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# The outline of the pubic symphyseal surface is sexually dimorphic and changes with age in humans

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**Summary -** *The bony symphyseal surface is an important trait for age-at-death estimation from human skeletal remains. In this paper, we demonstrate for the first time that the outline of the human symphyseal surface is sexually dimorphic and that it changes with age. We present a geometric morphometric analysis based on a sample of 323 symphyseal pubic bones from males and females in the age range of 14 to 82 years. These bones were surface-scanned and the resulting surface models were measured along the ventral and dorsal borders of the symphyseal surface using two fixed and 36 curve semilandmarks. Our findings imply that age-related changes in the outline of the symphyseal surface differ between the sexes. According to our results age explains 5% of total shape variation in females, but less than 1% in males. These findings for the outline, could potentially complement existing sex and age-at-death estimation methods based on other features of the bony pubic surface.*

**Keywords** - *Geometric morphometrics, Pubic symphysis, Sex and age estimation, Ontogeny.*

## Introduction

The human pubic symphysis joint consists of a fibrocartilaginous disc, which fills the gap between the bony surfaces of the two pubic bones in the pelvis (Rosse and Gaddum-Rosse 1997). The symphysis is a robust joint that is highly resistant to sheering and compression and only capable of little movement in adults (Becker et al. 2010). In human pregnancy, the joint widens to allow for greater flexibility during childbirth. Various mammalian species have evolved a strongly sexually dimorphic pubic symphysis to accommodate different reproductive functions in males and females, as only females need to be able to give birth (Grunstra et al. 2019). In humans, the pelvis is the most sexually dimorphic region of the skeleton, and sexual dimorphism in the pelvis is well studied (e.g., Tague 1992; Arsuaga and Carretero 1994; Walrath and Glantz 1996; Kurki 2011; Fischer and Mitteroecker 2015, 2017). However, so far, it has not been assessed if the shape and size of the outline of the symphyseal bony surface are sexually dimorphic in humans, which is the objective of this study.

The symphyseal surface of the pubis is the most commonly chosen feature for age-at-death estimation based on skeletal remains (Garvin and Passalacqua 2012). An accurate estimation of sex and age of a skeleton is one of the principal goals in physical and forensic anthropology as sex and age are two of the four essential components of the biological profile, with ancestry and stature remaining. Any positive identification of skeletal remains will depend on these four parameters (Steadman et al. 2006; Konigsberg et al. 2008; Algee-Hewitt 2017).

Various methods for age-at-death estimation have been developed in the last 100 years (Todd 1920; Gilbert and McKern 1973; Brooks and Suchey 1990), and further improved thanks to technological advances in medical imaging and multivariate statistics (e.g., Pasquier et al. 1999; Stoyanova et al. 2015, 2017). When scientists noticed that the symphyseal surface of the pubis exhibits age-related morphological changes, they developed methods based on these changes for the purpose of age-determination of human skeletons. Todd (1920) established a system of 10 different phases based on macroscopic changes of the articular surface of the pubis, which is still in use to date. Brooks and Suchey (1990) reduced Todd's system to 6 overlapping phases. The overlap between the last ones of these 6 phases is rather large, resulting in coarse estimations (estimates spanning more than 20 years). Additionally, qualitative visual comparison between a model feature, often shown in a picture, and the actual skeletal material makes this phase-related estimation somewhat subjective. For example, the quality of the estimation depends crucially on an individual researcher's skills to identify and access an appropriate reference sample (Soto et al. 2018). Algorithms for age-at-death estimation try to reduce this subjective element (see e.g., Stoyanova et al. 2015, 2017; Kim et al. 2019). The macroscopic characteristics that the classic age-at-death estimation methods use are (i) the transformation from a billowed and irregular symphyseal surface typical for young individuals to a flatter one at around 35 years old, (ii) the formation of a ventral rampart and an outer rim with age, and (iii) the transition of the bone texture from uneven and granular to fine grained or dense along the maduration process. After these changes, further degenerative changes associated with old age affect the articular surface and produce more irregular and eroded aspects (Todd 1920; McKern and Stewart 1957; Meindl et al. 1985; Brooks and Suchey 1990).

