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# Population variation in skeletal sexual dimorphism

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ABSTRACT

Research has documented considerable population variation in sexual dimorphism related to human growth and development. This variation represents both genetic and environmental factors which impact methodologies used to estimate sex from human skeletal remains. This article provides an overview of known variation in skeletal sexual dimorphism among populations through documented research on samples from around the world. Variation in juvenile growth patterns of populations and differences in adult skeletal size and characteristics are discussed. This recognized variation should be considered by forensic anthropologists when estimating sex from skeletal remains and appropriate population-specific data should be utilized.

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## 1. Introduction

Reliable estimation of the sex in the analysis of human skeletal remains represents an important and frequently encountered goal of forensic anthropology. Sex estimation is a key component of the individual biological profile that skeletal analysis seeks to construct [1,2]. Historically, it represents one of the deep-rooted features of skeletal analysis in forensic anthropology [3]. Techniques of sex estimation generally fall into one of two categories: those methods concentrating on size and robusticity of features and those involving evaluation of features of the pelvis related to the female child-bearing functions. Both approaches involve a wide range of methods that continue to evolve with new research that incorporates critical perspectives within the forensic sciences [4,5].

Size-related methods are both metric and those involving observations of morphological features [6]. Metric approaches range from single measurements using well-defined landmarks to complex equations employing multiple measurements [7]. Frequently employed examples of the former include vertical height of the head of the femur or humerus or maximum length of the femur [3]. Single measurement approaches have the greatest historical depth [8] and continue to be used extensively today.

More complex equations that employ multiple measurements and reflect sophisticated statistical analyses offer estimates coupled with expressions of the probabilities and errors involved [9]. Examples of such approaches include the custom discriminate function equations featured in the Fordisc system [7] and three dimensional morphometric systems [10].

Size-related methods not involving measurement consist of visual assessment and classification of skeletal features known to be sexually dimorphic. Such cranial features include morphology of the supraorbital ridges, mastoid processes, nuchal areas of the occipital, and supraorbital margins. Published classification systems are available [11] with large size and robusticity suggesting male and small size and gracility indicating female.

With all size-related methods, the extremes offer enhanced probabilities of accurate sex estimation. Intermediate values are more likely to be shared by both sexes and thus have decreased value for sex estimation. The overlapping, sex- related bell-shaped curves of size attributes have long been recognized [12,3] and limit applications to many recovered skeletons.

For decades, researchers have noted that evaluation of pelvic features related to the childbirth function of females offers a superior approach to sex estimation [3]. As with size-related methods, the pelvic indicators also are applicable to adults following termination of growth in both sexes. Key pelvic features include the subpubic angle, width of the greater sciatic notch, ventral arc, subpubic concavity, breadth of the medial surface of the ischiopubic ramus, and preauricular sulcus [11]. Other important features include morphology of the sacrum and pubic pitting [3].

Published research also acknowledges the difficulty of accurately estimating sex of immature remains. Certainly sexual differences exist in the immature skeleton [13], but they are not sufficiently pronounced to enable accurate estimation in the analysis of recovered remains. Features that have been researched

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in this regard include the greater sciatic notch [14]. Hunt and Gleiser [15] offered a method that compared the stage of skeletal development with less variable dental formation. They found that this approach was more accurate with increasing immature age. However, even in older children a significant error remained, limiting the usefulness of this approach in forensic applications. More recently, Gonzalez [16] reported an accuracy ranging from 78 to 89% in his study of 83 juveniles of European descent who participated in the Michigan Craniofacial Growth Study. Gonzalez utilized a longitudinal sample of lateral cephalometric radiographs representing 47 males and 36 females.

Research and global applications of methods to evaluate sexual dimorphism have gradually revealed that population variation represents an important factor, especially in regard to size-related approaches [17]. Of course, population variation has long been recognized in stature estimation methodology since global variation in body size, living stature and limb proportions are very well documented. Researchers have produced sample specific stature estimation equations [18] that recognize this obvious variation. Although such population variation also has been found in morphological expressions of sexual dimorphism, it is less reflected in established methodology. However, investigations of global variation in body size and proportions are relevant since they provide context for the examination of such variation in sexual dimorphism. This manuscript focuses specifically on the various factors contributing to sexual dimorphism in the skeleton and how this information can be utilized to estimate sex from skeletal remains.

