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Is Adulthood Required? Examining the Accuracy of Pelvic Sex Estimation Throughout Pubertal Growth

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ABSTRACT Reliable morphological sex estimation in non-adult skeletons continues to be problematic in juvenile osteology. Methodological exploration has focused on infants and children (0–12 years of age), but less attention has been given to adolescents (12–19 years of age). A critical challenge to non-adult sex estimation is that the full expression of sexual dimorphism in areas of the skeleton that have garnered the most attention due to their use in adult sex estimation (i.e., pelvis) does not occur until adulthood. Little research has been conducted to determine if a threshold along the pubertal growth curve that may yield high sex estimation accuracy exists. This study examined the relationship between pelvic sexual dimorphism and stages of pubertal growth from four skeletal traits. Eighteen pelvic traits outlined by Schutkowski (1993) and Rogers and Saunders (1994) were examined on 128 non-adults (4 months–20 years of age) from the Hamann-Todd and Terry Collections. Pubertal stage was examined on 98 individuals between 8 and 20 years of age. Sex estimation accuracies for each trait and combined traits were assessed for each stage. Statistical significance of correct sex estimates was tested using chi-square and Fisher's exact tests. This study demonstrated that reaching the post-pubertal period was not required for the full expression of sexual dimorphism of all 18 traits. Surpassing peak height velocity, the period of fastest growth, was more critical given that high accuracy (i.e., > 80%) was observed for sex estimates using five individual pelvic traits and the combination of all 18 traits by the deceleration stage.

Keywords: Sexual dimorphism; adolescents; puberty stages; pelvis; morphological traits

La estimación del sexo morfológico en esqueletos de subadultos fiable sigue siendo problemáticas en la osteología juvenil. La exploración metodológicas se han concentrado en los infantes y niños (0–12 años de edad), pero los adolescentes (12–19 años de edad) han recibido menos atención. Un reto crítico para la estimación del sexo de los subadultos es la idea que la expresión completa del dimorfismo sexual en áreas del esqueleto que han atraído mas atención debido a su uso en la estimación del sexo en adultos (como el pelvis) no ocurre hasta la edad adulta. Pocas investigaciones se han realizado para determinar si existe un límite durante la curva de crecimiento puberal que pueda producir una precisión alta en la estimación del sexo. Este estudio examinó la relación entre el dimorfismo sexual de la pelvis y las etapas del crecimiento puberal usando cuatro rasgos esqueléticos. Dieciocho rasgos pélvicos delineados por Schutkowski (1993) y Rogers and Saunders (1994) fueron examinados en 128 subadultos (4 meses–20 años) del las colecciones Hamann-Todd y Terry. Etapas puberal fueron examinados en 98 individuos entre 8 y 20 años de edad. Se evaluaron las precisiones de la estimación del sexo de cada rasgo y los rasgos combinados para cada etapa. La significación estadística de las estimaciones correctas del sexo se probó utilizando las pruebas de chi-square y Fisher's exact test. Este estudio demostró que alcanzar el periodo pos-puberal no era necesario para la expresión completa del dimorfismo sexual de los 18 rasgos. En cambio, superar la velocidad de altura máxima, el periodo de crecimiento más rápido, fue más critico

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dado que se observó una alta precisión (es decir, > 80%) para las estimaciones de sexo utilizando cinco rasgos pélvicos individuales y la combinación de los 18 rasgos empezando en la etapa de desaceleración.

Palabras claves: dimorfismo sexual; adolescencia; etapas de la pubertad; pelvis; rasgos morfológicos

Sex estimation is one of the most integral components of assessing the adult biological profile since it aids in the reconstruction of the demographic profile of a skeletal assemblage and is critical to explore sex-based differences, as a proxy for gendered differences, in labor, treatment in death and burial, and disease susceptibility in the past (e.g., Agarwal and Wesp 2017). Sex estimates can also inform the appropriate standards necessary for subsequent analyses of skeletal remains, such as adult age estimation or stature assessment (Horbaly et al. 2019; Ousley 1995). While sex estimation can yield high accuracy for adult skeletons, determining this biological parameter remains one of the most challenging areas of analysis for non-adult skeletons. Despite high accuracies reported for a number of morphological traits initially proposed by Schutkowski (1993) and Weaver (1980), research focusing on reliable sex estimation methods failed to reproduce consistent results (Cardoso and Saunders 2008; Lamer et al. 2021; Olivares and Aguilera 2016; Sutter 2003; Vlak et al. 2008) and, as a result, non-adult sex estimation has often been cautioned, if not discouraged. The search for reliable sex estimation methods for non-adults, however, has focused substantially on infant (0–3 years of age) and child (3–12 year of age) remains, but adolescents (12–20 years of age) have largely been absent as the sole focus of inquiry until recently (e.g., Corron et al. 2021; Hsiao et al. 2010; Klales and Burns 2017; Rogers 2009; Stock 2018; Sutherland and Suchey 1991). With the growing focus on adolescence in bioarchaeology, as exemplified by this special issue, it is important to ensure that the most appropriate methods are applied to adolescent remains to obtain the most accurate estimate of sex to confidently explore and reconstruct the nuances of how this key period in the human life cycle was experienced in the past. Although advances in biomolecular methods of sex estimation (such as ancient DNA and peptide analysis) are promising for non-adult skeletons, these analyses are destructive and financially restrictive, and there remain issues with consistency of results, false positives and negatives, and refinement of methods (Lewis 2018; Stewart et al. 2017). These issues with biomolecular methods make exploring and refining new and reliable approaches for morphological sex estimation in non-adult remains an important area of research in anthropology.

One factor that has been proposed as potentially impacting the ability to reliably estimate the sex of non-adult skeletons includes the fact that most morphological methods developed for non-adult sex estimation focus on areas of the skeleton that are most effective for adult sex estimation, namely the pelvis and skull (Klales and Burns 2017; Rissech and Malgosa 2005; Rogers 2009). Given that sex differences in these areas of the skeleton are secondary sex characteristics, they develop during puberty and the full expression of dimorphism does not manifest until the post-pubertal period. Prior to their full expression, sexually dimorphic traits in the pelvis and skull are believed to be unreliable. Indeed, defining characteristics in the pelvis between males and females become distinguishable during the hormonal surge that occurs during puberty, as it is a time where pelvic remodeling occurs in anticipation for reproduction and to accommodate for the increase in volume of internal organs (Bogin 1999; Dunsworth 2020). The pelvic cavity and birth canal dimensions, for example, have been shown to be larger in females than in males, a divergence that occurs between eight and 18 years of age (Arsuaga and Carretero 1994; LaValle 1995; Wood and Chamberlain 1986). Further widening of the true pelvis continues in females until 25 to 30 years of age (Huseynov et al. 2016), likely resulting in more pronounced dimorphism in this pelvic feature in adults.

