Received: 1 April 2020 | Revised: 9 November 2020 | Accepted: 19 November 2020

DOI: 10.1002/ajpa.24196

RESEARCH ARTICLE

American Journal of PHYSICAL ANTHROPOLOGY WILEY

The association of parturition scars and pelvic shape: A geometric morphometric study

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Funding information
H2020 European Research Council, Grant/Award Number: 676828

Abstract

Objectives: Pelvic features, mostly known as parturition scars, have been extensively studied in the last decades and are frequently investigated in archaeological and forensic contexts. It is still unclear, however, whether they really relate to pregnancy and birth, or whether these features are caused by other biomechanical factors. Because the length and difficulty of labor correlates with the form of the birth canal, we studied the association between the expression of pelvic features and pelvic shape using geometric morphometrics.

Materials and Methods: We scored the expression of the preauricular sulcus, margo auricularis groove, sacral preauricular extension, dorsal and ventral pubic pitting for 54 individuals from a 19th century collection and 19 individuals from the Bronze Age cemetery of Hainburg-Teichtal, Austria. Based on photogrammetric surface models, pelvic shape was captured by 331 landmarks and semilandmarks. The multivariate association between pelvic features and pelvic shape was explored by partial least squares analysis.

Results: Within the female subsample, we detected a significant association of a constrained birth canal with a strong expression of the preauricular sulcus, the margo auricularis groove, and a retroverted position of the acetabulum. No significant association was found among males.

Discussion: This suggests that difficult or prolonged labor may indeed cause more strongly expressed pelvic features, presumably because of increased strain of the pelvic ligaments during birth. Furthermore, the retroversion of the acetabulum, which is known to cause sacroiliac joint dysfunction, changes the strain on pelvic ligaments and can thus also result in the development of pronounced pelvic features.

KEYWORDS

childbirth, geometric morphometrics, parturition scars, preauricular sulcus, retroverted acetabulum

1 | INTRODUCTION

Pelvic features (also called parturition scars) have been described and analyzed for more than 150 years (Zaaijer, 1866). First interpreted as racial differences between populations in the second half of the 19th century (Zaaijer, 1866), these bony depressions, grooves, craters, cavities or pits at specific locations on the pelvis are more likely caused by the stressful event of birth (Angel, 1969; Houghton, 1974, 1975; Putschar, 1976; Stewart, 1970; Ullrich, 1975). However, the actual origin of pelvic features remains largely unclear because some multiparous females never present pelvic features, and nulliparous females or even males occasionally exhibit them (Holt, 1978). Additionally, degenerative changes of the pelvis are often stronger developed in females than in males (Meindl et al., 1985; Todd, 1921). These differences are probably also caused by pregnancy and childbirth, as occupation as a main cause cannot explain the observed dimorphism. Pelvic features are associated with body size and the size and shape of the pelvic canal in both sexes and therefore cannot be caused solely by childbirth (Decrausaz, 2012). We thus suggest to use the more general term “pelvic features” introduced by Pany-Kucera et al. (2019) over parturition scars, which implies a specific cause of the pelvic changes (Stewart, 1970).

Pelvic features can be found near the pubic symphysis (dorsal pubic pitting, ventral pubic pitting, extended pubic tubercle), next to the iliac auricular surface (preauricular sulcus, interosseous groove), and on the sacrum (margo auricularis groove, sacral auricular extension).

The preauricular sulcus, also known as paraglenoid sulcus (Loehr, 1884; Schemmer et al., 1995), is a horizontal groove at the inferior border of the auricular surface of the ilium (Derry, 1909; Houghton, 1974, 1975; Zaaijer, 1866). The preauricular sulcus is more often observed and more pronounced in mature females than in young individuals (Bergfelder & Herrmann, 1978). Houghton (1974, 1975) differentiated two types of preauricular sulcus: the groove of ligament (GL), a smooth, shallow, and straight-edged groove, often starting at a piriform tubercle; and the groove of pregnancy (GP), which exclusively occurs in females and presumably is a sign of parturition. It exhibits a scooped floor and uneven inferior margin and usually extends more superiorly at the anterior margin in comparison to the GL.

Sometimes, grooves also occur at the margin of the facies pelvina of the sacrum, adjacent to the preauricular sulcus, generally known as “sacral scarring” (Cox, 1989). Ullrich (1975) described grooves at the sacrum, similar to the preauricular sulcus (“interosseous grooves”). They occur at the margin of the sacral auricular facet, often adjacent to the preauricular sulcus (Kelley, 1979). The more specific term margo auricularis groove was adapted by Rebay-Salisbury et al. (2018). This feature is probably more linked to age or sex than births (Cox, 2006; Maass, 2012).

Pany-Kucera et al. (2019) described thin, ventrally pointing osseous extensions at the ventrosuperior margin of the sacral wings in female individuals. Presumably, these extensions are caused by microtraumata especially during traumatic birth events, inducing heterotrophic ossification in the overlying ligaments. They may also be influenced by ligament laxity and a postural change caused by weight gain during pregnancy. In an Austrian Bronze Age sample, Pany-Kucera et al. (2019) observed sacral preauricular extensions in approximately 15% of female individuals of all ages, often appearing unilaterally and together with other pelvic features.

Stewart (1970) hypothesized that impressions at the dorsal side of the pubis, parallel to the symphyseal margin, can occur in parous females after hemorrhages and cyst formations in this area. Gilbert and McKern (1973), who used samples of known obstetric history, reported a trend for large pits in multiparous females. Further possible causes of dorsal pubic pitting include inflammatory pathological lesions of the pubic bone after traumata or infections (Angel, 1969; Ashworth et al., 1976), congenital anomalies, metabolic diseases, degenerative pathologies, or tumors (Gamble et al., 1986).