For sex estimation based on the pubic bone the situation is quite similar. Phenice's method for sex identification (Phenice 1969) depends on a visual qualitative comparison of the sample with a model with respect to the ventral arc, the subpubic concavity and the medial aspect of the ischiopubic ramus. The outline of the pubic symphyseal surface is difficult to compare accurately by visual examination, which might be a reason why it has not been integrated so far in sex and age-at-death estimation methods.

In medicine, the pubic symphysis is relevant for orthopedics as well as obstetrics, as this joint needs to maintain the stability of the pelvic girdle while allowing for a certain degree of flexibility, particularly in pregnancy and birth (Becker et al. 2010). Instability of the pelvic girdle can, for example, cause exercise-related symphyseal pain in athletes or pelvic girdle pain in pregnant women (Becker et al. 2010). In late pregnancy, hormonal excretion of estrogen and relaxin softens and widens the pubic symphysis and sacro-iliac joint in preparation for birth (Schwabe and Büllesbach 1990; Becker et al. 2010), which can lead to instability of the pelvic girdle and cause significant pain for the affected women when walking (Becker et al. 2010). Under intense strain during birth, widening or even rupture of the pubic symphysis joint can occur, resulting in an enlarged gap between the pubic bones called symphysis diastasis (Boland 1933; Petersen and Rasmussen 1992; Becker et al. 2010; Chawla et al. 2017). Such a gap at the symphysis is a disabling and painful condition that requires treatment and, in some cases, even surgery (Vleeming et al. 2008). At birth, the pelvis is unfused and three primary ossification centers are present in each os coxa: those giving rise to the ilium, ischium and pubis (Wall-Scheffler et al. 2020). These are later followed by several secondary ossification centers that fuse in a temporal sequence by adulthood (Verbruggen and Nowlan 2017). Although subtle sexual dimorphism in the pelvis is present already in early ontogeny, the majority of the sex differences appear during adolescence (Cunningham et al. 2016, Verbruggen and Nowlan 2017). Females generally show growth and maturation in the pelvis during the adolescence earlier than males (Wall-Scheffler et al. 2020). Different pelvic growth trajectories in females and males from puberty to 25-30 years of age lead to larger obstetrically relevant dimensions in females (Huseynov et al. 2016).

Because of the central role of the pelvis and symphysis for biomechanics and birth, the overall morphology of the pelvis (Fischer and Mitteroecker 2015, 2017; Huseynov et al. 2016; Torres-Tamayo et al. 2018) and particularly of the pubis (Lottering et al. 2014; Slice and Algee-Hewitt 2015; Estévez et al. 2017; Mallard et al. 2017) has been thoroughly studied. However, the symphyseal surface of the pubis itself is difficult to measure quantitatively because of the absence of clear anatomical measurement points on this surface. Here we focus on the morphology of the outline of the symphyseal surface using predominantly curve semilandmarks (Gunz and Mitteroecker 2013). The dorsal and the ventral borders of the symphyseal bony surface change through adult life (Todd 1920). In this study, we track these age-related changes using geometric morphometric techniques.

The aims of this study are (1) to explore if the shape of the outline of the human pubic symphysis is sexually dimorphic, (2) to assess if and how sexual dimorphism of the symphyseal surface varies with age, and (3) to identify if the outline of the symphyseal surface could be informative for age-at-death estimation.

## Material and methods

This study is based on pubic bones from a skeletal collection at the Laboratory of Anthropology and the Institute of Legal Medicine in Granada, Spain. The skeletons stem from the late 20th and the 21st century. Sex, age, cause of death, and certain pathologies of the persons are known and the age-at-death of these individuals ranges from 14 to 69 years in females and from 15 to 82 years in males. Information about parturition status and stature was not available for the individuals.

For this study, the left symphyseal surface of the pubis of 117 females and 206 males was measured. Complete ossa coxae were not available but partial pubic bones, obtained from autopsies, were used. We scanned left pubic bones only, because the sample size was larger for the left than for the right side, and produced 3D surface models of the symphyseal surfaces using a surface scanner (Artec Spider, Artec group). Every individual pubic bone was positioned on a turning table and scanned in one full rotation.

