficulty in shaping anatomically correct breast shapes and its lack of biofidelity especially when compared to human breast tissue.

The potential alternative of using 10% ballistic gelatine may be suitable for low velocity 9mm projectiles, however when the energy of the projectile increases the measurement of BFS in 10% ballistic gelatine becomes more variable. With ballistic gelatine only having a short workable life (typically 2 to 3 days) or if it is not within calibration after being manufactured and having to be disposed of, requires a constant production of new blocks. This can make the use of ballistic gelatine a labour-intensive option. Also, in a similar way to RP1, the properties of ballistic gelatine are sensitive to temperature, as previously identified, meaning the workable time after removal from a conditioning chamber may limit its effectiveness in a test facility. Whilst ballistic gelatine is a proven material for the use in wound ballistics and enables the dynamic BFS to be recorded, not being completely translucent can make measuring the BFS more difficult. As ballistic gelatine is a food grade product and non-hazardous, its disposal post

²⁴ In the UK since the introduction of the UK body armour standards using RP1, no UK police officer has lost their life because of BABT or failure of a body armour.

usage is simple with an expected low environmental impact. As ballistic gelatine when initially made is in liquid form before it is allowed to set, it can be used in various shaped moulds, therefore making a suitable female form with breast surrogates practicable.

SEBS gel may be a viable alternative to both RP1 and 10% ballistic gelatine, as it is stable at room temperature, has an extended life and has a range of methods to ensure between batch consistency. In the same way as gelatine, it is also mouldable, so could be used as a potential surrogate for the female form. However, with the formulation used in this work (30 / 70), at the lower energy of the 9mm projectile, it had the greatest spread of results in measured BFS which is not ideal for testing body armour. The relationship between diameter and depth of BFS would also need to be investigated to understand how the material is responding, and if that affects the potential to use energy transfer to assess potential BABT injuries.

At this current time, no one material is the optimal for testing body armour. However, the possibility of being able to have a material that has a more human like response to impact and can be formed to create breast surrogates in a life like shape has many advantages. More research is urgently required to understand the potential injury mechanisms of the breasts and the affect breast tissue has on the properties of armour materials.

Of the materials tested in this research, SEBS gel is the most usable for further development of a test form that enable more realistic testing of body armour, particularly those designed for female wearers, with its ability to be moulded and its long usable life span.

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5.9 References

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6 DISCUSSION

6.1 Introduction

The work presented in this thesis came about due to the paucity of research into female body armour with regards to potential injury over the female breasts. This led to the development of the original research proposal:

“To understand factors affecting female police officers when wearing body armour to enhance comfort and fit and drive improvements in the protection and coverage of the breast area.”

The evolution of the research presented in this thesis had two pathways: firstly, investigating comfort and fit of body armour; secondly investigating alternative backing materials, Figure 1-3 (p13). To understand issues with female body armour and develop the literature base, research was designed to collect data relating to the female police population in England and Wales, including aspects such as comfort, ability to perform typical work activities, and key anthropometric data. The work also reviewed extant materials that can be used to measure the back face signature from a ballistic impact to a body armour with consideration to the applicability to the female form.

This discussion links these pathways, bringing together the overall findings and how this work could be used to improve comfort, fit, design and testing of future body armour for female police officers.

6.2 Structure of discussion

The first part of this discussion provides a short summary of the four papers which present the research conducted for this thesis. The second part discusses the key outcomes of the research, bringing the research from the individual papers together and how the work has established new knowledge to drive a potential step change in female body armour design and testing.

6.3 Summary of research findings presented in each chapter

Chapter 2 describes the initial survey conducted of female police officers across England and Wales with regards to bra size, type of bra, and issues when wearing body armour. This survey consisted of 3213 sets of respondent's answers, which was close to 9% of the total number of female police officers serving at the time of the survey. The key data from the survey was: 71% wore an underwired bra and 17% wore a sports bra; most common declared bra size was 34B; most rubbing and / or discomfort was noted around the anterior mammary regions and the posterior-sacral region. It was also identified that wearing body armour was uncomfortable when standing, and certain actions were difficult to perform (e.g., running, driving a car and self-defence) regardless of bra type.

