Archaeological and Anthropological Sciences (2026) 18:180
https://doi.org/10.1007/s12520-026-02533-2

RESEARCH

The invisible evidence of birth: evaluating the relationship between pelvic shape and parity with a pelvic pattern index

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Received: 9 July 2025 / Accepted: 6 July 2026

Abstract
It is well known that parity affects the human skeleton through biomechanical strain during pregnancy and birth, lactation, and sexual steroid hormone expression. Pelvic features are bony exostoses and lesions found on the pelvis and are frequently interpreted as parturition scars, although the direct causal factors remain unclear. In this study, we created a weighted pelvic pattern index (PPI) by combining all pelvic features (preauricular sulcus, dorsal pubic pitting, extended pubic tubercle, ventral pubic pitting & exostoses, margo auricularis groove, sacral preauricular extension & notch) to statistically evaluate its association with parity in three samples (one modern, and two from the 19th century). The PPI was significantly associated with parity and age at death. A pelvis shape analysis revealed an association with an increase in pelvic width. However, bone modelling in older women weakened the association of the PPI with parity. The PPI showed differences between the modern and historical samples, suggesting that factors such as lifestyle and obstetrical practices affect the relationship between the PPI and actual parity. We propose the PPI as a useful tool for assessing parity, but the predictive accuracy may vary across populations. We present a software tool for an easy application of the PPI in bioarcheological and anthropological studies.

Keywords Parturition scars · Preauricular sulcus · Dorsal pubic pitting · Obstructed birth · Pregnancy

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Introduction

The estimation of parity based on the human skeleton provides crucial data for demographic studies in archaeology and the forensic sciences. It is well documented that pregnancy and parturition exert both direct and indirect effects on the human skeleton. For example, sexual maturation and the secretion of steroid hormones during puberty gives rise to the sexual differences in the bony pelvis (Fischer and Mitteroecker 2017; Rogol et al. 2002; Wells 2007). During pregnancy, further hormones, such as relaxin, are secreted. This hormone softens pelvic ligaments and allows for an easier birth process (Cunningham et al. 2014; Grunstra et al. 2019; Jockenhövel 1989; Owens et al. 2002). Additionally, the weight of the gravid uterus alters the mother's posture during gait (hyperlordosis of the lumbar spine), which affects the biomechanics of the human skeleton (Amiel 1981; Hagen 1974; Ritchie 2003; Whitcome et al. 2007) and increases the risk of pelvic and back pain. The birth process also has long-term impacts on the female body, including

Published online: 05 August 2026

higher risks of hemorrhages and cyst formations in pelvic joints and ligaments resulting from hyperextension (Ashworth et al. 1976; Becker et al. 2010; Stewart 1970) as well as an elevated risk of pelvic floor disorders (Ashton-Miller and DeLancey 2007; DeLancey et al. 2003; Stansfield et al. 2025; Weidner et al. 2006). Pelvic floor disorders frequently manifest years or decades after the birth event, although they can be directly attributed to parity. Breastfeeding impacts the female skeleton due to an increased calcium and vitamin D requirement, which directly affects bone metabolism (Bae and Kratzsch 2018; Dawodu and Tsang 2012; Pearson et al. 2004; Sowers 1996).

Even though "pelvic features" (Pany-Kucera et al. 2019), including parturition scars, are largely unknown in the clinical fields, they are commonly discussed as indicators of parity in anthropology. These changes are defined as depressions, pits, grooves, or exostoses at the bony pelvis, which are commonly attributed to pregnancy and birth (Angel 1969; Houghton 1975; Pany-Kucera et al. 2019; Putschar 1976; Stewart 1970; Ullrich 1975). Pelvic features are located in close proximity to the sacroiliac joint, including the preauricular sulcus, margo auricularis groove, and sacral preauricular extension or notch. Additionally, they are situated in the vicinity of the pubic symphysis, exhibiting features such as ventral pubic lesions and exostoses, dorsal pubic pitting, and the extended pubic tubercle. The most prominent feature, a well-developed preauricular sulcus, is employed as a diagnostic criterion for sex estimation based on the bony pelvis in anthropology as it can be commonly observed in the female pelvis (Bruzek et al. 2022; Pérreard-Lopreno et al. 2022). It is a horizontal sulcus or groove located at the superior margin of the greater sciatic notch of the ilium, in close proximity to the sacroiliac joint (Houghton 1974). Cox and Scott (1992) observed a higher, though not statistically significant prevalence of the preauricular sulcus in android pelves. Waltenberger et al. (2021a) identified an association between the preauricular sulcus and extensive biomechanical strain caused by a retroverted acetabulum. Another sulcus may be observed on the lateral margins of the facies pelvina of the sacrum (also known as "sacral scarring", or "margo auricularis groove", as documented by Cox and Scott 1992; Pany-Kucera et al. 2022b). Yet, this feature is likely more associated with age or sex than with the number of births (Cox 2006; Maass and Friedling 2016). A third feature in close proximity to the sacroiliac joint is the sacral preauricular extension, a trait that is exclusive to females (Pany-Kucera et al. 2019, 2022a, b). It is an osseous, ventrally pointing expansion situated at the ventrosuperior margin of the sacral ala, at the level of the terminal line. It is distinguished from the sacral auricular facet by a slight line of demarcation that sets it apart from other alterations in this region. This feature can be accompanied by a corresponding facet at the ilium. On rare occasions, a notch (sacral preauricular notch) may be identified at the same location. On the ventral or dorsal aspect of the pubic body, lytic pits may occasionally develop (ventral and dorsal pubic pitting, Angel 1969). The formation of dorsal pubic pitting may be attributed to a hypertrophic posterior transverse ligament, inflammatory processes or traumata like ligament avulsions, and the deep pits by oedematous bone necrosis (Angel 1969; Ashworth et al. 1976; Becker et al. 2010; Kamieth and Reinhardt 1955; Maurer-Gesek et al. 2022; Pany-Kucera et al. 2022a). Dorsal pubic pitting is associated with parity, sex, age, and a higher BMI (Gilbert and McKern 1973; McFadden and Oxenham 2018; Snodgrass and Galloway 2003; Waltenberger et al. 2022) and may provide a method for the prediction of parity, although it is highly variable across individuals (Waltenberger et al. 2022). Another feature is called the extended pubic tubercle, an exostosis located at the arcuate line of the superior pubic ramus. This should not be confused with the anatomical structure known as the "pubic tubercle" (Angel 1969; Maass and Friedling 2016; Snodgrass and Galloway 2003). Cox (1989) and Bergfelder and Herrmann (1980) identified an association with parity, while other studies have also reported a correlation with body height, age, sex, and BMI (Maass and Friedling 2016; Snodgrass and Galloway 2003). Naturally, there are differences in the significance and occurrence of the mentioned features in relationship with pregnancies and births. Dorsal pubic pitting, for instance, has been shown in several clinical studies, to be a more reliable indicator of pregnancy and birth, as compared to features like sacral scarring (Pany-Kucera et al. 2022b). Importantly, it is clear that the presence of one of the features is not sufficient to securely assess parity.