Despite the lack of a consistent definition, the extended pubic tubercle has been described as a pelvic feature in the literature (Angel, 1969; Bergfelder & Herrmann, 1978; Cox & Scott, 1992; Owsley & Bradtmiller, 1983; Snodgrass & Galloway, 2003; Ullrich, 1975). Ullrich (1975) and Bergfelder and Herrmann (1978) described it as an elongation of the anatomical “pubic tubercle,” which is located just superior-anterior to the pubic articulation surface. Others referred to the “extended pubic tubercle,” which often forms to variable extents at the arcuate line of the superior pubic ramus (Angel, 1969; Decrausaz, 2012; Maass, 2012; Snodgrass & Galloway, 2003). Bergfelder and Herrmann (1978) interpreted an extended pubic tubercle as evidence for parturition, and Cox (1989) found a significant relationship with birth events in the Spitalfields collection. However, Snodgrass and Galloway (2003), Decrausaz (2012), Maass (2012), and Aurigemma (2015) also reported a correlation with body height in both sexes.

Strongly expressed pelvic features are more frequently observed in older individuals than in young ones (Bergfelder & Herrmann, 1978; Cox, 1989; Maass, 2012), which may owe to the higher average number of children in older ages. However, in contrast to males, the female pelvis continually remodels and changes in shape during the reproductive period, which may also alter its biomechanical properties. Young females tend to have a smaller pelvic inlet in comparison to older females. In the twenties and thirties, the female pelvis becomes wider and more gynecoid, which facilitates childbirth. After menopause, the female pelvis remodels toward a more android pelvis (Auerbach et al., 2018; Huseynov et al., 2016; Mitteroecker & Fischer, 2016). These shape changes are likely to be related to hormones and sex-biased gene expression (Mitteroecker & Fischer, 2016; Parsch & Ellegren, 2013; Williams & Carroll, 2009), but also stature and body mass is related to pelvic shape (Fischer & Mitteroecker, 2017; Ruff, 2000).

2 | AIM OF THE STUDY

For most historical and archaeological collections of skeletons, data on parity and parturition are not available, preventing a direct correlation of pelvic feature expression with the number of children and the length of labor. For modern collections or clinical records, by contrast, the number of children tends to be much smaller and also the length and difficulty of labor (as a potential cause of pelvic features) vary considerably less due to obstetric interventions compared to (pre)historic collections. The contribution of childbirth to the development of pelvic features may thus be small in modern populations relative to other biomechanical, age-related, and genetic factors.

We studied the expression of pelvic features and their association with pelvic shape in a 19th-century sample and a Bronze Age sample using a comprehensive 3D geometric morphometric approach. Parity status is unknown for these individuals, but age at death, stature, and body mass are well documented for the historical collection. Thus, we studied the obstetric and biomechanical factors leading to pelvic features indirectly, as far as they are mirrored in pelvic shape. If childbirth indeed contributed to the development of pelvic features, then we expect a stronger expression of pelvic features in females with a more constrained birth canal because these females experience, on average, longer and more difficult births (Nkata, 1997; Pavličev et al., 2020; Proisy et al., 2014; Rosenberg & Trevathan, 1995). Clearly, delayed or arrested labor can also occur for numerous other reasons than pelvic shape (e.g., uterine contractions, fetal dimensions and presentation), but they presumably all act in the same way on the development of pelvic features, namely through prolonged or increased stress and strain of the pelvic ligaments. Hence, even though we have no direct data on these birth-related factors, the influence of delayed labor on pelvic features would, nonetheless, be reflected by the association of relative birth canal dimensions and pelvic feature expression. Likewise, multiple biomechanical factors unrelated to birth can increase stress and strain of pelvic ligaments. However, certain aspects of pelvic geometry, for example, the form, position, and orientation of the acetabula, affect the biomechanics of the pelvis, especially at the sacroiliac joint (Dalstra & Huiskes, 1995; Morgan et al., 2013). Associations between pelvic feature expression and such locomotion- and posture-related aspects of pelvic shape would reflect biomechanical factors that are unrelated to childbirth. Therefore, our dataset comprises landmarks on the entire pelvis, including the acetabula, to capture birth-related and other biomechanical signals. We also included body height and age at death as covariates in the analysis as these variables may be associated both with pelvic shape and feature expression.

3 | METHODS

We used two collections of human skeletal remains curated in the Natural History Museum in Vienna ($n = 73$). We included only complete pelves of adult individuals whose sacrum was at least partially fused with little or no fragmentation. We excluded individuals with lumbarization or ante mortem traumata of the pelvis, the lower long bones, and the spine.

Nineteen human pelves (12 females, 7 males) are part of an Early Bronze Age (2,200–1,600 BC) skeletal collection excavated in Hainburg-Teichtal, Lower Austria, during the 1920s (Beninger et al., 1930; Teschler-Nicola, 1992). Age at death, sex, and body height were estimated from the skeletons (Brooks & Suchey, 1990; Bruzek, 2002; Ferembach et al., 1979; Lovejoy et al., 1985; Miles, 1963; Ruff et al., 2012; Stloukal & Hánaková, 1978; Szilvassy, 1977).

As a second sample, we used 54 individuals of the Weissbach collection, a well-studied and documented 19th-century anatomical collection with some known background information about the deceased (Breitinger, 1990; Weissbach, 1866). This collection contains pelves of young male soldiers from the Austrian Imperial and Royal Army, as well as remains of 27 females, which we all included in our sample. The collection also includes some crania and lumbar vertebrae of the individuals. Data on sex, age, body height, and body weight were collected from the inventory book of the Department of Anthropology at the Natural History Museum. Most individuals died of tuberculosis and were underweighted at the time of death. Parity was rarely recorded, but some females died in puerperal fever. Likewise, nutrition status, and occupation were not reported for all individuals. To yield a similar age distribution for both sexes, we randomly chose a male specimen with the same age at death for every female individual (Figure 1). If there was no individual available with the same age, we

