UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE BIOCIÊNCIAS

Maria Rita Guedes Carvalho

A relação entre o parto, a morfologia pélvica humana e a ocorrência de marcas nas superfícies das articulações pélvicas: evidências obtidas em uma amostra brasileira contemporânea

The relationship between birth, human pelvic morphology, and the occurrence of pelvic features at the pelvic ligaments' attachment sites: evidences taken from a contemporary Brazilian sample

São Paulo
2022

MARIA RITA GUEDES CARVALHO

A relação entre o parto, a morfologia pélvica humana e a ocorrência de marcas nas superfícies das articulações pélvicas: evidências obtidas em uma amostra brasileira contemporânea

The relationship between birth, human pelvic morphology, and the occurrence of pelvic **features at the pelvic ligaments' attachment sites: evidences taken from a contemporary** Brazilian sample

Versão corrigida

Dissertação apresentada ao Instituto de Biociências da Universidade de São Paulo para obter o título de Mestre em Ciências.

Área de Concentração: Biologia Genética

Orientador: Maria Mercedes Martinez Okumura

São Paulo
2022

Catalogação na publicação
Serviço de Biblioteca e Documentação
Instituto de Biociências da Universidade de São Paulo

Guedes Carvalho, Maria Rita
A relação entre o parto, a morfologia pélvica humana e a ocorrência de marcas nas superfícies das articulações pélvicas: evidências obtidas em uma amostra brasileira contemporânea / Maria Rita Guedes Carvalho ; orientadora Maria Mercedes Martinez Okumura -- São Paulo, 2022.
81 p.

Dissertação (Mestrado) -- Instituto de Biociências da Universidade de São Paulo. Programa de Pós-Graduação em Genética e Biologia Evolutiva.

1. Morfometria Geométrica. 2. Parto. 3. Pelve. 4. Dilema Obstétrico. 5. Pelvic Features. I. Martinez Okumura, Maria Mercedes, orient. II. Título.

Mª Mercedes Martinez Okumura

Nome: Carvalho, Maria Rita Guedes

Título: The relationship between birth, human pelvic morphology, and the occurrence of pelvic features at the pelvic ligaments' attachment sites: evidences taken from a contemporary Brazilian sample

Dissertação apresentada ao Instituto de Biociências da Universidade de São Paulo para obtenção do título de Mestre em Ciências

Aprovado em:

Banca Examinadora

Profa. Dra. Maria Mercedes Martinez Okumura
Instituição: Universidade de São Paulo
Julgamento: ____

Profa. Dra. Sabine Eggers
Instituição: Naturhistorisches Museum Wien
Julgamento:____

Dr. Diogo Amaral Rebouças Melo
Instituição: Princeton University
Julgamento: ____

ACKNOWLEDGEMENTS

I want to thank all those who made this research financially, intellectually and bureaucratically possible. To my family, who took care of me in every possible way, my friends and lab colleagues who helped me throughout the process; I owe you everything. My supervisor, Mercedes Okumura, deserves a special thanks for believing me and being so patient. Another very special thanks to my committee members, Sabine Eggers and Doris Pany-Kucera, for the important contributions and ideas shared. To the Faculty of Medicine, especially Paulo Saldiva and Khallil Chaim, thanks for allowing me to collect data. I am also thankful to all those who develop free softwares; without them, this research would not have been possible, in particular Arthur Porto and Slicermorph's development team.

The present work was carried out with the financial support of the "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES)", process number: 88887.502939/2020-00.

“It is in the nature of beginnings that something new is started that cannot be expected from whatever may have happened before. This character of startling unexpectedness is inherent in all beginnings and in all origins. Thus, the origin of life from inorganic matter is an infinite improbability of inorganic processes, as is the coming into being of the earth viewed from the standpoint of processes in the universe, or the evolution of human out of animal life. The new always happens against the overwhelming odds of statistical laws and their probability, which for all practical, everyday purposes amounts to certainty; the new therefore always appears in the guise of a miracle. The fact that man is capable of action means that the unexpected can be expected from him, that he is able to perform what is infinitely improbable. And this again is possible only because each man is unique, so that with each birth something uniquely new comes into this world. With respect to this somebody who is unique it can be truly said that nobody was there before. If action as beginning corresponds to the fact of birth, if it is the actualization of the human condition of natality, then speech corresponds to the fact of distinctness and is the actualization of the human condition of plurality, that is, of living as a distinct and unique being among equals.” (Arendt, 2013/1958, p. 178)

RESUMO

Durante a evolução do gênero Homo, a pelve óssea acomodou, em sua morfologia, uma série de novas e potencialmente conflitantes demandas funcionais, relacionadas à evolução do bipedalismo, à termorregulação e ao parto. Pelo caráter único do parto humano em relação ao de outros "apes", com um mecanismo de rotação fetal e uma altíssima proporção cefalopélvica, a evolução do canal de parto em Homo sapiens ainda é matéria de investigação; assim como sua possível integração com outras partes do esqueleto, especialmente a caixa craniana, que sofreu um aumento dramático de tamanho durante este processo. Nesta pesquisa foi realizada uma análise de variação da forma da pelve em uma amostra de tomografias computadorizadas, com o objetivo de quantificar e descrever a variação da forma da pelve na amostra por métodos de morfometria geométrica e também de testar estatisticamente a possibilidade de haver integração entre a forma da pelve e outras dimensões do corpo, especialmente da cabeça. Uma análise paralela foi feita na superfície das reconstruções tridimensionais dos ossos pélvicos, com o objetivo de identificar e quantificar "pelvic features", que são pequenas marcas nas superfícies articulares da pelve hipoteticamente associadas a episódios de gravidez e parto, de modo a checar a viabilidade da visualização destas marcas osteológicas em contexto virtual. Essas marcas estão supostamente relacionadas à ocorrência de eventos de gravidez e parto, mas nunca houve consenso entre autores sobre esta relação, então a associação entre a ocorrência das marcas e as variáveis sexo e idade foram testadas neste estudo. Nenhuma das "pelvic feartures", porém, apresentou associação com grupos de sexo ou idade nesta amostra, sugerindo que a sua ocorrência não deve estar relacionada somente a eventos de parto e gravidez. As marcas demonstram, porém, ser adequadamente reconhecíveis em reconstruções tridimensionais de ossos. Os resultados obtidos para a variação de forma geral da pelve na amostra e sua possível integração a outras partes do esqueleto corroboram a hipótese de que a forma pélvica é primariamente associada à variável sexo, presumivelmente devido à sua função obstétrica, mas nenhuma outra associação clara pôde ser observada entre a forma da pelve e outras dimensões corporais, exceto por aquelas que também variam de acordo com o sexo, como a estatura e o tamanho do centroide do crânio.

Palavras Chave: Morfometria Geométrica, Parto, Pelve, Dilema Obstétrico, Pelvic Features.