The etiology of pelvic features remains incompletely understood, with some parous women never exhibiting such changes, while others, including some nulliparous women and men develop some of them (Cox and Scott 1992; Holt 1978). Hence, a number of additional factors beyond those associated with parity may also give rise to comparable features. Moreover, several earlier studies, including those that initially described pelvic features, were based on skeletal remains with an uncertain or reconstructed birth history (Cox and Scott 1992; Ullrich 1975). The interpretation of the features as pelvic features related to parity in unknown samples is based on the observation of higher frequencies in female individuals and is therefore highly speculative. In recent years, researchers have begun to re-examine this topic, attempting to identify the causal factors underlying the development of pelvic features, rather than merely searching for an association with parity in their samples (Maass and Friedling 2016; Pany-Kucera et al. 2022a; Waltenberger et al. 2021a, 2022). The highly variable expressions of pelvic features and the differences between populations suggest that multiple factors are involved in their development, including biomechanical stress and pelvic shape (Maass and Friedling 2016; Waltenberger et al. 2021a).

Waltenberger et al. (2021b) observed that pelvic features become more pronounced between puberty and menopause in females, whereas this trend reverses in postmenopausal women, who are likely to experience atrophic reorganization of pelvic features in advanced age (Bergfelder and Herrmann 1980). In a separate publication (Waltenberger et al. 2022), the authors could not detect an association between age, parity and single pelvic features. These results suggest a weak association between parity and the *tendency* to develop pelvic features.

Aim of the study

Despite the weak and inconsistent correlation between most isolated pelvic features and parity, Waltenberger et al. (2021b) demonstrate that already a simple composite score of all pelvic features exhibits a notable association with age at death and the number of birth events in females during their reproductive years. Pany-Kucera et al. (2022b) proposed a formula for calculating a pelvic pattern index (PPI). This index combines the expression of all pelvic features as a proxy for parity in archaeological data, which provides a flexible option for handling missing data. In the context of osteological analyses, Pany-Kucera and colleagues frequently observed the occurrence of combinations of expressed pelvic features in females. The PPI was developed with the objective of summarizing the records of single pelvic feature expression, thereby enhancing the comparability and quantification of the resulting data. As the PPI was developed on prehistoric skeletons and tested on historical identified skeletal collections containing information about baptism and other historical records (Cox and Scott 1992), this study will test the PPI in a recent sample with known information about pregnancy and birth. Moreover, although an association between the PPI and parity was previously identified by Pany-Kucera et al. (2022b), with multiparae showing combinations of expressed features along a higher index on average, the precise nature of what the PPI measures, remains uncertain. Testing various causal factors, including a geometric morphometric analysis of pelvic shape, facilitates the implementation of an accessible and straightforward approach to investigating parity in archaeological case studies. The presented tool in this study has been specifically designed for researchers who are not proficient in programming and data analysis.

Material & methods

The sample comprised three datasets: a 21st century CT dataset of female individuals with known background information obtained by autopsy recordings and next-of-kin-interviews, and two 18th to 20th century historical collections: the Simon Identified Skeletal Collection, University of Geneva, Switzerland (Abegg and Desideri 2019) and the Christ Church Spitalfields crypt Collection, Natural History Museum London, UK (Cox 1989; Cox and Scott 1992). Obstetric histories of the females based on baptism and other historical records are available for parts of the collections. The modern dataset contained pseudonymized forensic CT data of 183 corpses obtained from the New Mexico Decedent Image Database (NMDID; Edgar et al. 2020). NMDID includes over 15,000 whole-body CT scans of individuals deceased in New Mexico between 2010 and 2017. CT scans were obtained with a Philips Brilliance Big Bore 16 CT scanner and the scanning protocol for adults and thin sectioned bone (Pixel size: 0.5 mm, slice thickness 1 mm) developed by the Office of the Medical Investigator (OMI). Our sample comprised 45 nulliparae, 45 primiparae, and 45 multiparae. Each of these groups were composed of three age subgroups of the same size: 19–29 years, 30–49 years, and older than 50 years. Additional 15 juvenile female individuals were included (12–17 years, all nullipara) to cover the onset of sexual maturity and the development of sexual dimorphism in pelvic shape in response to sex steroid hormone secretion during puberty (Fischer and Mitteroecker 2017; Huseynov et al. 2016), which probably affects the development of pelvic features (Waltenberger et al. 2021b). Exclusion criteria were artificial hip or knee joints, a BMI higher than 35, trauma to the femur or pelvis, heavily decomposed cadavers, mummification, congenital defects, neoplastic diseases, and other diseases that influence pelvic shape. Thirteen female individuals were excluded during the analysis because of missing pelvic data or pelvic traumata that have not been mentioned in the metadata. Because pelvic shape and pelvic features vary across populations (Kurki 2011, 2013) and the pelvic score was developed based on the Simon and Spitalfields collection (of British, Swiss and largely French origin), we limited the sample to individuals labeled as “European Ancestry”. CT scans were downloaded and semi-automatically segmented in the software Amira 6.7. following the segmentation protocol of Spoor et al. (1993). The segmented models were exported as surface mesh for further analysis. One observer (L.W.) placed 77 anatomical landmarks and 250 semilandmarks on all important anatomical structures of the human pelvis (software: EVAN Toolbox 1.72, Phillips et al. 2017). Anatomical landmarks are based on the definitions of Reynolds et al. (1982). The expression of pelvic features (dorsal and ventral pubic pitting, extended pubic tubercle, sacral preauricular extension, preauricular sulcus, Fig. 1) were assessed based on adapted scoring systems of Stewart (1970), Ullrich (1975), Steckel et al. (2006), Maass and Friedling (2016), and Pany-Kucera et al. (2019), Table 1.

Parity was estimated based on a visual grading of pelvic features as described in Rebay-Salisbury et al. (2018) and the Pelvic Pattern Index (PPI) developed by Pany-Kucera et al. (2022b). This index aims to reflect the various factors that exert strain on the pelvis during pregnancy and birth. Statistically, it can be considered an estimate of a latent variable (pregnancy- and birth-related strain) that underlies pelvic feature expression. To calculate the PPI, the highest recorded score of each pelvic feature and left or right side per individual is used. The unweighted PPI is calculated as an average of the feature scores, expressed as a fraction of the maximally possible degree of expression (adapted from Pany-Kucera et al. 2022b):

$$PPI = \frac{100}{a} \sum{}_{i=1}^{a} \frac{x_i}{x_i^{max}}$$

where a is the number of assessable pelvic features (the number of all features rated ≥ 0), x_i, is the grading of the i^{th} pelvic features, and x_i^{max} is the maximal possible expression degree of the i^{th} feature. The PPI ranges from 0.0 to 1.0.