For each individual, we collected 38 landmarks (two anatomical landmarks and 36 curve semilandmarks) on the dorsal and ventral margin of the symphyseal surface of the pubis. The first anatomical landmark was defined as the point where the margin of the symphyseal surface forms an edge with the upper surface of the pubis, where it meets the pubic crest (Fig.1). The second anatomical landmark was defined as the point at the edge of the symphysis where it falls away from the insertion of the subpubic ligament, which is usually visible as a mark on the bone. These two landmarks were connected by two curves of semilandmarks formed by 18 points each. Jointly, these 38 landmarks defined the outline of the symphysis (Fig. 2).

We assigned landmarks on the symphyseal surface models in 3D, using the software Viewbox 4 (www.dhal.com). Then, the 3D semilandmarks were slid along the outlines to the Procrustes average by minimizing the bending energy between each specimen and the sample mean (Gunz et al. 2005; Gunz and Mitteroecker 2013). After that, we projected the 3D point configurations onto a least-squares-fitted plane to the landmarks for each individual using Wolfram Mathematica 12. This resulted in a configuration of 38 2D landmarks per individual. After the 2D projection, the semilandmarks were slid again in 2D to their average by minimizing the bending energy between each specimen and the sample mean (Gunz and Mitteroecker 2013). Resliding was carried out in R (R-Core Team 2017) using the package morpho (Schlager 2017).

We considered the biometric variables sex (male or female) and age-at-death (in years) in our analysis of the landmark data. We additionally divided age into four groups that corresponded to the different states of the development of the symphysis as described by Meindl et al. (1985). Note that the allocation to age groups A-D is not 100% accurate in terms of actual age, but instead follows Meindl's (1985) descriptions.

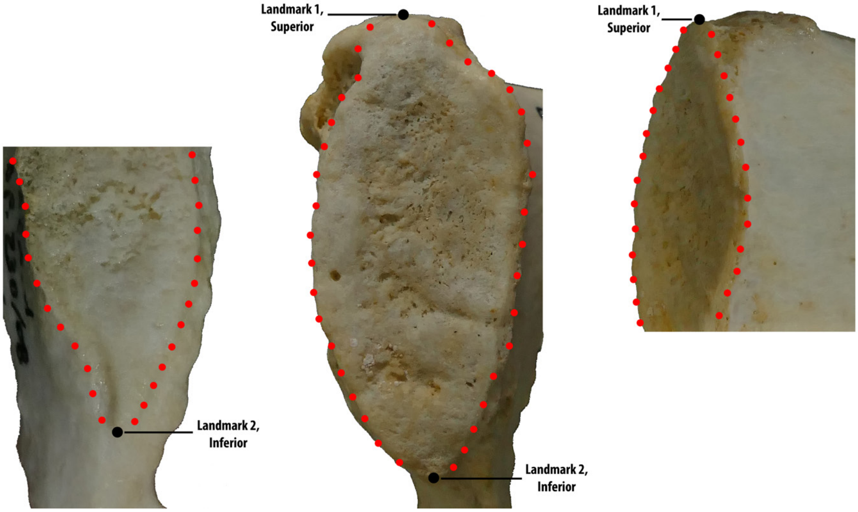


***Fig. 1** - Landmark template for the outline of the pubic symphysis surface. The template of 38 points consists of two anatomical landmarks (black), positioned in the most superior and most inferior parts of the articular surface, and 36 semilandmarks (red), placed along the outline of the symphyseal surface.*

Group A: 14 to 29 years; this is what Meindl described as "preepiphyseal phase". The billowed surface of the symphysis suffers the most important changes. Our sample consisted of 45 males and 27 females in this age group.

Group B: 30 to 40; this group is formed by Meindl's "active epiphyseal phase" and "immediate postepiphyseal phase"and corresponds to the ventral rampart formation and its textural transition of the ventral border from uneven and granular to fine grained or dense (46 males, 26 females).

Group C: 41 to 49; corresponds to the last pre-degenerative changes and the dormant period of the symphysis. The first degenerative changes that we can find in this group start at the dorsal margin (46 males, 22 females).