ABSTRACT

The bony pelvis has accommodated a series of new functional demands during the recent evolution of the genus Homo, related to thermoregulation, birth, bipedal locomotion, upright posture, and its actual morphology supposedly reflects all of them. The relationship between birth and pelvic morphology, however, is of special interest due to some unique features of the species, like the high cephalo-pelvic proportion and the rotational mechanism of birth, just as much as the possibility of integration between the pelvis and other parts of the skeleton, especially the crania, that has dramatically expanded during this process. In this research, I analyzed the variation of shape in the pelvises of men and women in a sample of CT scans through geometric morphometrics methods. The objective was to understand the variation of shape within the sample and to test for statistical covariations between pelvic shape and other body dimensions, especially head shape and size. A parallel analysis was carried out with the tridimensional reconstructions of the pelvises, with the objective of identifying and quantifying pelvic features, which constitute minor changes at the surfaces of some ligaments' attachment sites, in order to check if they are visible in virtual reconstructions. These changes, called pelvic features, are supposed to have a relationship with birth, but authors have not been unanimous about that, so their possible association to sex and age was statistically tested in this study. The features, however, showed no relationship with sex or age groups in this sample, suggesting that their occurrence may not be related to birth or pregnancy only. They seem, however, to be fairly detectable in virtually reconstructed bones. The results obtained for pelvic shape and its possibilities of integration with the rest of the skeleton support the hypothesis that the pelvis shape is primarily associated with sex, presumably because of its obstetric function, but there is no clear association between pelvis shape and other body dimensions, except for those that also vary according to sex, like stature or cranial centroid size.

Keywords: Geometric Morphometrics, Birth, Pelvis, Obstetric Dilemma, Pelvic Features.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

3D	Tridimensional
BMI	Body mass index
BBH	Basion-bregma height
CT	Computed tomography
GOL	Glabellum-occipital length
GPA	Generalized Procrustes Analysis
LM	Landmark
Mya	Million years ago
NOL	Nasio-occipital length
OD	Obstetrical dilemma
PCA	Principal Component Analysis
XCB	Maximum cranial breadth
ZYB	Bizygomatic breadth

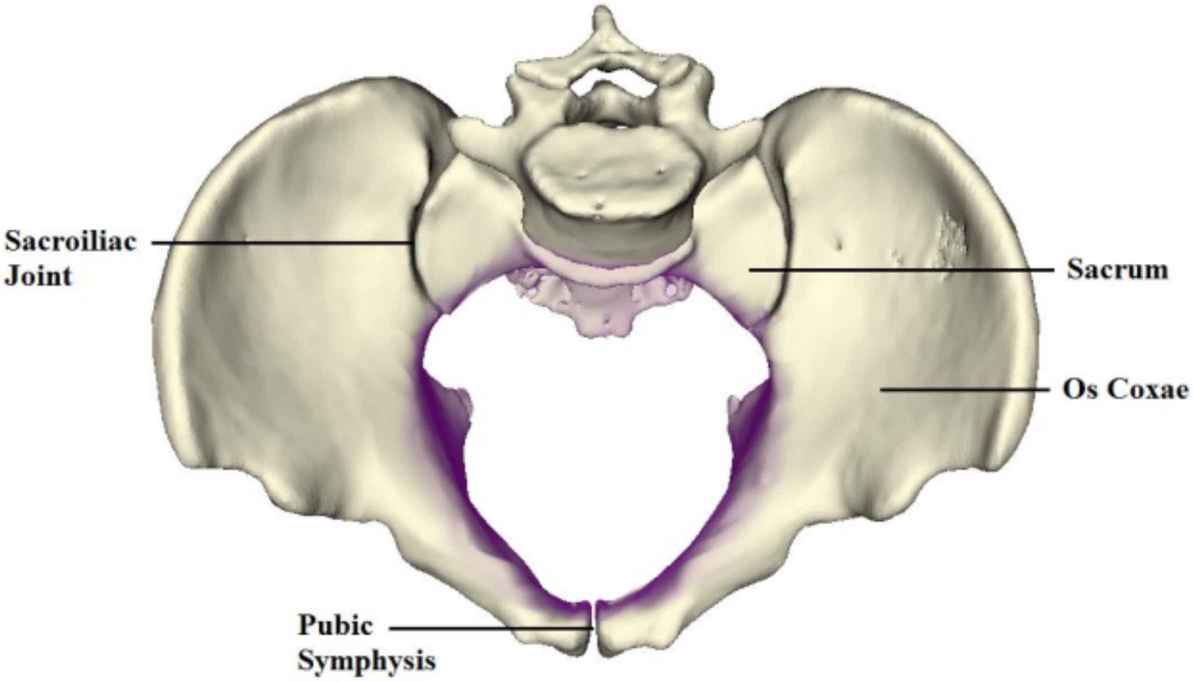
TABLE OF CONTENTS

1. INTRODUCTION

1.1. The evolutionary history of human pelvic bones and its relationship with birth

The bony pelvis' architecture, in human species (Figure 1), has been for decades a matter of interest to biologists and anthropologists for having allowed bipedalism in our lineage, at the same time that it conciliated other possibly conflicting functional demands, in particular, birth (Stansfield et al. 2021, Fischer et al. 2021, Laudicina et al.2019, Betti 2017, Mitteroecker et al. 2016, Brown 2015, Ruff 2010, Simpson et al. 2008, Tague 2000, Abitbol 1995, Tague 1992, Washburn 1960). For the dramatic changes in the position of the body's center of gravity and in the biomechanics of walking required by bipedalism, it is supposedly the reason why the pelvis and the lower limbs have gone through some unique morphological changes in the hominin lineage. From an adaptationist point of view, it is indeed possible to associate the functional changes that occurred in hominins' pelvic muscles and the morphological changes of the pelvic bones as adaptations for bipedalism and its biomechanical requirements, like the shortening of the ilium, the rotation of the iliac blades, and the hypertrophy of the gluteus maximus (Lovejoy 1988).