## 2. Growth and development

Studies have recognized the obvious sex differences in height, weight, and related variables during development, including age-related velocity of growth [19]. Ruff [20] suggested that modern levels of sexual dimorphism in body size can be traced back over 150,000 years. Nettle [21] added that the evolution of body size sexual dimorphism is related to reproductive success. Environmental factors in addition to genetics also have been emphasized by Perez and Monteiro [22] in their studies of craniofacial variation in southern South America.

## 3. Population variation in growth

Population variation in the expression of sexual dimorphism in the skeleton results from influences in growth and development. The vast literature on population variation in growth and development provides context to understand skeletal variation. In 1990 Eveleth and Tanner [23] summarized the worldwide data available at that time documenting the extent and nature of sex differences in the variables examined and their regional variations. This synthesis provided a detailed, sample-specific view of variation in patterns of growth for both sexes. Sex differences were apparent and varied in their expression within different samples. Universally, boys were slightly taller than girls of the same age until initiation of the female adolescent growth spurt. Then, girls were taller until termination of their adolescent growth. Boys then became taller, since their growth spurt follows that of girls, a difference of about two years. They note “sex dimorphism, however, differs from one population to another, both before and, more strikingly, after puberty” [23,p. 28]. Comparison with older databases revealed regional secular trends and other complexities of the interpretation of sex differences in growth and development on a global scale.

Working in Japan, Ashizawa et al. [24] used radiographs to measure the RUS (radius–ulna–short bones) growth of the left wrist of 704 girls and 753 boys ages 3–18 years. The authors found differences in skeletal maturation compared to reference data from the UK, Belgium, southern China and north India, with children from Tokyo reaching RUS maturity 1–2 years earlier than their European and Chinese counterparts. In 2005, Ashizawa et al. published a similar study in Beijing, using RUS data for 631 boys and 642 girls, and aimed to provide an urban Chinese sample for comparison [25].

Concentrating on craniometric variation, Relethford [26] argued that the extent of craniometric variation in modern humans is comparable in scope to the amount of genetic variation. In 2002, Strand et al. [27] noted that in the ontogeny of the modern human facial skeleton, facial form features can occur very early in life. The authors suggested that ontogenetic trajectories vary considerably. Early morphology does not predict adult morphology since environmental factors have considerable influence.

Longitudinal data collected in Sweden [28], Norway [29], Switzerland [30], North America [19], Korea [31], China [32], and Japan [33] demonstrate regional variation in growth velocity and terminal adult height for males and females (Tables 1 and 2). Also in Sweden, Gustafsson et al. [34] suggested that stature increase was not linked to dimorphism.

Bulygina et al. [35] added important detail on the ontogeny of facial dimorphism and patterns of individual development. Their research turned to the Denver Growth Study; a U.S. based longitudinal study of 14 males and 14 females from one month of age to adulthood. They found that sexual dimorphism was present at one month but that its expression changed with age. They called attention to four key influencing factors: 1. prenatal differences in size and shape; 2. differences in the pattern of association of size and shape; 3. male hypermophosis (extended growth period) and 4. differences in growth trajectories. They noted that adult patterns are established very early.

In 2003, Silventoinen noted that body height reflects both genetics and the environment [36]. Within the last decade numerous additional studies have emphasized the influence of environmental factors in addition to genetics in producing regional variation.

Working in Finland, Saari et al. [37] documented growth in length/height for age, weight for length/height, and body mass in individuals from birth to 20 years. They found a secular trend involving increased height for age.

Brzobohatá et al. [38] studied sexual dimorphism in the tibia using samples from 20th and 21st century samples from the Czech Republic. Their work documented a secular trend in sexual dimorphism of the tibia. They studied 61 adult tibiae of known age and sex from the 20th century sample. They included 57 individuals from the 21st century represented by CT scans.