The unweighted index above rests on the assumption that pregnancy- and birth-related strain similarly increases the degree of expression for every pelvic feature, which is not necessarily realistic. To optimize this score and maximize its association with the number of birth events (R^2 of linear regression models), we used a machine learning approach to evaluate all possible combinations of the expression score of single pelvic features and considered weightings of 0, 10, 25, 50, 75, and 100 for each expression level. No weightings were assigned to the scores of the margo auricularis groove due to its rare occurrence in the sample. The corresponding facet of the sacral preauricular extension was excluded because of its high correlation with the sacral auricular facet, thus avoiding and overproportionate the weighting of a single anatomical area (the apex of the sacroiliac joint). As both excluded features were defined as pelvic features by Pany-Kucera et al. (2022b) and included in their (unweighted) PPI, we used the two features only for calculating the unweighted PPI, not for the weighted PPI. The weight combinations yielding the highest R^2 values in the NMDID sample were selected for the final weighted PPI (provided in Table 1). This approach was preferred over multiple regression, which only linearly weights the predictor variables, whereas we allowed nonlinear monotonic weightings.

To calculate the weighted PPI, the sum of the weighted scores w_i are divided by the sum of the maximally possible expression scores, w_i^{max}, of the observable features, multiplied by 100. The weighted PPI can thus take on numbers from 0 to 100.

$$PPI_{weighted} = 100\frac{\sum{}_{i=1}^{a} w_i}{\sum{}_{i=1}^{a} w_i^{max}}$$

For providing a user-friendly option to calculate the PPI, we developed an open-access software implementation, which can be downloaded via GitHub (https://github.com/luwa44/PPI-calculator/releases/latest).

The morphometric and statistical analyses in this paper were performed in R 4.4.1 (R Core Team 2013) using the packages Geomorph 4.0.8 (Adams et al. 2018) and Morpho 2.12 (Schlager 2017). First, the PPI was analyzed using linear regression to explore its association with parity and other potential causal factors in the NMDID sample. Using Geomorph, the semilandmarks were slid using the minimum bending energy criterium (Gunz and Mitteroecker 2013; Gunz et al. 2005), followed by a standardization for differences in overall location, scale and orientation by Generalized Procrustes Analysis (Mitteroecker and Gunz 2009; Rohlf and Slice 1990). The multivariate association between pelvic shape, PPI, age at death, body weight, height, the number of birth events (all standardized to the same variance) was explored by partial least squares (PLS) analysis (Mitteroecker and Bookstein 2007; Rohlf and Corti 2000). We estimated the type I error by permutation tests (1,000 random permutations, explained total variance as test statistic). Data were visualized using the package ggplot2 (Wickham 2016). Finally, the observed shape changes depicted by the PLS were validated by using length measurements of the AP-diameter, the ML-diameter, pubic length, ischium length, iliac breadth and height. These distances were reassessed based on the landmarks placed for the GM analysis. All *p*-values were corrected by the Bonferroni–Holm method to avoid a cumulation of alpha errors (Holm 1979).

Results

Females in the NMDID sample ($n = 134$) had an average age of 44.5 years, an average of 1.56 children per woman (ranging from 0 to 10) and an average of 1.82 pregnancies (ranging from 0 to 13), including abortions and miscarriages. The preauricular sulcus was observed most frequently in the sample ($n = 118$ [88%]), followed by lesions and exostoses at the ventral pubic surface (both: $n = 38$ [28%]). Single pelvic features were only weakly correlated with each other (Table 2). In the Simon collection ($n = 67$) and the