Figure 1 The bony pelvis

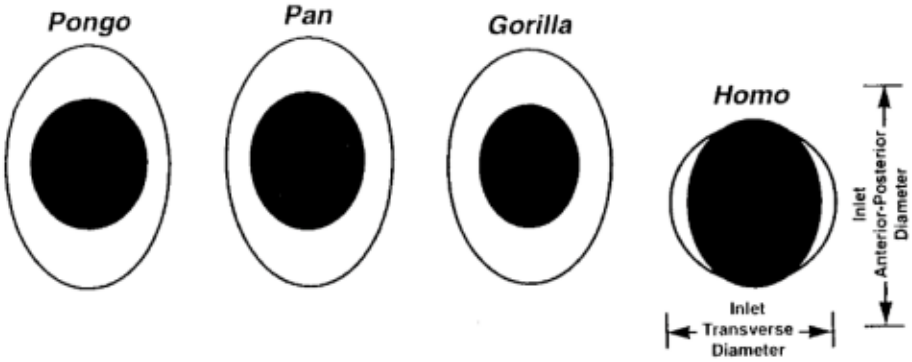


3D rendering showing the bones that compose the bony pelvis (sacrum, coccyx, and the 2 innominate bones), with the true pelvis highlighted in purple. The true pelvis refers to the bony structure and joints that compose the birth canal (Cunningham et al. 2014)

Fossil evidence corroborates the hypothesis that these morphological changes are related to the transition into bipedalism. These evidences are related not only to pelvic bones or muscles, but they include both footprints, like Laetoli footprints in Tanzania (Leakey & Ray 1979), and changes in the cranial bones, like the dislocation of the forame magno position to a more horizontal position, already visible in the Sahelanthropus tchadensis (7.7 mya - Zollikofer et al. 2005), and in other post cranial bones. Despite this, the exact origin of bipedalism is still unclear (Stern 2000), with some authors considering it to be fully established only in Homo erectus (around 2 mya), while others, like Lovejoy et al. (2009), for example, consider the pelvis of the Ardipithecus ramidus (4.4 mya), already suitable for efficient bipedal walk. In addition, pelvic morphology has apparently responded to other selective pressures in more recent years of our evolution. When hominins started inhabiting other parts of the globe, pelvis width started to show positive correlations with latitude, suggesting an adaptation to thermoregulation, as cold environments would have favored larger pelvises for better retaining heat, while hot environments would have favored narrower pelvises (Ruff 1991, 1994).

However, among all possible sources of morphological variance in the bony pelvis, the enlargement of the brain, and, consequently, of the crania, was considered to be the most imperative selective pressure on pelvic morphology, based on the assumption that a highly encephalized neonate would require more space in the birth canal during delivery. This idea is not new, and is grounded on the observation that most of the difficulties for birth in our species are due to the tight fit between the neonate's head and the mother’s birth canal, which is called “cephalopelvic proportion”. Indeed, when compared to other apes, humans appear to have the highest cephalopelvic proportion; our closest primate species (the great apes) display a considerable safety margin in the birth canal (Rosenberg 1992, Kawada et al. 2020- Figure 2). Humans also have a unique mechanism of rotational birth that adds more risk to the process of delivery, as the positioning of the baby becomes crucial for a successful delivery, and the occiput anterior position, which is the most common fetal presentation (facing the mother’s back) makes it difficult for the mother to guide the infant from the birth canal by herself as other primates do (Rosenberg & Trevathan 1995).

Figure 2- Cephalopelvic proportions in apes



Black filled circles represent neonate's head size, bigger circles around represent birth canal size. Source: Rosenberg & Trevathan (1995, p. 162)- adapted.

Thus, these compared anatomy observations combined with data coming from public health status of many societies, which show high maternal mortality and morbidity related to complications during delivery (when proper medical assistance is not available) inspired the idea that this complicated, and even risky, birth process should be the result of an evolutionary trade-off between bipedalism and brain expansion in the evolutionary history of Homo sapiens. Birth, according to this line of thought, would be one of the last selective bottlenecks of our evolution, deciding for the survival of those mothers whose pelvis were able to accommodate the fetus's head, and, consequently, the survival of these fetuses (Haeusler et al. 2021).

Speculations about possible evolutionary explanations for difficulties in birth first appeared in the scientific literature in the early years of the 20th century, and were better described by Krogman, in 1951, who called these difficulties a "scar of human evolution". For him, our complex mechanism of birth was the result of the combination between the morphological adaptations of the bony pelvis to bipedalism and the enlargement of the brain in the species. Later, this hypothesis became popular with the name given by Washburn (1960): "The obstetric dilemma". According to Washburn, the birth canal has narrowed in our species during the evolution of bipedal walking because a narrow pelvis would be more efficient for walking in two legs, and, afterwards, with the enlargement of the brain, came the dilemma, making birth even more risky. He also hypothesized that the altriciality of human newborns was an adaptation to this new situation, when they would have to leave the uterus before a certain time of maturation, otherwise they would be too big to pass the birth canal.

The hypothesis of the obstetric dilemma, however, has been questioned on several grounds, especially regarding the metabolics of bipedalism and pregnancy. Studies on the efficiency of bipedal walking have shown that large pelvises are not less efficient than narrow pelvises when walking or running (Warrener et al. 2015, Warrener 2017). Moreover, human babies were found to be born comparatively later than other apes, not earlier as Washburn supposed (Dunsworth et al. 2012), and to be actually bigger than the expected for an ape (with 6% of the mother's body mass, on average, when other apes are about 3%, DeSilva 2011).

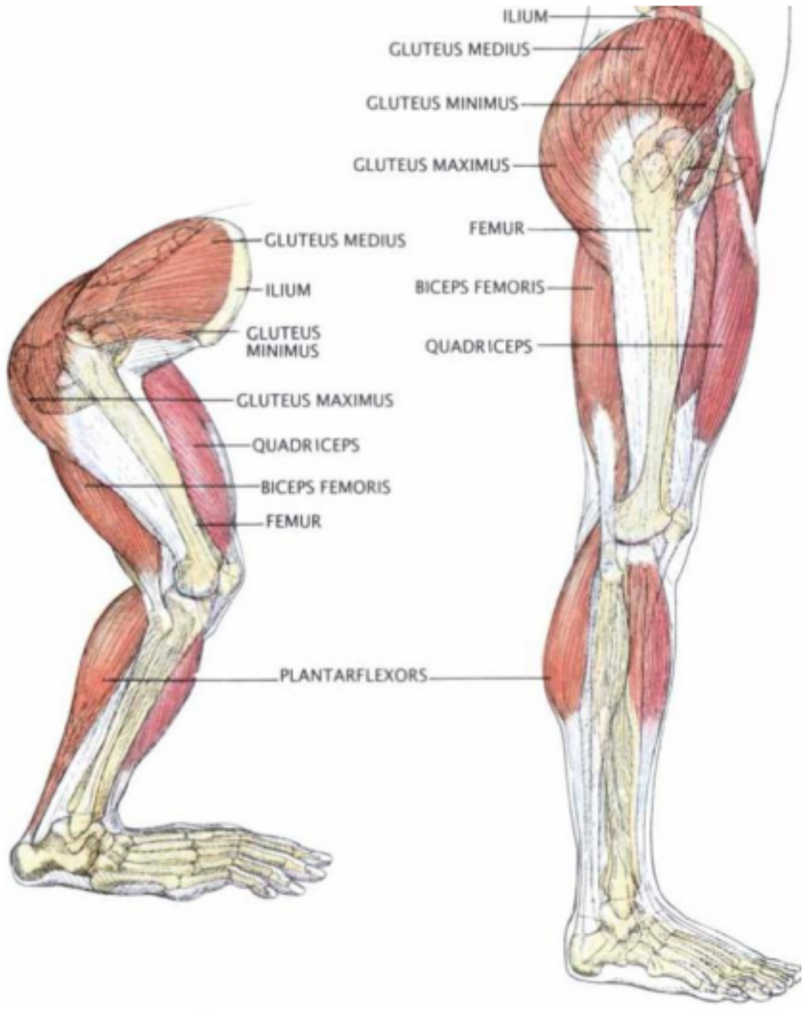
Also, other ecological factors need to be taken into account to evaluate the possibilities of obstructed labor in Homo sapiens. Wells et al. (2012, 2021) pointed out that the transition to agriculture may have changed the nutritional status of human societies in a way that the delicate balance between the size of the neonates and the birth canal may have been endangered. Due to a decrease in mothers' stature and an increase in fetuses' growth and adiposity, caused by the dietary change, the obstetrical dilemma would have been exacerbated, especially because a neonate's head size and mass have very limited plasticity, while body mass can vary much more. Other possible causes for obstructed labor which were much more likely to happen after the agricultural transition were nutritional deficiencies that cause deformities, like rickets, that contribute to a severe flattering of the pelvis, which makes delivery sometimes impossible, and was the most common cause of obstructed labor from the 17th to early 20th centuries in western countries. Moreover, the problems with hygiene coming from the first hospitalized births may have inflated the number of maternal deaths due to infectious diseases (Wells 1975).