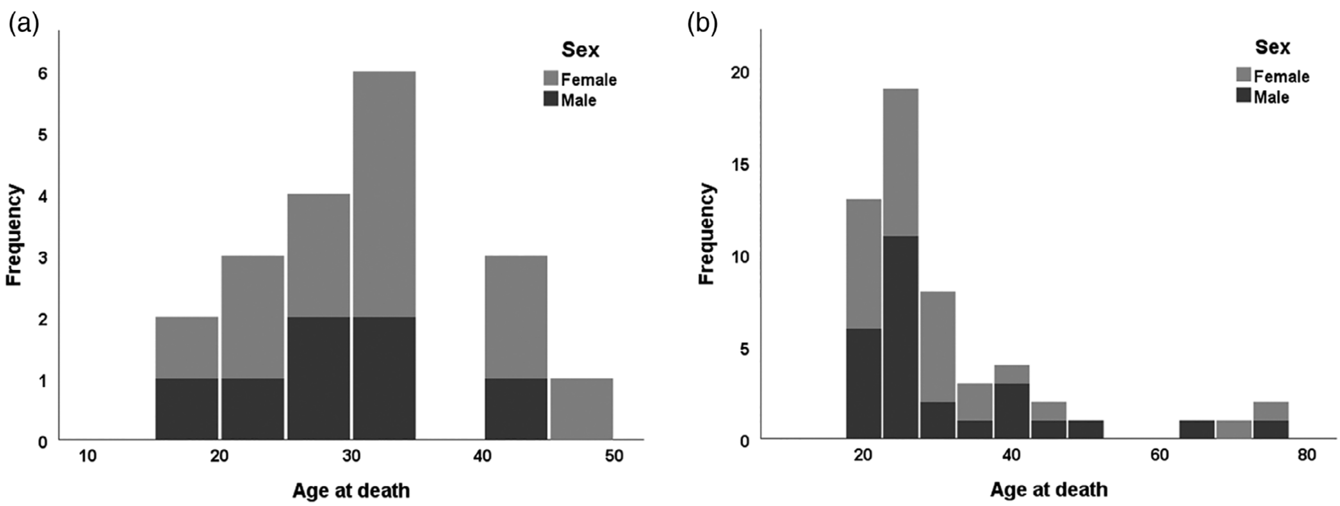

FIGURE 1 Distribution of age at death a) in the Bronze Age sample from Hainburg-Teichtal, Lower Austria, and b) in the Weissbach sample

TABLE 1 Scoring systems to evaluate pelvic features, developed in the framework of the "Value of mothers to society" project, partially adapted for the present study (Rebay-Salisbury et al., 2018)

Dorsal pubic pitting (adapted from Stewart (1970) and Ullrich (1975))	Ventral pubic pitting (adapted from Rebay-Salisbury et al. (2018))	Preauricular sulcus type (Houghton (1974))	Preauricular sulcus stage (adapted from Cox (1989) and Houghton (1975))	Margo auricularis groove (adapted from Ullrich (1975))	Extended pubic tubercle (adapted from Maass (2012))	Sacral preauricular extension (adapted from Pany-Kucera et al. (2019))
0 = smooth surface, no lesion present 1 = small lesion present (<2 mm) 2 = medium to large lesion present (>2 mm)	0 = smooth surface, no lesion present 1 = small lesion present (<2 mm) 2 = medium to large lesion present (>2 mm)	0 = area is smooth, with no clear evidence of a sulcus 1 = groove of ligament 2 = groove of pregnancy	0 = area is smooth, with no clear evidence of a sulcus 1 = shallow, poorly marked 2 = shallow, straight-edged even floor 3 = developed, well-defined platform 4 = developed pitted 5 = irregular floor and/or margins, projecting dorsal margin	0 = area is smooth, with no clear evidence of a sulcus 1 = shallow, poorly marked 2 = shallow, straight-edged even floor 3 = developed, well-defined platform 4 = developed pitted 5 = irregular floor and/or margins, projecting dorsal margin	0 = absent 1 = present	0 = absent 1 = present

chose the individual with least age difference. We represented the expression of pelvic features by ordinal variables, separately for the left and right sides (Table 1). Using photogrammetry, we created 3D surface meshes of the articulated pelves after inserting an artificial pubic disc with a thickness of 5.2 mm for females and 6.0 mm for males (Vsianska, 2007) to simulate a realistic size of the pelvic inlet.

In a previous study, we showed that photogrammetry yields reliable 3D models of human pelves, comparable to 3D structured light scanner and CT scanning (Waltenberger et al., n.d.). We used a Nikon DSLR-camera D5300 equipped with an AF-P Nikkor 18–55 mm 1:3.5–5.6G lens. Distortions were minimized by taking a medium focal length (Linder, 2016) and leaving space between the pelvis and the margin of the photo. We took all pictures with a resolution of 24 megapixels, an exposure time of 1/100, an ISO-value of 100 and a focal ratio of 4.8. Additionally, a diffuse LED ring flash device (Neewer) helped to reduce shadows and increase the photo quality. We took approximately 110–120 pictures in six circles around each object: one circle was directed horizontally to the object, the second one obliquely in a 45° angle, and the third one in a steep angle at approximately 80°. Then, the pelvis was placed upside down and we repeated the three circles.

We placed 331 landmarks and semilandmarks at all important anatomical structures of the human pelvis (Table 2, Figure 2). Anatomical landmarks are based on the definitions by Reynolds et al. (1982). All landmarks were placed by a single observer (L. W.). To evaluate intraobserver error, all landmarks were placed three times on 10 different pelves. If a pelvis exhibited a sacralization, the posterior pelvic inlet was adjusted along the first transverse ridge between S1 and S2 instead of the promontorium.

We performed the morphometric and statistical analysis in R 3.6.1 (R Core Team, 2013) using the packages Geomorph 3.2.0 (Adams et al., 2013) and DiscriMiner 0.1-29 (Sanchez, 2013). All semilandmarks were slid along their corresponding curve in order to minimize the bending energy between each individual and the sample mean shape (Gunz et al., 2005; Gunz & Mitteroecker, 2013). Subsequently, they were standardized for differences in overall location, scale, and orientation by a Generalized Procrustes Analysis (Mitteroecker & Gunz, 2009; Rohlf & Slice, 1990). The resulting shape coordinates were explored by a principal component analysis (PCA), and the multivariate association between pelvic shape and pelvic features (all standardized to the same variance) was studied by partial least squares (PLS) analysis (Mitteroecker & Bookstein, 2007; Rohlf & Corti, 2000) separately for male and female individuals of the Weissbach and Hainburg-Teichtal samples. We repeated the PLS analysis after removing allometry and age by regressing out centroid size and age at death from the shape data and the pelvic features.