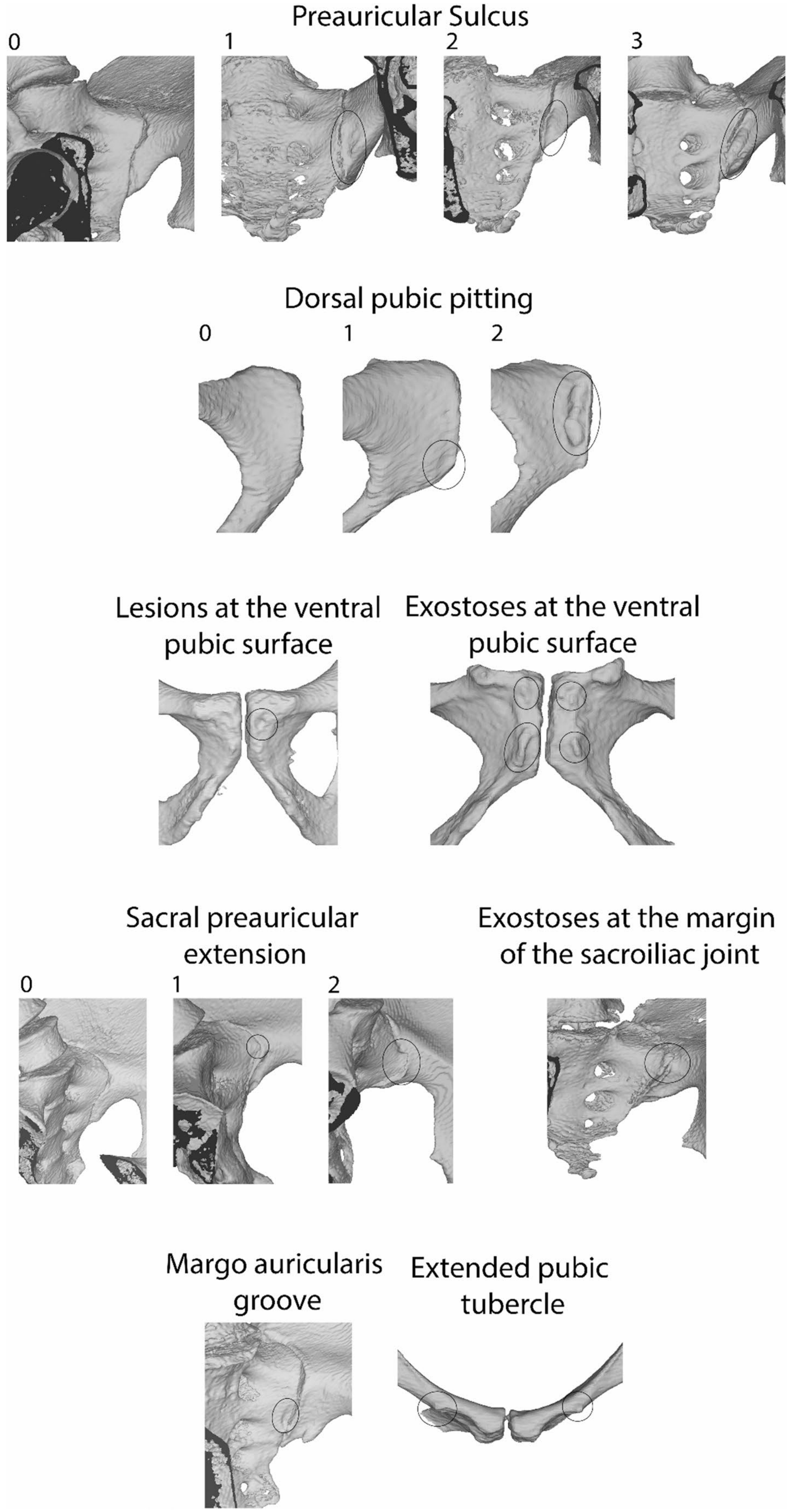

Fig. 1 Observed expressions of the recorded pelvic features (preauricular sulcus, dorsal pubic pitting, lesions and exostoses at the ventral pubic surface, sacral preauricular extension, exostoses at the margin at the margin of the sacroiliac joint, margo auricularis groove, extended pubic tubercle) in the NMDID. The numbers correspond to the scores described in Table 1

Table 1 Pelvic features and their expression scores used to calculate the PPI. The last two features are counted to the sum of present pelvic features but will not be included in the calculation for the PPI as it did not increase the quality of this index

Pelvic feature	unweighted score	weighted score	Definition
preauricular sulcus stage (after Steckel et al. 2006)	NA	NA	trait unobservable
	0	0	area is smooth, with no clear evidence of a sulcus
	1	25	a small, weakly developed preauricular sulcus is clearly present
	2	50	a preauricular sulcus is moderately developed
	3	100	a large, well-defined sulcus is present
dorsal pubic pitting (after Stewart 1970 and Ullrich 1975)	NA	NA	trait unobservable
	0	0	smooth surface, no lesion present
	1	75	small lesion(s) present (<2 mm)
	2	100	medium to large lesions present (>2 mm)
extended pubic tubercle (after Maass 2012)	NA	NA	trait unobservable
	0	0	surface of extended pubic tubercle is smooth
	1	10	extended pubic tubercle present
exostoses at the margin of the sacroiliac joint (after Rebay-Salisbury et al. 2018)	NA	NA	trait unobservable
	0	0	no exostoses present
	1	10	exostoses present
exostoses at the ventral pubic surface (after Rebay-Salisbury et al. 2018)	NA	NA	trait unobservable
	0	0	smooth surface, no exostoses present
	1	10	exostoses present
lesions at the ventral pubic surface (after Rebay-Salisbury et al. 2018)	NA	NA	trait unobservable
	0	0	smooth surface, no lesions present
	1	10	lesions present
Sacral preauricular extension or preauricular notch (after Pany-Kucera et al. 2019)	NA	NA	trait unobservable
	0	0	no sacral preauricular extension or preauricular notch
	1	50	sacral preauricular extension (smaller than 2 mm) or preauricular notch present
	2	100	sacral preauricular extension (larger than 2 mm) present
Corresponding facet of the sacral preauricular extension at the ventral apex of the iliac auricular facet (after Pany-Kucera et al. 2019)	NA	NA	trait unobservable
	0	0	smooth surface, no corresponding facet visible
	1	0	corresponding facet visible
Margo auricularis groove (after Rebay-Salisbury et al. 2018)	NA	NA	trait unobservable
	0	0	smooth margin of the facies pelvina of the sacrum
	1	0	groove at the margin of the facies pelvina of the sacrum at the attachment site of the anterior sacroiliac ligaments

Spitalfields collection ($n=27$), individuals died on average in their mid-forties. As expected, the numbers of live births were much higher in comparison to the modern sample, with three to four birth events on average and a maximum of 15 births in both historical collections. Here, the most frequently observed pelvic features were the preauricular sulcus (Simon collection: $n=41$ [61%], Spitalfields collection $n=16$ [59%]). More details about the sample composition can be found in Tables 3 and 4, and SI1.

We tested the PPI in linear regression models using the modern data of the NMDID sample with detailed background information about the deceased. The unweighted PPI was only weakly and non-significantly associated with parity ($R^2=0.0098$, $p=0.2997$, $\beta_{birth}=1.278$). The weighted PPI, by contrast, was slightly stronger and significantly associated with birth ($R^2=0.1366$, $p<0.001$, $\beta_{birth}=6.489$, Fig. 2). By including age at death as a covariate and standardizing the data, we could show that in this model, the effect of age and birth on the PPI is approximately equal ($R^2=0.1772$, $p<0.001$, $\beta_{birth}=0.302$, $\beta_{age}=0.271$). Similar results were obtained for the historical data ($R^2=0.2025$, $p<0.001$, $\beta_{birth}=0.280$, $\beta_{age}=0.266$). Body height was only weakly and non-significantly associated with the PPI in all samples. In Waltenberger et al. (2021b); Waltenberger (2021) we could show that pelvic features predominantly develop during the reproductive time in females, whereas

Table 2 Correlation matrix showing the associations between single pelvic features (Kendall's τ): no correlation: $\tau \leq 0.1$; weak correlation: $0.1 < \tau \leq 0.3$; moderate correlation: $0.3 < \tau \leq 0.5$; strong correlation: $\tau > 0.5$

Preauricular sulcus	Dorsal pubic Pitting	Extended pubic tubercle	Exostoses at the margin of the sacroiliac joint	Exostoses at the ventral pubic surface	Lesions at the ventral pubic surface	Sacral preauricular extension	Sacral preauricular notch	Margo auricularis groove
	0.266[1]	0.065	0.278	0.267	0.089[1]	0.003	-0.015[1]	0.015[1]
Dorsal pubic Pitting	1	0.083	0.212	0.125	0.011[1]	-0.080	0.047[1]	-0.065[1]
Extended pubic tubercle		1	0.197	0.183	-0.018	0.074	0.132[1]	0.051[1]
Exostoses at the margin of the sacroiliac joint			1	0.270	-0.045	0.194	0.034[1]	0.175[1]
Exostoses at the ventral pubic surface				1	0.115[1]	0.042	0.012[1]	0.047[1]
Lesions at the ventral pubic surface					1	-0.109[1]	0.035[1]	0.150[1]
Sacral preauricular extension						1	-0.086[1]	-0.110[1]
Sacral preauricular notch							1	-0.033[1]

[1]The association should be interpreted cautiously, as rank overlap was limited for at least one category combination

Table 3 Descriptive statistics of the three collections

	NMDID			Simon collection			Spitalfields collection		
	mean	sd	IQR	mean	sd	IQR	mean	sd	IQR
age at death	44.54	21.55	31.5	43.25	17.04	24	45.70	16.03	23.5
no. of live births	1.56	1.68	2	2.91	3.29	4.5	3.85	3.66	3
no. of pregnancies	1.82	2.13	3	-	-	-	-	-	-