So, despite some principal assumptions of the obstetrical dilemma being proven false, the problem of the tight fit still persists. It actually became more intriguing that our evolution has reached a point where there is such little risk margin for birth once a larger pelvis is not inefficient for walking, not to mention the fact that human babies are being born bigger, in terms of body mass, which makes the situation even more problematic. New hypotheses have been proposed in the recent years to explain the situation, one of them is that our upright posture would have required increased strength and stability from pelvic floor muscles to bear the weight of abdominal organs in a vertical posture, and that would have made the bony pelvis so narrow and inflexible (Stansfield et al. 2021). Another hypothesis is that a modular pattern of covariation between cranial and pelvic bones would be alleviating the effects of the obstetrical dilemma, with the pelvic shape varying together with stature and cranial dimensions in a way that diminishes the probability of a disproportion in the moment of birth (Fischer & Mitteroecker 2015).

1.1.2. Pelvic morphology and bipedalism evolution

Bipedal locomotion was reasonably one of the most compelling selective pressures on pelvis morphology in the evolutionary history of Homo sapiens, as it compromised the whole body, especially the inferior limbs, changing the gravity center of the body, the shape, and the function of important bones and muscles. According to Lovejoy (1988), the most dramatic changes in bones that allowed bipedalism are: the rotation and the shortening of the ilium, the rotation of the iliac blades (that now flare outwards carrying with them the upper attachment point of the gluteal muscles) and the widening of the sacrum. In muscles, the most important alterations happened in the role played by each muscle: the gluteus maximus, in the human body, prevents the trunk from pitching forward, and has hypertrophied to the point of becoming our greatest muscle. The gluteus medius and minimus, which functioned as hip extensors in quadrupedal walking, now have the function of stabilizing the pelvis and the trunk while the body is being supported by only one leg (as it tends to rotate) during the bipedal walk (Figure 3).

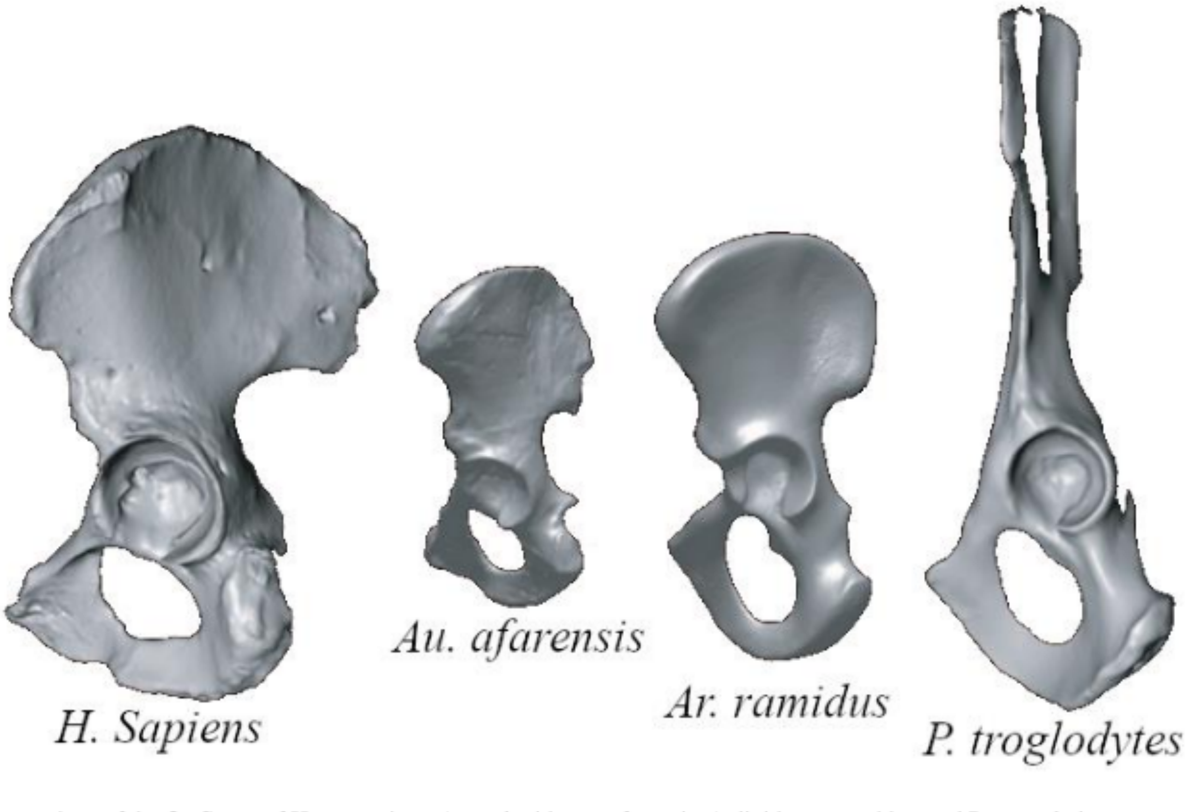
Figure 3- Lateral view of the lower limbs of a chimpanzee and a modern human



Comparison of the bones and muscles in the lower limbs of a chimpanzee (quadrupedal) and a modern human (bipedal).
Source: Lovejoy (1988, p. 120).