Collectively, the above published research documents the manifestations of sexual dimorphism in the growth process and its impact on measurements of various aspects of the human body. The literature recognizes the genetic component involved in human growth and morphology but also the extensive impact of environmental factors, especially morbidity and nutrition. Secular trends have been documented in many growth processes. All of these factors lead to considerable global variation in the manifestation of sexual dimorphism in human growth and development (Tables 1 and 2).

## 4. Population variation in skeletal indicators

The literature cited above provides perspective on factors that produce and influence population variation in human sexual dimorphism. How do these factors and processes affect the human skeleton and how should population variation be considered when estimating sex from the skeleton? The classic text “Essentials of Forensic Anthropology” by T. D. Stewart [3] provides a useful

**Table 1**
Male longitudinal growth reference values for height (cm).

| Age (years) | Sweden | Norway | Switzerland | North America | Korea | China | Japan |
|---|---|---|---|---|---|---|---|
| 0 | – | 50.7 | 50.7 | – | – | 50.81 | 49.9 |
| 1 | 76.17 | 76.7 | 76.2 | – | – | 75.67 | 75.6 |
| 2 | 88.18 | 87.5 | – | 87.0 | – | 86.15 | 86.0 |
| 3 | 97.02 | 96.2 | – | 95.3 | – | 94.15 | 93.9 |
| 4 | 104.48 | 104.0 | – | 102.7 | – | 101.33 | 100.9 |
| 5 | 111.15 | 110.8 | 111.3 | 109.5 | – | 109.09 | 107.4 |
| 6 | 117.66 | 117.6 | – | 115.9 | 118.05 | 114.47 | 113.2 |
| 7 | 124.70 | 124.6 | – | 121.9 | 123.01 | 120.42 | 188.4 |
| 8 | 130.80 | 130.8 | – | 127.7 | 128.83 | 125.93 | 124.0 |
| 9 | 135.47 | 136.3 | – | 133.1 | 133.63 | 131.02 | 129.3 |
| 10 | 141.67 | 141.6 | 140.2 | 138.3 | 139.40 | 135.95 | 134.3 |
| 11 | 145.45 | 147.0 | – | 143.4 | 144.96 | 141.23 | 139.3 |
| 12 | 152.48 | 152.8 | – | 148.7 | 153.11 | 147.62 | 144.8 |
| 13 | 157.88 | 159.6 | – | 155.5 | 160.17 | 155.14 | 153.4 |
| 14 | 166.84 | 166.9 | – | 165.0 | 166.26 | 162.09 | 161.9 |
| 15 | 172.44 | 173.2 | 169.7 | 171.5 | 169.80 | 166.71 | 166.3 |
| 16 | 177.08 | 177.5 | – | 174.8 | 171.51 | 169.08 | 168.4 |
| 17 | 178.72 | 179.7 | – | 176.3 | 172.34 | 170.16 | 169.4 |
| 18 | 180.43 | 180.7 | 177.1 | 176.8 | – | 170.63 | – |
| 19 | – | 181.0 | – | | – | – | – |

Albertsson Wikland et al. [28], Júlísson et al. [29], Prader et al. [30], Tanner and Davies [19], Chae et al. [31], Leung et al. [32], Suwa et al. [33].

starting point for discussion of these issues. Published in 1979 and authored by the primary authority on forensic anthropology at that time, this volume has been used extensively throughout the world in human skeletal analysis. In the chapter "attribution of sex" Stewart summarizes the most useful methodologies available at that time. The techniques presented are largely drawn from studies conducted in North America and the UK. North American methods were developed extensively from the Robert J. Terry collection curated at the Smithsonian Institution in Washington D.C. [39]. This collection was assembled through studies of anatomy at Washington University, St. Louis, Missouri and largely reflects individuals who died in that region of the United States. Although Stewart mentions a study by Pons [40] in Spain and various early German publications, his classic text provides relatively few references to research outside of those discussed above. No discussion is provided on how population variation may affect the expression of sexual dimorphism in the human skeleton.