Table 4 Frequencies of the observed pelvic features and their corresponding scores (degree of expression)

Score	Preauricular sulcus	Dorsal pubic Pitting	Extended pubic tubercle	Exostoses at the margin of the sacroiliac joint	Exostoses at the ventral pubic surface	Lesions at the ventral pubic surface	Sacral preauricular extension	Sacral preauricular notch
NMDID								
NA	8 (6.0%)	8 (6.0%)	13 (9.7%)	13 (9.7%)	13 (9.7%)	8 (6.0%)	8 (6.0%)	14 (10.4%)
0	8 (6.0%)	92 (68.7%)	86 (64.2%)	92 (68.7%)	85 (63.4%)	107 (79.9%)	95 (70.9%)	120 (89.6%)
1	50 (37.3%)	13 (9.7%)	35 (26.1%)	29 (21.6%)	36 (26.9%)	19 (14.2%)	31 (23.1%)	0
2	38 (28.4%)	21 (15.7%)	-	-	-	-	-	-
3	30 (22.4%)	-	-	-	-	-	-	-
Simon collection								
NA	0	11 (16.4%)	27 (40.3%)	0	13 (19.4%)	17 (25.4%)	2 (3.0%)	2 (3.0%)
0	26 (38.8%)	46 (68.7%)	33 (49.3%)	38 (56.7%)	42 (62.7%)	28 (41.8%)	61 (91.0%)	63 (94.0%)
1	19 (28.4%)	1 (1.5%)	7 10.4%)	29 (43.3%)	12 (17.9%)	22 (32.8%)	4 (6.0%)	2 (3.0%)
2	19 (28.4%)	9 (13.4%)	-	-	-	-	-	-
3	3 (4.5%)	-	-	-	-	-	-	-
Spitalfields collection								
NA	0	2 (7.4%)	3 (11.1%)	0	1 (3.7%)	2 (7.4%)	1 (3.7%)	0
0	11 (40.7%)	11 (40.7%)	14 (51.9%)	22 (81.5%)	13 (48.1%)	17 (63.0%)	23 (85.2%)	27 (100%)
1	14 (51.9%)	7 (25.9%)	10 (37.0%)	5 (18.5 5%)	13 (48.1%)	8 (29.6%)	3 (11.1%)	0
2	2 (7.4%)	7 (25.9%)	-	-	-	-	-	-
3	0	-	-	-	-	-	-	-

after menopause this association is weakened by remodeling effects. Consequently, we calculated another regression model by just including individuals younger than 45 years ($p = 0.01$). In all datasets, the association of the weighted PPI and age vanished, suggesting that the age effect was predominantly caused by changes in postmenopausal females.

Comparing the distribution of the weighted PPI across different parous groups in the historical and recent data confirmed the trend for a higher PPI in multiparous females (Table 5). However, the PPI in the recent sample differs from the sample of the historical collections suggesting a changed pattern in the expression of pelvic features today. Most nulliparous females exhibited a maximum of two different pelvic features. Only two nulliparous females showed three pelvic features. In the Spitalfields collection individual 667, a 30-year-old-female, presumed nulliparous with

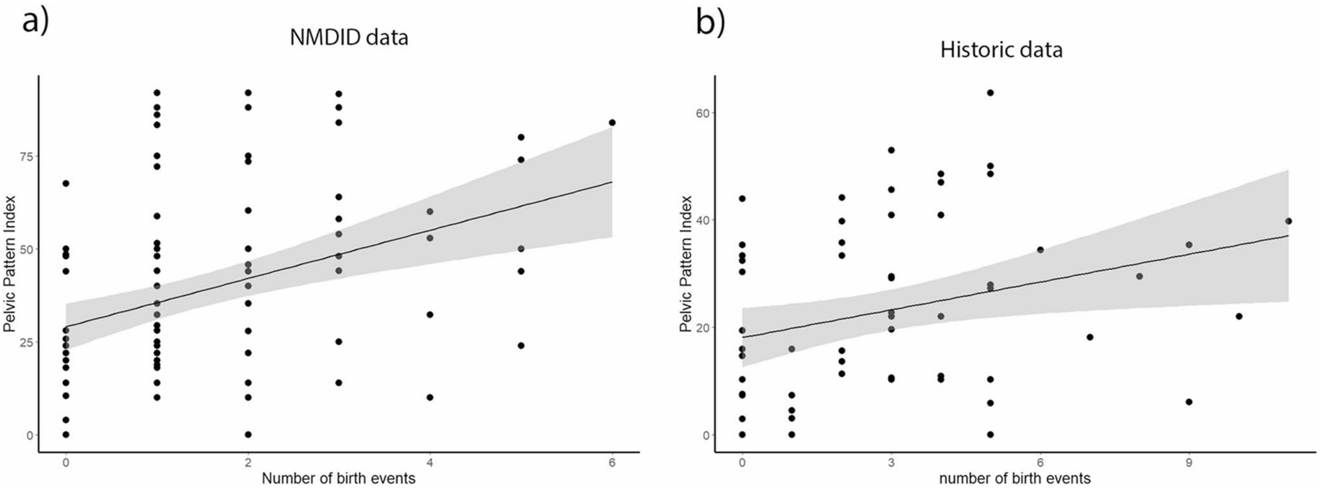

Fig. 2 Scatterplots of the number of birth events against the weighted PPI in (**a**) NMDID data and (**b**) the historical data. The grey area represents the 95% confidence region of the regression line

no further insights into birth history, exhibited dorsal pubic pitting, lesions at the ventral pubic surface and an extended pubic tubercle. In the recent sample one nulliparous individual exhibited three pelvic features (individual 166116), one four features (individual 114346). Individual 166,116, a 37-year-old female, exhibited a preauricular sulcus stage 3, a sacral preauricular extension stage 1 on the right side and exostoses at the margin of the sacroiliac joint (stage 1). In individual 114,346, a 43-year-old female, a weak preauricular sulcus, an extended pubic tubercle, lesions and exostoses at the ventral pubic surface were observed. However, this individual further presented possible evidence for a traumatic event with a possible healed compression fracture at L5, osteophytic lipping at L4, L5, and the sacral base, callus formation at the right acetabular rim and a divided pubic tubercle which likely affected the observed pelvic feature expression. No detailed medical history about the trauma was recorded in the NMDID for this individual. Next, we checked patterns of pelvic features in individuals with exactly three and four or more pelvic features. In individuals with three pelvic features present, most frequently a deep preauricular sulcus, deep dorsal pubic pitting and the extended pubic tubercle have been observed. Similarly in individuals exhibiting at least four features, these three pelvic features are also most common. Additionally, exostoses at the ventral pubic surface were observed in nine out of eleven cases (SI1).