Overall, morphological pelvic traits have not been comprehensively examined throughout adolescence to document their appearance, with the exception of the ventral arc and the subpubic concavity. The ventral arc is a common feature used in pelvic sex estimation, and its appearance has been noted to be the result of variation in the muscle attachment sites for the gracilis, adductor mangus, and adductor brevis muscles (Anderson 1990; Budinoff and Tague 1990). These muscles are laterally and cranially positioned in females, whereas in males, the muscles are positioned more medially and are parallel to the pubic symphysis (Budinoff and Tague 1990). The relationship between muscle position on the pubic bone and the presence of the ventral arc is believed to begin around the time of puberty when hormonal activity leads to the lengthening of the female pubis (Anderson 1990; Klales et al. 2012). While Phenice (1969) noted that the ventral arc does not appear in females until 20 to 23 years of age, Sutherland and Suchey (1991) noted the presence of what they coined as a “precursor arc” in females between 14 and 20 years of age. The precursor arc exhibited in adolescents is defined as a faint line on the ventral side of the pubis following the same course as the ventral arc occurring as "the lower extremity fills in with fine dense bone before the symphyseal rim becomes defined" (Sutherland and Suchey 1991:504 and Figure 5:505). In addition to the ventral arc, the subpubic concavity is another morphological pelvic trait whose developmental differences manifest during puberty and has recently been examined in adolescent individuals. The divergence in the male and female form of the subpubic concavity is believed to be the result of different directional growth at the middle of the ischiopubic ramus between the sexes and increased growth in the pubis and ischium in females resulting in an obtuse subpubic angle but an acute angle in males (Coleman 1969; LaVelle 1995). Phenice (1969) suggested that, like the ventral arc, the subpubic concavity was not well developed in females until 20 years of age. However, using a modified ordinal scale for scoring the subpubic concavity, Klales and Burns (2017) explored the utility of the subpubic concavity for sex estimation in individuals aged 20 years and younger. Through radiographic examinations of this trait on 334 individuals, the authors obtained promising results in early (12.6–15.5 years of age) and late (15.6–20.5 years of age) adolescents, with a combined accuracy of 85.3% and 97.2% respectively. Therefore, Klales and Burns (2017) demonstrated that the modified system of scoring the subpubic concavity could be applied to adolescents between 12.6 and 20 years of age, an age substantially younger than Phenice (1969) previously reported. The research on the ventral arc and subpubic concavity provides some evidence of Scheuer and Black's (2000:343) suggestion that secondary sex differences in the pelvis could be sufficiently advanced in females by mid-puberty.

The above examples of pelvic traits demonstrate that puberty is a critical time for the manifestation and full expression of sexual dimorphism in the pelvis. Given that puberty is a process and not a singular event, further research needs to narrow down the pubertal stage during and after that sexual dimorphism becomes prominent enough to allow for accurate sex estimation. Physical changes occurring as a result of puberty follow a specific sequence, where the pubertal growth spurt begins with the acceleration of growth velocity, which accelerates until peak height velocity (PHV) is reached. Following peak height velocity, growth returns to a slower rate known as the deceleration period, and pubertal growth ends with full maturation, which is marked skeletally by the epiphyseal fusion of long bones (Hägg and Taranger 1982; Shapland and Lewis 2013; Rogol et al. 2000). Generally, females tend to enter and complete each puberty stage earlier than males and reach PHV 1 to 2 years earlier than males (Bogin 1999). While traditional signs characteristic of puberty are primarily related to soft tissue changes, clinical studies have shown that skeletal maturation of certain elements is closely related to sexual maturation given that epiphyseal fusion is triggered by estrogen release in females, or androgen in males, during adolescence (Cutler 1997; Dunsworth 2020; Grumbach 2000; Hassell and Farmer 1995). In their seminal studies, Shapland and Lewis (2013, 2014) identified a total of six osteological indicators strongly correlated with the six pubertal growth stages that can be of use in bioarchaeological analyses: ossification of the hamate hook, fusion of the phalangeal epiphyses, iliac crest ossification, fusion of the distal radius epiphysis, mineralization of the mandibular canine, and cervical vertebrae maturation. The various developmental stages of these osteological indicators are linked to specific stages of pubertal growth and when used together, inferences on the pubertal process in past populations can be and have been made (Arthur et al. 2016; DeWitte and Lewis 2020; Doe et al. 2019, 2021; Henderson and Padez 2017; Lewis et al. 2016a, 2016b). Although pubertal stage analysis has thus far been applied for interpretive purposes, if coupled with data on sexual dimorphism, it may be possible to link stages of puberty with substantial dimorphism in the pelvis to determine whether or not the full expression of sexual dimorphism does, in fact, occur once the post-pubertal period is reached. Pubertal stages may also be used as an avenue to help ameliorate the common issue of using pooled age groups that previous studies have often resorted to, which may only serve to mask or miss sex differences that emerge from differing ontogenetic trajectories (Stull et al. 2020; Wilson and Humphrey 2017).

The aim of this study was to explore the relationship between pubertal stage and sex estimation accuracy rates using morphological pelvic traits. The overall objectives of this study were to determine: 1) the critical stage during pubertal growth at which pelvic traits become sufficiently dimorphic to provide an accurate sex estimate and 2) how pubertal stage assessment can help inform best practices for accurate pelvic sex estimation of adolescent skeletons. For the purpose of this study, an 80% accuracy threshold was employed to classify a trait as having "high accuracy," which is higher than the 75% goal suggested for nonadult sex estimation (DiGangi and Moore 2013:107) and is typical of studies that use 80% to 85% accuracy. By integrating pubertal stage analysis when examining the manifestation of sexual dimorphism in the pelvis, this study addresses an integral component of understanding when, during growth and development, sex estimation can be conducted with confidence. With the growing focus on adolescence in bioarchaeology, reliable sex estimates of adolescent remains will allow for more refined reconstructions of the ways this vital period of social transition may have been experienced between the sexes in past populations, and contribute to a nuanced understanding of gender-based differences associated with this social transition in terms of dietary practices, divisions of labor, mortality rates, and disease patterns.

Materials

The sample examined in this study consists of 102 individuals from the Hamann-Todd Collection curated at the Cleveland Museum of Natural History and 26 individuals from the Terry Collection housed at the Smithsonian Institutes National Museum of Natural History in Washington, DC. The combined sample of 128 non-adults consists of individuals between the ages of 4 months and 20 years of age (Fig. 1). The Hamann-Todd collection is of anatomical origin and consists of 3,100 individuals who died between 1912 and 1938 in Cleveland, Ohio. The individuals in this collection either could not afford burials or were found on the street and are unclaimed persons. Many were transient individuals, from the Cleveland and Cuyahoga County morgues, city and charity hospitals, poorhouses, and asylums (Alioto 2020; Quigley 2001). The substantial number of non-adults in this collection has been attributed to T. Wingate Todd's interest in environmental and cultural factors impacting growth, development, and overall health (Muller et al. 2017). Similarly, the Terry collection is also an anatomically derived collection that is comprised of approximately 1,728 individuals who died between 1917 and 1965 in St. Louis, Missouri (Hunt and Albanese 2005). The collection consists of individuals who were unclaimed by relatives at the time of death from local hospitals, coroner facilities, and poor houses in Missouri (Hunt and Albanese 2005; Muller et al. 2017). While initial iterations of the Terry collection contained a large number of older adults, it was not until Mildred Trotter's management of the collection that collecting efforts focused on younger individuals (Hunt and Albanese 2005). While the exact provenience and circumstances surrounding the inclusion of the non-adults to the Hamann-Todd and Terry collections cannot currently be ascertained, the individuals in these collections represent the lower class and marginalized in society (Alioto 2020; de la Cova 2010; Hunt and Albanese 2005). It is likely that this extended to the non-adults, and the low economic status of their families, and themselves, was a reason for their inclusion into these collections. Both skeletal collections have documented demographic information, such as age, sex, and cause of death, associated with each individual.

The male bias present in the study sample in the youngest and oldest ages (Fig. 1) could impact and be reflected in trait specific and overall sex estimates, making it appear as if estimates based on specific traits, or the combination of all traits, are accurate when it might reflect accurate sex estimation of males. Sex-specific accuracy rates were therefore calculated to mitigate, in part, the male bias present in the sample.