4 | RESULTS

Shape variation between repeated measures was small relative to the variation between individuals. In fact, the largest shape difference between the repeated measurements was less than half in magnitude

TABLE 2 List of landmarks used in this study (anatomical landmarks after Reynolds et al. (1982)). Bilateral landmarks were collected on the left and right side (L + R)

Sacrum		Os Coxa (L + R)	Semilandmarks	
Promontorium		**Posterior superior iliospinale**		**No. placed landmarks**
S1 posterior body		Posterior inferior iliospinale	Lateral ischial tuberosity	5
S1 lateral body	L + R	Apex of sciatic notch	Medial ischial tuberosity	5
First segment union point		Iliospinale	Acetabulum	10
S1 center		Anterior inferior iliospinale	Pelvic inlet	40
Second segment union point		Iliocristale summum	Lateral iliac crest	20
Third segment union point		Ischio-spinale	Medial iliac crest	20
Fourth segment union point		Pubotubercle	Alar auricular ridge curvature	10
Caudion		Anterior acetabulion	Lateral sacral ridge	10
Inflection		Inferior acetabulion	Greater sciatic notch	10
Lateral alar auricular point	L + R	Anterior iliac base point	Inferior pubic ramus	5
Anterior alar point	L + R	Acetabulion, center point	Obturator foramen	10
Mid alar point	L + R	Pubic eminence point		
Inferior sacro-iliac junction	L + R	Superior pole, pubic symphysis		
Sacral canal anterior floor		Anterior symphyseal point		
Sacral canal anterior roof		Posterior symphyseal point		
Sacral canal anterior wall	L + R	Inferior symphyseal pole		
Superior articular facet: medial superior	L + R	Obturator tubercle point		
Superior articular facet: lateral superior	L + R	Superior tuberosity point		
Superior articular facet: medial inferior	L + R	Ischiale		
Superior articular facet: lateral inferior	L + R	Inferior tuberosity point		
Posterior alar-auricular point	L + R	Posterior ischial border point		
Posterior sacral tubercle	L + R			
Dorsal spine of the first sacral vertebra				
Dorsal spine of the second sacral vertebra				
Sacral canal, posterior roof				
Posterior caudion				
Lateral caudion	L + R			

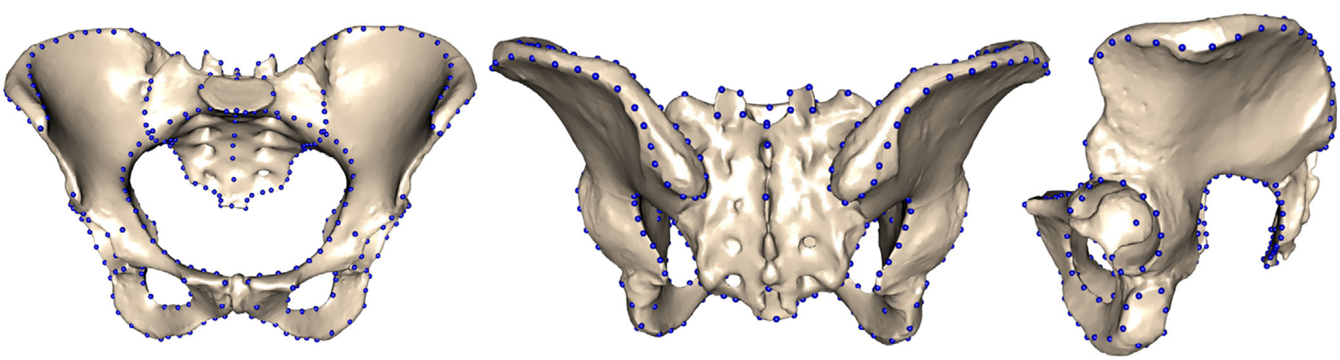

FIGURE 2 Landmarks and semilandmarks placed on the three-dimensional surface meshes

as the smallest shape difference between the different specimens (Procrustes distances of 0.0378 and 0.0808, respectively).

Age at death and body height were similarly distributed in the females and males of the Hainburg-Teichtal and Weissbach samples (Table 3). Eight specimens of the Weissbach collection (four males and four females) and two females of the Hainburg-Teichtal sample showed sacralizations. Only few individuals lacked anatomical parts and were excluded in the corresponding statistics of the pelvic

TABLE 3 Distributions (range, mean, and standard deviation) of age at death and body height in the Hainburg-Teichtal and Weissbach collections. The exact age at death and body height were documented for the Weissbach collection. Age at death and body height were estimated from the skeletal material for the Hainburg-Teichtal sample

	Hainburg-Teichtal						Weissbach					
	Female 12			Male 7			Female 27			Male 27		
n	Range	Mean	*SD*	Range	Mean	*SD*	Range	Mean	*SD*	Range	Mean	*SD*
Age at death	19–45	32.04	8.302	19–40	28.0	7.577	20–77	30.2	13.61	21–75	31.26	13.55
Body height	144–161	153.17	5.477	150–172	162.83	7.679	144–163	154.2	8.167	156–187	169.6	8.493