The results of the partial least squares analysis showed a significant association between pelvic shape and the weighted PPI, number of birth events and age ($p = 0.003$). The first PLS dimension accounted for 77% of the total squared covariance and was positively associated with the weighted PPI, age at death, and the number of birth events (Fig. 3).

Individuals with a high PPI showed a relative increase of the mediolateral diameter of the pelvic canal, a small decrease of the anterior-posterior diameter relative to the overall pelvic dimensions, and an increase of relative coxal height. The effect of the pelvic inlet was predominantly caused by a broader sacrum and a slight decrease in the width of the iliac blades. (Fig. 4). Age was the strongest factor affecting the pelvic shape. The weighted PPI and the number of birth events were also significantly associated with pelvic shape, although their loadings were lower than that for age.

-4sd). (b) Pelvic shape corresponding to a high score for age, the number of birth events, and the weighted PPI (extrapolation +4sd). A relative increase of the mediolateral pelvic inlet caused by a wider sacrum, and an increase of the coxal height are associated with the tested variables.

We repeated the PLS by excluding nullipara or females who developed less than three pelvic features as they were suspected to increase the variability in the dataset. The PLS containing only parous females showed a higher loading for the weighted PPI and a decrease of the loading of the number of birth events ($p = 0.013$, details see SI2), whereas the PLS with only females expressing more than two pelvic features showed an insignificant association between both blocks of data ($r = 0.636$, $p = 0.175$, *effect-size* $= 0.934$), probably related to the decrease of the sample size from 109 cases to 51. The corresponding pelvic shape changes showed similar patterns as in Fig. 3. The results in the shape pattern visible in the PLS can also be reproduced based on absolute length measurements of pelvic dimensions (linear regression of length measurements on the PPI). Here only the ML-diameter of the pelvic canal was significantly associated with the PPI ($R^2 = 0.073$, $p = 0.002$, $\beta_{ML} = 0.6532$). Other pelvic dimensions (AP-diameter, pubis length, ischium length, pelvis height, ilium width) were only weakly and non-significantly associated with the PPI.

Table 5 Descriptive statistics for females who died during their reproductive time (before menopause), and further divided into the groups nulliparae, parae (further divided into primi- and multiparae) for each sample separately

	Simon collection					Spitalfields collection					NMDID				
	n	mean age	mean PPI	min. 3 features	min. 4 features	*n*	mean age	mean PPI	min. 3 features	min. 4 features	*n*	mean age	mean PPI	min. 3 features	min. 4 features
females during the reproductive phase	22	32.41	15.81	4	2	14	32.86	22.25	5	3	60	28.42	29.31	20	6
nulliparae	10	29.40	11.05	0	0	4	27.25	13.24	1	0	17	31.24	18.46	2	1
parae	12	34.92	19.77	4	2	10	32.63	21.15	4	3	43	31.49	38.42	17	5
primiparae	4	32.75	7.71	0	0	1	35	NA	0	0	22	30.82	34.36	9	3
multiparae	8	36.00	25.81	4	2	9	35.11	28.73	4	3	21	32.19	42.88	18	10

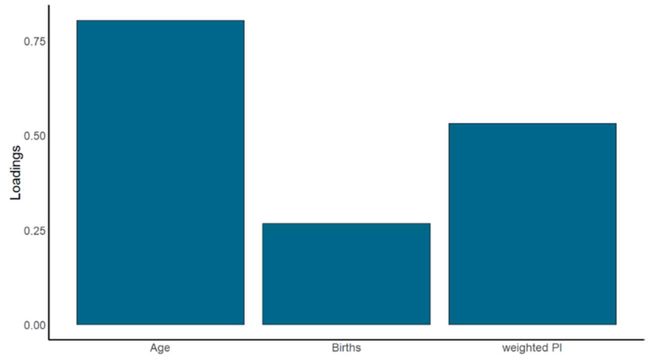

Fig. 3 Loadings of age, the number of birth events, and the weighted PPI on the first dimension of the partial least squares (PLS) analysis in the female sample. The loadings are proportional to the covariance between each feature and the corresponding pelvis shape feature depicted in Fig. 4 (they are no partial coefficients as in the multiple regression above)

Discussion

The findings of this study indicate that the presence of several expressed pelvic features and their combination into a single weighted score is significantly associated with birth events in chronologically diverse populations of European ancestry. However, the expression of pelvic features is highly variable. Some individuals express pelvic features without a history of parity, albeit to a small extent, whereas multiparae may not develop them. Nonetheless, several studies, including this one, could show a general trend of more pelvic features in multiparous individuals (Gilbert and McKern 1973; Pany-Kucera et al. 2022a, b; Stewart 1970; Waltenberger et al. 2022). Although the PPI was significantly associated with parity in both the modern and the historical samples, the average PPI in the NMDID sample was considerably higher than that in the historical collections. This appears to be inconsistent with the later onset and lower frequency of births in the modern sample; however, several biological and methodological factors may explain this pattern. Females of the recent sample gave birth, on average, to 1.6 children, whereas the average number of birth events was much higher in the 19th century samples (2.9 and 3.9 children,), matching the well described general decline of fertility during the last century (Roser 2014). Furthermore, the age at which they had their first child is usually earlier than it is today (Pany-Kucera et al. 2022a). In young females with incompletely developed pelves, the risk of obstructed birth is elevated (World Health Organization 2004), which may result in an increased prevalence and stronger expression of pelvic features. The shorter periods between pregnancies in historical populations affect the development of pelvic features due to insufficient time for the full completion of pelvic remodeling and the full formation of pelvic features. Unfortunately, obtaining detailed