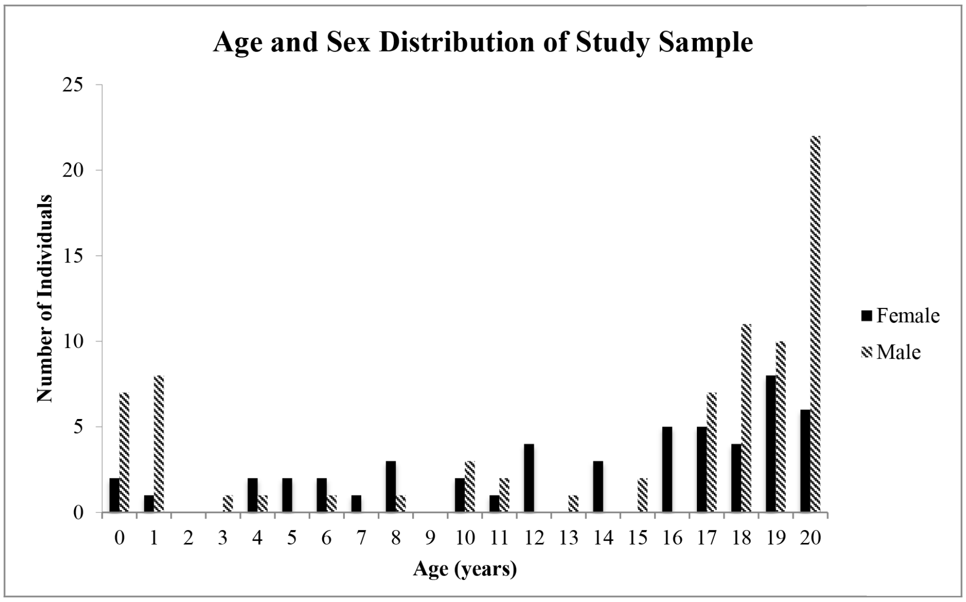

Figure 1. Age and sex composition of the study sample

Methods

As standard practice in osteological studies, the left os coxa was selected for examination in this study, with the right being substituted in the event that poor preservation obfuscated analysis on the left element. Given the comprehensive list of pelvic traits examined, there was some variation in the degree and location of damage when present. If the extent of the damage impacted the majority of morphological traits examined, the individual was not included in this study. All 128 individuals met the criteria for inclusion in this study.

Sex estimation methods

In order to conduct this study blind, an assistant selected three individuals at random for examination and ensured any identifiers of documented sex were not visible. Sex assessment was conducted for each individual using 18 morphological pelvic traits listed in Table 1. The traits selected for this study correspond to pelvic traits often used for adult sex estimation and those proposed for non-adult sex estimation. Fifteen of the traits examined derive from a list of traits for adult sex estimation that have been comprehensively tested by Rogers and Saunders (1994) for accuracy and precision and were originally proposed by Phenice (1969), Krogman (1962), Kelley (1979), and Bass (1987). The remaining three traits are those that have been proposed by Weaver (1980) and Schutkowski (1993) for non-adult sex estimation that are non-duplicates of adult traits. Given that little research on the appearance of these pelvic traits in adolescents has been done, all but one trait were scored based on the criteria set out for adults. The ventral arc, however, was scored for both the expression identified by Phenice (1969) and the expression of the precursor arc identified by Sutherland and Suchey (1991) and was also considered during examination of this trait. Therefore, the ventral arc was considered "present" if either the ventral arc, as per Phenice's (1969) definition, or the precursor arc were observed. While traditionally used as a sign of parturition in the past, dorsal pubic pitting has also been applied for adult sex estimation. A meta-analysis of this trait demonstrated that there is a weak relationship between dorsal pubic pitting and parity but that the trait is a moderate predictor of sex (McFadden and Oxenham 2018). Although a modest, at best, indicator of sex, dorsal pubic pitting was still included in this study to be as comprehensive as possible when testing various pelvic traits.

Each individual was scored based on which trait expression they resembled the most. If a trait did not resemble either the male or female expression, the trait was scored as "indeterminate." A final sex estimate using all 18 traits was conducted for each individual using the "majority rules" approach, where a minimum of 11 out of the 18 traits had to correspond to a particular sex. In instances where there was no clear majority, the individual's sex was assessed as "indeterminate." Both trait-based and final sex estimates were compared to the documented sex of each individual to test for accuracy. Sex-specific accuracy was determined and refers to the percentage of correct sex estimates for each sex among the total number of individuals of that sex, which included individuals with indeterminate assessments. Total or overall accuracy refers to the percentage of individuals whose sex was correctly estimated out of the total number of individuals for each trait in their respective pubertal stage, which included individuals with an indeterminate assessment. Accuracy was determined to be high if a minimum of 80% was attained. Pearson's chi-square and Fisher's exact tests were also conducted to test the statistical significance of the number of individuals whose sex was correctly estimated for each trait and combined traits.

Pubertal stages

Pubertal stage analysis was conducted on 98 individuals; the remaining 30 individuals were too young to assess pubertal stage. Of the 30 non-adults, those between 3 and 7 years of age were later added to represent pre-pubertal children. An additional category of "Infant" was created for individuals between 4 months and 2 years of age, which represented the age at which the hypothalamus is initially active in the secretion of sex hormones (Bogin 1999). Four of the six pubertal stage indicators proposed by Shapland and Lewis (2013, 2014) were scored and include: ossification of the hamate hook, fusion of the phalangeal epiphyses, iliac crest ossification, fusion of the distal radius epiphysis. The use of four pubertal stage indicators still met the minimum requirement of three observable features required to assess an individual's pubertal stage (Lewis et al. 2016a). Given that this research was part of a larger study, time restriction and a lack of access to radiographs did not allow for the examination of cervical vertebrae maturation, canine tooth development, proximal ulna, and fusion of the humeral capitate. The developmental scores of each osteological indicator were combined and based on a majority rule (i.e., 3+ traits) approach each individual was allocated to one of six pubertal stages: 1) pre-puberty, 2) acceleration, 3) Peak Height Velocity, 4) Deceleration, 5) Maturation, 6) post-puberty following the criteria listed in Table 2. The results of pubertal stage analysis on the adolescents of the Hamann-Todd and Terry

Table 1. List of 18 morphological traits used for pelvic sex estimation

Trait	Male Expression	Female Expression
Subpubic Concavity[a]	V-shaped	U-shaped
Ischiopubic Ramus Ridge[a]	Ridge absent	Ridge present
Ventral Arc Presence[a]	Arc/Precursor arc absent	Arc/Precursor Arc present
Pubic Bone Shape[b]	Narrow	Broad, rectangular
Dorsal Pubic Pitting[c]	Absent	Present
Sciatic Notch Shape & Size[b]	Small, close, deep	Wide, shallow
Auricular Surface Height[d]	Not raised	Raised
Preauricular Sulcus Presence and Shape[b]	Absent or thin grooves	Large, circular depression
Ilium Shape[b]	High and vertical	Laterally divergent
Pelvic Inlet Shape[b]	Heart shaped	Elliptical
True Pelvis Size & Shape[e]	Small, narrow	Shallow and spacious
Obturator Foramen Shape[b]	Large, ovoid	Small, triangular
Acetabulum Size and Orientation[e]	Large, directed laterally	Small, directed anterio-laterally
Development of Muscle Markings[b]	Marked, rugged	Gracile, smooth
Sacrum Shape[b]	Long, narrow	Short, broad
Greater Sciatic Notch Angle[f]	Angle of sciatic notch is approx. 90°	Angle of sciatic notch is greater than 90°
Arch Criterion[f]	When drawing a cranial extension from the vertical side of the greater sciatic notch, the arch leads into the lateral rim of the auricular surface	When drawing a cranial extension from the vertical side of the greater sciatic notch, the arch formed crosses the auricular surface
Iliac Crest Curvature[f]	When viewed, iliac crest exhibits a marked S-shape	When viewed, iliac crest exhibits faint S-shape

[a] full description found in Phenice 1969
[b] full description found in Krogman 1962
[c] full description found in Kelley 1979
[d] full description found in Weaver 1980
[e] full description found in Bass 1987
[f] full description found in Schutkowski 1992

Table 2. Osteological indicators associated with pubertal stages. Modified from Lewis et al. (2016).

