



Article

Stature Estimation in Forensic Anthropology: Addressing the Current Status, Challenges and Future Prospects

Tooba Siddiqui ^{1,2,*}, Peter Zioupos ³ and Nicholas Marquez-Grant ^{1,*} ¹ Cranfield Forensic Institute, Cranfield University, Cranfield MK43 0AL, UK² Capital City College Group, London WC1X 8RA, UK³ Biomedical Engineering, School of Engineering, University of Hull, Kingston upon Hull HU6 7RX, UK; p.zioupos@hull.ac.uk

* Correspondence: t.siddiqui@cranfield.ac.uk (T.S.); n.marquezgrant@cranfield.ac.uk (N.M.-G.)

Abstract

Background: Stature estimation is a key parameter in biological profiling of human skeletal remains and thus in aiding in the identification process of the deceased. Various methods, including anatomical approaches, multifactorial regressions and organic correlation approaches, have been developed to estimate stature. Challenges arise from incomplete or altered remains, outdated reference samples, and the lack of population specific studies. This paper critically examines genetic influences and population-specific factors, the present status quo, recent developments and the challenges in stature estimation in forensic anthropology. **Methods:** The study appraises the current status, challenges, and future directions of stature estimation in forensic anthropology and bioarchaeology. The open-source literature is systematically identified, and relevant osteological and imaging-based studies are screened and prioritised when they report original empirical data or clearly defined methodological developments, enabling consistent extraction of sample and population descriptors, modelling strategies, and limitations. Included studies are then synthesised comparatively and summarised in a study table to support direct cross-study evaluation. **Results:** Stature estimation accuracy is shown to depend on population, ancestry, sex, time period, and environment, with cross-population or cross-temporal equation transfer identified as a key source of bias. Limitations include fragmented/altered remains and non-representative reference samples, while newer imaging and probabilistic approaches improve performance when supported by suitable data and explicit error quantification. **Conclusions:** In the present article, stature estimation is positioned as a context-dependent, evidence-weighted process rather than a fixed calculation.

Keywords: stature estimation; forensic anthropology; human skeletal remains; biological profile; identification



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1. Introduction

Stature estimation sits at the heart of biological profiling in forensic (biological) anthropology, bioarchaeology, and osteology [1]. When human skeletal remains are recovered, practitioners build a biological profile to assist in the identification of the deceased, involving various parameters, including minimum number of individuals, biological sex, age at death, population affinity, and stature (height) and any unique identifying features [1–4]. The biological profile derived from human skeletal remains can help to narrow down potential matches and expedite the identification process, often complemented by primary methods such as DNA analysis or odontology [1,5,6].

Research on stature has consistently shown it to be a sensitive indicator of nutrition, health, and broader socioeconomic conditions due to its measurability and phenotypic nature, influenced by both genetic material and environmental factors. Historical work has linked reduced stature to malnutrition, disease load, and poor living and working conditions, particularly during periods such as the industrial revolution [7–9]. Furthermore, studies have documented an increase in average human height since the mid-nineteenth century, although this trend has not been uniform across the globe and is heavily influenced by geographical location and living conditions [10,11]. More recently and conducted on a specific region, Orr et al. [12] indicated that short stature in England reflects both regional patterning and socioeconomic inequality. In addition, Mittal et al. [13] found that stature is strongly influenced by ethnicity, nutritional health, and climate, specifically highlighting how sustained malnutrition is a major driver of impaired skeletal growth and secular change in height. Concurrently, large-scale genetic studies have shown that common SNPs may account for 40–50% of phenotypic variation in human height, underscoring the substantial genetic component of stature, alongside environmental influences, thus supporting the genetic predisposition of stature [14]. In conclusion, to maximise the accuracy and interpretive value, both in bioarchaeology and forensic anthropology, there is a need to consider the population, ancestry, and environmental context when selecting or developing stature estimation methods.

Different methods have been developed for stature estimation from human bones, including ratio, anatomical, regression, and organic correlation approaches [15]. Anatomical methods are considered the most accurate if there are multiple well-preserved bones and they incorporate various variables to improve accuracy [16,17]. However, they may not be applicable in forensic and archaeological cases where remains are often incomplete or altered. Meanwhile, regression studies using single, multiple, and/or fragmentary bones are the next most accurate methods. However, the application of these methods requires specific information regarding biological sex, age of the deceased, and sometimes population affinity [15–17]. On the other hand, organic correlation studies, although less precise, do not rely on specificity and are very valuable [15]. While limb bones, especially the femur, are considered the most reliable indicators of stature, more recent studies based on other bones show promising potential. For instance, Pablos et al. [18] developed regression equations using foot bones, whilst Giurazza et al. [19] demonstrated the correlation between scapular measurements and stature estimation, with longitudinal scapular length proving to be most effective.

Amongst regression studies, Trotter and Gleser's [20,21] are evidently the most popular mathematical models for stature estimation in forensic anthropology and bioarchaeology, as suggested by AAFS standards [16], UK and Ireland surveys done by McIntosh et al. [22]. However, these methods were built for specific population groups: the original 1952 study created regression equations for American "White" and "Black" males using samples of USA casualties from World War II and the Terry Anatomical Skeletal collection for the female population. This was expanded upon in 1958 with the inclusion of U.S.A. Korean War casualties, which resulted in the creation of equations for Asian and Mexican male populations as well as additions to the "White" and "Black" groups [23]. The 1958 study did not produce equations for females. Furthermore, the 1958 method used the left- and right-sided bones separately for the new equations, while the 1952 equations were created using the average lengths of paired bones [23]. Additionally, the protocols detailed by Trotter and Gleser [20,21] in the measurement of the tibia were proven by Jantz et al. [24] to be inaccurate. Due to the historic nature of the samples utilised in their studies, sexual bias, and the inconsistencies of measurements taken, Trotter and Gleser's method [20,21] does not always accurately represent contemporary populations, especially outside of the USA.

Consequently, there is a need to develop standardised and systematic approaches that accurately represent the unique characteristics of specific populations in particular, such as, for instance, the contemporary British population. The present study, therefore, highlights the advancements, considerations, and research gaps in stature estimation in forensic anthropology, in particular with a focus in the UK. It underscores the importance of selecting appropriate tools and ensuring the representativeness of the reference samples. By advancing the accuracy and applicability of stature estimation, forensic anthropologists can contribute to more effective identification and profiling of individuals based on their skeletal remains.

2. Methodological Approaches

The purpose of this study was to analyse the approaches to stature estimation within forensic anthropology and bioarchaeological contexts, with the aim of appraising the current status of the discipline, identifying the current challenges, and outlining future prospects.

Primary data for this article was derived from open-source journal articles identified using the PubMed (<https://pubmed.ncbi.nlm.nih.gov>; accessed on 1 November 2025), Google Scholar, and ScienceDirect (<https://www.sciencedirect.com>; accessed on 1 November 2025) search platforms. The literature search was structured around the thematic classifications of ‘stature estimation’, ‘biological profiling’, and ‘disaster victim identification’. The retrieved studies were assessed for relevance to the estimation of stature from human remains or human-derived measurements, including osteological and imaging-based approaches where applicable.

Eligible publications were prioritised where they provided original empirical data or clearly described methodological developments (such as sample composition, population characteristics, and the statistical modelling approach) as well as where the article structure enabled consistent extraction of key study descriptors.

Following screening, the studies included in the final database were synthesised narratively and comparatively using the predefined extraction fields and summarised in a study table to allow for direct comparison of anatomical proxies, population contexts, modelling strategies, and limitations across the literature provided by open-source journal articles from Semantic Scholar, Google Scholar and Science Direct. The main themes were under the classifications for ‘stature estimation’, ‘biological profiling’, and ‘disaster witness identification’ when referred in the context of forensic anthropology and archaeology.