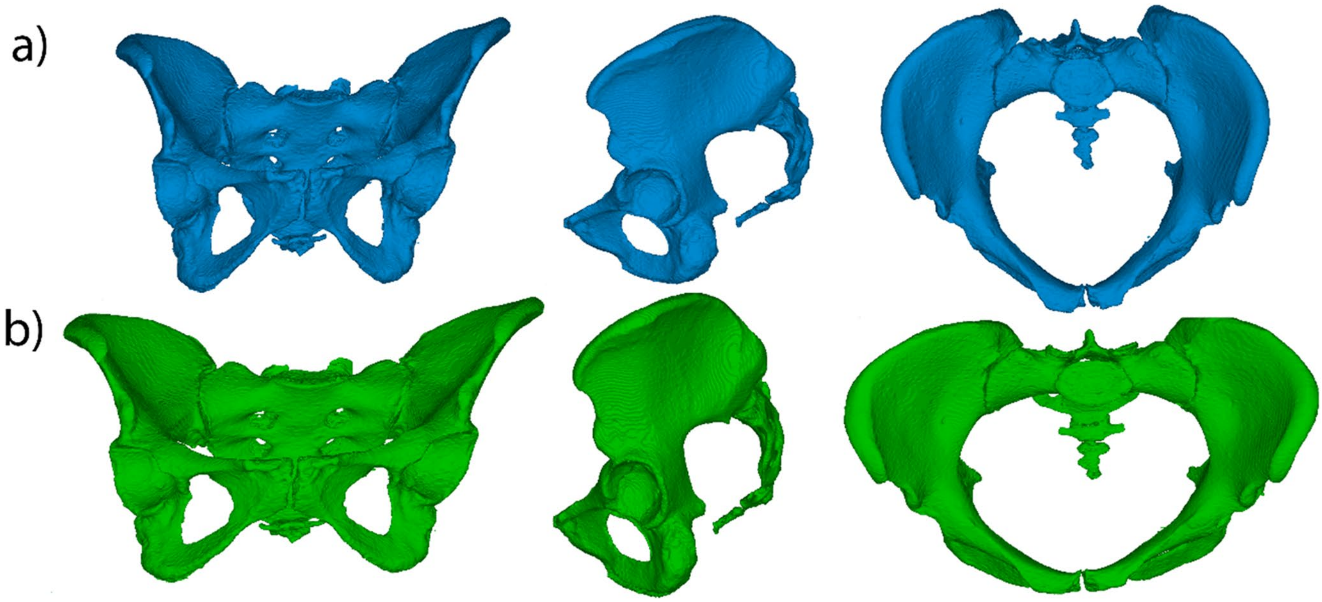

Fig. 4 The pattern of pelvic shape changes along the first dimension of the partial least squares (PLS) analysis (compare Fig. 3). (**a**) Pelvic shape corresponding to a low score for age, the number of birth events, and the weighted PPI (extrapolation

birth recordings for historical populations is challenging. To gain further insights, it would be beneficial to record the detailed birth dates of children based on the original baptism records in the historical samples.

Previous studies have suggested that pelvic features, such as the preauricular sulcus, may be linked to an increased biomechanical strain, particularly during gait (McFadden and Oxenham 2018; Ubelaker and De La Paz 2012; Waltenberger et al. 2021a). Additionally, studies have demonstrated a stronger correlation with biological sex than with parity (Maass and Friedling 2016; Praxmarer et al. 2020). Nevertheless, studies with large sample sizes and known background information have been able to verify a clear trend indicating that multiparous females exhibit on average a higher number and more pronounced pelvic features (Bergfelder and Herrmann 1980; Gilbert and McKern 1973; Pany-Kucera et al. 2019; Waltenberger et al. 2022). This suggests that parity may, at the very least, increase the probability and severity of pelvic features, if not act as the primary cause (Ives et al. 2024). Average pelvic shape may have undergone secular changes, influenced by a range of factors, including socioeconomic conditions, nutritional stress, disease, and biomechanical strain due to strenuous labor (Bogin et al. 2002; Narumoto et al. 2015; Wells et al. 2012). This may have an impact on the PPI. Moreover, pelvic shape is also speculated to be associated with factors such as occupation, which have been demonstrated to effect entheseal changes, and rates of osteoarthritis in the elderly (Gilbert and McKern 1973; Putschar 1976). The degeneration of the pubic symphysis is known to occur more rapidly in females than in males, as shown in the studies of Todd (1921) and Meindl et al. (1985). The age at death of parous women tends to be overestimated by up to 14 years when using the pubic symphysis for the age at death estimation. This observation suggests that the process is associated not only with age but also with increased biomechanical strain related to the female pelvic shape and/or parity. Similarly in the study of entheseal changes, researchers were able to identify two distinct causes in different age groups. Entheseal changes may occur in early adulthood, induced by microtrauma and overuse of the involved muscles. However, they may also manifest in the elderly associated with generalized degeneration of the soft and hard tissues (Dutour 1986; Villotte et al. 2010). The regression model was controlled for body height and weight, and it was found that these variables have a weak and insignificant effect on the PPI in all samples. Therefore, the observed increase in stature over the past century is an inadequate explanation for the observed differences between the populations.

The relative frequencies of individuals exhibiting at least three pelvic features are similar in both the historical and recent samples. Additionally, the preauricular sulcus, the extended pubic tubercle, and sacral preauricular extensions are more prevalent in the modern sample, whereas exostoses at the margin of the sacroiliac joint and lesions at the ventral pubic surface are more common in the historical samples. With regard to other pelvic features, comparable frequencies were observed across the various samples.

The field of obstetrics has undergone significant developments over the past century, with the advent of modern medical techniques. Consequently, the implementation of modern obstetric care, including antibiotic treatment, and the utilization of safe cesarean sections, has resulted in a lower incidence of lethal and prolonged obstructed birth, particularly in industrialized countries with access to high-quality medical treatment which may also influence the development of pelvic features. Further research on additional modern and historical samples is required to gain a deeper understanding of the underlying factors associated with the PPI and its association with parity. In particular, data regarding the mode of birth must be incorporated into the analysis to facilitate a more comprehensive understanding of the underlying causes of pelvic features.

Our findings revealed a significant association of the PPI, age, and parity with a specific pelvic shape, characterized by a widened pelvic canal in the mediolateral direction. However, this pelvic shape is most significantly influenced by age. From an obstetric perspective, a slight increase in the mediolateral dimensions of the pelvic canal is advantageous, given that there is no significant decrease in the anteroposterior-diameter observed in our study. This finding challenges the hypothesis that pelvic features are caused by extensive strain to the pelvis during birth as proposed by Cox and Scott (1992), Houghton (1974), and Putschar (1976). The associated pelvic shape would provide additional space within the pelvic canal, potentially facilitating the passage of the fetus through the birth canal as there would be more space for the shoulder girdle and the rotation of the body during the birth process (Abitbol 1991). However, the length measurements of the pelvic dimensions could not be used to accurately predict scarring. Stansfield et al. (2025) analyzed the association of pelvic shape with pelvic floor disorders. Their results showed that females with pelvic floor disorders have on average an increased pelvic outlet in mediolateral dimensions, which is similar to the pelvic shape presented in this study. As the largest risk factor for pelvic floor disorders is vaginal birth (Lukacz et al. 2006; Memon and Handa 2013), we suspect a connection between pelvic features and pelvic floor disorders as overstrain of the pelvic ligaments and pelvic floor as the underlying factor. As we did not have any information about the rates of pelvic floor disorders in historical and modern data, this theory needs to be tested in future studies with advanced data sets.

In addition, there are some interesting observations: Firstly, in the recorded NMDID dataset, no cases of dorsal pubic pitting were identified in male individuals (Waltenberger 2021). This finding is also consistent with the existing literature on the subject (Ashworth et al. 1976; Cox and Scott 1992).