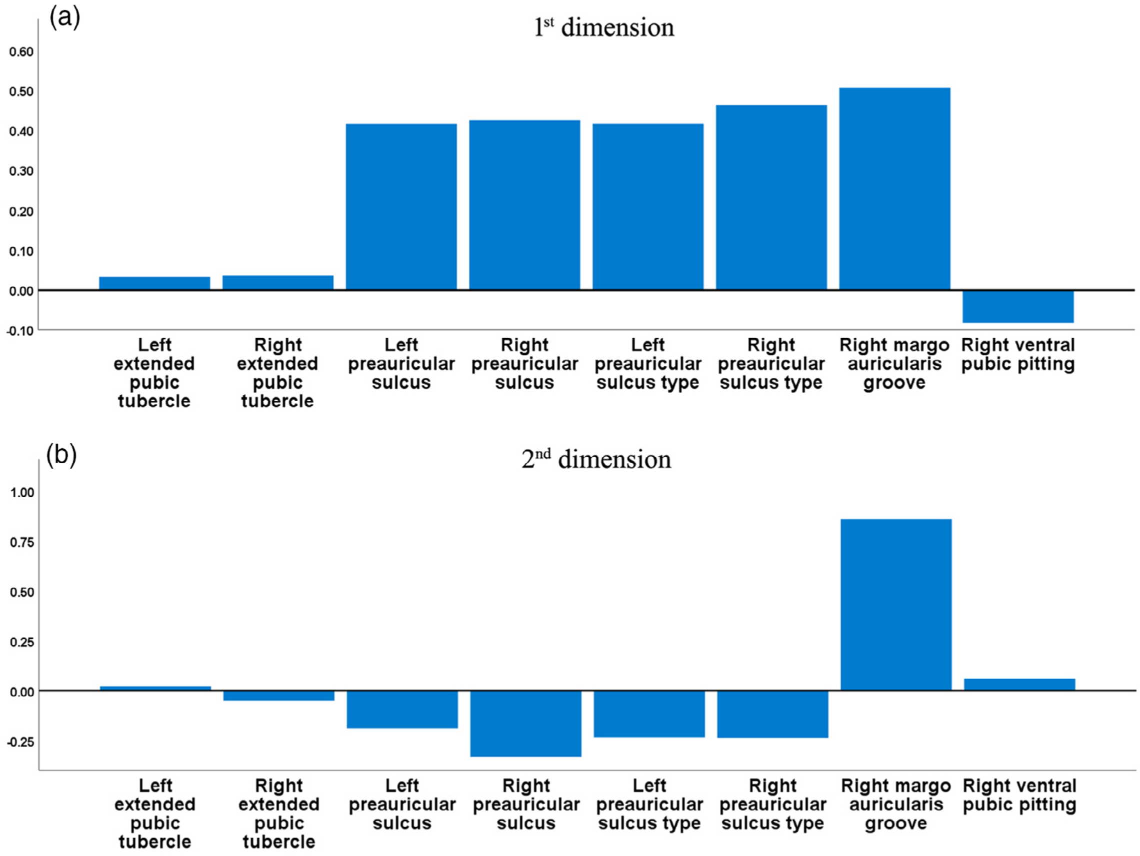

FIGURE 3 Loadings of the pelvic features on the first two dimensions of the partial least squares (PLS) analysis in the female sample, a) loadings of the 1st PLS dimension, b) loadings of the 2nd PLS dimension. The loadings are proportional to the covariance between each feature and the corresponding pelvis shape feature depicted in Figure 4

features. Ventral pubic pitting, sacral preauricular extensions, and margo auricularis groove occurred only in few individuals. Dorsal pubic pitting was not observed in the sample. Common features were the extended pubic tubercle and the preauricular sulcus. In the PCA of pelvic shape, the sexes could be separated along PC1 (accounting for 20% of total variance). Within the first five PCs (together accounting for 52.72% of total variance), however, no clustering of pelvic shape with respect to single pelvic features was observable (SuppInfo01–SuppInfo09).

As each *single* pelvic feature was not strongly associated with pelvic shape in our sample, we performed PLS analysis to explore the multivariate association between all pelvic features and pelvic shape. The first PLS dimension yields the combination of pelvic features that maximally covaries with pelvic shape. We excluded features that were expressed in less than three individuals (sacral preauricular extensions in all groups; ventral pubic pitting in Weissbach males; margo auricularis groove in Weissbach males). In the female Weissbach sample (n = 27), the first PLS dimension accounted for 48% of the total squared covariance (p = 0.015 based on 1000 random permutations; r = 0.84 between the corresponding pair of PLS scores). Preauricular sulcus and margo auricularis groove had similarly high loadings, whereas the extended pubic tubercle and ventral pubic pitting had loadings close to zero (Figure 3(a)). A weak expression of the preauricular sulcus and the margo auricularis groove was associated with

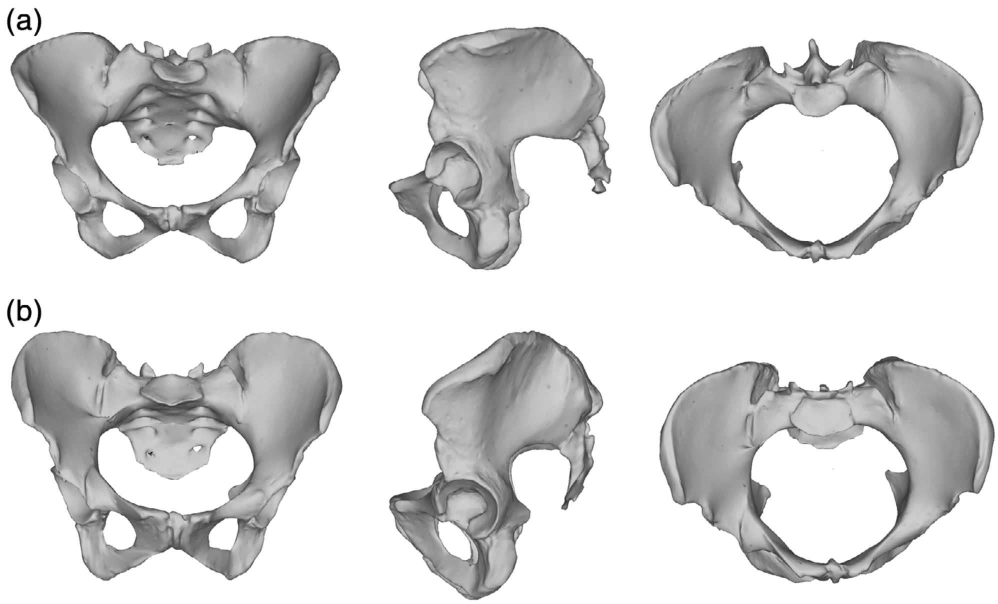

FIGURE 4 The pattern of pelvic shape change along the first dimension of the partial least squares (PLS) analysis (compare Figure 3). (a) Pelvic shape corresponding to a low score for the preauricular sulcus and margo auricularis groove (extrapolation −5sd). (b) Pelvic shape corresponding to a high score for the preauricular sulcus and margo auricularis groove (extrapolation +5sd). A narrow inlet, small subpubic angle, medially protruding ischial spines, a curved, inwardly protruding sacrum, and an inferior-posteriorly oriented acetabulum are associated with a strong expression of these pelvic features

a relatively wider pelvis, a larger subpubic angle, longer superior pubic rami, relatively short pubica, large greater sciatic notches, and a straight, inferiorly pointing sacrum. A strong preauricular sulcus and margo auricularis groove, by contrast, corresponded to a narrow and high pelvis, a small subpubic angle, short superior pubic rami, a strongly curved sacrum, and ischial spines protruding into the pelvic canal (Figure 4). Furthermore, a strong expression of pelvic features was associated with a more inferior-laterally aligned acetabulum, whereas in pelves with a weak feature expression the acetabulum was anteriorly oriented. Hence, a weak pelvic feature expression was generally associated with a more female-like pelvis shape and a relatively larger birth canal. In the second dimension (accounting for 25.03% of total squared covariance), the margo auricularis groove was highly loaded (Figure 3(b)). Here a strong expression was associated with vertically tilted coxal bones and a high, curved sacrum.