Since publication of the Stewart text in 1979, studies of the skeletal expression of sexual dimorphism have slowly emerged. For example, İşcan and Shihai [41] reported on femoral sexual dimorphism in a Chinese sample. They reported mean femoral head diameters of 46.2 mm. in males and 41.1 mm in females. Distal epiphyseal breadth produced the most dimorphic values enabling sex discrimination at 94.9% in their Chinese sample. Their sample consisted of 87 adults originating from cemeteries in Chang Chun City and Quingdao.

Loth and Henneberg [42] examined the morphology of the mandibular ramus flexure at the level of the occlusal surface for sexual dimorphism. The sample consisted of 300 mandibles (175 male and 125 female), from adult individuals of known age and sex, predominantly of black South African individuals. The sample was divided into "normative" (200 individuals: 116 male and 84 female) and "pathologic" (100 individuals: 59 male and 41 female) subsets. To add to the diversity of the sample, 85 White European and American and 96 Black American individuals from the Smithsonian Institution's Terry Collection along with 66 Native American individuals from other Smithsonian collections were included. The additional sample also contained both normative and pathologic specimens, but did not include any individuals with conditions that seriously altered the bone morphology. They found

**Table 2**
Female longitudinal growth reference values for height (cm).

| Age (years) | Sweden | Norway | Switzerland | North America | Korea | China | Japan |
|---|---|---|---|---|---|---|---|
| 0 | – | 50.4 | 49.9 | – | – | 50.22 | 49.6 |
| 1 | 74.68 | 75.2 | 74.5 | – | – | 74.14 | 74.6 |
| 2 | 87.14 | 86.7 | – | 86.0 | – | 85.05 | 85.0 |
| 3 | 96.11 | 94.9 | – | 94.6 | – | 93.36 | 92.9 |
| 4 | 103.98 | 102.6 | – | 102.2 | – | 100.69 | 100.0 |
| 5 | 110.74 | 109.8 | 109.6 | 109.0 | – | 107.40 | 106.7 |
| 6 | 117.34 | 117.0 | – | 115.4 | 117.40 | 113.58 | 111.8 |
| 7 | 123.94 | 123.8 | – | 121.5 | 122.17 | 119.33 | 117.0 |
| 8 | 130.17 | 129.8 | – | 127.4 | 128.14 | 124.88 | 122.7 |
| 9 | 134.89 | 135.0 | – | 133.1 | 133.38 | 130.66 | 128.0 |
| 10 | 141.49 | 140.5 | 138.4 | 138.9 | 140.27 | 136.98 | 133.8 |
| 11 | 146.16 | 146.7 | – | 145.6 | 146.67 | 143.56 | 141.3 |
| 12 | 154.23 | 153.3 | – | 153.9 | 152.97 | 149.29 | 148.7 |
| 13 | 159.33 | 159.4 | – | 159.8 | 155.82 | 153.32 | 152.9 |
| 14 | 163.77 | 163.4 | – | 162.8 | 158.20 | 155.70 | 155.1 |
| 15 | 167.97 | 165.5 | 162.7 | 163.7 | 158.88 | 156.97 | 156.2 |
| 16 | 166.67 | 166.5 | – | 163.8 | 159.16 | 157.62 | 156.7 |
| 17 | 166.61 | 166.6 | – | – | 159.45 | 157.96 | 157.0 |
| 18 | 167.59 | 166.8 | 164.4 | – | – | 158.13 | – |
| 19 | – | 167.2 | – | | – | – | – |

Albertsson Wikland et al. [28], Júlísson et al. [29], Prader et al. [30], Tanner and Davies [19], Chae et al. [31], Leung et al. [32], Suwa et al. [33].

that 81% of males from the normative sample exhibited bilateral flexure with 79% of females displaying straight borders or flexure either above or below the level of the occlusal surface. Ramus flexure or straightness was a diagnostic feature in 99.1% of males and 98.8% of females, for an overall accuracy rate of 99.0% in the normative sample. In the pathologic sample, accuracy rates were 93% in males and 88% in females for an average of 91%.