3. Results

3.1. The Origins

The development of stature estimation methods in biological and forensic anthropology can be traced back to the early nineteenth century. Orfila and Lesueur [25], in a French medico-legal context, were among the first to recognise systematically that skeletal remains, including bones that could be used for stature estimation, could be employed in the identification of human bodies. Although their techniques were largely descriptive and methodologically crude by modern standards, their work helped establish the principle that the skeleton could serve as a reliable source of information in medico-legal investigations [25].

In the latter part of the nineteenth century, this insight was expanded through the rise of anthropometry and more systematic empirical work. Topinard [26], a key figure in the classical French anthropometric tradition, used measurements of the body and limbs to investigate human variation and began to formalise the idea that overall height could be inferred from individual body segments. At roughly the same time, the British

surgeon and anatomist George Humphry [27] collected extensive skeletal measurements, including those of the limb bones, thereby providing some of the earliest empirical evidence linking limb bone length to adult stature in British and European material. Beddoe [28], focusing on European populations, used stature and body measurements to characterise putative “races” and population differences, reinforcing the emerging understanding that stature and its skeletal correlates are not universal but vary between groups; however, early understanding of different groups was limited to “race” characterisation rather than geographical population and historical ancestry. Concurrently, in France, Rollet [29] produced one of the first systematic datasets directly relating limb bone lengths to stature, providing an important empirical foundation for later quantitative work. Building on this, Manouvrier [30] developed indices and formulae relating limb proportions to stature and body build; his work marks an early transition from purely descriptive approaches to more explicitly mathematical prediction.

Parallel to these empirical advances, statistical theory was being developed that would underpin modern stature estimation. Galton [31] introduced key concepts such as correlation and regression, applying them to human traits, including height, thereby demonstrating how quantitative relationships between variables could be modelled. Pearson [32] subsequently formalised regression analysis and related statistical procedures, providing the mathematical framework upon which later stature estimation equations could be constructed. In the anatomical domain, Dwight [33] proposed that stature could be reconstructed by summing the lengths of skeletal segments, thereby introducing the conceptual basis of what would later be known as the anatomical method. This approach was refined significantly in the mid-twentieth century by Fully [34], who formalised the anatomical method, and by Raxter et al. [35], who further improved the Fully technique by revising correction factors and methodological details.

Because it derives stature from the summed contribution of all relevant skeletal elements, the anatomical method minimises assumptions about proportionality between limb segments and trunk and is therefore often used as a reference standard against which regression-based methods are evaluated [35,36]. However, despite its conceptual and empirical strengths, the anatomical method is not universally applicable in routine forensic or archaeological casework. The method presupposes the availability of an essentially complete or near-complete skeleton, including an intact vertebral column and both lower limbs, which is frequently not the case in archaeological contexts and some forensic cases, commingled assemblages, or archaeological burials where taphonomic processes have produced fragmentation or selective loss of elements [35,37–39]. Additionally, the anatomical method is comparatively time-consuming and technically demanding, requiring careful reconstruction of vertebral heights and alignment as well as access to appropriate measuring equipment; this can be challenging in high-throughput forensic laboratories, mass-fatality incidents or resource-limited settings [37,38]. For these reasons, even though the anatomical method is widely accepted as the most accurate approach when conditions allow, practitioners often need alternative strategies for stature estimation when skeletal completeness is limited [35,38].

3.2. Regression Equations

A distinct but related line of development involved the application of regression techniques directly to limb bone measurements to produce practical formulae for applications in forensic cases. Stevenson [40] was among the first to apply regression explicitly with regard to the relationship between limb bone length and stature. Subsequent studies [41,42] refined these regression-based approaches in medico-legal contexts. This trajectory culminated in the influential studies of Trotter and Gleser [20,21], who developed widely

used forensic stature estimation equations derived from limb bones of identified war-dead casualties. Trotter [43] later re-evaluated and consolidated these equations, providing updated recommendations for their application. Feldesman and Fountain [44] subsequently revisited Trotter- and Gleser-type equations using more modern statistical procedures, examining robustness, error structure and the influence of sample composition, and in doing so, they contributed important methodological refinements.

3.3. The Ethnicity Parameter

From the mid-twentieth century onwards, increasing attention was paid to population specificity and the critical evaluation of existing methods. Genovés [45] developed equations for Mexican populations and stressed the importance of population-specific standards. Olivier and Tissier [46] expanded the available European data and examined regional variations in the relationship between limb lengths and stature, while Rösing [47] offered a methodologically rigorous critique of stature estimation practices, highlighting the dangers of applying formulae beyond their reference populations and drawing attention to issues of measurement error. Lundy and Feldesman [48] produced and evaluated equations applicable to South African skeletal material, particularly among African and African-derived populations, thereby demonstrating substantial geographic and ancestral variation in limb–stature relationships within Africa. Sjøvold [49] provided a broad meta-analysis of stature estimation methods across populations and time periods, emphasising that both biological variation and methodological choices, such as bone selection and reference data, have profound effects on accuracy and bias. Hanson [50] contributed further by testing and developing equations in Scandinavian and northern European contexts, again underlining the limited transferability of formulae between populations.

3.4. Archaeological Applications

Studies in archaeological and more recent European settings further clarified these issues. Formicola [51] applied and evaluated stature estimation techniques in prehistoric and historic skeletal assemblages, systematically comparing anatomical and regression methods and demonstrating how secular and temporal changes in body proportions can affect the suitability of forensic-derived formulae for past populations. Feldesman and Fountain's [44] reassessment of regression-based methods strengthened the statistical foundations upon which such evaluations rest. Finally, Mendonça [52] developed stature estimation equations for Portuguese populations using limb bones, carefully assessing the performance of non-Portuguese formulae and emphasising sex- and population-specific differences. However, Mendonça's [52] study found high standard deviations and thus concluded that the formulae may not have a practical application, thus highlighting the need for robust method developments and statistical evaluation of regression formulae. Despite this, Mendonça's [52] work is widely cited as a modern European reference and strongly reinforces the principle that locally derived reference data are essential for accurate forensic stature estimation. Contemporary studies such as [53] support this need for population specificity.

Table 1 below provides an overview of the contribution of the historic development of research conducted for stature estimation.

Furthermore, Figure 1 provides a timeline of the historical development of stature estimation methods in forensic anthropology, showing the progression from early medico-legal and anthropometric observations through the establishment of statistical foundations [31,32] and into two major twentieth-century lineages: the anatomical method [33–35] and regression-based forensic equations [20,21,40–44]. Later population-specific formulae and critical evaluations (i.e., [45–52]) were grouped to highlight grow-

ing emphasis on methodological refinement, error assessment, and the need for locally appropriate standards.

Table 1. An overview of the key studies conducted since the early 18th century that have led to the development of modern-day stature estimation methods.

Author(s)	Year	Population	Country	Key Contribution	Current Status
[54] Sue	1765	General anatomical subjects (postmortem)	France	Foundation autopsy techniques for anatomical growth	Historical foundation
[25] Orfila & Lesueur	1831	Post-autopsy subjects	France	Post-autopsy measurements (discouraged for stature)	Historical reference
[26] Topinard	1885	General skeletal remains	France	Maximum limb bone length for accuracy	Historical reference
[27] Humphry	1858	Adult skeletons	England	First ratio-based approach in England	Superseded (regression issues)
[31] Galton	1886	Review of Humphry data	England	Identified regression towards mean problem	Historical critique
[28] Beddoe	1888	Review/correction of Humphry data	England	Attempted slope/intercept corrections	Historical correction attempt
[29] Rollet	1888	50 male + 50 female cadavers (ages 24–99 years)	France	Improved ratio method with correlation consideration	Historical foundation for modern methods
[30] Manouvrier, [33] Dwight	1894	General anatomical subjects	USA	Anatomical measurement guidelines	Still referenced for methodology
[32] Pearson	1899	French cadavers (Rollet data)	England (using French data)	Introduced linear regression equations	Foundation for modern regression
[34] Fully	1956	French deportees/concentration camp victims	France/Austria	Anatomical method for stature estimation	Still widely used (anatomical method)
[35] Raxter et al.	2006	Modern revision (various populations)	USA (multi-population)	Revised anatomical method	Current best practice (anatomical method)
[20] Trotter & Gleser	1952	WWII service members and Terry Anatomical Collection	USA	Regression equations for American populations	Outdated for modern populations
[21] Trotter & Gleser	1958	WWII and Korean War service members, and Terry Anatomical Collection	USA	Continued regression equation development	Outdated for modern populations
[43] Trotter	1970	WWII and Korean War service members, and Terry Anatomical Collection	USA	Further American population equations	Outdated for modern populations
[49] Sjøvold	1990	General populations	Norway	Organic correlation lines method	Alternative method (limited use)