By separating the preauricular sulcus expression into the groove of ligament and the groove of pregnancy (as two separate features with the scores averaged across both sides), the association between pelvis shape and pelvic features was still significant ($n = 26$, $r = 0.816$, $p = 0.04$) and the shape pattern of the first PLS dimension remains the same as in Figure 4. The groove of pregnancy had a higher loading than the groove of ligament (0.483 vs. 0.153) on the first dimension (accounting for 41% of total squared covariance, Figure 5). After removing allometric variation and age at death from the data, PLS yielded very similar results as for the raw data (not shown). There was no significant association of pelvic shape and pelvic features in the

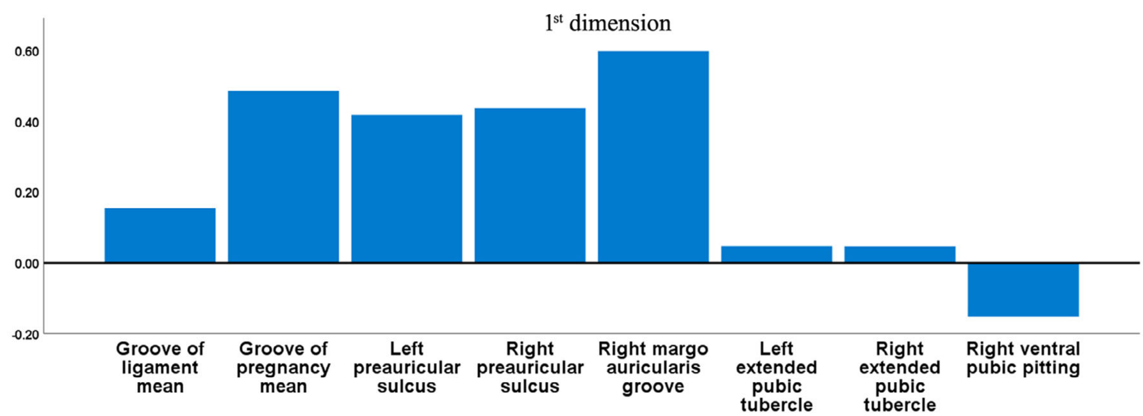

FIGURE 5 Loadings of the pelvic features on the first partial least squares (PLS) analysis dimension when separating the preauricular sulcus expression into the groove of ligament and the groove of pregnancy as two separate features. High loadings indicate a high covariance between pelvis shape and the corresponding pelvic features in females. The left and right grooves of ligament and grooves of pregnancy were pooled

males of the Weissbach collection (n = 27, p = 0.92). The Hainburg-Teichtal sample was too small to conduct a PLS analysis.

5 | DISCUSSION

5.1 | Pelvic features as parturition scars

Pelvic features are commonly assumed to be caused by increased strain on the pelvic ligaments during birth, although empirical evidence for this assumption is scarce. In this study, we explored the association between the expression of pelvic features and pelvic shape within samples of both sexes. We expected that females with a relatively smaller birth canal tend to have more strongly expressed pelvic features due to harder births as compared to females with a wider birth canal. In females but not in males, we indeed found that a strong expression of the preauricular sulcus, and the margo auricularis groove was significantly associated with a strongly curved, inward-projecting sacrum, a smaller subpubic angle, shorter pubic rami and elongated ischial spines, all of which narrow the pelvic canal and complicate birth (Abitbol, 1987; Leutenegger, 1972; Lovejoy et al., 1973). The additional strain on the pelvic ligaments and muscles during parturition may thus contribute to the development of the pelvic features.

Previous studies on pelvic shape and pelvic features (Cox, 1989; Jugert et al., 2018; Maass, 2012) were based on the classic pelvic types (anthropoid, gynecoid, android, platypelloid) defined by Caldwell and Moloy (1933, 1938). The gynecoid type, characterized by a round birth canal, is common in females and is considered most suitable for childbirth in the gynecological literature (e.g., Maharaj, 2010; Stewart et al., 1979), whereas the android type (heart-shaped, anteriorly narrow canal) is more common in males. This typological view, however, does not account for the continuous variation of pelvis shape in humans (Abitbol, 1987; Cunningham et al., 2014; Delprete, 2017; Fischer & Mitteroecker, 2017). Nonetheless, our results showed that females with weak expressions of pelvic features tend to have round, gynecoid pelvic canals, whereas strong feature expressions are more common in females with narrower, android pelves (Figure 4).

However, this is only indirect evidence of the association between parturition and pelvic features. Obstructed labor is caused by various other factors besides a small pelvic canal, including a large fetal head or shoulders, an abnormal position or presentation of the fetus, an incompletely developed pelvis in teenagers, and problems with soft tissues including a narrow vagina and perineum (Dy, 2013). For instance, the sacrum, ischial spines, and tuberosities are important attachment sites of the pelvic floor, a layer of flat muscles, fat, and ligaments in the pelvic outlet. A small pelvic canal challenges childbirth but supports the pelvic floor to uphold the pelvic and abdominal organs. Birth canal size, including the ischial spines, thus evolved by trading off its functions for parturition and pelvic floor support (Abitbol, 1988; Mitteroecker, 2019; Mitteroecker et al., 2016; Pavličev et al., 2020; Schimpf & Tulikangas, 2005; Woodman & Graney, 2002). Elongated and broadened ischial spines, however, can also be caused by remodeling in response to hypertrophic pelvic floor muscles, especially the coccygeal muscle (Antolak Jr. et al., 2002). The pubococcygeus muscles, which are partially attached to the ischial spine, and the sacrospinous ligament constantly pull the sacrum and coccyx anteriorly, which leads to their ventral tilt (Abitbol, 1987; Amiel, 1981; Paulsen & Waschke, 2010; Steele & Bramblett, 2003). This causes strain to the sacroiliac ligaments and might be one factor in the development of the preauricular sulcus and margo auricularis groove, unrelated to childbirth.