In 1998, Donnelly et al. [43] evaluated the accuracy of Loth and Henneberg's technique in a blind test using 96 complete mandibles. Their sample consisted of mostly Native American mandibles (80), with an additional 16 from the Tennessee forensic collection which contains White American, Black American, and Hispanic individuals. Donnelly et al. reported an accuracy rate of only 63–69%, much lower than that indicated by Loth and Henneberg. In 2000, Hill [44] conducted a similar investigation into the reported accuracy of the technique described by Loth and Henneberg. Hill's sample consisted of 158 mandibles from the Hamann–Todd Collection, which contains African Americans and European Americans. Of the 158 total mandibles, 16 were marked as "pathological" by "antemortem tooth loss of two or more posterior teeth" [44,p. 574]. Hill reported an accuracy of 91.3% for male mandibles and 56.4% for female mandibles, making the average accuracy 79.1% for the sample, again lower than was originally reported.

Working with both femora and tibiae from a White South African sample, Steyn and İşcan [45] were able to distinguish males from females with accuracies ranging from 86% to 91%. With a sample of 56 males and 50 females, they utilized six femoral and seven tibial measurements in discriminant function analysis. Of the individual measurements, the distal breadths of both the femur and tibia were the most dimorphic.

In 1998 İşcan et al. [46] studied sexual dimorphism of the humerus in a comparative study of Chinese, Japanese, and Thai samples. Male mean head diameters were 44.9 mm in Chinese, 44.1 mm in Japanese, and 44.4 mm in Thai samples. Female values were 39.7 in Chinese, 39.1 in Japanese, and 38.2 in Thai humeri. They found that the Chinese had the largest but least dimorphic humeri while the Thai values were the smallest but most dimorphic. Their samples consisted of 87 Chinese individuals, 90 from Japan, and 104 from Thailand.

Steyn and İşcan added data for sexual dimorphism of the humerus in South Africans in 1999 [47]. They reported in their White sample, measurements of the head and epicondylar diameters enabled separation accuracy of 96%. In their Black sample 95% accuracy was achieved using the head diameter and maximum length. For the White sample, they reported mean head diameters of 49 mm in males and 43 mm in females. In the Black sample, head diameters of 43 mm and 38 mm were found. Their samples consisted of 104 White individuals and 88 Black individuals.

In 2001, Asala added information on femoral head diameters in South African White and Black samples [48]. Asala reported mean values of 48.5 mm in males and 42.4 mm in females in White samples. The Black samples produced values of 44.6 mm in males and 40.0 mm in females. In comparison with previously published values, this report reveals population variation in the sexual dimorphism of the size of the femoral head (Table 3). Asala's samples consisted of 260 White individuals and 260 Black individuals.

In 2002 Bruzek introduced a new visual method to estimate sex from the os coxae based on five anatomical features. His test of this method on a sample of 402 adults of known French and Portuguese ancestry revealed correct sex assessment in 95 percent of applications. Subsequent studies by Bruzek et al. on the cranium [49], os coxae [50], tibia [51] and foramen magnum of the cranium [52] clarified aspects of the population variation involved [53].

**Table 3**
Mean maximum femoral head diameters (mm).

| | South Africa (White) | South Africa (Black) | China |
|---|---|---|---|
| Male | 48.40 | 44.45 | 46.16 |
| Female | 42.28 | 39.64 | 41.13 |

Asala [48], İşcan and Shihai [41].

In 2005, Franklin et al. published new discriminant function equations to estimate sex from South African crania [54]. Their sample of 332 (182 males and 150 females) was drawn from the R. A. Dart Collection in Johannesburg. The crania were prepared from dissecting room cadavers with known information regarding sex, age, and local Bantu-speaking group affiliation.