Chapter 3 focused on understanding if comfort was affected by bra type and fit, as well as understanding differences between bra type on key anthropometric measurements that could affect the sizing of a body armour. The research was based around a cohort of 31 female participants who were professionally fitted for both an underwired and sports bra. The key findings were: bra type has a statistically significant effect on key anthropometric data around the breast area (bust point to bust point length, chest circumference, bust prominence); 71% of participants stated the sports bra was more comfortable than an underwired bra; for underwired bras, 77% of participants were resized, and for sports bras 87% of participants were resized; bra size can vary within an individual between underwired and sports bra. The data showed an improvement in participants opinion on comfort when standing and while performing activities, particularly when wearing the sports bra.

Chapter 4 investigated the coverage of female body armour around the lateral sides of the breast. The research used the same cohort of 31 female participants who participated in the study of bra comfort from chapter 3, as well as including two additional male officers. The investigation was based on the analysis of photographs taken of the lateral sides of each of the participants in the trial. The key findings for females were: greater anterior exposed area than

posterior exposed area under the arm; the exposed area was the same for both bra types; there was a statistically significant difference between bra types for the maximum distance between the edge of the bra / body armour to the medial line of the body.

Chapter 5 investigated the differences between three materials, Roma Plastilina No1 (RP1), 10% ballistic gelatine, and SEBS gel, that could be used in the assessment of back face signature (BFS) when testing of body armour against a ballistic threat. All these materials were tested using the same ammunition and ballistic resistant test panel construction. The key findings were: a statistically significant difference between the materials in the measurement of BFS for both projectiles; 10% ballistic gelatine had a greater response to the initial impact for both projectiles than SEBS gel.

6.4 Outcomes of the research

The accumulation of the work presented in this thesis has three primary outcomes

1. Updated guidance from the Police Federation of England and Wales to its members regarding bra type and professional fitting
2. An understanding of the effect of bra type on key anthropometric data to improve the design and protective coverage of body armour for female wearers
3. An understanding of differences between three backing materials and their potential use for testing female body armour

Before this research began there had been very limited work looking at comfort for female police officers whilst wearing body armour, and guidance to female police officers on body armour and the effect of bra choice did not exist. The only guidance that has been identified was in relation to the wearing of underwired bras and the effect of a ballistic impact directly striking the wire part of the bra (Burrell et al., 2014). This only identified that there was no increase in risk from wearing an underwired bra but did not look at comfort issues.

However, their research was one of the first that used an anatomically shaped female form in testing.

The work presented in chapter 2 showed clearly that there was an issue with comfort for female police officers around the breast area, and this was amplified by the nature of the tasks they performed. Previous studies have looked at the fit of body armour for female soldiers, however, the effect of bra type and breast size had not previously been investigated (Davis, Lewis and Ellett, 2020; Mithchell, Garlie and Guerra, 2010). The effect of bra type has been previously studied with respect to comfort during sporting activities, but not on comfort and fit of wearing body armour (Brown et al., 2014; Milligan, Mills and Scurr, 2014). The knowledge gained from this research in chapter 2 highlighted the need to understand further the effect of bra type on comfort and fit.

In the initial research, 71% of the respondents reported wearing an underwired bra under their body armour, with only 17% opting for a sports bra, although no reason for the preference to an underwired bra was established or investigated. After the trial of underwired and sports bra (chapter 3), most of the participants (71%) identified they would be wearing a sports bra going forward. This was a significant shift from the original preference for underwired bras identified in the original research. The second factor that was significant in improving comfort was the number of participants who were professionally resized at the start of the trial using the best fit approach for their bras (77% underwired, 87% sports bra). This was the first comprehensive study to report this in the academic literature, although it was a commonly held belief, and widely reported in the popular media, that over 70% of women are wearing the wrong size bra (Davis, 2018; Moss, 2016; Perling and Colizza, 2019).