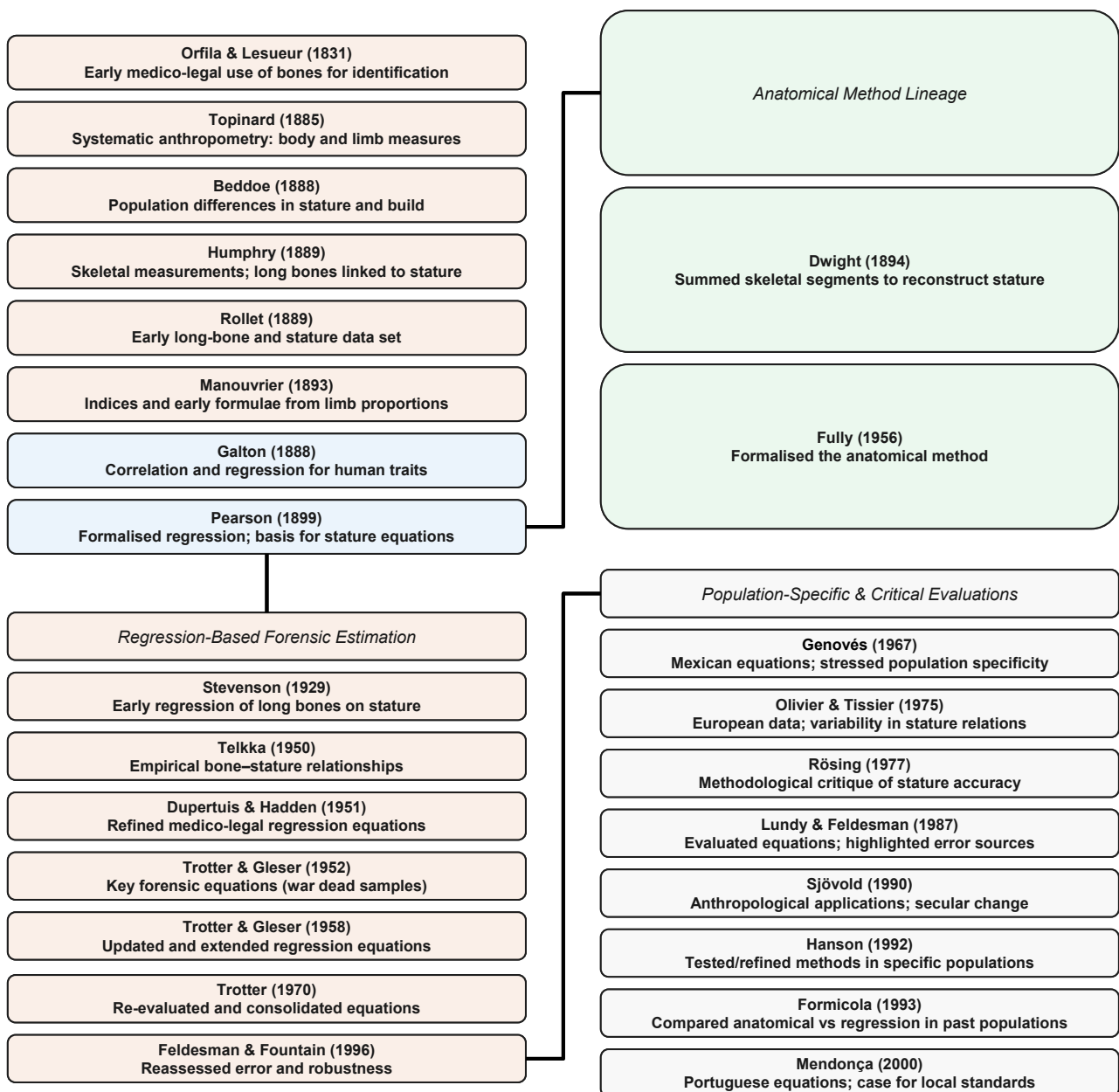


Figure 1. A timeline overview of the historic development of stature estimation method [20,21,25–35,40–52].

3.5. Stature Estimation in the Present Day

In the modern day, there are two broad methodological traditions that are utilised when estimating stature from skeletal remains: Fully’s anatomical method [34] and metric regression formulae, typified by the work of Trotter and Gleser [20,21]. The anatomical method reconstructs stature by summing the lengths of all skeletal components contributing to height (for example, cranial height, vertebral column, femora, tibiae, and ankle bones) and then applying a soft-tissue correction. Fully’s work [34] systematised this procedure, providing a transparent means of reconstructing “anatomical stature” from a largely complete skeleton. This method is conceptually robust and relatively independent of population-specific regression equations, but it is constrained by its requirement for well-preserved, nearly complete skeletal remains, which limits its use in many forensic and archaeological cases where remains are partial or fragmentary.

Meanwhile, Trotter and Gleser [20,21,43] developed regression equations for stature estimation based on North American historic samples from the Terry Anatomical Collection

as well as from WWII and Korean War service members [1]. However, although these methods are the most used today (as seen by a survey [22]), these equations are outdated and unsuitable for contemporary populations due to temporal and population-specific changes [1,55,56]. Furthermore, Trotter and Gleser [20,21] grouped individuals into vague “racial” categories such as “White”, “Black”, “Asian”, and “Mexican”. This racial categorisation is problematic, as it assumes genetic homogeneity within groups while neglecting significant intra-group variation [57]. Moreover, perceived race does not always correlate with genetic ancestry [58] and genetic isolation, which would appear to be necessary for meaningful racial classifications, no longer exists due to increased global migration and genetic mixing [59]. Additionally, genetic studies have debunked the biological basis of race, demonstrating that genetic diversity is often greater within so-called ‘racial groups’ than between them [60–62].

The research undertaken by Brahim [63] in her Master’s thesis addresses some of these shortcomings in contemporary British contexts. Drawing on modern skeletal and/or imaging-derived data from British populations, this work evaluates the performance of classical regression equations, including those of Trotter and Gleser [20,21,43], against observed statures, quantifying systematic bias and error when such historic, non-British reference data are applied to present-day individuals. In doing so, the yet unpublished thesis demonstrates that the widely used equations tend to misestimate stature in contemporary British samples, reflecting both secular changes in height and changes in body proportions that have occurred since the original reference collections were assembled. Building on this critique, Brahim’s [63] research tests revised population-appropriate regression models and explores the implications of mixed ancestry and heterogeneous life histories that characterise modern Britain, thereby moving beyond the outdated racial typologies embedded in older methods. In combination, this work complements the anatomical tradition of Fully [34] by reaffirming the value of conceptually transparent reconstruction when complete remains are available while simultaneously updating and refining metric approaches so that they are empirically grounded in current British data. It therefore provides an essential, locally relevant framework for stature estimation in contemporary UK forensic and archaeological practice.

In the contemporary context, population-specific regression equations remain the dominant method when a complete and well-preserved skeleton is not available [16,22]. Nevertheless, all these methods remain insufficient for contemporary British populations, as they were developed using historical datasets that fail to reflect modern secular trends in height, genetic mixing, and environmental influences, and yet, despite these conceptual and empirical limitations, many of these historical equations, including some from the nineteenth century, remain in routine use.