Group D: 50 to 82; the possible changes occurring in this group are chaotic and depend on many factors unrelated to the maturation. Lipping and the breakdown of the borders are the principal changes that we can find along the outline of the symphysis (69 males, 42 females).

For the analysis of symphysis outline shape, variation due to position, orientation, and size was removed from the landmark data by Procrustes superimposition (Gower 1975). The resulting shape coordinates were subjected to principal component analysis (PCA).

Based on the PC scores, we computed group means for the four age groups, separately for the sexes. We then plotted the ontogenetic trajectories based on the group means along the first four PCs, separately for females and males. To test for the effects of sex and age group on symphysis outline shape, we performed a Procrustes ANOVA of the shape coordinates (Goodall 1991; Anderson 2001).

Subsequently, we computed shape regressions (multivariate regressions), independently for females and males, using age as a continuous explanatory variable instead of the discrete age groups as used previously. These multivariate regressions produce vectors of regression coefficients that describe how all of the symphysis outline shape dimensions change together in response to one unit change in age (one year). We tested for statistical significance of these regressions using permutation tests (Good 2013).

## Results

The age distributions for males and females overlapped almost completely (males: mean age = 42.05, SD = 13.14, females: mean age = 41.95, SD = 14.33; in years), confirming that the male and female samples were comparable in terms of their age distributions and therefore suitable for the further analysis.

The size of the symphyseal bony surface was larger in males than in females, on average, both in terms of centroid size (males: mean = 87.54, SD = 7.8; females: mean = 80.01, SD = 7.22) and symphysis length, measured as the distance between anatomical landmarks 1 and 2 (males: mean = 40.19, SD = 3.8; females: mean = 37.45, SD = 3.43; in mm). To what extent the symphysis size differences were a consequence of overall body size differences between the sexes could not be determined based on our data, as we did not have a symphysis-independent measure of body size.

In our analysis of symphysis outline shape, the first 4 PCs jointly explained 77.4% of the total variance (PC 1: 38.4%, PC 2: 22.1%, PC 3: 9.2% and PC 4: 7.8%; Fig. 3). Sex differences were predominantly captured by PC 1.

The trajectories of the sex means across age groups supported this finding and indicated that the sex divergence along PC 1 occurred largely between age groups A and B (Fig. 4a,b). PC 2 contributed to the sex differences, while the shape changes with age captured by PC 3 and PC 4 were similar between the sexes.

Visualizations of the shape change of the outline of the symphysis based on deformation grids (Bookstein 1997) indicated that PC 1 corresponded to the relative width of the symphysis (Fig. 5). PC 2 described bulging of the superior part of the ventral margin of the symphysis, relative to its width. PC 3 corresponded to bulging in the middle of the ventral margin of the symphysis, relative to the width of the superior and inferior parts. PC 4 described the width of the inferior part of the symphyseal surface relative to the superior part (Fig. 5).

Based on the two-way Procrustes ANOVA, we identified a significant sex difference in symphysis shape ($F$ = 7.196, $p$ = 0.014), but shape differences between age groups were not statistically significant ($F$ = 0.788, $p$ = 0.49), neither were interactions between sex and age group (F = 1.767, p = 0.146). As the previous results suggested that shape change with age might be more pronounced in females, we also tested for differences between age groups in the female sample alone, but again found no statistically significant differences (F = 2.07, p = 0.102).

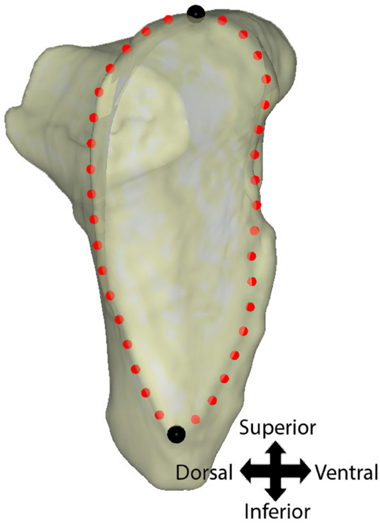


***Fig. 2** - Landmark template for the outline of the left pubic symphysis surface, consisting of 38 points. The anatomical landmarks are colored in black and the dorsal and ventral semilandmark curves, which contain 18 semilandmarks each, in red.*