Second, in Pany-Kucera et al. (2022b), no males or nulliparous females were observed to exhibit more than four distinct pelvic features. Moreover, the occurrence of nulliparous individuals with three pelvic features is infrequent as shown in this study. This may be indicative of elevated biomechanical stress levels in parous women for a number of potential reasons. The inclusion of postmenopausal females in the data set results in an increase in noise and a weakening of the association between PPI and parity. This is likely attributable to random factors influencing bone remodeling, which in turn affects the expression of pelvic features (Bergfelder and Herrmann 1980; Waltenberger et al. 2021b). Furthermore, it is probable that some of the variables recorded for the PPI will also manifest in the elderly. Nevertheless, in young females, there may be a tenuous correlation between these variables and parity, thereby enhancing the overall quality of the PPI. In postmenopausal females, the frequencies of nulliparous individuals exhibiting three pelvic features increase as a consequence of this phenomenon. It is recommended that studies analyzing parity in the past exclude females older than 45 years as their inclusion would artificially increase the PPI. It can be observed that females who are in the reproductive phase and who exhibit at least four pelvic features are likely to have been multiparous. Similarly, individuals with a high PPI are likely to have been multiparous, although definitive cut-off points cannot yet be established. All individuals in the historical collections and 77% of the modern sample exhibited at least four pelvic features and were multiparous.

However, to move beyond general associations and to create a quantifiable tool for estimating parity, a formal statistical approach was required. First, we applied a classical stepwise multiple regression approach, aiming to derive factors for a weighted PPI based on the resulting regression coefficients. However, as the inclusion of additional variables led to unexpected and unstable effects, we decided to calculate PPIs with different linear and non-linear weight scores beforehand to construct multiple PPIs, which were then tested in regression models against the number of birth events. Such approaches are frequently used in clinical risk modeling and supervised machine learning. However, they may introduce methodological issues, such as data snooping bias resulting from post-hoc model optimization. Given that PPIs with various weightings were repeatedly tested against parity in an exploratory framework, there is a risk of artificially inflating the observed correlation, potentially resulting in overly optimistic estimates. Nonetheless, our approach remains valid, as we did not optimize the original raw data. Instead, we selected from predefined weighting schemes the PPI that yielded the strongest correlation with parity. Moreover, we validated the weighted PPI using separate training and test samples, which produced consistent results and suggests that the PPI captures biologically meaningful variation related to parity. The partial regression coefficient of the number of birth events in the modern data and historical sample (0.3 and 0.28, respectively) indicate comparable magnitudes and directions of associations between parity and the PPI. While direct comparisons between populations are not possible with regard to the PPI, the similar slopes observed in both regression models indicate that the PPI is a consistent parity-related component in both datasets. As shown in Waltenberger et al. (2022), pelvic features show lots of variability and are unable to predict individual parity, but may help comparing average parity across groups.

We also want to highlight some observations regarding the data collection based on CT scans. All pelvic features, including subtle expressions, can be easily identified on dry bone material. However, the documentation of pelvic features on CT scans necessitates a high degree of expertise and training, particularly when working with 2D slides, which are commonly utilized in radiological assessment (Catic et al. 2026). In contrast, dorsal pubic pitting and the preauricular sulcus can be evaluated effectively on the slides (coronal and sagittal respectively), whereas the extended pubic tubercle, and sacral preauricular extension and notch are challenging to recognize on the 2D slides. If researchers work with CT data, we recommend considering segmenting the bones and creating 3D surface meshes, as this will facilitate more efficient and rapid evaluation. The utilization of three-dimensional models facilitates a more accurate comparison with data obtained from dry bone material as the evaluation process for both methods is analogous. Clinical CT scanners often lack sufficient resolution, and patients may move during the scan, potentially blurring the images and obscuring subtle pelvic features. The NMDID data were acquired using a maximum resolution of 0.5×0.5 mm per pixel and a slice thickness of 0.6 mm, which was sufficient for detecting even minor pelvic features. However, these parameters are rarely employed in clinical practice due to their increased radiation dose.

Conclusion

This study presents an index which sums up the weighted expression of pelvic features and demonstrates a significant association with parity in females. Additionally, we offer an easy-to-use application for the index calculation based on an excel spreadsheet and a computer program which can be used in research projects on parity based on pelvic features. The association of the PPI and parity was observed in diverse populations and across different time periods, potentially offering insights into reproductive patterns in unstudied populations. We found that multiparous females tend to exhibit a greater number and higher frequency of combinations of pronounced pelvic features. Furthermore, females exhibiting at least four pelvic features were in 77% to 100% of our subsamples multiparous. Therefore, the PPI can be used to at least capture part of the mothers in past populations. However, it is not possible to make a quantitative comparison between populations, as the underlying factors associated with the relationship between pelvic features and parity remain incompletely understood, particularly in relation to the differences between modern and historical populations. The PPI is significantly associated with an increase in the pelvic inlet in the ML direction, which is likely associated with a shift in the biomechanical strain to the pelvic ring and pelvic floor. Additionally, it is important to note that remodeling effects in postmenopausal females may dilute the associations with parity and potentially impact studies on this topic. We advise against the interpretation of pelvic features in elderly as they are less reliable.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-026-02533-2.

Acknowledgements We are grateful to the Natural History Museum London for permission to reuse data collected in 2020 for the VAMOS project on the skeletons from the Spitalfields collection, curated at the NHML, for this study. We also thank the team of the NMDID for granting access to the CT data and Sophie Beitel for her input on the development of the PPI. We would like to thank the Cantonal Museum of Archaeology and History in Lausanne (MCAHL), as well as the Commission for Anthropological Collections (CCA) of the Faculty of Science at the University of Geneva, for granting access to the Simon Identified Skeletal Collection.

Author contributions LW: Conzeptualizaton, Methodology, Software, Investigation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & EditingKRS: Conzeptualization, Ressources, Investigation, Writing- Review & Editing, Project administration, Funding aquisitionJD: Ressources, Writing- Review & EditingPM: Methodology, Formal analysis, Writing - Review & EditingMSS: Methodology, Ressources, Investigation, Writing- Review & EditingDPK: Conzeptualizaton, Methodology, Ressources, Investigation, Writing - Original Draft, Writing - Review & Editing.

Funding Open access funding provided by University of Vienna. This study was undertaken within the ERC-funded project "The value of mothers to society: responses to motherhood and child rearing practices in prehistoric Europe (VAMOS)." This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant 676828, PI: Katharina Rebay-Salisbury).

Data availability Based on the regulations of the NMDID, Simon collection, and Natural History Museum of London, no raw data may be published. Case numbers of individuals used in this study and the expression of pelvic features for each case are available upon request.

Declarations

Competing interests The authors declare no competing interests.

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