If the percentages resized was indicative of all female police officers in England and Wales, it is feasible that somewhere between 27000 to 31000 could improve their comfort when wearing body armour by being refitted for correct bra size.

In a recently published article, the issuing of sports bras that were designed and fitted for female military recruits undertaking basic training showed a reduction

of 18% in upper body pain (Burbage et al., 2021). However, no reference is made to the wearing of these new sports bras with body armour.

A second report in the popular media reported on the optimising the fit and comfort of sports bras for female GB Olympic athletes (BBC Sport, 2021). They identified that female athletes were not always pushing themselves 100% due to concerns over causing breast injuries or pain. However, no evidence has yet been published regarding if this optimisation of fit has improved performance of the athletes.

The research presented in chapters 2 and 3 along with the more recent work identified for both female military and GB athletics team, showed that for female police officers, bra comfort, fit and support are critical. As a direct result of this work the Police Federation of England and Wales are developing guidance to all female police officers regarding the selection and fit of bras for work when wearing body armour. This is the first time such guidance will have been issued. Although the final decision to the best type of bra to wear will always be an individual's preference, being aware of the facts will help ensure improvements in comfort can be achieved for a female police officer through the optimisation of bra fit and type. This work could also benefit other occupations where personal protective equipment is worn which could be affected by bra type, such as firefighters.

The initial part of this discussion has focused on comfort, and highlighted the importance of correct bra fitting, and choice. The second part of this discussion focuses on the fit of the body armour which is critical to the safety of the wearer. Badly fitting body armour can result in additional risks for the wearer in terms of protection. If the armour does not fit closely to the body, airgaps between the body armour and the body can be created, which has been shown to increase the risk of a perforation of a ballistic round (Tilsley et al., 2018). Badly designed or fitted body armour can also result in insufficient coverage of the body and an increased risk to the wearer, as shown in Figure 4-11 and Figure 4-12 (p94), and also has the potential to fail to cover the essential organs (Breeze et al., 2016). To ensure the fit of body armour is as close to the body as possible,

accurate anthropometric data is needed (Carr, Wilson and Laing, 2012). What has been highlighted by this research is the criticality of being measured for a body armour in a correctly fitted bra of the style the police officer intends to use whilst wearing body armour. Between the underwired and sports bra there were statistically significant differences in bust point to bust point length, chest circumference, and bust prominence measurements. All of these may affect the way a body armour fits to the female form.

Whilst there are several anthropometric data sets already published, such as ANSUR II²⁵ and CAESAR²⁶ and commercial packages that utilise this data such as myAnthro²⁷ and PeopleSize 2020²⁸, the data is generally not specific to an occupational population set. The information collected as part of the 3D scanning research only consisted of a small sample size (n = 31), however, it is bespoke to the police population. The expansion to include a larger population size of female police officers would enable a more accurate anthropometric data set to be developed.

As well as ensuring a better fit to the female torso, as has been shown in chapter 4, protection of the lateral sides of the female breast is lacking. This lack of protection has not previously been reported but has the potential to be an area of risk. In the work by Carr et al on people trained in knife attack, they highlighted that the body armour could help highlight exposed and unprotected areas (Carr, Godhania and Mahoney, 2019). For a female police officer where protection to the lateral sides is lacking, this could pose a more significant risk of sustaining a potentially life changing injury.

The area under the arm is a key concern for females, as it has been shown to have a greater exposed area when wearing body armour due to breast tissue, and which will be challenging to address for both ballistic and stab protection. By extending the coverage provided by the body armour to completely protect

²⁵ ANSUR II – 2015 US Army Anthropometric Survey

²⁶ CAESAR – Civilian American and European Surface Anthropometry Resource

²⁷ <http://www.mattparkinson.com/>

²⁸ <https://openerg.com/psz/>

this area, using additional armour materials will inevitably lead to restriction in movement and decreased comfort. However, only extending the coverage to a smaller area using additional material would be ineffective as the edge effects for ballistic resistance would be highly likely to negate any benefits (Rice et al., 2014). Although it is unknown from a stab resistance perspective how effective any additional coverage may be.