Pubertal Stage	Hamate Hook	Phalangeal Epiphysis Fusion	Distal Radius Epiphysis	Iliac Crest Ossification
Pre-Puberty	Stage G: hook absent	Distal hand phalanges unfused	Unfused	Epiphysis not present
Acceleration	Stage H or H.5: hook appearing or developing	Distal hand phalanges unfused	Unfused	Epiphysis 50% complete, unfused
Peak Height Velocity	Stage I: Hook Complete	Distal hand phalanges unfused	Unfused	Epiphysis 50–75% complete, unfused
Deceleration	Stage I: Hook Complete	Distal hand phalanges fusing	Unfused	Epiphysis 75–100% complete, non to partial fusion
Maturation	Stage I: Hook Complete	Distal hand phalanges fusing/fused	Partially fused	Epiphysis 100% complete, partially fused
Post-Puberty	Stage I: Hook Complete	Distal hand phalanges fused	Fused	Epiphysis fused

Table 3. Summary of mean age and age range for each pubertal stage for both sexes. F_T = total number of females, M_T = total number of males.

Pubertal Stage	F_T	Females Range (yrs)	Female Mean (yrs)	M_T	Males Range (yrs)	Male Mean (yrs)
Pre-Puberty*	5	8–13	10.0	3	8–11	9.7
Acceleration**	2	8–12	10.0	3	10–17	12.3
PHV**	2	12	12.0	3	13–15	14.3
Deceleration**	5	14–16	15.2	9	17–19	17.9
Maturation**	6	17–19	18.0	13	17–20	19.0
Post-Puberty	18	14–20	18.3	27	18–20	19.3

*data only reflect those who were selected for pubertal stage analysis; does not include the 3-7 year olds later added to this stage
**stages that correspond to the pubertal period

collections have been reported in detail elsewhere (Sanchez and Hoppa 2019; Sanchez 2021), but the age ranges corresponding to each pubertal stage are summarized in Table 3. The accuracy of sex estimates for each trait and final sex estimate was then determined for each pubertal stage. In total, 18 individuals were in the infant category (4 months–2 years of age), 18 individuals were in the pre-pubertal period (3–13 years of age), 43 were in the pubertal period (8–19 years of age), and 45 individuals were in the post-pubertal period (14–20 years of age).

Results

Infancy and pre-puberty

Overall, the two youngest categories examined in this study did not yield promising results. While five traits, pubic bone shape, preauricular sulcus, auricular surface height, ventral arc, and dorsal pubic pitting, provided accuracies between 83% and 93% for the infant category, these traits were only effective for the correct identification of males but not females. In all but one trait (pubic bone shape), the accuracy of correct female classification was 0%. None of the 18 pelvic traits, or the final sex estimate, achieved an accuracy of 80% or greater for the pre-puberty stage. The highest accuracy achieved in this developmental stage was 76.5% for the greater sciatic notch size and shape, however female classification accuracy (100%) far exceeded male classification accuracy (20%).

Acceleration

Three traits (ilium shape, greater sciatic notch angle, and auricular surface height) achieved an overall accuracy of 80% in the acceleration stage. Despite the high overall accuracy of these three traits, each trait demonstrates a degree of sex bias. A Fisher's Exact Test determined that the number of individuals with a correct sex estimate using the three traits were not statistically significant (Table 4). The remaining 15 traits and final sex estimate failed to achieve the minimum threshold set out for this study.

Peak height velocity

Nine traits and final sex estimates achieved accuracies ranging between 80% and 100% in individuals in the PHV stage of the pubertal growth curve (Table 5). Six of the nine traits achieved 100% accuracy, although sample size ranged from two to five individuals. The remaining three traits and final sex estimates, all achieving an accuracy of 80%, demonstrated a male bias in correct sex classification. Despite the high accuracies observed in the PHV stage, the number of individuals whose sex was correctly estimated using these traits was not observed to be statistically significant.

Deceleration

Within the deceleration stage, there were six pelvic traits and the final sex estimate that exceeded the threshold for accuracy set out in this study. Three of the six traits and the final sex estimate also meet or

Table 4. Summary of accuracy rates and chi-square values for correct sex estimates of each trait in the acceleration stage. Significant p-values ($p < 0.05$) are bolded. N = total number of individuals, including those with incorrect and indeterminate estimates; $\%_T$ = total accuracy, N_F = total number of females, $\%_F$ = female accuracy, N_M= total number of males, $\%_M$ = male accuracy.

Trait	N	Correct Class.	$\%_T$	N_F	$\%_F$	N_M	$\%_M$	X^2	p-value
Ilium Shape	5	4	80	2	100	3	66.7	2.222	0.400
Pubic Bone Shape	5	3	60	2	0	3	100	–	–
Greater Sciatic Notch Angle	5	4	80	2	100	3	66.7	2.222	0.400
Obturator Foramen Shape	5	3	60	2	0	3	100	–	–
Preaurciular Sulcus	5	3	60	2	0	3	100	–	–
Acetabulum Size & Orientation	4	2	50	2	50	2	50	0.000	1.000
Auricular Surface Height	5	4	80	2	50	3	100	1.875	0.400
Subpubic Concavity	5	3	60	2	0	3	100	–	–
Ventral Arc	5	3	60	2	0	3	100	–	–
Ischiopubic Ramus Ridge	5	3	60	2	0	3	100	–	–
Greater Sciatic Notch Size & Shape	5	3	60	2	100	3	33.3	0.833	1.000
Sacrum Shape	3	2	66.7	1	0	2	100	–	–
Dorsal Pubic Pitting	5	3	60	2	0	3	100	–	–
Iliac Crest Curvature	5	3	60	2	50	3	66.7	0.139	1.000
Development of Muscle Markings	3	1	33.3	1	100	2	0	–	–
Arch Criterion	5	3	60	2	100	3	33.3	0.833	1.000
Final Sex Estimate	5	3	60	2	0	3	100	1.875	0.400

Table 5. Summary of accuracy rates and chi-square values for correct sex estimates of each trait in the peak height velocity stage. Significant p-values ($p < 0.05$) are bolded. N = total number of individuals, including those with incorrect and indeterminate estimates; $\%_T$ = total accuracy, N_F = total number of females, $\%_F$ = female accuracy, N_M = total number of males, $\%_M$ = male accuracy.

Trait	N	Correct Class.	$\%_T$	N_F	$\%_F$	N_M	$\%_M$	X^2	p-value
Ilium Shape	5	5	100	2	100	3	100	5.000	0.100
Pelvic Inlet Shape	2	2	100	1	100	1	100	2.000	1.000
Pubic Bone Shape	5	4	80	2	50	3	100	1.875	0.400
Greater Sciatic Notch Angle	5	4	80	2	100	3	66.7	2.222	0.136
True Pelvis Size & Shape	2	2	100	1	100	1	100	2.000	1.000
Obturator Foramen Shape	5	5	100	2	100	3	100	5.000	0.100
Preaurciular Sulcus	5	4	80	2	50	3	100	1.875	0.400
Acetabulum Size & Orientation	5	3	60	2	50	3	66.7	2.917	0.233
Auricular Surface Height	4	3	75	1	0	3	100	–	–
Subpubic Concavity	5	3	60	2	0	3	100	–	–
Ventral Arc	5	3	60	2	0	3	100	–	–
Ischiopubic Ramus Ridge	5	3	60	2	0	3	100	–	–
Greater Sciatic Notch Size & Shape	5	3	60	2	50	3	66.7	0.139	1.000
Sacrum Shape	3	3	100	1	100	2	100	3.000	0.333
Dorsal Pubic Pitting	5	3	60	2	0	3	100	–	–
Iliac Crest Curvature	5	5	100	2	100	3	100	5.000	0.100
Development of Muscle Markings	5	2	40	2	100	3	0	–	–
Arch Criterion	5	3	60	2	100	3	33.3	0.833	1.000
Final Sex Estimate	5	4	80	2	50	3	100	5.000	0.082

Table 6. Summary of accuracy rates and chi-square values for correct sex estimates of each trait in the deceleration stage. Significant p-values ($p < 0.05$) are bolded. N = total number of individuals, including those with incorrect and indeterminate estimates; $\%_T$ = total accuracy, N_F = total number of females, $\%_F$ = female accuracy, N_M = total number of males, $\%_M$ = male accuracy.