However, using age as a continuous variable in the shape regressions identified significant associations between symphysis shape and age for both males and females (permutation tests with 1000 permutations, p<0.001 for females, p<0.01 for males). Based on these regressions, age explained 5% of the total variance in symphysis outline shape in females, whereas in males, it explained only 0.7%. Additionally, there was a lot of individual variation around the mean age patterns in both sexes (Fig. 6). Visualizations of symphyseal surface outline shape with respect to age based on these regressions indicate that

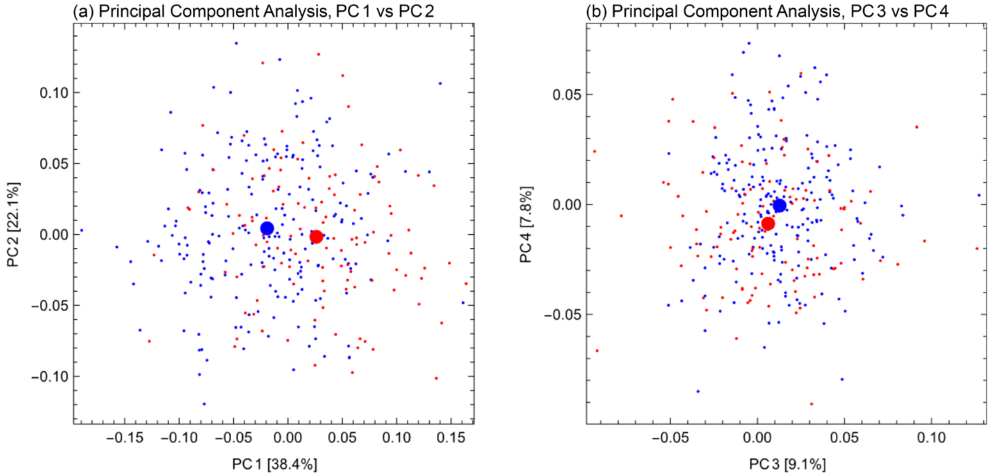


***Fig. 3** - Mean sex differences in symphysis outline shape. Principal component analysis of the individual shape data, PC 1 and PC 2 are shown in (a) as well as PC 3 and PC 4 in (b), females in red and males in blue. Each small point corresponds to an individual. Sex means are shown as large points in the same colors. Sex differences are captured predominantly by PC 1.*