The combination of improved anthropometric data bespoke to the UK female police population set, and improved design considerations to increase protection are a fundamental outcome of this thesis. However, the final significant factor that has been investigated is in how body armour for female police officers is tested. The current methods for testing are not ideal as they do not consider the additional soft tissue that comprises the female breast and how this would respond to a ballistic impact. Chapter 5 compared the commonly used extant material, Roma Plastilina No1 (RP1), against 10% ballistic gelatine and SEBS gel, both of which are semi-transparent materials that have a dynamic response to impact and can be moulded into various shapes. The research clearly showed that it is not possible to assume that test criteria utilised for one material can be translated onto an alternative material. However, it did identify that SEBS gel may be a viable alternative, but at present there is insufficient data that relates to female breasts and potential injury to enable a new approach to be adopted.

The move to a more responsive material to test female body armour may be critical as the interaction between body armour material and backing material may change the way a body armour reacts to a ballistic or stab impact.

Body armour has always been a compromise between protection and wearability. To enable a police officer to perform their job their body armour has to be comfortable for the duration of a shift, ensuring they can, if needed, defend themselves without undue hinderance.

When considering the factors presented in this thesis to achieve the goal of enhanced comfort and protection for female police officers, no one single factor is key. By the provision of new guidance on the selection and importance of the

fit of a bra, comfort can be significantly improved, but that may lead to unintentional consequences

- The introduction of extra air gaps under the body armour, or the body armour not having been fitted to the shape and form of the female breast created by the bra, resulting in an increased risk of a projectile perforating the body armour
- The measurement of female officers not wearing the style or type of bra they plan to wear whilst wearing body armour, affecting the key anthropometric dimensions used in fitting body armour
- The lack of protection to the lateral sides of the breast for female officers which can be affected by the type of bra selected

The research presented has identified key aspects of new knowledge including: improvement in comfort by the correct sizing and selection of bra type; the effects bra type has on key anthropometric data; exposure of the lateral sides of the breast; opportunities to improve the testing of female body armour. These findings have already started to be implemented through the new guidance being developed by the Police Federation to be provided to female police officers in England and Wales. The greater understanding of the significance of accurate anthropometric data when considering the design of a body armour has been highlighted which could enhance the design of future solutions. The data set comparing backing materials has highlighted strengths and weaknesses across the materials and provides a strong basis to continue to develop more appropriate systems for the testing of female body armour, not only for the police but across all wearers of body armour.

6.5 Conclusions

Research in this thesis has extended the knowledge for comfort, fit and protection of body armour for female police officers.

The work concluded that

1. New data was presented evidencing that female police officers have issues with comfort of body armour, particularly when performing actions

common to the role, such as self-defence, running and driving a car (chapter 2)

2. Evidence, for the first time, demonstrated that comfort of body armour for female police officers was significantly improved by professional fitting of bras and wearing a sports bra rather than an underwired bra (chapter 3)
3. New data was presented demonstrating that key anthropometric measurements, around the breast area, for the fitting of body armour can be significantly affected by the type of bra worn (chapter 3).
4. For the first time, a qualitative assessment of protection to the lateral side of the breast was conducted. It was identified that, for female police officers, the anterior lateral area around the breast lacked protection, typically with greater than 55% of the total exposed area being in the anterior region (chapter 4)
5. New evidence presented shows that test criteria set for Roma Plastilina No1 (RP1) cannot be applied to a different backing material, and that for RP1 there is statistically significant variance between test shot location on a test panel (chapter 5)
6. The test data for 10% ballistic gelatine at higher energies (780 J) and SEBS gel at lower energies (543 J) has confirmed that the response of the formulations of materials tested are sensitive to impact energy when measuring the back face signature (BFS) (chapter 5)

A key outcome from the research presented in this thesis is that the Police Federation of England and Wales is developing new guidance for all female police officers on the importance of correct bra fitment and the benefit of considering the use of a sports bra.