The last known hominin fossil species, the Sahelanthropus tchadensis (7 mya), is already supposed to be a bipedal because of some morphological characteristics of the cranium that would favor a bipedal posture, like the anterior position of the Foramen magnum and the flat and horizontal nuchal plane (Zollikofer et al. 2005), but there are no other parts of the skeleton available for further biomechanical analyses. Other early hominin species, the Ardipithecus ramidus (4.4 mya), display morphological features in the post-crania that would have favored bipedalism. The pelvis of Ardipithecus ramidus, in special, brings together some chimp-like morphological features with more derived features that are fundamental for bipedal walking, particularly the vertical flattering of the ilia and the highly prominent anterior inferior iliac spine, which is the attachment site of important gluteal muscles that stabilize the body during bipedal walk (Figure 4)- Lovejoy et al. 2010.

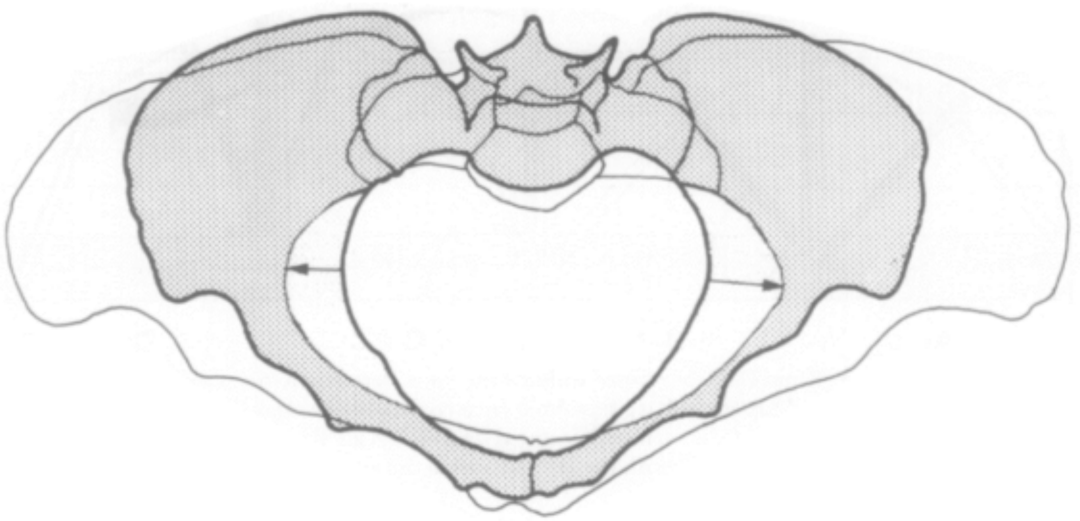
Figure 4- Iliac bones



Comparison of the Os Coxae of Homo sapiens, Australopithecus afarensis, Ardipithecus ramidus, and Pan troglodytes.
Source: Lovejoy et al. (2009, p. 71)- adapted.

For its wide, platypelloid morphology, Lovejoy (1988) argues that Lucy's pelvis (3.3 mya, Australopithecus afarensis- Figure 5) was better adapted to bipedal walking than that of modern humans', simply because it would have responded only to the selective pressures related to bipedal walking, long before brain size has increased so sharply, demanding an expansion of the birth canal. Following the same line of thought, it can be assumed that other selective pressures on pelvis morphology would have taken place in the Erectus era, when our ancestors inhabited new latitudes around the globe and had to give birth to more encephalized neonates.

Figure 5- Lucy's and a female modern human's pelvis



Lucy's pelvis superimposed on a modern human pelvis, with scale adjusted for body weight. Source: Rak (1991, p. 285).

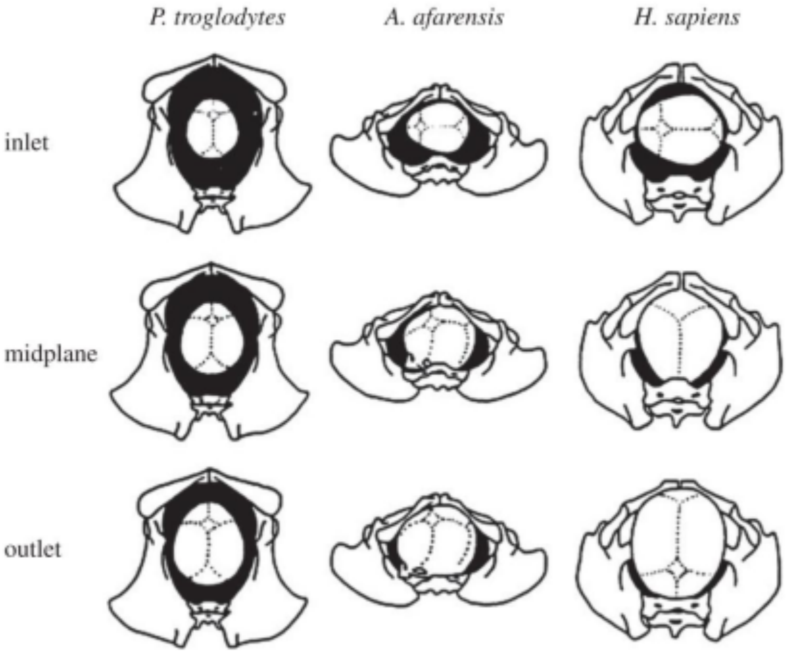
In fact, the anteroposterior diameter of the pelvis has increased, making it less platypelloid during the origins of the genus Homo and this can be associated to a slightly higher degree of encephalization. For the same reason, the stable morphology of the pelvis in the Homo erectus era can be interpreted as a result of the stability of the proportion between brain and body size, with both increasing proportionally. Greater anteroposterior diameters, within the range of modern humans, only appeared in the species of middle Pleistocene (Homo heidelbergensis, Homo neanderthalensis, and Homo sapiens), and this shift to a rounder pelvis shape is reasonably associated with selective pressures other than locomotion, once it has already reached a modern state in the Homo erectus (Gruss & Schmidt 2015).

Brain size is now one of the most distinctive characteristics of the human species when compared to other apes, weighing, on average, 1400g (three times more than a Chimpanzee's), and with other distinctive characteristics, such as different macroscopic structure and a delayed maturation time, which happens majorly postnatally (Gunz et al. 2020). It's a plausible assumption that this enlargement is positively correlated with advances in cognition, and much has been debated on how different parts of the brain have evolved throughout this process (if it was mostly an enlargement or if some rearrangement has happened), and how much it may have affected different cognitive functions (Reyes & Sherwood 2015). The major structural changes that happened were the loss of the lunar sulcus, present on Australopithecines and the appearance of a sulcal pattern that reflects two rami of the Sylvian fissure (R, R') in modern humans, both visible in endocasts. For pelvis evolution, however, only the increase in general size is understood as a selective pressure for an expansion of the true pelvis, following the idea of the obstetric dilemma. From the fossil evidence, only the anterior-posterior diameters have increased throughout this process to be associated with a selective pressure for a large birth canal.