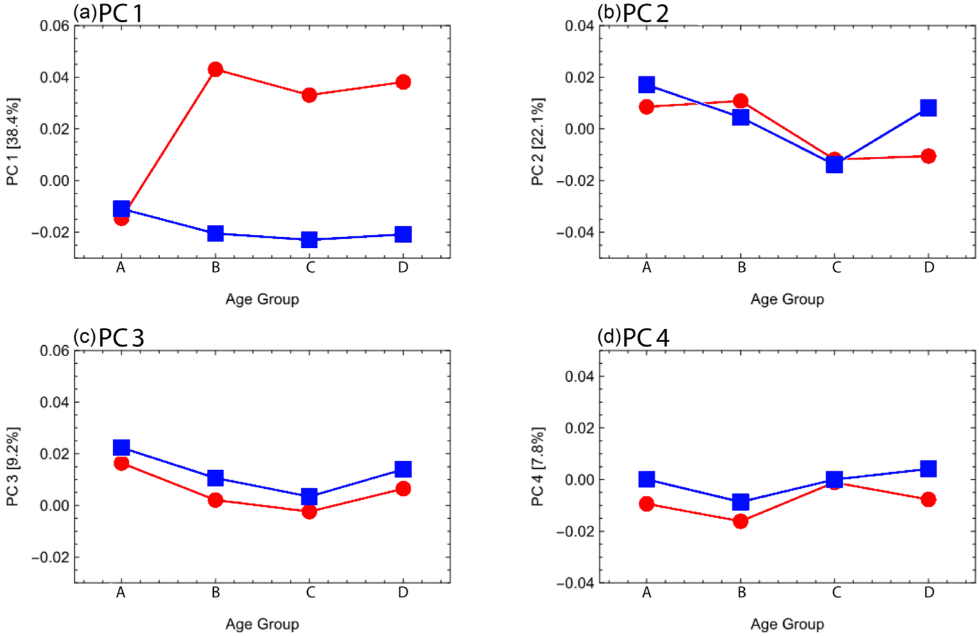


***Fig. 4** - Trajectories of shape change in symphysis outline shape with age, separately for females (red) and males (blue). Shown are the PC scores mean female and male shapes across age groups A-D for PC 1 (a), PC 2 (b), PC 3 (c), and PC 4 (d). The difference along PC 1 emerges with the second age group (30-40 years). Females have consistently lower scores along PC 3 and PC 4, but the age-related changes that are captured by these axes are similar between the sexes.*

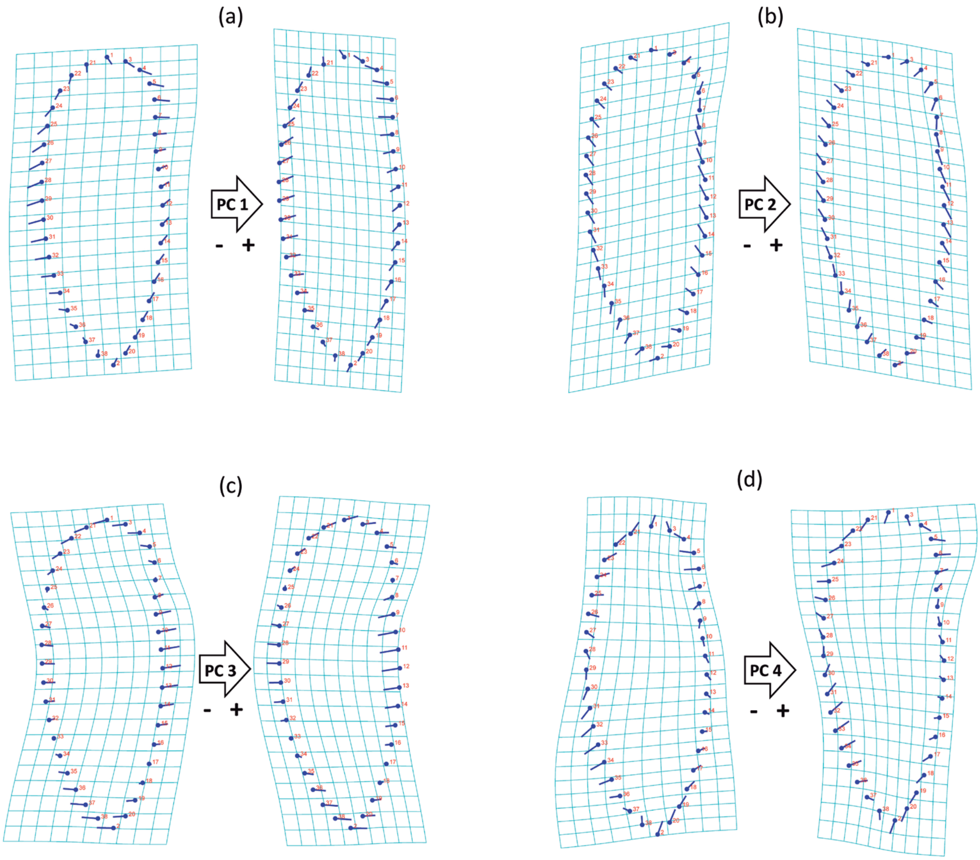


***Fig. 5** - Shape change of the symphysis outline corresponding to the first 4 PCs. The visualizations correspond to 0.2 units of Procrustes distance. PC 1 describes the relative width of the symphysis. PC 2 describes bulging of the superior part of the ventral margin of the symphysis. PC 3 corresponds to bulging in the middle of the ventral margin of the symphysis, relative to the width of the cranial and caudal parts. PC 4 described the width of the inferior half of the symphyseal surface relative to the superior half.*

outlines, on average, become relatively narrower and more pointed at the inferior end, and more bulged at the ventral margin while the dorsal margin becomes more irregular as a person ages. This occurs in both females and males, but is more pronounced in the latter. (Fig. 7).