This will be the first time this guidance is issued and has been identified as a key change for all female police officers.

However, even though comfort has been shown to improve, there are still issues regarding protection and fit of female body armour which will need to be addressed in the future; with the area under the arm exposing the lateral side of the breast being of key concern and which will be challenging to address.

Understanding factors affecting the key anthropometric measurements will enable designers to improve how they design female body armour solutions in the future, ensuring consideration is given to bra type.

The research relating to backing materials also plays a key part in the future design of female body armour solutions. More responsive backing materials and the ability to measure BFS will enable designers to optimise their designs, which will be another key factor in improving female body armour

The future of the design of body armour, ensuring the correct balance between comfort and protection will require a combined effort between end user representatives, compliance standard writers, designers, and consideration against the strategic threat and risk assessments.

Whilst this work has focused on female police officers based in England and Wales, the concepts and research can be applied to all female wearers of body armour across different occupations and worldwide, with consideration to population datasets of concern.

6.6 Future research

This research has developed a strong basis for further development of future body armour designs and testing for females.

This research now enables further work to be done in developing an enhanced female testing system, not only with the aim of improving the protection for female users, but also the design of female body armour in the future to aid comfort and fit.

Suggestions for further work include

1. Research into injury mechanisms and response of the female breast to a Behind Armour Blunt Trauma to understand the risks for female police officers and how armour materials react over the breast
2. Further investigation into the use of SEBS gel as a female test form, using the form developed in the 2017 Home Office body armour

standard, including the development of a method of recording the back face signature from impact

3. The development of body armour solutions that increase protection for female police officers against the threat they face. This may entail a zoned body armour being developed that provides different protection around the lateral sides of the breast, based on risk assessment, to ensure wearability and ergonomics are not affected
4. The review of how female officers are fitted for body armour, and support and guidance provided on the fitting and selection and type of bra worn

6.7 References

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Appendix A Questionnaires

A.1 Initial national survey of female police officers in England and Wales

Q1 I confirm that I have been informed about the aim and objectives of this research project and agree to give my inputs. I understand that all information that I provide will be treated with the strictest confidence and my name will not be used in any report, publication or presentation. I understand that the information I provide will be used by Cranfield University for the purpose of research only. The data will be stored on a secure network accessed only by authorised users in accordance with the Data Protection Act (1998). I understand that the results of the research may be published in scientific journals, and an anonymised version of the data may be published in support of these results. I understand that I am not required to answer a question if I prefer not to provide a response. I understand that I am free to withdraw from this survey at any stage.

☐ By ticking this box, I confirm that I am happy to participate (1)

Q2 What is your primary role?

- ☐ Routine Patrol (1)
- ☐ Firearms (2)
- ☐ Public Order (3)
- ☐ Dog Handler (4)
- ☐ Mounted Branch (5)
- ☐ Traffic (6)
- ☐ Other (please specify) (7) _____

Q3 How many years have you been wearing body armour?

- ☐ < 2 (1)
- ☐ 2 to 5 (2)
- ☐ 6 to 10 (3)
- ☐ 11 to 15 (4)
- ☐ 16 to 20 (5)
- ☐ >20 (6)

Q4 What size bra do you normally wear?