Trait	N	Correct Class.	$\%_T$	N_F	$\%_F$	N_M	$\%_M$	X^2	p-value
Ilium Shape	14	12	**85.7**	5	100	9	77.8	7.778	**0.021**
Pelvic Inlet Shape	13	11	**84.6**	5	80	8	87.5	5.923	**0.032**
Pubic Bone Shape	14	11	78.6	5	60	9	88.9	6.862	**0.032**
Greater Sciatic Notch Angle	14	10	71.4	5	100	9	55.6	4.321	0.086
True Pelvis Size & Shape	13	8	61.5	5	40	8	75	0.325	1.000
Obturator Foramen Shape	14	10	71.4	5	60	9	77.8	1.998	0.266
Preaurciular Sulcus	14	10	71.4	5	20	9	100	1.938	0.357
Acetabulum Size & Orientation	14	12	**85.7**	5	80	9	88.9	6.644	**0.023**
Auricular Surface Height	13	12	**92.3**	4	75	9	100	8.775	**0.014**
Subpubic Concavity	14	13	**92.9**	5	100	9	88.9	10.37	**0.003**
Ventral Arc	12	10	83.3	3	33.3	9	100	3.273	0.250
Ischiopubic Ramus Ridge	13	10	76.9	5	60	8	87.5	3.259	0.217
Greater Sciatic Notch Size & Shape	14	10	71.4	5	80	9	66.7	2.800	0.266
Sacrum Shape	14	9	64.3	5	40	9	77.8	0.498	0.580
Dorsal Pubic Pitting	14	8	57.1	5	0	9	88.9	0.598	1.000
Iliac Crest Curvature	19	14	73.7	6	66.7	13	76.9	1.998	0.266
Development of Muscle Markings	14	8	57.1	5	100	9	33.3	2.121	0.258
Arch Criterion	14	7	50	5	80	9	33.3	0.280	1.000
Final Sex Estimate	14	12	**85.7**	5	80	9	88.9	10.516	**0.005**

exceed 80% accuracy for both males and females. Two of the remaining three traits marginally failed to achieve 80% for one sex over the other, whereas the ventral arc performed markedly better for males than females. A Fisher's exact test determined that the number of individuals with correct sex estimates from five of the six pelvic traits were statistically significant (Table 6). Additionally, the individuals with correct sex estimates from a final sex estimation for this pubertal stage was observed to be statistically significant using a Pearson's chi-square. Although the ventral arch achieved an overall accuracy of 83%, the number of individuals whose sex was correctly estimated using this trait was not statistically significant. The pubic bone shape marginally failed to achieve an overall accuracy of 80%. A Person's chi-square showed that the number of individuals with correct sex estimation attained using this trait was statistically significant. Additionally, the trait performed better for males than females.

Maturation

There was a substantial increase in the number of pelvic traits that exceeded the 80% threshold for overall accuracy in the maturation stage, with 13 pelvic traits meeting the criteria. The frequency of individuals with

Table 7. Summary of accuracy rates and chi-square values for correct sex estimates of each trait in the maturation stage. Significant p-values ($p < 0.05$) are bolded.. N = total number of individuals, including those with incorrect and indeterminate estimates; $\%_T$ = total accuracy, N_F = total number of females, $\%_F$ = female accuracy, N_M= total number of males, $\%_M$ = male accuracy.

Trait	N	Correct Class.	$\%_T$	N_F	$\%_F$	N_M	$\%_M$	X^2	p-value
Ilium Shape	19	18	**94.7**	6	83.3	13	100	14.792	**0.001**
Pelvic Inlet Shape	18	16	**88.9**	5	80	13	92.3	9.411	**0.008**
Pubic Bone Shape	19	19	**100**	6	100	13	100	19.000	**< 0.001**
Greater Sciatic Notch Angle	19	16	**84.2**	6	83.3	13	84.6	8.146	**0.010**
True Pelvis Size & Shape	18	18	**100**	5	100	13	100	18.000	**< 0.001**
Obturator Foramen Shape	19	17	**89.5**	6	83.3	13	92.3	10.871	**0.003**
Preaurciular Sulcus	19	17	**89.5**	6	66.7	13	100	10.978	**0.004**
Acetabulum Size & Orientation	19	18	**94.7**	6	83.3	13	100	14.702	**0.001**
Auricular Surface Height	19	15	79	6	66.7	13	84.6	4.997	**0.046**
Subpubic Concavity	19	18	**94.7**	6	83.3	13	100	14.702	**0.001**
Ventral Arc	17	15	**88.2**	4	50	13	100	7.367	**0.044**
Ischiopubic Ramus Ridge	18	16	**88.9**	6	83.3	12	91.7	10.125	**0.004**
Greater Sciatic Notch Size & Shape	19	17	**89.5**	6	66.7	13	100	10.978	**0.004**
Sacrum Shape	17	14	**82.4**	5	60	12	91.7	5.236	0.530
Dorsal Pubic Pitting	19	14	73.7	6	16.7	13	100	2.287	0.316
Iliac Crest Curvature	19	14	73.7	6	66.7	13	76.9	3.352	0.129
Development of Muscle Markings	19	15	79	6	100	13	69.2	7.892	**0.005**
Arch Criterion	19	13	68.4	6	83.3	13	61.5	3.316	0.141
Final Sex Estimate	19	18	**94.7**	6	83.3	13	100	19.000	**< 0.001**

Table 8. Summary of accuracy rates and chi-square values for correct sex estimates of each trait in the post-puberty stage. Significant p-values ($p < 0.05$) are bolded. N = total number of individuals, including those with incorrect and indeterminate estimates; $\%_T$ = total accuracy, N_F = total number of females, $\%_F$ = female accuracy, N_M= total number of males, $\%_M$ = male accuracy.

Trait	N	Correct Class.	$\%_T$	N_F	$\%_F$	N_M	$\%_M$	X^2	p-value
Ilium Shape	45	42	**93.3**	18	88.9	27	96.3	14.702	**< 0.001**
Pelvic Inlet Shape	44	43	**97.7**	17	100	27	96.3	40.016	**< 0.001**
Pubic Bone Shape	44	42	**95.5**	18	94.4	26	96.2	36.115	**< 0.001**
Greater Sciatic Notch Angle	45	41	**91.1**	18	94.4	27	88.9	30.375	**< 0.001**
True Pelvis Size & Shape	45	43	**95.6**	18	94.4	27	96.3	37.052	**< 0.001**
Obturator Foramen Shape	45	39	**86.7**	18	77.8	27	92.6	26.548	**< 0.001**
Preaurciular Sulcus	45	41	**91.1**	18	83.3	27	96.3	29.887	**< 0.001**
Acetabulum Size & Orientation	45	44	**97.8**	18	100	27	96.3	41.053	**< 0.001**
Auricular Surface Height	44	40	**90.9**	17	82.4	27	96.3	28.719	**< 0.001**
Subpubic Concavity	45	41	**91.1**	18	77.8	27	100	30.484	**< 0.001**
Ventral Arc	43	36	**83.7**	17	58.8	26	100	19.929	**< 0.001**
Ischiopubic Ramus Ridge	44	35	79.5	18	61.1	26	92.3	17.789	**< 0.001**
Greater Sciatic Notch Size & Shape	45	40	**88.9**	18	94.4	27	85.2	27.515	**< 0.001**
Sacrum Shape	44	37	**84.1**	17	76.5	27	88.9	19.258	**< 0.001**
Dorsal Pubic Pitting	44	27	61.4	17	5.9	27	96.3	0.114	1.000
Iliac Crest Curvature	45	34	75.6	18	83.3	27	70.4	12.465	**0.001**
Development of Muscle Markings	45	39	**86.7**	18	94.4	27	81.5	28.902	**< 0.001**
Arch Criterion	45	35	77.8	18	83.3	27	74.1	16.273	**< 0.001**
Final Sex Estimate	45	44	**97.8**	18	100	27	96.3	45.000	**< 0.001**