## Discussion

In this study, we investigated outline shape of the pubic symphyseal surface in the context of three objectives: (1) To explore if the shape of the outline of the symphyseal surface is sexually dimorphic, (2) to assess if and how sexual dimorphism in the outline of this surface varies with age, and (3) to identify if variation in the outline could be informative for age-at-death estimation.

We show here, for the first time, that the shape of the outline of the bony symphyseal surface is sexually dimorphic. Our results therefore document a novel aspect of sexually dimorphic morphology in the human pelvis and highlight a new feature that adds to the various aspects of pelvic

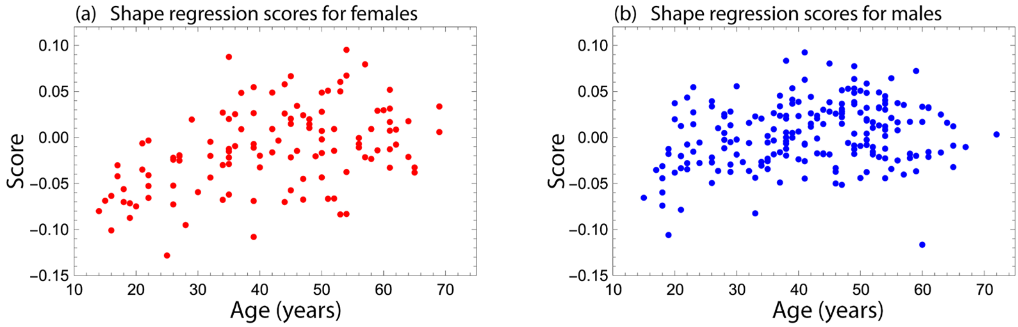


***Fig. 6** - Shape regression scores. Shown are scatterplots of age versus the regression scores from the regressions of symphysis outline shape on age, separately in red for females (a) and blue in males (b). These scores are projections of individual symphysis shapes on the corresponding vector of regression coefficients. The regression scores are computed separately for females and males.*

sex differences that have been identified and studied previously (e.g., Tague 1992; Arsuaga and Carretero 1994; Walrath and Glantz 1996; Kurki 2011; Fischer and Mitteroecker 2015, 2017). Our results show that the male pubic symphyseal surface is rounder and the dorsal margin is more pronounced, while in females, this dorsal border is flatter, giving the female symphyseal surface an elongated appearance. The trend of a flatter dorsal border in females is present across all age groups. Already Todd (1920) considered it necessary to make a distinction between males and females when applying his method for age-at-death estimation because sex differences could potentially affect the age signal in the morphology of the symphyseal surface. However, so far it was unclear if and how the sexes differed quantitatively in their outline shapes of the symphyseal surfaces and how these sex differences interacted with age-related changes.

Sexual dimorphism develops in many different human skeletal systems (Bastir et al. 2006; Huseynov et al. 2016; García-Martínez et al. 2020) and it does so in response to a variety of developmental processes. While in early postnatal ontogeny differences between males and females are usually only subtle, during adolescence and afterwards skeletal differences become more and more marked (Cunningham et al. 2016). For the pubis, it has been shown that sex differences appear predominantly after puberty (Todd 1920; Meindl et al. 1985). Maybe surprisingly, our results show that male and female symphyseal surface outline shapes diverge predominantly after age group A (14-29 years), which coincides with part of the female reproductive period, but not with its beginning. We propose that these differential changes with age could be a result of a different mineral metabolism in males and females. While males can channel their calcium into skeletal maintenance, the calcium metabolism in pregnant women must meet the demands created by both fetus and mother. During pregnancy and lactation, the calcium demand of the offspring is particularly high (Watney and Rudd 1974; Kovacs 2011). To meet this demand, the maternal metabolism adapts and mobilizes calcium, which can lead to short-term depletion of skeletal mineral content. In the lactation period, bone resorption provides most of the calcium for breast milk (Kovacs 2011). According to our results, the divergence in symphyseal surface outline shape between the sexes occurs between age groups A and B. We suggest that this could be a consequence of the cumulative calcium demand of multiple pregnancies and lactation periods in females. It has previously been shown for women that bone mineral content decreases with increasing parity (Gur et al. 2003). The resulting cumulative effect could be responsible for the sex differences appearing after age group A in the symphyseal surface outline shapes. The divergence in the outline shapes of the pubic symphyseal surface between males and females, which we identified here, occurs after the obstetrically relevant dimensions in females have completed growth (Huseynov et al. 2016; Verbruggen & Nowlan 2017; Auerbach et al. 2018).