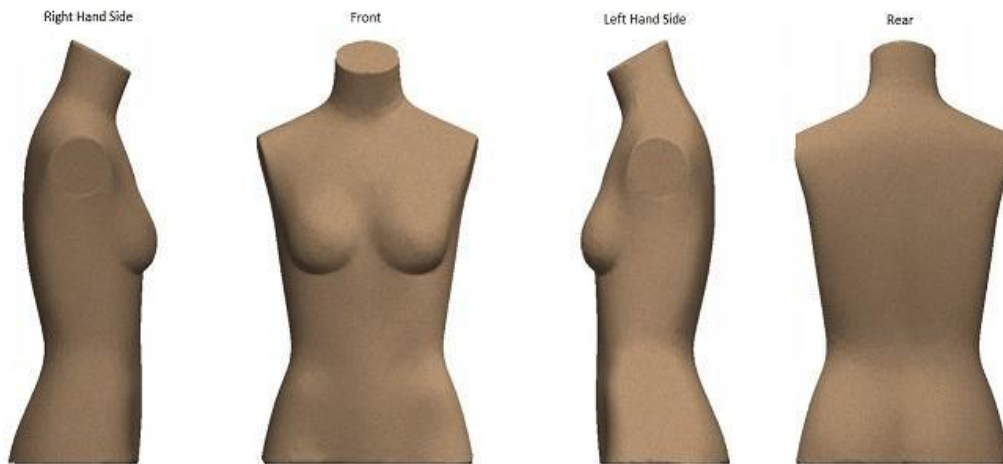
Q5 What type of bra do you normally wear under your body armour

- ☐ No bra (1)
- ☐ Sports bra (2)
- ☐ Underwired bra (3)
- ☐ Padded/push up bra (4)
- ☐ Other (please specify) (5) _____

Q6 When standing wearing your body armour, how comfortable is it?

- ☐ Very Comfortable (1)
- ☐ Comfortable (2)
- ☐ Uncomfortable (3)
- ☐ Very Uncomfortable (4)

Q7 On the images below, please indicate any areas that are uncomfortable or rub when wearing your body armour. (click on image with mouse, maximum of 10 points)



Q8 Whilst wearing your body armour, please rate the following actions (if applicable)

	Very Easy (1)	Easy (2)	Difficult (3)	Very Difficult (4)	Not applicable (5)
Sitting in a car (passenger) (1)	☐	☐	☐	☐	☐
Driving a car (2)	☐	☐	☐	☐	☐
Walking (3)	☐	☐	☐	☐	☐
Running (4)	☐	☐	☐	☐	☐
Self defence techniques (5)	☐	☐	☐	☐	☐
Using a pistol/TASER (6)	☐	☐	☐	☐	☐
Using a carbine (7)	☐	☐	☐	☐	☐
Riding (horse) (8)	☐	☐	☐	☐	☐
Riding (pedal cycle) (9)	☐	☐	☐	☐	☐
Riding (motorbike) (10)	☐	☐	☐	☐	☐

Q9 Please indicate which items of equipment you routinely carry on either your body armour, or on a belt

	Body Armour (1)	Belt (2)	Not applicable (3)
Handcuffs (1)	☐	☐	☐
Irritant spray (2)	☐	☐	☐
TASER (3)	☐	☐	☐
Police radio (4)	☐	☐	☐
Police mobile phone (5)	☐	☐	☐
Personal mobile phone (6)	☐	☐	☐
Notebook (7)	☐	☐	☐
Baton (8)	☐	☐	☐
Body worn video (9)	☐	☐	☐
Other (please specify) (10)	☐	☐	☐

A.2 Pre bra trial questionnaire

Q1 Please enter your unique identifier

Q2 What type of bra do you normally wear under your body armour?

Q3 Prior to being measured for this study, what size is the bra you normally wear under your body armour?