In addition to the anatomical and metric approaches, many practitioners now use stature estimates generated by FORDISC (currently, at the date of this publication, at version 3.1), a computer program that applies multivariate and univariate regression equations derived from reference collections such as the Terry and Hamann–Todd skeletal series and later-added modern forensic datasets [64,65]. For stature, FORDISC typically employs simple and multiple linear regressions that predict living height from limb bone lengths, often stratified by biological sex and broad ancestry/population affinity group [64,65]. Practitioners are able to select the relevant reference groups and skeletal measurements, and the program outputs estimated stature along with associated standard errors and confidence intervals [64,65]. However, because FORDISC’s stature equations are ultimately based on many of the same historical North American collections and ancestry categories that underpin earlier regression work, they inherit similar limitations: they assume that contemporary casework individuals are biologically and demographically

comparable to the reference samples and that broad ancestry labels adequately capture variation in body proportions [64,65]. As a result, while FORDISC provides a convenient and standardised implementation of regression-based stature estimation, its equations are not well calibrated for modern British populations, particularly in the context of secular trends, mixed heritage, and the increasing recognition that traditional racial groupings have little biological validity [66].

3.6. Limb Bones vs. Small Bones

While limb bones, particularly the femora, have traditionally been regarded as the most reliable indicators of stature, recent studies have explored alternative approaches [67,68]. Reel et al. [69] and Pablos et al. [18] proposed studies based on footprints and foot bones, respectively, which can be particularly useful in cases where skeletal remains are not present, but footprints are available. Additionally, Guirazza et al. [19] demonstrated the potential of scapular measurements for stature estimation, with longitudinal scapular length showing the strongest correlation. Table 2 provides some of the most prominent studies found that utilise different elements of the skeleton in regression equations for stature estimation. While the earlier studies all utilised limb bones, the skull and other non-limb bones were also investigated to develop estimates for stature.

Table 2. An overview of some of the prominent studies that have developed stature estimation methods using different bones.

Study	Year	Primary Focus	Population
[32] Pearson	1899	Humerus, Femur, Tibia	European
[42] Dupertuis & Hadden	1951	Femur, Tibia	USA
[20] Trotter & Gleser	1952	Humerus, Ulna, Radius, Femur, Tibia, Fibula	USA
[34] Fully	1956	Various bones related to anatomical height	European
[21] Trotter & Gleser	1958	Humerus, Ulna, Radius, Femur, Tibia, Fibula	USA
[70] Patel et al.	1964	Femur, Tibiae, Fibula, Foot length, Foot breadth	Indian
[45] Genovés	1967	Humerus, Ulna, Radius, Femur, Tibia, Fibula	Mesoamerican
[71] Steele & McKern	1969	Humerus, Femur, Tibia	USA
[43] Trotter	1970	Humerus, Ulna, Radius, Femur, Tibia, Fibula	USA
[68] Byers et al.	1989	Metatarsal	USA
[72] Abdel-Malek et al.	1990	Hand length, Hand breadth	Egyptian
[73] Simmons et al.	1990	Femur	USA
[49] Sjøvold	1990	Humerus, Ulna, Radius, Femur, Tibia, Fibula	European
[74] Feldesman	1992	Femur	USA
[75] Meadows & Jantz	1992	Metacarpal	USA
[55] Jantz	1992	Femur, Tibia	USA
[24] Jantz et al.	1995	Tibia	USA
[56] Ousley	1995	Femur	USA
[76] Holland	1995	Tibia	USA
[77] Chiba & Terazawa	1998	Skull	Japanese
[78] Muñoz et al.	2001	Humerus, cubitus, ulna, femur, tibia, fibula	Spanish
[79] Ozaslan et al.	2003	Trochanteric height, thigh length, lower leg length, leg length, and foot height, breadth, and length	Turkish

Table 2. Cont.

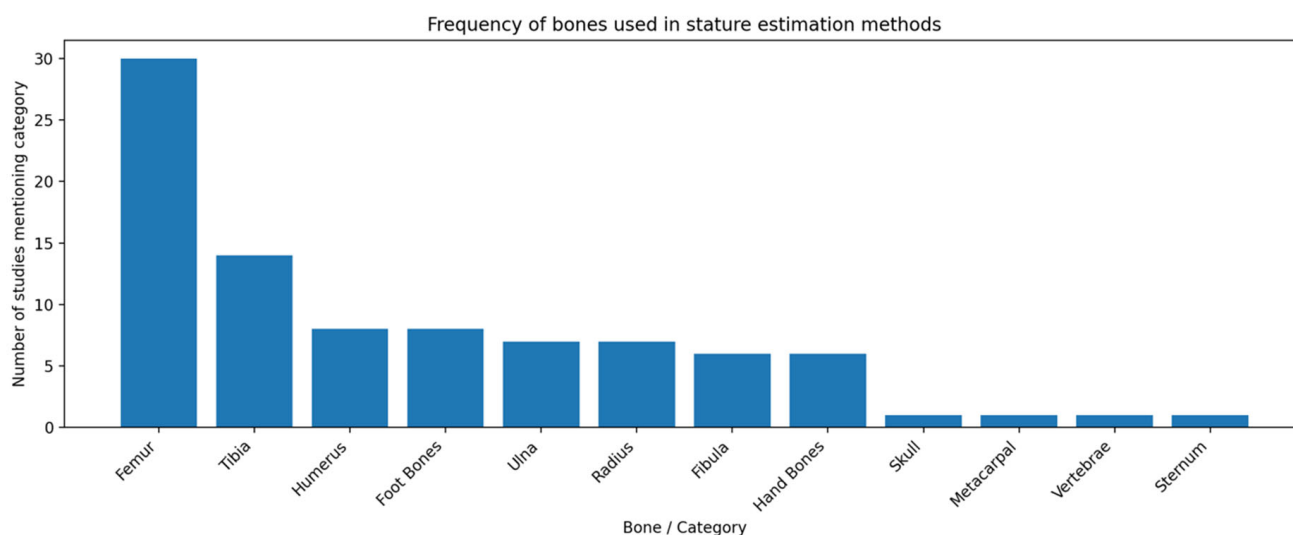
Study	Year	Primary Focus	Population
[80] Duyar & Pelin	2003	Tibia	Turkish
[81] Sanli et al.	2005	Hand length, Foot length	Turkish
[82] Hauser et al.	2005	Femur	German
[83] Pelin et al.	2005	Vertebrae	Turkish
[35] Raxter et al.	2006	Humerus, Ulna, Radius, Femur, Tibia, Fibula	USA
[84] Celbis & Agritmis	2006	Radius, Ulna	Turkish
[85] Petroveckí et al.	2007	Humerus, Ulna, Radius, Femur, Tibia, Fibula	Croatian
[86] Bidmos	2008	Femur	South African
[87] Agnihotri et al.	2008	Whole hand	Indian
[88] Zeybek et al.	2008	Whole foot	Turkish
[89] Kanchan et al.	2008	Whole foot	Indian
[90] Dayal et al.	2008	Humerus, Ulna, Radius, Femur, Tibia, Fibula	South African
[91] Maijanen	2009	Various bones related to anatomical height	Finnish
[92] Hasegawa et al.	2009	Humerus, Femur Tibia	Japanese
[93] Cordeiro et al.	2009	Metatarsals	Portuguese
[94] Ilayperuma et al.	2010	Whole foot	Sri Lankan
[36] Auerbach & Ruff	2010	Femur, Tibia	American
[95] Karakas et al.	2011	Sacrum	Turkish
[96] Mahakkanukrauh et al.	2011	Humerus, Ulna, Radius, Femur, Tibia, Fibula	Thai
[97] Ruff et al.	2012	Humerus, Ulna, Radius, Femur, Tibia, Fibula	USA
[98] Krishan et al.	2012	Whole hand, Whole foot	Indian
[99] Akhlaghi et al.	2012	Left upper limb, arm, forearm, length and breadth of the hand, and length of the second to fifth fingers	Iranian
[19] Giurazza et al.	2013	Scapula	Italian
[100] Albanese et al.	2016	Humerus, Ulna, Radius, Femur, Tibia	Lisbon and Forensic Anthropology Databank
[101] Mays	2016	Femur	British