1.1.3. Pelvic morphology and birth evolution

When it comes to obstetrics, it's important to remember that the tight fit that endangers a proportion of human births is not the only source of birth problems in nature, and humans are not the only species that suffers from that. Other kinds of complications during birth are known in mammalian species. As an example, in Guinea pigs, a true separation between the pubic rami is necessary for delivery (Hisaw 1929), and among hyenas, the mortality rates and risks of injury are considerably high for primiparous females, as they give birth through a penile-like clitoris canal (Steinetz et al. 2009). Humans are also not the only ones who give birth to large-headed neonates, but, curiously, there is not much sexual dimorphism in our bony pelvis, as is common among these species, and the human pelvic ring has highly inflexible joints (Pavlicev et al. 2019, Grunstra et al. 2018). Among apes, humans are the ones that display the highest cephalopelvic ratio and also the only ones that have a rotational mechanism of birth (Figura 6).

Figure 6- Rotational birth



Appropriate fetal head position for delivery in the 3 planes of the birth canal in Pan troglodytes, Australopithecus afarensis, and Homo sapiens. Source: Gruss & Schmidt (2015, p. 3)- adapted.

The exact origin of the rotational mechanism is a matter of disagreement, with some authors defending that it evolved more recently, during the origins of the genus Homo (Tague & Lovejoy 1998), while others have concluded from pelvis reconstructions that some rotation was necessary for birth in australopithecines (Häusler & Schmidt 1995). According to Laudicina et al. (2019), Australopithecus sediba's fetus already had to put their heads in an oblique position to enter the mother's pelvic inlet, like Homo sapiens do, but proceeded downwards without rotation. In 2017, DeSilva et al. suggested that such a specific mechanism of birth should not be interpreted as having a monolithic evolution, because during early Pleistocene, there was considerable post cranial variation in our lineage, so we can assume that a diversity in birth mechanisms should also exist.

Behavioral adaptations are also supposed to have appeared in response to the increased risks of birth in humans. Rosenberg in 1992 suggested that seeking assistance for birth can be literally interpreted as an adaptation to this new situation. As midwives are present in virtually all societies, and humans are the only species that experience birth as a social event, she theorized that this would not be a matter of cultural heritage of some specific society, but an imperative for modern human societies. According to her, the obstetrical difficulties that appeared in our lineage (like the tightening in cephalopelvic proportions, the rotation of the fetus, and the occiput anterior presentation) favored this cooperative behavior (Rosenberg & Trevathan 1996).

In more recent times, other behavioral and cultural changes, especially the ones related to the emergence of agriculture and medicine have played a major role in increasing or reducing the risks of birth (Wells et al. 2021). The influence of nutritional status, physical activity, and access to prenatal care is now crucial to a successful birth, even more than a possible obstruction or other kinds of emergency that could have been a cause of death for our ancestors (Wells 1975, Wells et al. 2012).

1.2. Pelvic Features: potential osteological marks of pregnancy and birth

Another aspect of pelvic morphology that can be assessed in order to seek for evidence about what may have happened in our evolution in terms of pregnancy, for individuals, and fertility, for populations, are the minor anatomical changes in the bony pelvis that supposedly indicate events of pregnancy, called pelvic features (Holt 1978, Houghton 1974, Cox 1992, Igarashi et al. 2020, Maas & Friedling 2016, Pany-Kucera et al. 2019, Pany-Kucera et al. 2021). Paleodemographers have used some marks on the pelvic joints (sometimes called parturition scars or pelvic scars) as visible imprints left by events of pregnancy and parturition in osteological remains. Sometimes, the degree of change in the surface of the bone was used as an indicator of the number of pregnancies and, consequently, as an indirect indicator of fertility in past populations (Acsádi & Nemeskéri 1970).

However, anthropologists have never been unanimous about the relationship between these skeletal marks and pregnancy events because the results of many studies have been contradictory (Ubelaker & LaPaz 2012). The features occur in the attachment sites of the ligaments of the pelvic girdle. Considering that these ligaments are highly stretched during pregnancy, and that the effects of relaxin and estrogen make them even more lax in this period, pregnancy, and especially the moment of birth, are supposed to cause microtrauma in these attachment sites. What seems to be problematic in these skeletal marks is their possible relationship with other sources of biomechanical stress, like overweight, pathological processes, or physical overloads (Holt 1978, Maass & Friedling 2016). Moreover, female pelvic architecture is possibly more likely to exhibit pelvic features due to its greater flexibility, as it needs more ligamentous stabilization, and also age could be affecting somehow the manifestation of pelvic features, due to bone remodeling and hormonal fluctuations throughout life (Andersen 1986). Once those studies found no clear relationship between these marks and pregnancy, and even revealed them on men and nulliparous women, other possible causes for these bone imprints ought to be considered and new research needs to establish the levels of reliability of each feature.

In this study, five pelvic features were assessed on the surface of bones virtually segmented from CT Scans in order to check their detectability in virtual contexts, and to check their possible association with age and sex: the preauricular sulcus, the extended pubic tubercle, the dorsal pubic pits, the sacral preauricular extension and the sacral preauricular notch.

1.2.1. Preauricular Sulcus

The preauricular sulcus (Figure 7) has been identified as a female exclusive skeletal mark in the beginning of the 20th century (Derry 1909), and was discussed since then as a possible indicator of pregnancy (Ubelaker & La Paz 2012). The placement of the sulcus indicates that it is caused by strain on the sacroiliac joint, as it coincides with the attachment of the anterior sacroiliac ligament, which connects the sacrum and the ilium. The sacroiliac joint is particularly affected by weight bearing, as it transfers the weight of the trunk to the lower limbs, therefore, the sulcus is a possible consequence of the relaxation of this joint during pregnancy, due to the gestational hormone relaxin, and the weight gain (Houghton 1975).

Many studies found positive relationships between sex and the preauricular sulcus (Dee 1981, Spring et al. 1989, Schemmer et al. 1995), but the relationship between parity and the presence of the sulcus was not so clearly observable when data about fertility was available (Cox & Scott 1992, Lopreno et al. 2021, Igarashi et al. 2019).

Figure 7- Preauricular sulcus

Fragment of an Ilium, with arrows pointing the preauricular sulcus. Source: Rebay-Salisbury et al. (2018)- adapted.

1.2.2. Extended Pubic Tubercle

The pubic tubercle (Figure 8) appears at the attachment site of the inguinal ligament, which holds the Rectus abdominis (the muscle responsible for ventral flexion and for containing the anterior abdomen). Its supposed relationship with parity is due to the stretches in the Rectus abdominis caused by pregnancy, which pulls the attachment site of the bone out (Cox & Mays 2006). Once more, results from different studies led to different conclusion, with some authors finding a significant relationship between the presence (or the extension) of the tubercle and pregnancy (Cox & Scott 1992), while others failed to find this association (Bergfelder & Herrmann 1980, Snodgrass & Galloway 2003, Decrausaz 2014, Maass 2012).

Arrow pointing an extended pubic tubercle on a pubic bone. Source: Praxmarer (2019, p. 25).