Working with Guatemalan forensically identified samples of 68 males and 50 females, Frutos [55] studied sexual dimorphism of the humerus. Frutos found male mean head diameters to be 43.4 mm in males and 47.4 mm in females. Classification accuracy ranged from a low of 76.8% for maximum diameter at midshaft to 95.5% for the head diameter. A stepwise discriminate function analysis utilizing multiple measurements increased accuracy to 98.2%. Comparison with previous studies reveals considerable population variation of sexual dimorphism in the size of the humeral head (Table 4).

Also in 2005, Schaefer and Black [56] published important new data on population variation in the timing of epiphyseal closure. Working with a sample of 114 identified males from Bosnia, they compared the timing of epiphyseal closure with the American male sample of 325 individuals utilized in the classic study by McKern and Stewart [57] on soldiers who died during the Korean conflict. They found that epiphyseal fusion in Bosnian males occurred two years earlier than in the American sample. Although this study focused on age estimation, the values reported impact sex evaluation as well. The maturation differences reflected in epiphyseal union document the extent of population variation involved, at least in males.

In 2007, Carmargo et al. [58] published evidence for sexual dimorphism in frontal sinus size, utilizing a Brazilian radiographic sample of 100 individuals (50 males and 50 females). In 2014, Belaldavar et al. [59] added that sexual dimorphism in frontal sinus size varies in samples from India and other groups.

Also in 2007, Kurki investigated the effects of overall body size on the preservation of birth related features in the female pelvis. The study used samples from 59 small-bodied Later Stone Age (LSA) foragers in South Africa, 80 large-bodied European–Americans from the Hamann–Todd (H–T) Osteological Collection, and 80 contemporary Portuguese individuals from the Coimbra-Identified Skeletal Collection (CISC) to represent an intermediate body size. It was reported that males from the LSA had the smallest absolute pelvic canal size while LSA females displayed pelvic canals of comparable size to those of females from the CISC and H–T samples. [60].

In 2008, Steyn and İşcan added metric sex data for modern Greeks. They developed mathematical functions specific for a modern sample of 97 male and 95 female Greek individuals who had lived on Crete and died within the preceding 50 years [61]. Kranioti and Michalodimitrakis [62] examined sexual dimorphism of the humerus in a sample of contemporary individuals from Crete, Greece. In their study of 168 left humeri, they found that of all variables examined, the best single indicator proved to be the vertical diameter of the head with a separation accuracy of 89.9%. An accuracy of 92.9% was achieved when all variables were considered together.

Akhlaghi et al. [63] used a metric approach to sex estimation using three measurements of right patellae from 113 (57 male and 56 female) fresh cadavers of Iranian individuals from Tehran's

**Table 4**
Mean maximum humeral head diameters (mm).

| | South Africa (White) | South Africa (Black) | China | Thailand | Japan | Guatemala |
|---|---|---|---|---|---|---|
| Male | 49.0 | 43.7 | 44.9 | 44.4 | 44.1 | 43.4 |
| Female | 43.2 | 37.7 | 39.7 | 38.2 | 39.1 | 37.4 |

Steyn and İşcan [47], Frutos [55], İşcan et al. [46].

Legal Medicine Organization. Mean patella height in males from the sample was 4.47 cm and 3.83 in females. Mean patella width was 4.55 in males and 4.01 in females. The mean thickness of the patella was 2.19 in males and 2.03 in females. When considered individually, thickness gave an accuracy rate of 74.3%, height presented 89.4% accuracy, and width provided 91.2%. All three measurements gave a 92.9% accuracy rate when used together.

Working in Greece in 2011, Charisi et al. [64] examined sexual dimorphism of the bones of the arm using a sample of 111 males and 93 females. In contrast to the Kranioti and Michalodimirakes study cited above, they found that maximum length and epiphyseal widths performed best. They achieved a separation accuracy of 90% for the ulna and 95.7% for the humerus.

Also in 2011, Saini et al. examined sexual dimorphism in the craniofacial region using a northern India sample. They examined 82 males and 30 females, finding that the measurement of bizygomatic breadth was the most discriminating. Univariate separation accuracies ranged from 48% to 86% [65].