We suggest that the differences between the sexes in the age trajectories of the symphysis outlines should be taken into account when studying male and female individuals jointly. Indeed, Gilbert and McKern (1973) already mentioned the need for separate age-at-death estimation methods for males and females that are based on the pubic symphyseal surface. Although part of the age change is clearly sex-specific (captured by PC 1, PC 2 in our analysis), other age patterns are similar in males and females (captured by PC 3, PC 4). Changes that occur in both females and males are associated predominantly with the ventral border of the symphysis, especially with the notch of the superior third of the margin that appears at advanced ages in some individuals (compare Todd 1920). Changes described by PC 4 in the relative widths of superior and inferior parts of the symphysis occur independent of sex with increasing age. This is likely related to degenerative processes at older ages (compare the “old” column in Figure 7).

We show here that the outline of the symphyseal surface of the pubis changes with age in its shape. However, our results indicate that these associations have estimating power only until around 50 years of age, and that the age signal seems to disappear at older ages (compare Fig. 6). These findings are in line with the results of Meindl et al. (1985) who suggest that the capability of the pubic symphysis for age determination disappears in the last phase that Todd (1920) described, around 50 years of age. Several recent studies on age-at-death estimation based on the pubic symphyseal surface have indicated this upper limit for the potential of age estimation (e.g., Meindl and Russell 1998; Dudzik and Langley 2015; Kotěrová et al. 2019). Obviously, there is not a single skeletal indicator that can reliably be used for age determination of the entire human age range. Some authors recommend

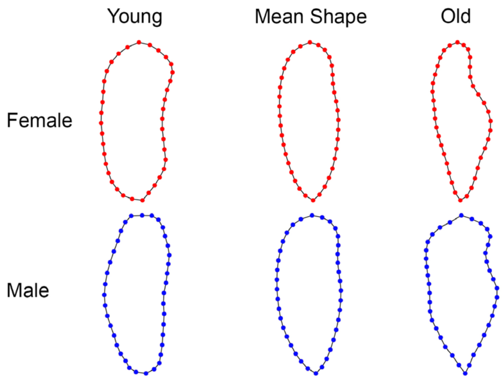


***Fig. 7** - Age-related change in symphysis outline shape. Old shapes (right column) and young shapes (left column) depict two standard deviations from the mean shapes (middle column) in the direction determined by the shape regression vectors, calculated independently for females in red (top row) and males in blue (bottom row). Notice the notch in the superior third of the ventral margin in older states as a “depression” in the margin.*

to use the pubic symphysis only for estimating the age-at-death of young adults (Martrille et al. 2007; Xanthopoulou et al. 2018).

For a century, age-at-death estimation has been carried out based on features of the symphysis (e.g., Todd 1920; Brooks and Suchey 1990). Usage of algorithms for age-at-death estimation has become more popular as it promises to avoid subjectivity (Slice and Algee-Hewitt 2015; Stoyanova et al. 2015, 2017). The algorithm “ForAge” (Stoyanova et al. 2015, 2017), for example, scores the ventral border of the symphysis following the progressive formation of the ventral rim and its posterior erosion, showing that the ventral border can be discriminant for age. Our novel findings that the outline shape of the symphyseal surface is sexually dimorphic and that it changes with age could potentially be used to improve the reliability of existing sex and age-at-death estimation methods by adding symphyseal surface outline shape to the variables these age-at-death estimation algorithms are currently based on.

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*This work is part of the doctoral dissertation of GBM, thereby coming under the appropriate intellectual property protections of its class. University of Granada, program of biomedicine: Human evolution. Physical and forensic anthropology. Title of the thesis: "Geometric morphometrics and 3D in physical anthropology, age-at-death estimation".*

## Author contributions

*GBM designed the study and acquired the data. MCBL provided access to the collection and assisted with data collection. GBM, BF and MB analyzed the data and wrote the paper.*

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