1.2.3. Dorsal Pubic Pits

Like the other pelvic features, dorsal pubic pits (Figure 9) are marks left on the bone surface in the exact point where a ligament of the pelvic ring attaches the bone, and, consequently, where injuries are supposed to appear during pregnancy due to the increased stress on ligaments (Ubelaker & La Paz 2012). It can be manifested as a huge depression, or like multiple little holes in the dorsal area of the pubic symphysis (Houghton 1975). However, as other pelvic features, some authors have found a relationship between them and childbirth (Suchey et al 1971, Cox 2000, Angel 1969) while others have not (Stewart 1970, Holt 1978, Waltenberger et al. 2021, McFadden & Oxenham 2018).

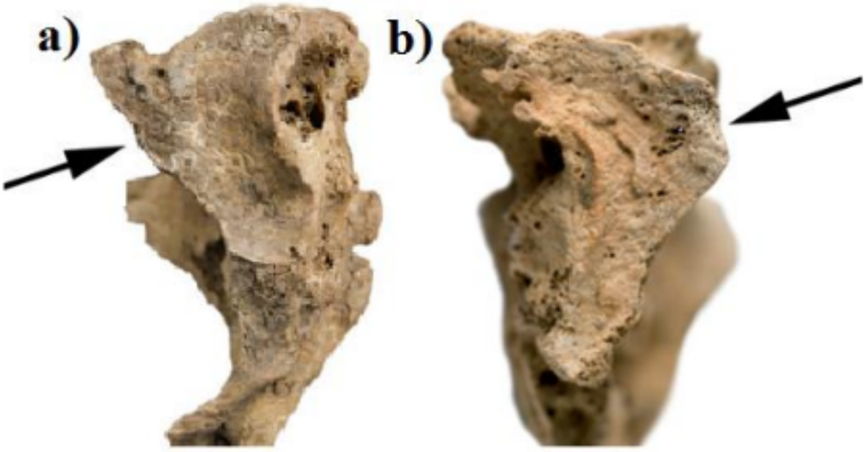
Figure 9- Dorsal pubic pits

Dorsal surface of the pubic bones with arrows pointing the dorsal pits. Source: Pany-Kucera et al. (2021, p. 11)- adapted.

1.2.4. Sacral Preauricular Extension and Sacral Preauricular Notch

Sacral preauricular extensions and notches were recently described (Pany-Kucera et al. 2019) as morphological abnormalities on the sacroiliac joint only found in females so far. The extension can be defined as an exostosis that is located at the ventral apex of the auricular facet of the sacrum (Figure 10- a). The sacral preauricular notch, on the other hand, can be described as a loss of the extremity of the sacral bone at the exact same point, in the form of a notch (Figure 10-b) -Pany-Kucera et al. 2021.

Figure 10- Sacral preauricular extension and notch



a) Lateral view of a sacral bone with an arrow pointing a sacral preauricular extension. b) Lateral view of a sacral bone with an arrow pointing a sacral preauricular notch. Source: Pany-Kucera et al. (2019, p. 1016).

2. OBJECTIVES AND HYPOTHESES

2.1. General objectives:

Data about pelvimetry studies are available for many populations in the world, including the archaeological ones, but data about contemporary Brazilian samples are scarce. Therefore, one of the purposes of this research is to increase knowledge about human diversity, in this case, a population of highly mixed genetic background, and to test some hypotheses that have been discussed in biological anthropology about the human pelvis morphology and its evolution.

The data collected includes information of shape, size and the occurrence of pelvic features on the joint's surfaces of each pelvis. The idea is to discuss the results of the pelvimetry in terms of what it tells about the magnitude of variation in the shape and size of the bony pelvis in the sample, what covariances with other variables possibly means and eventually bring new insights to the broader discussions about the evolution of pelvis morphology. For the pelvic features, though, the expectation is that the results will primarily show the feasibility of this kind of osteological survey on a virtual 3D material, whenever the features are visible or not, what the minimal resolution for a CT Scan to properly show these details is, to establish a visual guide of their appearance in 3D surface models, and then discuss to what extent they can be interpreted as correlated with birth or pregnancy.

2.2. Objectives of the pelvimetry study:

Both traditional and geometric morphometrics methods were used in order to allow a more comprehensive understanding of the variation in pelvis shape and size in the sample. While classic morphometrics discusses general and relative size, and allowed comparisons between subgroups, geometric morphometrics offers more accurate information about the variance of shape and allowed testing for covariance and regression with other variables.

The dimensions of the true pelvis were compared within men and women in terms of size, and covariance tests were performed according to the hypothesis that pelvis shape covaries with other body dimensions to alleviate the obstetric dilemma, especially stature and head size (Fischer & Mitteroecker et al. 2015).

The hypotheses tested are:

- Hypothesis 1: Pelvis shape is associated with sex;
- Hypothesis 2: Pelvis shape is associated with stature;
- Hypothesis 3: Pelvis shape is associated with body mass;
- Hypothesis 4: Pelvis shape is associated with BMI;
- Hypothesis 5: Pelvis shape is associated with cranial centroid size;
- Hypothesis 6: Pelvis shape is associated with cranial shape.

2.3. Objectives of the pelvic features' assessment

The first objective of this analysis was to evaluate the potential of CT Scans (and 3D renderings) to provide information about these morphological details in bones' surfaces. Then, the presence of the scars was statistically correlated with some relevant anthropometric variables (like age and sex), so their relationship with events of parturition or pregnancy could be discussed.

The hypotheses tested are:

- Hypothesis 1: The occurrence of pelvic features is positively associated with age;
- Hypothesis 2: Pelvic features are more frequently found among women.

3. MATERIAL AND METHODS

3.1. Material

This study used 100 Dicom images of post-mortem full-body CT Scans, acquired on a SOMATOM Emotion 16-slice (Siemens, Erlangen, Germany), starting from the top of the head to mid-leg. The images were obtained from the PISA project (Plataforma de Imagens na Sala de Autópsia) virthopsy database. The spiral images were acquired with 130kV, 110 mAs (CareDose active), 16x1.2mm collimation. The raw data were reconstructed with 1.5 mm and 5.0 mm slice thicknesses and a smooth convolution kernel filter (B20) applied. All the 100 individuals (54 males and 46 females) were anonymized and their personal information (sex, age, BMI, stature, and body mass) were obtained via patient registration number. This research was approved by the ethics committee of the University of São Paulo (CAAE: 45130021.8.0000.5464).

The virtopsies used here were carried out between 2015 and 2016, in the Faculty of Medicine of the University of São Paulo, where PISA is located. The fact this material was obtained at this specific place was of great importance in terms of the representativeness of the sample: the Faculty of Medicine is associated to the biggest public hospital in Brazil (Hospital das Clínicas da Universidade de São Paulo), that provides care to patients from the entire country. So, considering that the country's current population derives from extensive interethnic crossings and that this specific hospital receives patients from all around the country, the sample was considered to be representative of a population of highly admixed background, a property which is expected to be advantageous for association studies in comparison to isolated populations (Suarez-Kurtz 2005).