Q4 Before starting this trial, when was the last time you were fitted for a bra

- ☐ Within the last year (1)
- ☐ Within the last 2 years (2)
- ☐ Within the last 3 years (3)
- ☐ Within the last 5 years (4)
- ☐ Can't remember (5)
- ☐ Never been measured before (6)

Q5 What is your main duty (i.e. routine patrol, firearms etc)

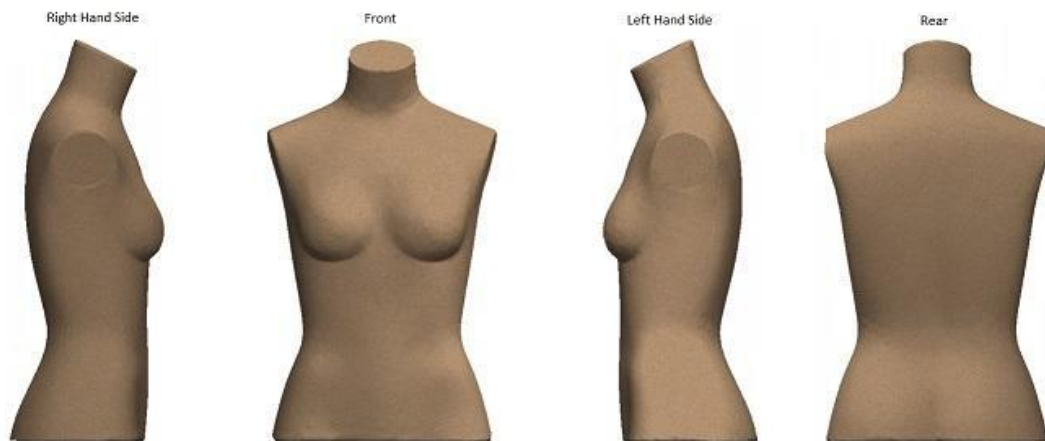
Q6 What type of armour are you issued with?

- ☐ Routine patrol (1)
- ☐ Firearms, no plates (2)
- ☐ Firearms with plates (3)

Q7 When standing wearing your body armour, how comfortable is it?

- ☐ Very Comfortable (1)
- ☐ Comfortable (2)
- ☐ Uncomfortable (3)
- ☐ Very Uncomfortable (4)

Q8 On the images below, please indicate any areas that are uncomfortable or rub when wearing your body armour. (click on image with mouse, maximum of 10 points)



Q9 Whilst wearing your body armour, please rate the following actions (if applicable)

	Very Easy (1)	Easy (2)	Difficult (3)	Very Difficult (4)	Not applicable (5)
Sitting in a car (passenger) (1)	☐	☐	☐	☐	☐
Driving a car (2)	☐	☐	☐	☐	☐
Walking (3)	☐	☐	☐	☐	☐
Running (4)	☐	☐	☐	☐	☐
Self defence techniques (5)	☐	☐	☐	☐	☐
Using a pistol/TASER (6)	☐	☐	☐	☐	☐
Using a carbine (7)	☐	☐	☐	☐	☐

A.3 Post bra trial questionnaire

Q1 Please enter your unique identifier

Q2 What bra type have you been wearing?

Q3 What size is it?

Q4 How many times have you washed the bra?

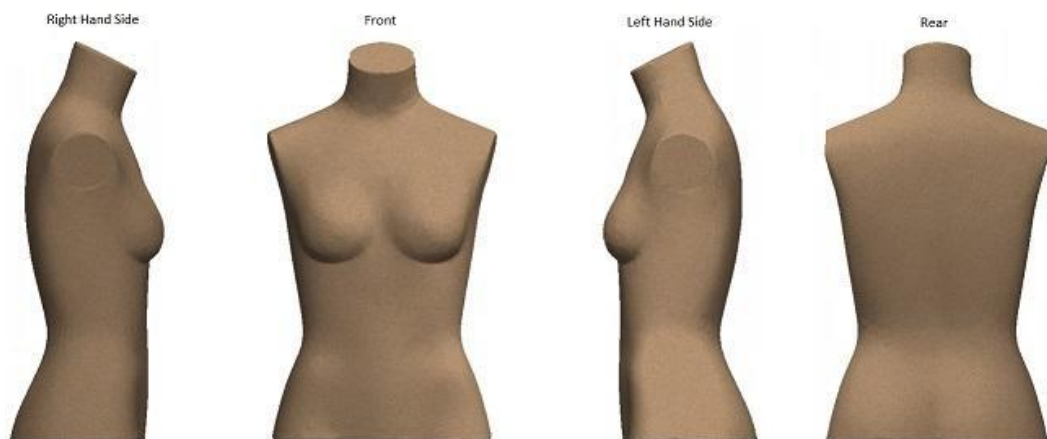
Q5 How many of each shift have you done whilst wearing this bra?