Bone is continually remodeled during life, and the female pelvis has been shown to change in shape throughout the reproductive period (Auerbach et al., 2018; Huseynov et al., 2016; Mitteroecker & Fischer, 2016). Likewise, the expression of pelvic features tends to increase with age (Bergfelder & Herrmann, 1978; Cox, 1989; Maass, 2012). This joint dependence of female pelvic shape and pelvic feature expression on age may thus induce a spurious correlation and explain why this association was only found in females, not in males, even though the preauricular sulcus, the margo auricularis groove, and the extended pubic tubercle were found in both sexes (Cox, 1989; Decrausaz, 2012; Holt, 1978). We therefore included age at death as a covariate to account for spurious associations mediated by age. However, after regressing out age from both blocks of variables, the association between pelvic shape and pelvic features basically remained the same and only slightly weakened in magnitude, demonstrating that it is not an artifact of age-related variation.

The extended pubic tubercle, ventral and dorsal pubic scarring are suspected to be associated with body weight and body height (Aurigemma, 2015; Decrausaz, 2012; Maass, 2012; Snodgrass & Galloway, 2003). Snodgrass and Galloway (2003) speculated that increased hormone levels resulting from obesity destabilizes the pelvic girdle and causes dorsal pubic pitting. Decrausaz (2012) found a correlation between body height and the size and position of the extended pubic tubercle in both sexes. We found the expression of the extended pubic tubercle to be positively correlated with both body height and weight, but we found no consistent pattern of correlation for the preauricular sulcus and the margo sacralis (the analyses were strongly limited by sample size, and weight and height data were not available for all individuals). Also pelvic shape, including size and shape of the pelvic canal, shows an allometric association with body height (Fischer & Mitteroecker, 2015, 2017; Kurki, 2011; Tague, 1992; Wood & Chamberlain, 1986). However, removing allometry from our shape data did not change the results of the PLS analysis. Hence, the association between pelvic features and pelvic shape that we found is unlikely to be driven by variation in body height.

Two types of the preauricular sulcus are known (after Houghton, 1975). The groove of ligament was interpreted as triggered by biomechanical stress because it is found in both sexes, whereas the groove of pregnancy is only found in females. Except for the different morphological expression of the sulcus in both types; however, their development still remains unclear. Our results indicated a considerably stronger association of a constrained pelvic canal with the groove of pregnancy than with the groove of ligament (Figure 5). Nevertheless, also the groove of ligament showed a weak association with a narrow pelvic canal, which may be due to misclassifications of weakly expressed grooves of pregnancy as grooves of ligament.

5.2 | Pelvic features and a retroverted acetabulum

Biomechanical aspects related to pelvic shape were largely neglected in the literature as potential causes of pelvic features. Our results, however, showed that not only the pelvic canal, but also the position and orientation of the acetabula are associated with the expression of pelvic features (Figure 4). The acetabulum was more anteverted in females with weak feature expression, whereas in individuals with strong feature expression the acetabulum was more retroverted, that is, inferior-posteriorly located. A retroverted acetabulum occurs in 48% of all individuals, with a slightly higher rate in males than in females and an increased retroverted orientation in higher ages (Grant et al., 2012; Klasan et al., 2019; Tannenbaum et al., 2014). In a retroverted acetabulum, the posterior brim experiences increased strain during daily life activities and often causes pelvic pain, osteoarthritis, femoroacetabular impingement, and femoral head fractures (Eckstein et al., 2007; Reynolds et al., 1999; Siebenrock et al., 2003; Tannast et al., 2008; Tannenbaum et al., 2014). A retroverted acetabulum can be pathologically caused by hip disorders like Legg–Calvé–Perthes disease, slipped capital femoral epiphysis or hip dysplasia (e.g., Cibulka, 2014; Siebenrock et al., 2003; Tannast et al., 2012) but acetabular orientation can also change during life (Klasan et al., 2019).

The position of the femoroacetabular joint affects the biomechanics of the pelvis, especially at the sacroiliac joint (Dalstra & Huiskes, 1995; Morgan et al., 2013). Body weight inclines the sacrum anteriorly and inferiorly, where females tend to have laxer ligaments than males, and thus larger nutation (Calvillo et al., 2000; Kissling et al., 1990). The margo auricularis groove and sulcus preauricularis are both located beneath the anterior sacroiliac ligament, which prohibits a tilt or dislocation of the sacrum and is prone to increased strain. These sulci are thus likely caused by lateral tensions to the pelvic ligaments (Hirschberg et al., 1998).

Our results indicate that—in addition to pregnancy and childbirth—biomechanical aspects, such as those related to a retroverted acetabulum, also contribute to pelvic feature development. The ischial spine sign and the crossover sign, both used to diagnose a retroverted acetabulum in orthopedics, and the retroverted position of the acetabulum are clearly visible in our results (Figure 6). The common prevalence of retroverted acetabula in males appears to be at odds with this claim. However, the general sexual dimorphism in pelvic shape and hormonal regime may account for different bone remodeling in response to mechanical stress in females and males. For instance, the sacrum is more horizontally positioned in females (Vleeming et al., 2012) and the sacroiliac joint surface is smaller and less undulated compared to males (Vleeming & Schuenke, 2019). Ligament relaxation in response to relaxin secretion, along with weight gain during pregnancy, increases the strain on pelvic ligaments and changes pelvic posture (Hagen, 1974; Ribeiro et al., 2013; Vleeming et al., 2012). Therefore, a long-term positional shift of the coxal bone relative to the sacrum during pregnancy or birth could also contribute to the expression of pelvic features.