From all the skeletal elements analysed and published in the literature, the femur remains the most extensively studied and described bone in relation to stature estimation. Its robustness, preservation, and reliable correlation with height make it the preferred choice in forensic anthropology [102]. However, there are some exceptions. Genovés [45] found that the maximum tibial length had the most correlation with stature in a Mesoamerican sample. Similarly, Patel et al. [68] found that the tibia produced the highest correlation with stature out of the bones analysed. Garmendia et al. [103] also found that for males, stature had the highest correlation as well as the lowest mean absolute error and best fitting with the tibia, whilst the opposite was true for females. The comparative accuracy of utilising femoral versus tibial lengths in regression equations indicates that both bones can serve as reliable predictors for stature estimation. The studies mentioned in this research have shown that the length of the femur and tibia can be effectively used for stature estimation using specific regression equations being developed for different populations (Table 3). However, it has been noted by Bidmos and Brits [104] that sex-specific regression equations for the tibia may significantly underestimate stature for males, while combined measurements of the femur and tibia have shown varying accuracy, particularly for females. Overall, amongst the limb bones, the femur and tibia are used most frequently because of their strong correlation with living height and their relatively high recovery and preservation rate in archaeological and forensic anthropology contexts [20,38,102].

Table 3. Preference of femur vs. tibia for stature estimation in the literature.

Study	Population	Preferred Bone
[20] Trotter & Gleser (1952)	USA	Femur
[21] Trotter & Gleser (1958)	USA	Femur
[34] Fully (1956)	French	Anatomical method
[45] Genovés (1967)	Mesoamerican	Tibia
[43] Trotter (1970)	USA	Femur
[49] Sjøvold (1990)	Not stated	Femur
[55] Jantz (1992)	USA	Femur
[56] Ousley (1995)	USA	Femur
[35] Raxter et al. (2006)	USA	Femur
[85] Petroveckí et al. (2007)	Croatian	Femur
[86] Bidmos (2008)	South African	Femur
[90] Dayal et al. (2008)	South African	Femur
[96] Mahakkanukrauh et al. (2011)	Thai	Femur
[19] Giurazza et al. (2013)	Mediterranean	Scapula
[105] Brough et al. (2013)	British	Femur
[15] Zeman et al. (2014)	Slovak	Multiple bones
[100] Albanese et al. (2016)	Multiple	Femur
[101] Mays (2016)	British	Femur (Trotter–Gleser)
[103] Garmendia et al. (2018)	Mexican	Tibia (males), Femur (females)
[102] Noussios et al. (2019)	Greek/Review	Femur

Figure 2 highlights the primary focus of each study mentioned in Table 2; while this is not an exhaustive list, it provides a good representation of stature-related studies conducted. Although the scientific literature does not provide a single, universal ‘better-performing’ bone between femur and tibia, it demonstrates that the relative performance of both depends on the population, sex, measurement protocol and statistical approach [103,104].

**Figure 2.** Histogram on the frequency of using certain bones in stature estimation methods based on studies from Table 2.

As reflected in Figure 2, in most studies, the lower limb bones tend to outperform upper limb bones in predictive power, with the femur usually giving smaller standard errors than the tibia when considered individually; however, combining femur and tibia lengths improved accuracy further [20,21]. This pattern of high predictive value of both bones, with small, population-specific differences between them, is echoed in many studies, such as those mentioned in Table 3.

The preference of femur over tibia is due to many factors. The femur is most often considered as the best individual bone for stature estimation across many populations.

Thus, it is the preferred bone across many continents. This is largely because it is the longest bone in the body, and thus it represents a substantial portion of the lower limb length and has a strong linear relationship with stature [38,106]. Numerous population-specific studies have reported high correlation coefficients (often $r > 0.85$) and relatively low standard errors of estimate (SEE) when using maximum femoral length alone. For instance, in a contemporary Chinese sample, Zhang [107] found that the maximum femur length showed a very strong correlation with stature (with a prediction accuracy of 3.84 cm for unknown sex) and produced a lower SEE than most of the other limb bones studied in their research. Also, in a South African context, Steyn and Smith [108] showed that the maximum femoral length provided the most robust stature estimates, though they also emphasised the inter-population differences in proportionality of bones and stature. Similarly, studies by Ruff [106] and Auerbach and Ruff [36] examined the broader patterns of body and size and limb proportionality and confirmed that the maximum femoral length was highly informative about overall body size and stature. In addition, an advantage of using the femur over the tibia may be due to the relative robust morphology of the femur, which correlates to its better preservation as compared with other less dense bones; this allows for the femur's frequent use in forensic and archaeological cases [37,38].

In contrast, the tibia is also well correlated with stature, as it also represents a major component of lower limb length. Some studies on Latin American and Mediterranean populations have found that the tibia outperformed the femur in stature calculations [103]. Some recent validation research comparing population-specific and non-population-specific equations for tibia-based stature estimation indicates that tibial regressions can perform well when derived and applied within the same or a closely matched reference population [109–111].

However, some studies have shown that tibia-based equations may be more prone to systematic bias if applied outside of the population for which they were developed [103,107–109]. For instance, in some studies, sex-specific tibial regression equations underestimated male statures, particularly when non-local equations were used [104,109–111]. Furthermore, the tibia can also be more affected by variation in body proportions related to climate-adapted limb segment ratios (Allen's ecogeographical rule), with relatively longer distal segments in warm-adapted populations [106]. This means that tibia-to-stature proportionality may differ between populations more sharply than for the femur in some cases, increasing the risk of error when inappropriate reference data are used [106].

Overall, the femur has a long history of validated equations across multiple populations and is regarded as a widely applicable predictor of stature. It also has a slightly lower SEE in many published regression sets. However, the tibia is still an invaluable predictor for stature, especially in situations where the femora is absent, incomplete, fragmented or when the established population-specific regression equations for tibia outperform the femoral equations for a particular population [104].

3.7. Technological Advancements

Recent advances in non-invasive studies like CT and DXA imaging, along with 3D reconstruction, have revolutionised bioarchaeology [112]. These techniques allow for in-depth examinations of human remains and in cases with fleshed remains or charred remains without causing damage [112,113]. They have facilitated research on larger databases, particularly in visualising and measuring human remains. For instance, Raxter et al. [35] utilised CT scans to examine Late Neolithic human remains, estimating stature based on femoral head breadth and comparing results with prehistoric European skeletons.

Robinson et al. [114], on the other hand, explored the use of multi-detector CT scans to measure lower limb and foot bones during decomposition stages, though limitations such as distortion in plastic bags were noted. Similarly, Kim et al. [115] assessed the reliability of 3D rendering of CT images for measuring pig bones, highlighting the importance of reducing inter-observer error. Stull et al. [116] examined skeletal measurements from 3D reconstructions of CT images with soft tissue, identifying partial volume effects but overall minor differences. Arifi [117] conducted a large-scale study on Kosovan adults to validate metric analysis on CT reconstructions, while Milani et al. [118] developed stature estimation formulae based on DXA imaging of Italian Caucasians, albeit with a low accuracy.

Further studies, like those by Pomeroy et al. [112] and Colman et al. [119], focused on refining stature estimation techniques using DXA and CT imaging, respectively, on different populations (see also [63]). Additionally, Ebert et al. [120] explored statistical shape modelling to reconstruct femora, demonstrating promise for fragmented remains. However, using measurements from such models for stature estimation reduces the precision of the estimate and thus cannot be relied on for accuracy.

Kira et al. [121] used automated 3D reconstruction for stature estimation in Japanese adults, emphasising the effectiveness of specific measurements. Carvalho et al. [122] utilised the Trotter and Gleser [20] stature estimation formulae to aid in the identification of victims who died in the 1755 earthquake in Lisbon; this included the assessment of 1039 comingled bones, including 324 whole bones and 715 fragments. Due to the degree of comingling and the absence of antemortem data, biological sex and age could not be utilised in the stature calculation, which lowered the accuracy of the estimates.