Vance et al. [66] demonstrated that morphological features of the humerus can be used without measurement to evaluate sex. In their study of the humeral morphology in 420 men and 188 women they found that olecranon fossa shape, the angle of the medial epicondyle, and the trochlear extension allowed separation accuracies of 77% of females and 74% of males.

In 2012 Milner and Boldsen compared humeral and femoral head diameters in recent skeletons classified in terms of ancestry as White. They examined seven samples of documented skeletons from the United States, Crete (Greece) and South Africa. The mean values (mm) for the humerus ranged from 41.1 to 43.2 in females (95 individuals) and from 46.4 to 49.0 in males (97 individuals). Femoral values ranged from 42.0 to 43.0 in females (96 individuals) and from 48.0 to 48.5 in males (112 individuals) [67].

Srivastava et al. [68] reported on the results of their study of sexual dimorphism in the femur in a sample of 94 males and 28 females from north India. Individual variables provided classification accuracies ranging from 70.5% to 83.6%. Use of stepwise discriminant function analysis increased the accuracy to 90.2%. Of the individual traits, they found epicondylar breadth, proximal breadth and antero-posterior diameter of the lateral condyle to be the most discriminating. Also working with North India samples, Saini et al. [69] found that stepwise analysis of eight measurements of the mastoid process resulted in sex classification with an accuracy of 87%. Srivastava et al. [70] also worked with ulna samples from north India finding accuracies of 84.9% with maximum length, 84% with a measurement of the radial notch and 88.7% using a combined stepwise procedure.

Comparative population data on sexual dimorphism can also be found embedded in research publications addressing other topics. For example, Gocha et al. [71] studied 49 male and 15 female skeletons from the collections at Khon Kaen University in northeast Thailand. Although the purpose of their study was to generate new formulae to estimate living stature from various skeletal measurements, they also published new sex-specific measurement data. Values of 13 variables for males and females from different areas of the skeleton became available for comparison with studies done in other regions.

Albanese [72,73] recognized the impact of population variation on skeletal sexual dimorphism by combining data from different samples. His constructed diverse reference sample reflects the concept that methodology derived from greater sample diversity augments case applications in different regions.

In 2014, Betti examined sexual dimorphism in the size and shape of the os coxae in 20 different global samples. This study reported significant variation in both size and shape, reflecting the effects of microevolutionary processes [74].

Some insight into population/sample variation also can be found when methods developed from particular samples are tested using different samples, including those from other regions and different populations. For example, Pavia and Segre [75] reported their Brazilian study of sexual dimorphism in measurements of the mastoid process area of the cranium. Using a sample of 30 males and 30 females they defined a triangular area. Calculation of the total area within the triangle allowed sexual classification with 95% accuracy in both men and women. However, Kemkes and Göbel [76] tested the Brazilian method on samples from Germany (97 individuals) and Portugal (100 individuals) and found the method to be of reduced accuracy. These findings illustrate the value of testing a method developed from a specific sample on a different one. The results also reflect population variation in the morphological area of the mastoid process utilized in the sex assessment.

Comparative studies of population variation in skeletal sexual dimorphism are vitally needed but influencing factors need to be addressed. Experience of the investigator represents one such factor. Methods involving measurements tend to involve less inter-observer error than the more subjective observational approaches as long as the landmarks used to produce the measurements are well-defined and easily located. For traits involving observation, experience plays a key role. For example, in 1969 Phenice published a now-classic article defining three traits on the pelvis useful to evaluate sex. These three traits are the ventral arc, the subpubic concavity and the medial aspect of the ischio-pubic ramus. His study of skeletons of known sex in the Smithsonian's Terry collection produced methodology that would classify sex with 96% accuracy [77]. Subsequently, the "Phenice method" has been used extensively in routine analysis within forensic anthropology [78]. However, at the time of his research analysis, Phenice was an experienced osteologist from the University of Kansas who was aware of other aspects of pelvic anatomy useful to evaluate sex. Was his analysis based solely on the three traits in question or did his experienced eye also consider other pelvic factors such as the width of the sciatic notch, a preauricular sulcus, or pubic pitting? To examine this issue, Ubelaker and Volk [79] published a study in which one author (Volk) represented a student with no prior knowledge of pelvic skeletal anatomy. After being trained in the Phenice methodology, Volk classified individuals from the Terry collection for sex, using the three traits. This procedure resulted in a classification accuracy of 88.4%, substantially lower than the accuracy reported in the original Phenice study. When Volk was subsequently trained in all aspects of sexual dimorphism of the pelvis, the accuracy increased to 96.5%. Clearly experience and knowledge of all useful anatomical traits represent important factors.