correct sex estimation for all traits, with the exception of the sacrum shape, was observed to be statistically significant (Table 7). Nine of the 12 statistically significant traits performed well for both sexes. Sex estimates using these traits either met or exceeded 80% accuracy. The remaining three traits, while achieving an overall accuracy exceeding 80%, performed substantially better on males than females, where the highest female accuracy was approximately 67%. The auricular surface height and development of muscle markings just failed to meet the 80% threshold. Despite this, a substantial sex bias was observed for both traits, where accuracy rates were higher for males than females using the auricular surface height and the opposite pattern was observed using development of muscle markings. The overall sex estimate for this pubertal stage achieved a high accuracy (approximately 95%) and performed well on both sexes. The number of correct sex estimate using all 18 traits was observed to be statistically significant using a Fisher's exact test.

Post-puberty

Fourteen traits achieved an overall accuracy that exceeded the 80% in post-pubertal individuals. The number of individuals whose sex was correctly estimated for each of the 14 traits was observed to be statistically significant (Table 8). Ten of those traits

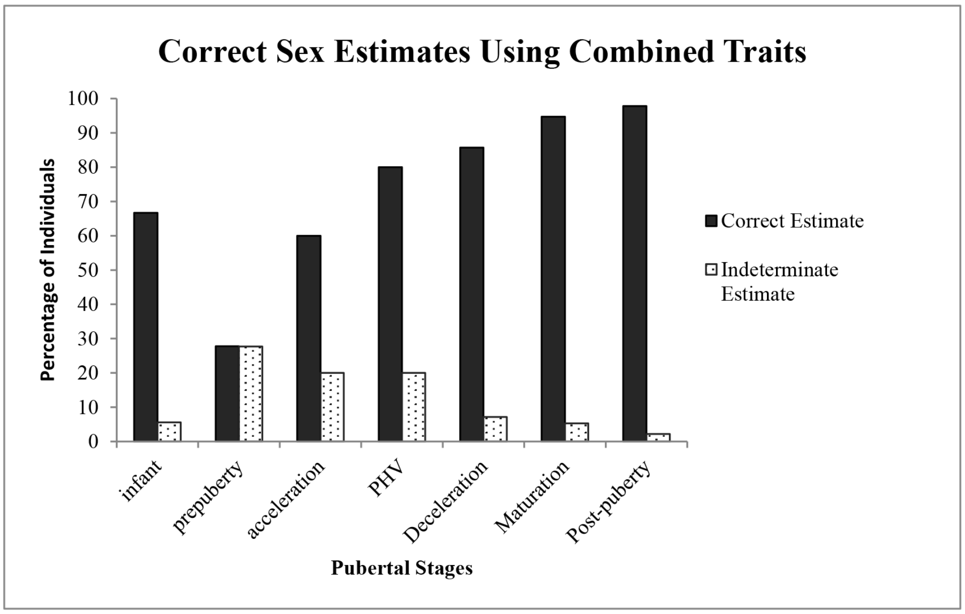

Figure 2. Percentage of correct sex estimations and indeterminate estimates for each pubertal stage

performed well for both males and females, where both sex-specific accuracies surpassed 80%, while four traits exhibited a male bias. The ischiopubic ramus ridge, iliac crest curvature, and arch criterion did not meet the minimum threshold set out in this study. A Fisher's exact test showed that sex estimates obtained using these traits were observed to be statistically significant. Despite this, the latter two traits (iliac crest curvature and arch criterion) performed better in females than males whereas the former trait exhibited the opposite pattern. Dorsal pubic pitting was the only trait in the post-puberty stage that performed poorly and sex estimates were not statistically significant. Similar to the previous two pubertal stages, the final sex estimate using all traits achieved a high overall and sex-specific accuracies. The sex estimates obtained using all 18 traits were observed to be statistically significant.

Overall, the percentage of correct sex estimates obtained when all 18 pelvic traits are used increases from the pre-puberty stage to the post-puberty stage. While the percent of indeterminate cases is equal to the percent of correct sex estimates in the pre-puberty stage, the percentage of indeterminate cases gradually decreases and becomes very minimal by the post-puberty stage (Fig. 2).

Discussion

Adolescence is a crucial period in human growth for biological and social reasons (Arthur et al. 2016; Bogin 1999; Rogers 2009; Shapland and Lewis 2013). Biologically, puberty is a time that marks a person's sexual maturity and outward signs of this growth process appear, such as deepening of the voice and body hair growth in males, and breasts beginning to develop in females, as well as the inception of menarche (Bogin 1999). In times when chronological age was not rigorously recorded, these biological changes would mark a child's transition into adulthood, thereby leading to a shift in their social identity (Arthur et al. 2016; Bogin 1999). The pubertal period has also been identified as a critical period in which sexual dimorphism in the human pelvis begins to develop until its full expression in the post-pubertal period (Klales and Burns 2017; Rissech and Malgosa 2005; Rogers 2009). The results of this study, however, provide a nuanced understanding of the relationship that exists between pubertal development and the expression of sexual dimorphism in the pelvis.

This research suggests that nine morphological pelvic traits show some promise of having high accuracy in the determination of sex, during the peak height velocity stage (PHV). The results obtained for the ilium shape and pelvic inlet shape for adolescents in the PHV stage may, in fact, truly be promising given that the decrease in accuracy seen between PHV and deceleration still yield high accuracies in the latter pubertal stage. In comparison, the remaining seven seemingly promising traits (pubic bone shape, greater sciatic notch angle, true pelvis size & shape, obturator foramen shape, preauricular sulcus, sacrum shape, and iliac crest curvature), demonstrate a marked decrease in accuracy in the deceleration stage to the extent that the accuracies do not meet the 80% threshold set out in this study. The sex estimates obtained using these traits were not observed to be statistically significant in the deceleration stage. It is therefore likely that the patterns observed in the PHV stage for the seven traits are a reflection of low sample size in this pubertal stage (n = 2-5) and may not be truly promising. Further examination of these traits on a skeletal collection with a higher number of adolescents in the PHV stage may clarify these results.