Concurrently, Palamenghi et al. [123] applied Trotter and Gleser's [21] formulae to transgender individuals in Italy, highlighting the importance of considering non-gendered approaches to the biological profiling of the deceased. However, the individuals studied in this research were not positively identified, and thus the results of the study cannot be assessed for accuracy [123].

Polcerová and Králík [124] utilised the "Stature" software combining multiple studies, whilst more recently, the application of AI has been explored. Simon et al. [125] utilised AI for limb bone measurements in Austrians, noting discrepancies in traditional formulae due to secular changes in stature. Despite these advancements, Loubser's et al. [126] evaluation of its accuracy on South African populations underscores the necessity for continuous assessment and adaptation of studies. Moreover, Hamza et al. [127] demonstrated the potential of mandibular morphology in estimating sex and stature, offering alternative approaches where limb bones are unavailable.

These studies collectively highlight the importance of technological advancements and methodological diversity in forensic anthropology. Streamlining the process of stature estimation is another key goal of forensic anthropologists, in an effort to do this, Polcerová and Králík [124] created a software called "Stature" to aid in stature estimation of adult human remains by combining 13 of the most popular studies in 22 variations, using 53 dimensions from various bones [20,32,34,35,41,49,128–132]. The program claimed to be useful for forensic cases as well as archaeological ones; however, most of the studies included in the software rely on historic samples and are not appropriate for the stature estimation of contemporary populations; the only exceptions to this are Fully's [34] and Raxter et al.'s [35] anatomical studies. Nevertheless, this program allowed for estimation of stature by automating the calculations as well as giving the researcher the ability to utilise multiple studies simultaneously, which in turn allows for a more accurate estimation of stature as multiple studies and variables can be combined [124].

These studies provide valuable insights into the accuracy, reliability, and precision of radiographic imaging and 3D reconstructions for stature estimation. However, further

research with larger sample groups and diverse age ranges is needed to enhance the reliability of these studies and ensure their applicability in different contexts.

3.8. Non-Adult Studies

Juvenile (<18 years of age) stature estimation presents challenges due to ongoing growth and variability in growth rates [133]. Orr et al. [12] conducted a study on 7,062,071 children aged 4 to 5 years in England, mapping the prevalence of short stature across different regions from 2006 to 2019. The study revealed a social gradient and regional variation in short stature, indicating the influence of socioeconomic status on children's height [12].

Because there were few skeletal collections of identified juveniles, early non-adult or subadult stature estimations leaned heavily on clinical radiographic studies of long-bone growth. Maresh's [134] longitudinal study on limb bone lengths in children provided some of the earliest detailed datasets describing the developments in diaphyseal lengths from infancy through to adolescence. While these were not specifically developed for forensic identification, these data underpinned many of the subsequent works utilised in forensic identification [135].

Individual studies regarding stature estimation methods for non-adults can be dated back to Telkkä et al. [136], where Finish foetal and infant limb bones were analysed from radiographic images. One of the first existing methods for juvenile stature estimation was developed by Feldesman [74], who examined the relationship between femur length and stature in individuals between 8 and 18 years of age. This was a global study based on previous data of 13,000 individuals taken from four growth studies [74,137–139] that analysed this data statistically to create ratios for male and female juveniles. The author found a consistent correlation between femur length and stature, whilst there was little difference between the male and female ratios [74].

Juvenile identification progressed significantly following the publication of 'Developmental Juvenile Osteology' [140], which provided a comprehensive guide to juvenile osteological examination.

Similarly, Smith [141] developed regression equations from long bone measurements for the stature estimation of juveniles between the ages of 3 and 10 years. Meanwhile, Brough et al. [105] used multi-detector computed tomography (CT) scans to measure juvenile clavicle accuracy. The use of this emerging technology has become more prevalent in modern research and investigation; thus, an effort is being made to create standardised methods using the technology [105]. The emergence of this technology will be discussed further in the current research.

Meanwhile, Orr et al. [12] mapped geographic locations across England by the prevalence of short stature between 2006 and 2019. This medical study of 7,062,071 juveniles aged between 4 to 5 years found a social gradient in short stature with a region-specific variation [12]. Furthermore, the research findings suggest that the population's socioeconomic status affects the growth in children's height [12].

Despite the rapid growth of research into juvenile osteology, juvenile stature estimation remains one of the most difficult areas within biological profiling due to the rapid and variable growth rate of non-adults. Furthermore, as compared to age, sex, and population affinity, stature estimation is not a leading feature aiding in the identification of children [141]. However, as identified by Smith [141], it can be useful in differentiating remains in cases of comingling, as was the case in the Oklahoma case of 1967, where two children were found of a similar age and required separation and identification [142]. Furthermore, height is reportedly the most reliable measure of growth rate and can be used to infer information regarding the child's health and nutritional status [143].

4. Discussion

4.1. Current International Practices

In the last 15 years, multiple countries have developed population-specific stature studies, often with substantial sample sizes. Meanwhile, the UK has only two small studies published [101,105], and current stature estimation practices rely largely on historical samples, which are not adequate as references for analysis of today's diverse UK population groups. This imbalance across countries clearly supports the need for new, modern stature estimation methods for UK populations, ideally based on contemporary skeletal/PMCT data and reflecting current demography and secular height changes. A summary of the key stature studies published in the last 15 years is tabulated below (Table 4). This list is not exhaustive but is reflective of the open-source and available journal papers available.

Table 4. A summary of the key stature estimation studies published since 2010.

Study	Anthropometric Variables	Population	Sample Size	Age Group (in Years)
[105] Brough et al. (2013)	Clavicles	Scotland	20	Juvenile
[19] Giurazza et al. (2013)	Scapulae	Italy	200 (100 M, 100 F)	42–86
[18] Pablos et al. (2013)	Tarsals and metatarsals	USA	94 (48 M, 46 F)	17–50
[144] Chourasia et al. (2014)	Crania	India	506 (255 M, 251 F)	18–25
[145] Jørgkov (2015)	Femora	Denmark	357 (181 M, 176 F)	Adult
[101] Mays (2016)	Humeri, ulnae, femora, tibiae, fibulae	UK (10–19th century AD)	25 (14 M, 11 F); sex estimated using skull and pelvis	Adults
[146] Esomonu et al. (2016)	Tibia	Nigeria	600 (300 M, 300 F)	21–45
[147] Zech et al. (2016)	Femora	Switzerland	226 (143 M, 83 F)	20–95
[148] Shresta et al. (2016)	Nasal bones	Nepal	214 (110 M, 104 F)	25–35
[23] Jeong & Jantz (2016)	Multivariate—various bones related to anatomical height	Korea (14th–20th century)	113 (63 M, 50 F)	17–60
[149] Moorthy & Asogan (2016)	Whole foot	Malaysia	110 (50 M, 60 F)	18–56
[150] Athani et al. (2016)	Femora	India	100 M	Adult
[151] Moustafa (2017)	Hands and feet	Egypt, Saudi Arabia	97 (55 M, 42 F)	21–45
[118] Milani et al. (2017)	Vertebral bodies	Italy	209 F	Average: 65.5
[152] Nikita & Chovalopoulou (2017)	Humeri, ulnae, femoram tibiae, fibulae	Modern Greece	75 (44 M, 31 F)	16–94
[153] Koulapur et al. (2017)	Third hand phalanx	India	150 (75 M, 75 F)	21+
[154] Caplova et al. (2018)	Whole feet	Slovakia	132 (68 M, 64 F)	18–33
[155] Chourasia & Kumar (2018)	Whole hand	India	506 (255 M, 251 F)	18–25
[156] Ibrahim et al. (2018)	Whole hand	Saudi Arabia	350 (150 M, 150 F, 50 control sample)	20–30
[112] Pomeroy et al. (2018)	Humeri, ulnae, femora, tibiae, fibulae	India	160 (80 M, 80 F)	Early 20s
[103] Garmendia et al. (2018)	Humeri, tibiae and femora	Mexico	86 (56 M, 30 F)	19–91
[157] Bjelica et al. (2019)	Upper limb bones	Kosovo	1623 (830 M, 793 F)	18–20
[119] Colman et al. (2019)	Os coxae	Netherlands	27 (13 M, 14 F)	50+
[158] Natarajan et al. (2019)	Ulnae	India	153 (76 M, 77 F)	20–22
[159] Singh et al. (2019)	Limbs, knees, hands, and feet	Nepal	226 M	18–48
[160] Rosenstock et al. (2019)	Limb bones	Near East and Europe (ca. 10,000–1000 BC)	6098	Adult
[161] Soon et al. (2020)	Sacra	Malaysia	373	10–79
[162] Zhang et al. (2020)	Femora	Denmark	78 (41 M, 37 F)	23–45
[163] Gupta & Sehrawat (2020)	First and third phalanges	India	270 (144 M, 126 F)	20–45
[164] Verma et al. (2020)	Limbs, hands, and feet	India	344 (172 M, 172 F)	18–25
[165] Açıkgöz et al. (2021)	Limb bones	Turkey	167 (97 M, 70 F)	18–65
[166] Shakya et al. (2021)	Humeri	Nepal	150 (75 M, 75 F)	18–55