- ☐ Early (1) _____
- ☐ Late (2) _____
- ☐ Night (3) _____
- ☐ Other (4) _____

Q6 When standing wearing your body armour and this bra, how comfortable is it?

- ☐ Very Comfortable (1)
- ☐ Comfortable (2)
- ☐ Uncomfortable (3)
- ☐ Very Uncomfortable (4)

Q7 On the images below, please indicate any areas that are uncomfortable or rub when wearing your body armour and this bra (click on image with mouse, maximum of 10 points).



Q8 Whilst wearing your body armour and this bra, please rate the following actions (if applicable)

	Very Easy (1)	Easy (2)	Difficult (3)	Very Difficult (4)	Not applicable (5)
Sitting in a car (passenger) (1)	☐	☐	☐	☐	☐
Driving a car (2)	☐	☐	☐	☐	☐
Walking (3)	☐	☐	☐	☐	☐
Running (4)	☐	☐	☐	☐	☐
Self defence techniques (5)	☐	☐	☐	☐	☐
Using a pistol/TASER (6)	☐	☐	☐	☐	☐
Using a carbine (7)	☐	☐	☐	☐	☐

Q9 If you have any comments regarding the bra you have been wearing please comment below.

Q10 When you have worn both bras for 10 shifts please answer the next two questions

Which bra did you find most comfortable?

Q11 What type of bra will you use from now?

Appendix B Image analysis process

1. The image scale was set using the inbuilt “Set Scale” tool using the photographic scale in the image as reference.
2. A 1cm grid was applied to the image to aid alignment of boundaries.
3. The exposed torso area was divided into the anterior and posterior lateral areas as shown in Figure 4-3 by setting boundaries described below
 - a. The vertical boundary identified as the most anterior visible point at which the front of the arm joined the torso.
 - b. The horizontal boundary identified as the lowest visible point at which the underneath of the arm joined the torso at the armpit.
4. The anterior area, Figure 4-4, was identified using a polygon tool with the following boundaries
 - a. Uppermost boundary was the horizontal boundary identified in 3b from the point it intersects the anterior edge of the body armour to the point it intersects the vertical boundary identified in 3a.
 - b. Right hand side boundary was the vertical boundary identified in 3a from where it intersects the horizontal boundary identified in 3b to the point it intersects the edge of the body armour at the bottom of the image.
 - c. The final boundary was traced following the edge of the body armour and exposed torso or bra from the point the horizontal boundary intersected the anterior edge of the body armour to the point where the vertical boundary intersects the edge of the body armour at the bottom of the image.
5. The anterior area was then recorded using the ImageJ software to the nearest integer value.
6. The largest visible horizontal distance from the vertical boundary and below the horizontal boundary to the bra / body armour boundary was measured to 1 decimal point
7. The posterior area, Figure 4-5, was identified using a polygon tool with the following boundaries

- a. Uppermost boundary was the horizontal boundary identified in 3b from the point it intersects the anterior edge of the body armour to the point it intersects the vertical boundary identified in 3a.
 - b. Right hand side boundary was the vertical boundary identified in 3a from where it intersects the horizontal boundary identified in 3b to the point it intersects the edge of the body armour at the bottom of the image.
 - c. The final boundary was traced following the edge of the body armour and exposed torso from the point the horizontal boundary intersected the anterior edge of the body armour to the point where the vertical boundary intersects the edge of the body armour at the bottom of the image.
8. The posterior area was then recorded using the ImageJ software to the nearest integer value.