The ilium shape, pelvic inlet shape, acetabulum size and orientation, and subpubic concavity can all be applied to adolescents in the deceleration stage with confidence given that the accuracy of these traits range from 84.6% to 92.9%. The correct sex estimates obtained using these traits were observed to be statistically significant. All four traits increase in accuracy as pubertal stages progress, suggesting that the dimorphism of these traits becomes more pronounced throughout development. By the deceleration stage, the accuracy for ilium shape attained in this study becomes comparable to that found in adults, 83.7%, by Rogers and Saunders (1994). Acetabulum size and orientation, however, does not achieve an accuracy that is comparable to adults, 91.7% per Rogers and Saunders (1994) until the maturation stage (94.7%). Given that the ilium shape and acetabulum size and orientation have not been examined from an ontogenetic perspective, comparisons relating to growth cannot be made. Klales and Burns (2017), however, conducted an ontogenetic investigation on the utility of the subpubic concavity in non-adults. In their study, the authors demonstrated that the subpubic concavity could provide an accuracy of approximately 85% in adolescents 12.6 to 15.5 years of age, and 97% accuracy among 15.6 to 20.5 year olds. While the age ranges are not directly comparable between Klales and Burns (2017) and this study, there is some overlap in ages since the deceleration stage in this study includes 14 to 19 year olds, sexes combined. Unlike Klales and Burns (2017), the female expression of the subpubic concavity was not observed in females under 14 years of age. The slight age differences between Klales and Burns (2017) and this study may reflect differences in data sets given that the former study was performed on radiographs of modern non-adults born after 1990. As a result, the patterns found by Klales and Burns (2017) may demonstrate secular trends in growth and development, which tend to lower the age of puberty and may lead to an earlier appearance of sexual dimorphism in contemporary samples. While the morphology of the pelvic inlet has not been examined in adolescents, metric changes in pelvic cavity dimensions have been explored. Studies have shown that among 18 year olds, females have larger pelvic cavity and birth canal dimensions, which seems to occur between 8 and 18 years of age (Arsuaga and Carretero 1994; Fornai et al. 2021; Huseynov et al. 2016; LaValle 1995). These observations are further corroborated in this study, since high accuracy was found for the pelvic inlet shape in the adolescents in the deceleration stage (14–19 year olds). Therefore, it is possible that by 14 years of age the size differences in the pelvic inlet between males and females are pronounced enough to visually differentiate the two sexes.

Pubic bone shape, greater sciatic notch angle, true pelvis size and shape, and obturator foramen shape can all be applied confidently as of the maturation stage. The results obtained for the pubic bone shape in this study differ slightly compared to previous research. Bilfeld and colleagues (2015) demonstrated that significant sex differences in the pubic bone are apparent after 13 years of age, although shape differences can be seen as young as 9 years of age. Although significant differences in pubic bone shape were seen in the deceleration stage (12–15 year olds), the trait failed to meet the criteria for accuracy set forth in this study. Therefore, given that the age range for the maturation stage in this study corresponds to 17 to 20 year olds, sex estimation with high accuracy is obtained at a much older age compared to Bilfeld and colleagues (2015). However, unlike Bilfeld and colleagues (2015), sex differences in pubic bone shape were not observed in anyone below 12 years of age in this study. It is possible that differences in the source of data, three-dimensional reconstructions versus dry bone observation, may account for the different patterns observed between Bilfeld and colleagues (2015) and this study. The accuracy achieved in the maturation and post-puberty stages when using the pubic bone shape exceeds the adult accuracy obtained by Rogers and Saunders (1994), which may be the result of population differences in the appearance and level of expression of sexual dimorphism. Given that the greater sciatic notch angle is a trait proposed specifically for non-adult sex estimation, this trait has not been examined in adolescents. This study, however, shows that this trait could be of use for sex estimation of adolescents in the maturation and post-puberty stages. The patterns observed for the true pelvis size and shape substantiate previous studies that have suggested that among 18 year olds, females have larger pelvic cavity and birth canal dimensions (Fornai et al. 2021; Huseynov et al. 2016; LaValle 1995; Wood and Chamberlain 1986). Dimorphism in the obturator foramen becomes pronounced enough for accurate sex estimation in the maturation and post-puberty stages (89.5% and 86.7%, respectively), but the accuracy achieved in this study does not reach the level seen in adults, approximately 94% (Rogers and Saunders 1994). Although the use of the obturator foramen shape for sex estimation has been cautioned until extensive tests of validity and reliability are conducted for this trait (Klales 2020), the level of dimorphism observed in this study suggests visual examination of this trait may be conducted with confidence in individuals as young as 17 years of age.

The preauricular sulcus, auricular surface height, greater sciatic notch size & shape, and development of muscle markings are traits that do, in fact, become sufficiently dimorphic only once the post-pubertal stage has been reached. The accuracy obtained for the preauricular sulcus (91%) and greater sciatic notch size and shape (89%) are comparable to the accuracies achieved for adults when tested by Rogers and Saunders (1994), 91.6% and 86%, respectively. Auricular surface height and development of muscle markings performed markedly better in this study compared to the accuracies obtained by Rogers and Saunders (1994). The pattern of increasing accuracy with age that is observed for the auricular surface, however, mirrors Mittler and Sheridan's (1992) observations. The authors found that accuracy of the auricular surface height (elevation) increased particularly in females between 14 and 18 years of age. Contrary to this study, the increase in accuracy found by Mittler and Sheridan (1992) did not reach 80% and the authors cautioned the use of this trait in a population setting. Despite meeting the criteria set forth in this study, the use of muscle markings should be used with caution since they tend to be heavily linked with age, activity pattern, and body size (Klales 2020). This trait should, therefore, not be used in isolation and only in conjunction with other pelvic indicators of sex.

Dorsal pubic pitting, ventral arc, iliac crest curvature, and arch criterion all proved to be ineffective for sex estimation in all pubertal stages and should not be used for skeletal sex estimation of adolescent remains. It is not unexpected that the dorsal pubic pitting performed poorly given that this trait has also performed poorly on adult previous studies and is a trait that is no longer encouraged for sex estimation of skeletal remains (Ashworth et al. 1976; Maass and Friedling 2016; McFadden and Oxenham 2018; Rogers and Saunders 1994). The high accuracy in the infant category when using dorsal pubic pitting is likely an artifact of its absence representing the male expression and is not a true representation of sexual dimorphism. The ventral arc, despite achieving overall accuracies of above 80% beginning in the deceleration stage, consistently performed well for males but poorly for females (highest accuracy = 59%). However, observations in this study mirror those of Sutherland and Suchey (1991) where the precursor arc appeared at 14 years of age and was the primary form of expression observed in the individuals examined. Although the presence/absence of the ventral/precursor arc does not perform equally well for males and females, the presence of the ventral/precursor arc holds more predictive value than the absence of the arc does. Overall correct female sex classification may be low for this trait, but the presence of the arc was exclusively seen in females. Therefore, although not all females may have exhibited the ventral or precursor arc, males never exhibited this trait, which was also observed by Sutherland and Suchey (1991). As a result, there is a level of certainty that when an individual exhibits the ventral/precursor arc, they are female, but absence of the trait is less clear. Finally, despite being a trait proposed for non-adult sex estimation, the arch criterion consistently performed poorly in this study, which mirrors the poor accuracy this trait exhibited when tested on individuals less than 15 years of age by Cardoso and Saunders (2008) and in infants by Olivares and Aguilera (2016). The poor results obtained for the arch criterion and iliac crest curvature may be the result of subtle differences in the expression between the sexes. The subtle sex differences of these traits do not seem to become more pronounced with age and should not be used for sex estimation.

The majority of traits, with the exception of ilium shape and greater sciatic notch angle, exhibiting the earliest levels of substantial dimorphism are anterior pelvic traits associated with the lesser (true) pelvis. These features (i.e., pubic bone shape, subpubic concavity, and obturator foramen shape) are believed to be partially responsible for the widening of the hips in females for parturition, which may account for their early expression. This mirrors patterns found by Fornai and colleagues (2021) who found a high degree of bone remodeling in the lesser pelvis of adolescent females. In contrast, traits exhibiting a high level of dimorphism in the post-puberty stage, or late dimorphic traits, tend to be posterior traits, such as auricular surface height, sacrum shape, and greater sciatic notch size and shape, and in an area that has been associated with sex-specific adaptations to bipedal locomotion (Brůžek 2002). However, given that early dimorphic traits are not exclusively anterior pelvic traits, sex estimates using all 18 traits is ideal. In the event that preservation of the pelvis allows for the observation and scoring of most, if not all, of the 18 traits examined in this study, substantial accuracy for a sex estimate using a "majority rule" approach can be achieved in adolescents beginning in the deceleration stage. The accuracy for a final sex estimate increased as pubertal stages advanced. Moreover, the sex estimates obtained were observed to be statistically significant by the deceleration stage. Overall accuracy for final sex estimates reached the 80% threshold in the PHV stage, but this may reflect the small sample size in that stage (n = 5) since the correct sex estimates obtained were not statistically significant. A higher number of adolescents in the PHV stage could help determine whether the high accuracy observed is, in fact, promising.