Table 4. Cont.

Study	Anthropometric Variables	Population	Sample Sample Size	Age Group (in Years)
[167] Tuncel Çini & Ari (2021)	Humeri	Turkey (13th century late Byzantine)	96 M	N/A
[120] Ebert et al. (2022)	Left femora	Europe	42 (28 M, 14 F)	20+
[168] Monteiro et al. (2021)	Tibiae	Belgium	91 (43 M, 48 F)	Adult
[169] Jeamamornrat et al. (2022)	Sterna	Thailand	199 (104 M, 95 F)	26–94
[121] Kira et al. (2022)	Femora	Japan	300 (150 M, 150 F)	Adult
[122] Carvalho et al. (2023)	Whole and fragmented humeri, radii, ulnae, tibiae, and fibulae	Portugal	1039 bones (324 whole, 715 fragments)	Not recorded
[123] Palamenghi et al. (2023)	Limb bones	Italy	3 (transgender women)	Not recorded
[125] Simon et al. (2023)	Limb bones	Austria	4200 (1674 M, 2526 F)	18–95
[170] Wolska et al. (2023)	Pre- and post-burned humeral, radial, and femoral heads.	Portugal	46 (18 M, 28 F)	62–89
[126] Loubser et al. (2024)	Multivariate—various bones related to anatomical height	South Africa	60 (40 M, 20 F)	Adult
[127] Hamza et al. (2024)	Mandibles	India	150 (105 M, 45 F)	18–65

A more careful inspection of Table 4 highlights that the majority of these studies are specific to their country and, more often, to a region. Furthermore, most studies have also outlined specific age groups and sex of the samples used in their study. This is seen in both archaeological and forensic anthropology research. The parameters of biological sex, age at death, and population affinity are known to influence stature, and the importance of taking these into account has been highlighted elsewhere (e.g., [15,171]).

4.2. Population Specificity

Where the anatomical method [34–36] cannot be applied because of missing bones or fragmentation, mathematical regression equations based on the dimensions of individual limb bones or other skeletal elements are the most commonly used alternative worldwide [20,21,38]. These methods model the linear relationship between living stature and the maximum lengths (or other measurements) of bones such as the femur, tibia, humerus, radius, fibula and occasionally smaller elements, allowing stature to be estimated from one or more preserved bones by applying an equation of the general form (see below) with an associated standard error [20,21,38]:

$$\text{stature} = a + b \times (\text{bone length})$$

Body proportions and the relationship between bone length and stature vary between populations as a function of genetic ancestry, sex, secular change, nutrition and broader environmental and socioeconomic factors [60,172]. Consequently, regression equations derived from one reference group may yield biased estimates when applied to another group with different average limb–trunk proportions or differing secular trends in height [60,172]. For instance, de Beer [173] studied the trends in the height of the Dutch population from the late Middle Ages to the present and found that the Dutch population was taller in the late Middle Ages and early modern than in the first half of the nineteenth century [173]. Stature then increased exponentially in the second half of the nineteenth and twentieth centuries, which resulted in the Dutch population being the tallest recorded in the world at the end of the 20th century [173]. This illustrates the need for population specificity for stature estimation.

There are a number of guidelines emphasising that regression equations for stature estimation should, wherever possible, be developed from samples that are demographically and temporally appropriate to the target population [37–39,52,106]. This has driven a substantial international literature developing population-specific formulae based on modern skeletal collections or radiographic/clinical datasets in diverse regions (Table 5).

While the anatomical method remains the standard in many countries, since the pioneering development of Trotter and Gleser's [20,21] regression formulae for USA populations, regression-based methods have become the routine choice in many countries for stature reconstruction in forensic anthropology when only partial remains are available, as they can be applied to isolated bones and are relatively quick and straightforward in practice [37,38]. For example, Simmons et al. [73] reassessed the Steele method [69] for stature estimation using fragmented remains and presented new identification markers for segments of the femur for accurate reconstruction and stature estimation. The study utilised 800 individuals from the Terry Collection and created new regression equations for maximum femoral length. Similarly, Barreiro et al. [174] tested the performance of methods developed by Cordeiro et al. [93] and Mendonça [52] on fragmented and burnt long bones. The results from this study found that the stature estimation methods of [93] and [52] can be applied to fragmented bones burnt at a temperature below 700 °C, although the methods were designed for whole bones. This suggested that low-intensity burning did not have a major impact on metric methods.

In continental Europe, several countries have created equations to estimate human height that match the body proportions of their populations, including Germany, France, Netherlands, Spain, Portugal, Czech Republic, Greece, and Romania. These equations usually use measurements of limb bones and sometimes include other bones such as those in the feet, the clavicle, or the vertebrae (e.g., [19,85,148,152,154,162,168,170,175]).

Outside Europe, Australia has developed equations for stature estimation from various limb bones, derived from contemporary Australian skeletal or radiographic series, in recognition of differences between Australian populations and those on which earlier North American formulae were based [176]. Meanwhile, in East and South-East Asia, country-specific studies have been published for Japan, South Korea, Malaysia and Thailand, producing regression models based on local samples and addressing the well-documented differences in limb-to-trunk proportions between East and South-East Asian and Western populations [149,161,169,177].

Similarly, in South Asia, India, Nepal and Bangladesh have been particularly active in developing regression equations, including work on limb bones, hand and foot dimensions and other skeletal or soft-tissue measurements, often stratified by region, sex and ancestry, to reflect internal diversity within national populations [98,146,147,150,155,158,159,163–165,178]. In Western Asia and North Africa, Iran, Egypt and Turkey have produced their own regression-based formulae from limb bones and other skeletal elements, again motivated by the need to avoid systematic bias introduced by relying on equations derived from non-local populations [81,151,165,179].

Post-conflict regions have also contributed to this methodological landscape. For instance, in Bosnia and Herzegovina, large-scale identification efforts associated with the investigation of mass graves have stimulated the derivation and application of population-specific stature equations, often using incomplete remains, to support victim identification programs [180].

Overall, the cumulative result of this work is that many countries, including Germany, France, the Netherlands, Portugal, the Czech Republic, Greece, Romania, Australia, India, Iran, Bosnia and Herzegovina, Bangladesh, Egypt, Guatemala, Japan, Malaysia, Mexico, South Africa, Thailand and Turkey, now have at least some published, population-specific regression formulae for estimating stature from a range of skeletal elements, although

coverage within each country varies by sex, ancestry group, time period and type of bone utilised [37,38].

4.3. Looking into the Future: Stature Estimation Methods for Contemporary British Populations

In contrast to the broad international trend of population-specific method development for biological profiling, the United Kingdom has comparatively few recent, population-specific regression studies for stature estimation based on large modern British skeletal or radiographic reference samples [38,101,181]. British forensic practice has historically drawn heavily on American-derived equations (such as those of Trotter and Gleser [20,21]) and on more general European formulae, rather than on equations developed specifically from contemporary British populations [38,101,181].