## 5. Genetic contributions

Obviously, genetic factors contribute to the development of population variation in the expression of sexual dimorphism in the

skeleton. In addition, advances in genetics and applied biology have created the option for genetic approaches to the evaluation of sex from skeletal remains. Genetic approaches can be particularly useful in the determination of sex in subadults, who have not yet developed reliably dimorphic features. Cases in which only small fragments or skeletal elements insufficient for anthropological sex estimation are recovered represent another area that can benefit from DNA analysis [2].

Amelogenin, a protein which has copies on both the X- and Y-chromosomes [80], is involved in dental development and formation early in life [81]. Because amelogenin is present from early in life, it is useful in the forensic investigation of sex in skeletal material with sufficient molecular preservation. Since dental enamel displays excellent preservation, it is especially useful in amelogenin analysis. This method indicates sex by the number of products in a sample. Two different products, from the X- and Y-chromosomes should be seen in males, while females should only exhibit the product of the X-chromosome [82].

In 2016, Thomas et al. investigated the accuracy rates of traditional anthropological approaches of sex estimation compared to DNA typing. Their sample involved 360 case files from the FBI laboratory from 1974 to 2013 which contained a sex determination from both anthropological analysis and DNA typing from the amelogenin locus. DNA typing revealed the distribution of sex in the sample to be 252 males and 108 females. The average success rate of sex estimation by anthropological methods was 94.7% with an expected increase in the accuracy rate (to 97.8%) when a nearly complete skeleton was analyzed. The lowest accuracy rate (60.0%) was found when only the mandible was examined [83].

While genetic approaches provide high rates of accuracy for sex estimation in forensic contexts, they are restricted by the resources of the lab running the analysis and are subject to the effects of contamination and degradation of DNA [84]. DNA typing is an important tool when available, though the literature reflects the potential for traditional anthropological analyses to also provide high rates of success.

## 6. Discussion

An abundant and growing scientific literature documents the complex factors that lead to population variation in the expression of human sexual dimorphism. Certainly genetics plays a key role, however, general environmental factors, morbidity, nutrition, secular change and other influences contribute as well. In addition assessment of population variation of the expression of sexual dimorphism in the skeleton also can reflect issues of sampling and mortality bias [85].

In relation to the assessment of sexual dimorphism from skeletal remains, this literature reveals global diversity in values and methodology. Of course global population variation does not cluster neatly into racial or even national categories [86]. However, studies of samples within particular regions document aspects of variation that provide useful insights critical to forensic interpretation. Like many other areas of analysis in forensic anthropology, investigators should consult local data and methodology in making assessments of sex from skeletal attributes. If local data and methods are not available, forensic anthropologists should conduct a thorough analysis of the ancestry of the remains and select methodological approaches that relate as closely as possible.

## 7. Conclusions

The expression of sexual dimorphism in the human skeleton reflects genetic and environmental factors influencing growth and development. Global variation in these factors produces considerable differences in the manifestations of human skeletal sexual dimorphism that impact methodology and casework. Gradually, research and new techniques have begun to address this issue, especially reflecting new documented skeletal collections that have become available in recent years. Much of this research has documented many aspects of global variation in the expression of sexual dimorphism in the human skeleton. These efforts have clarified that comprehensive and up-to-date data for specific groups are necessary to achieve the level of accuracy in the assessment of sex from skeletal evidence that modern forensic science demands.

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