5.3 | Limitations of the Weissbach sample

Although age at death and stature are reliably documented for the Weissbach collection, parity is unknown for most individuals. Therefore, associations between pregnancy, parturition, and pelvic features are only

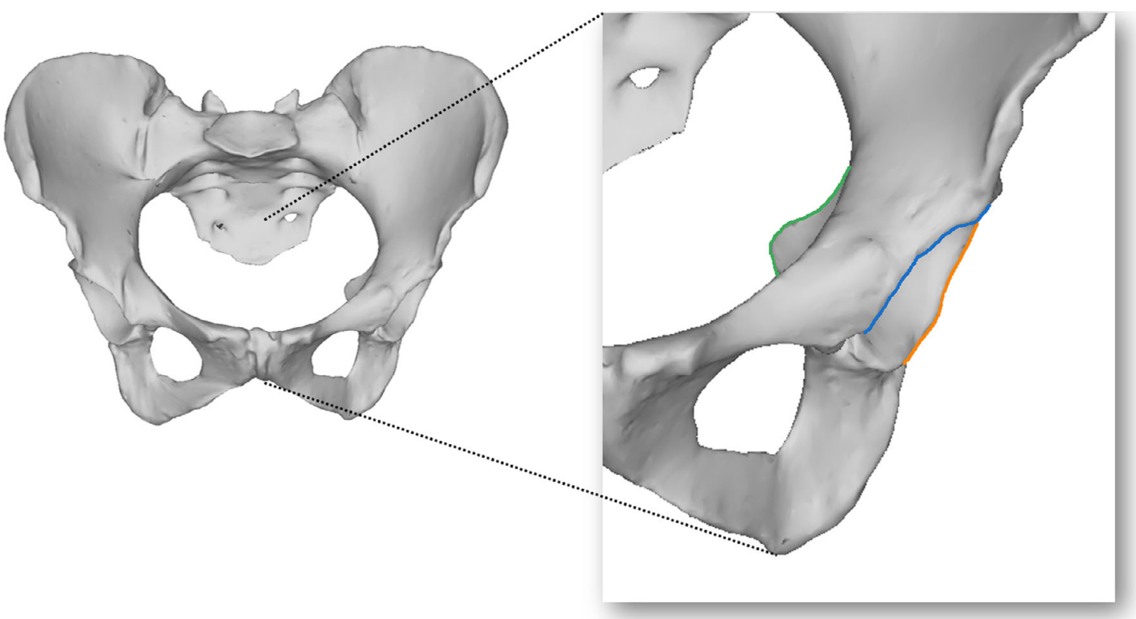

FIGURE 6 Pelvic shape corresponding to a strong expression of the preauricular sulcus and margo auricularis groove (extrapolation +3*SD*; see Figures 3 and 4). The ischial spine sign (green) and crossover sign (anterior acetabular margin: blue, posterior acetabular margin: orange) are clearly visible

indirectly captured by the association between pelvic shape and pelvic features; the actual magnitude of the association may thus be underestimated by our approach. On the other hand, given the large variation in the length of gestation, fetal dimensions, and the length and difficulty of labor, the number of children may not be the best predictor of pelvic feature expression either. It would require well-documented clinical data to assess all these factors, but modern populations show less variation in these factors compared with historical and prehistorical populations.

It is not documented by which criteria, if any, Weissbach collected the specimens. The collection, especially the small sample of females, thus may not be representative of a European 19th century population with regard to biometric properties and parity. It is very unlikely, however, that the association between pelvic features and pelvic shape, as assessed here, is affected by any potential sampling bias.

By studying the association between pelvic features and pelvic shape, we were also able to detect biomechanical signals unrelated to childbirth. What we are completely missing, however, is individual variation in hormone levels, especially estrogen and relaxin secretion, both of which are likely to affect pelvic bone remodeling during pregnancy. Likewise, effects of physical stress, occupation, lifestyle, and nutrition on pelvic feature expression are not captured by our analysis.

Due to the limited sample size, some pelvic features occurred in too few individuals to be included in the analysis. Future studies with larger samples are necessary to study these rare pelvic features. Few specimens of the Bronze Age Hainburg-Teichtal sample were complete enough to be included in a geometric morphometric study. The PLS for this small sample did not reach statistical significance (and, therefore, was not shown here), but the shape pattern closely resembled that of the Weissbach collection.

6 | CONCLUSIONS

Our study demonstrates that the occurrence of a pronounced preauricular sulcus and margo auricularis groove are correlated with a narrow birth canal owing to shorter pubica, elongated ischial spines, and a strongly curved sacrum. By contrast, a pelvis with weakly expressed pelvic features tends to have a gynecoid shape with long pubic bones, a wide subpubic angle, a wide greater sciatic notch, and a straight sacrum. Age-related and body size-related variation do not account for this association. A long and difficult birth process may thus contribute to the expression of these pelvic features. However, the correlation between pelvic feature expression and the orientation of the acetabulum suggests that other biomechanical aspects also affect the development of pelvic features.

ACKNOWLEDGMENTS

This study was performed in the framework of the project "The value of mothers to society: responses to motherhood and child rearing practices in prehistoric Europe" and has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 676828). The authors thank Karin Wiltschke-Schrotta, Margit Berner, and Sabine Eggers from the Department of Anthropology at the Natural History Museum in Vienna for granting us access to the skeletal collections and their support of our research. Moreover, the authors would like to thank Michaela Spannagl-Steiner for their help with data acquisition. The authors are grateful to Anne Le Maître and Barbara Fischer for their support of the data analysis and Sophie Beitel for her input on the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Lukas Waltenberger and **Philipp Mitteroecker**: Designed the study and performed the statistical analysis. **Lukas Waltenberger** and **Doris Pany-Kucera**: Collected the material. **Lukas Waltenberger**, **Philipp Mitteroecker**, and **Katharina Rebay-Salisbury**: Wrote the manuscript.

DATA AVAILABILITY STATEMENT

The data used in this study are available via DRYAD data repository (doi: 10.5061/dryad.6q573n5xg).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Waltenberger L, Pany-Kucera D, Rebay-Salisbury K, Mitteroecker P. The association of parturition scars and pelvic shape: A geometric morphometric study. *Am J Phys Anthropol*. 2021;174:519–531. https://doi.org/10.1002/ajpa.24196