Several authors have noted that the limited availability of extensive, demographically representative modern skeletal collections from the UK, combined with ethical and logistical constraints on the use of hospital radiographic datasets, has contributed to a relative lag in the development of British population-specific regression equations compared with the situation in many other countries listed above [38,101,181]. As a result, there remains a recognised need for updated, methodologically robust stature estimation protocols grounded in contemporary British reference data, to reduce potential biases associated with applying non-British equations to modern U.K. casework [38,181].

In the historical context of England, the advancement of stature estimation techniques can be attributed to the pioneering work of George Humphry [27]. Humphry [27] introduced a ratio-based approach that relied on the relationship between average stature and average bone length. This methodology was formulated based on measurements obtained from a sample of 25 adult skeletons [27]. Following this, Pearson [32], using Rollet's [29] data, rejected the prevailing ratio studies and proposed the adoption of linear regression equations. This marked the inception of regression equations for stature estimation based on limb bone lengths [32]. Pearson [32] also cautioned researchers against applying his equations to individuals not represented within the reference population to ensure accuracy.

Since the research conducted by [27] and [32], there has not been much further research into the development of stature estimation studies for a UK population, with the two exceptions of Brough et al. [105] and Mays [101]. Brough et al. [105] researched the accuracy of using multi-detector computer tomography (MDCT) scans, as compared to traditional osteometry, of 33 juvenile clavicles from the Scheuer collection in Dundee, Scotland. The results of this study found the use of MDCT scans to be accurate for anthropometric analysis of skeletal remains, as it found there to be no significant difference between the use of scans and direct osteometric measurements. Mays' [101] research aimed to assess the reliability of Trotter and Gleser's [20,21] regression equations, particularly concerning their "White" population group for a British population dating from the 10th to the 19th centuries [101]. The accuracy of Trotter and Gleser's stature estimation equations was evaluated through comparison of calculated stature with anatomically reconstructed stature [101]. However, it is important to note that this study relied on postmortem estimation of sex and living height since antemortem data was unavailable, creating the possibility of inaccuracies pertaining to the precision, repeatability, and subjectivity of measurements [101]. This gap in research necessitates the need for further research of UK populations to ensure that stature can be assessed accurately for these populations in archaeological and forensic investigations.

Despite extensive research, no single method has been sufficiently validated for use in contemporary British populations. The primary issues include the fact that most of the stature estimation equations derive from 19th- and 20th-century European and American samples, which fail to account for modern secular trends in height and increasing genetic

diversity in Britain. Similarly, studies such as those by Cole [11] and Will et al. [182] suggest ongoing shifts in average human height due to improvements in nutrition, healthcare, and socioeconomic conditions. Existing equations do not incorporate these changes.

Furthermore, regression equations, particularly those developed by Trotter and Gleser [20,21], rely on overgeneralised racial categories rather than precise genetic ancestry, leading to inaccurate estimations for Britain's multi-ethnic population. Environmental and socioeconomic variability has been proven by many scientists. For instance, it has been demonstrated [12] that short stature prevalence varies significantly across different regions in England, reflecting disparities in socioeconomic status. Current methods fail to adjust for these environmental and regional variations.

As mentioned earlier in this paper, McIntosh et al. [22] has conducted a survey of archaeologists and anthropologists in the UK and Ireland to find out which methods are used for stature estimation most prominently. Their findings illustrated that 12 out of 16 responders relied on Trotter and Gleser [20,21,43] despite the shortcomings highlighted by many stature researchers [11,12,182]. Some of the shortfalls identified by researchers are summarised in Table 5.

Table 5. Key research which highlights the issues of using Trotter and Gleser's [20,21,43] methods for stature estimation.

Author(s)	Population Studied	Key Finding	Error Range (cm)
[24] Jantz et al. (1995)	21st century USA	Secular change makes T&G equations obsolete	3–5
[56] Ousley (1995)	21st century USA	Significant errors in modern populations	4–6
[36] Auerbach & Ruff (2010)	Global populations	Population-specific equations needed	2–8
[91] Maijanen (2009)	Finnish	Poor accuracy for Northern Europeans	3–4
[86] Bidmos (2008)	South African	Inappropriate for African populations	5–7
[90] Dayal et al. (2008)	South African Whites	Systematic bias in South Africans	4–6
[96] Mahakkanukrauh et al. (2011)	Thai	Asian populations require different equations	3–5
[175] Radoinova et al. (2002)	Bulgarian	Eastern European populations differ significantly	2–4
[84] Celbis & Agritmis (2006)	Turkish	Mediterranean populations show poor fit	3–5
[85] Petroveckii et al. (2007)	Croatian	Balkan populations need specific equations	2–4
[19] Giurazza et al. (2013)	Italian	Southern European bias demonstrated	3–4
[183] Spradley & Jantz (2011)	21st century USA	Temporal changes invalidate historical equations	4–7

In summary, unlike countries such as the Netherlands [173] and Switzerland [147], Britain lacks updated population-specific regression equations, making stature estimations based on foreign datasets potentially unreliable. The current stature estimation techniques remain insufficient for contemporary British populations due to reliance on outdated reference populations, failure to account for secular trends and regional variability, and inappropriate 'racial' categorisation. Future research should focus on developing new regression equations using large-scale, diverse British datasets, incorporating genetic, environmental, and socioeconomic factors to enhance accuracy and applicability in forensic, archaeological, and anthropological contexts. The creation of standards for the UK could lead to conversations around possible ethical access to Biobank data, clinical data of living

patients, post-mortem CT scans, or through donor programs at medical schools if that is at all possible. It must be remembered that this type of research, as with other parameters of the biological profile, is to help identify the deceased and provide closure to families.

The current practice reflects a clear hierarchy of methods. The anatomical stature estimation using the Fully–Raxter approach remains the international reference standard in terms of accuracy when sufficiently complete skeletons can be examined [34–36,38,184]. However, the practical realities of fragmentary or incomplete remains mean that, in most countries, daily forensic and archaeological work depends primarily on population-specific regression equations derived from limb bones and other skeletal elements [20,21,37].

Many nations across Europe, Asia, Africa, Australasia and the Americas—including Germany, France, Australia, the Netherlands, Spain, India, Iran, Bosnia and Herzegovina, Bangladesh, Egypt, the Czech Republic, Greece, Guatemala, Japan, Malaysia, Mexico, Portugal, Romania, South Africa, Thailand and Turkey—have responded to this need by developing their own equations tailored to local populations and casework demands [37–39]. The United Kingdom, by contrast, has seen comparatively limited recent development of such methods and still relies heavily on regression formulae derived from non-British samples, highlighting an important gap in current stature estimation protocols and underscoring the desirability of targeted method development based on contemporary UK data [181].

5. Conclusions

In conclusion, while archaeological applications may find the existing stature estimation studies acceptable, forensic investigations within the UK population demand a higher level of precision. The potential consequences of misidentifications and the inherent inaccuracies in reported height underscore the need for a nuanced and accurate approach to stature estimation from skeletal remains, reinforcing the critical role that forensic anthropology plays in aiding law enforcement and providing closure to families affected by tragic circumstances. This study lays a solid foundation for future practice in forensic anthropology and bioarchaeology, employing more refined and innovative tools in stature estimation. Integration of emerging technologies, collaborative interdisciplinary efforts, and the development of standardised protocols are essential for advancing the field, while extensive application and collaboration with practitioners across the various other forensic contexts will refine this present tool even further. Moreover, this investigation sheds light on the diverse landscape of stature estimation studies in forensic anthropology. By offering a systematic assessment of existing techniques, it provides valuable insights for forensic practitioners and researchers alike.

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Stature estimation in forensic anthropology: addressing the current status, challenges and future prospects

Siddiqui, Tooba; Zioupos, Peter; Márquez-Grant, Nicholas

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