The patterns observed in this study demonstrate that examining the expression of sexual dimorphism in the pelvis in relation to pubertal stage development is beneficial for obtaining a more nuanced understanding of when dimorphism becomes pronounced enough to yield accurate estimates of sex. Through this approach, this study has demonstrated that the post-pubertal period is not necessarily required for the full expression of all pelvic traits. Peak height velocity appears to be the critical stage required to surpass in order to exhibit pronounced dimorphism in some traits, where accuracy increases in subsequent stages. Applying this approach can further be beneficial for non-adult sex estimation given the secular trends in puberty seen with lower ages of menarche, testicular volume, and breast development (Arthur et al. 2016; Henderson and Padez 2017; Stull et al. 2020). As a result of these secular trends in puberty, accurate sex estimations in contemporary populations could be possible for individuals younger than those in this study (12–14 years of age). Population variation should also be taken into consideration since secular trends seen in the onset of puberty have also been attributed to differences in environmental conditions (Stull et al. 2020). As a result, adolescents living in favorable environments may reach each pubertal stage earlier than observed in this study, thus resulting in accurate sex estimates for young adolescents or older children. The non-adults incorporated in this study represent low socioeconomic status individuals (Alioto 2020) and the results obtained are likely reflective of those who did not live in optimal conditions. It is possible then, that the patterns observed in this study are comparable, and therefore of use, to bioarchaeological populations living in conditions of overcrowding and poor sanitation, which are the conditions the non-adults of the Hamann-Todd and Terry collection lived in (Alioto 2020). Linking observed sex traits to clear morphological indicators of puberty, irrespective of estimated biological age, is critical, then, given that the various stages of puberty can be quite variable in terms of age of attainment both between and within a population or sex. The utility of a maturation-based approach to understand the development of sexual dimorphism was also shown by Corron and colleagues (2021). While Corron and colleagues (2021) used a sex estimation method not examined in this study (i.e., Santos et al. 2019), they demonstrated that accurate sex estimations could be achieved in individuals by examining the fusion state of four pelvic epiphyses (ischiatic tuberosity, the triradiate cartilage, superior acetabular epiphysis, and antero-superior iliac spine). When these epiphyses are fusing or fused, which corresponded to individuals as young as 13 to 14 years of age, sex estimation exceeding 90% accuracy was achieved. Although Corron and colleagues (2021) examined computed tomography (CT) scans of contemporary individuals, both the present study and theirs showed that sufficient sexual dimorphism could be achieved only after a certain degree of maturation is reached. Both studies also show that a maturation approach has the potential to incorporate younger individuals than previously thought. Using a maturation-based approach, in this instance pubertal stages, when examining the expression of sexual dimorphism in non-adults can, therefore, effectively account for the substantial age variability and provides an avenue of investigation that avoids the issues associated with using "traditional" or *a priori* age groupings (Stull et al. 2020; Wilson and Humphrey 2017). This is particularly important for bioarchaeology given that chronological age is unknown and cannot always be accurately estimated, and secular trends in development exist. The successful application of pubertal stage analysis already demonstrated in bioarchaeology (Arthur et al. 2016; DeWitte and Lewis 2020; Doe et al. 2019, 2021; Henderson and Padez 2017; Lewis et al. 2016a, 2016b) and the comprehensive list of pelvic traits examined in this study that accounts for differential preservation of the pelvis in archaeological contexts, suggests that the approach utilized in this study to understand the threshold of when accurate sex estimation can be achieved could be useful in bioarchaeology. If this approach to sex estimation is applied to archaeological skeletal assemblages, more nuanced reconstructions on how puberty and the social transitions associated with this developmental period were experienced between the sexes can be made with more confidence, particularly for adolescents in the deceleration, maturation, and post-pubertal stages.

Although this study demonstrated that the post-pubertal period is not necessarily required for the full expression of sexual dimorphism, it has substantiated the claim that dimorphism prior to puberty may be minimal at best. This is confirmed by the lack of sex differences existing in the infant, pre-puberty, and acceleration groups. The five traits that exhibited high overall accuracy in the youngest developmental group only reflected high male sex classification accuracy since female sex classification was poor (0%). Correct classification of females continued to be very low in the pre-puberty and acceleration stages, demonstrating that sufficient time since the onset of puberty must pass before dimorphism becomes pronounced. Given that the male expression of many pelvic traits is the absence of feature, and time is required for the presence of a trait to appear, which tends to be the female expression, many pelvic traits are not truly dimorphic until the male *and* female expressions are formed. Since many female pelvic traits do not develop until the early teenage years (Sanchez 2021), the absence of a trait (male expression) will artificially inflate the accuracy for male sex estimation than the presence of a trait (female expression) in younger individuals. Thus, the high male sex classification in the young developmental stages (prior to the deceleration stage) likely reflects the period prior to the divergence of male and female forms of a trait. The results of this study show that, since the average age of the acceleration stage occurred at 10 years in females and 12.3 years in males, and the deceleration stage was attained at 15.2 and 17.9 years of age, respectively, pronounced dimorphism may take approximately 5 to 6 years after accelerated growth has begun to manifest and yield accurate sex estimates.

The patterns observed in this study could, of course, be impacted by two common issue researchers encounter when studying non-adult remains: unequal sampling of ontogeny and uneven distribution of males and females (Wilson and Humphrey 2017). An attempt to mitigate the impacts of the latter issue was made through statistical testing of the accuracies obtained in each pubertal stage. The unequal sampling of ontogeny, however, has likely clouded any definitive patterns for the acceleration and PHV stages because of their low sample sizes (n = 5). Moreover, some ages are represented by only one sex, 12 and 14 year olds only represented by females, 13 and 15 year olds only by males, which may further impact the results obtained for the pubertal stages. Despite these limitations, patterns still emerge and are observed at statistically significant levels. Moreover, the approach used in this study could be applied to different populations since universal markers of puberty are used and can be scored on an individual from any population, thereby ensuring its applicability. As a result, further research on skeletal collections with larger numbers of adolescents, such as the Luis Lopes, Coimbra, or Certosa Collections, in the acceleration and PHV stages could help ascertain more definitive patterns of the expression of sexual dimorphism in the pelvis and clarify if any of the promising traits observed in these stages can, in fact, be used for sex estimation.

Conclusion

Sex estimation is a critical component of the biological profile and the novel approach used in this study to investigate the developmental period during puberty at which pelvic sex differences manifest provides a new avenue that could be applied and help re-conceptualize the way non-adult sex estimation methods are explored. While sex estimation remains the “holy grail” (Lewis 2007) for those under 14 years of age, the results of this study provide a better understanding of the complexity of the development and full manifestation of sexual dimorphism in the pelvis. This study provides evidence that, while surpassing peak height velocity appears to be the critical stage for sufficient dimorphism to be observed in the pelvis, not all pelvic traits fully manifest sex differences at the same time, and must be taken into consideration when conceptualizing future studies. Additionally, this research has shown that pubertal stage analysis could provide a means to incorporate young individuals for sex estimation. Applying a developmental approach, through the use of pubertal stage analysis, has proven to be an effective strategy to explore sexual dimorphism in non-adults that considers sexual dimorphism in terms of sexual maturity and avoids the common pitfall of underrepresentation or masking ontogenetic changes that occurs when arbitrary age-cohorts are used. This approach is, therefore, beneficial for bioarchaeological contexts where chronological ages are unknown and age estimates may not always be accurate. When pubertal stage analysis and estimates of sex are combined, nuanced sex differences in the adolescent experience can be reconstructed in past populations with higher confidence. Further research is recommended to determine if the patterns observed in this study are found using documented skeletal collections elsewhere.

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