3.2. Methods

3.2.1. Data selection and 3D reconstruction

The selection criteria for the CT scans were the availability of associated information (sex, age, body mass, and stature) and the minimum age of 20 years old, as pelvis' morphology is considered to be not fully established before that age (Huseynov et al. 2016). Cases of fractures and severe malformation were also excluded from all analyses.

3D surface models of the pelvic and cranial bones were created for every individual with Segmentation and Model Maker tools in 3D Slicer 4.11 (Fedorov et al. 2012). The 3D models created were used both for placing the landmarks (used for the morphometric analyses) and for assessing the occurrence of pelvic features on the joints' surfaces.

3.2.2. Landmarks placement

Landmarks are discrete anatomical loci, detectable in all specimens of a study (Zelditch et al. 2012). The landmarks of cranium and pelvis were automatically applied on the 3D Surfaces by ALPACA (3D Slicer Extension - Porto et al. 2020), and then manually adjusted to reach the exact position (Figures 12 and 13).

Table 1- Cranial Landmarks

	Landmark	Description
A	Glabella	"The most anterior midline point on the frontal bone, usually above the frontonasal suture" (Buikstra & Ubelaker 1994, p. 72)
B	Opistocranium	"Instrumentally determined most posterior point of the skull not on the external occipital protuberance" (Buikstra & Ubelaker 1994, p. 72)
C	Nasion	"The point of intersection between the frontonasal suture and the midsagittal plane" (Buikstra & Ubelaker 1994, p. 72)
D	Bregma	"The ectocranial midline point where the coronal and sagittal sutures intersect" (Buikstra & Ubelaker 1994, p. 71)
E	Basion	"The midline point on the margin of the foramen magnum" (Buikstra & Ubelaker 1994, p. 72)
F	Euryon (right)	"Instrumentally determined ectocranial points on opposite sides of the skull that form the termini of the line of greatest cranial breadth" (Buikstra & Ubelaker 1994, p. 71)
G	Euryon (left	"Instrumentally determined ectocranial points on opposite sides of the skull that form the termini of the line of greatest cranial breadth" (Buikstra & Ubelaker 1994, p. 71)
H	Zygion (right)	"Instrumentally determined as the most lateral point of the zygomatic arch" (Buikstra & Ubelaker 1994, p. 71)
I	Zygion (left)	"Instrumentally determined as the most lateral point of the zygomatic arch" (Buikstra & Ubelaker 1994, p.71)

Table 2- Pelvic Landmarks

	Landmark	Description
A	Sacral Promontorium	"The most superior and anterior point in the median sagittal plane" (Franklin et al. 2014, p. 863)
B	Superior pole, pubic	"Most anterior superior point on the symphyseal

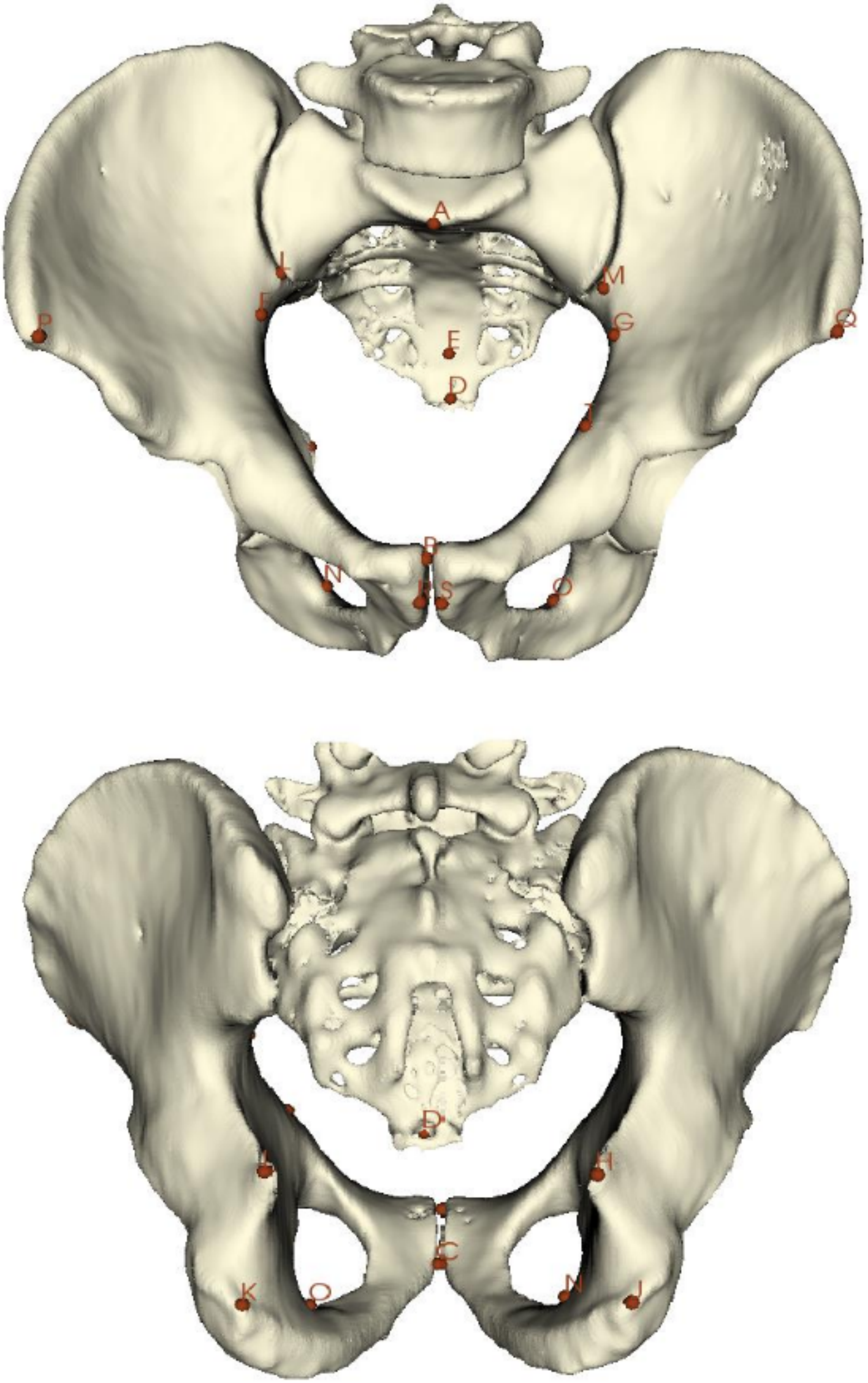
	symphysis	surface" (Franklin et al. 2014, p. 863)
C	Inferior symphyseal pole	"Most inferior point on the symphyseal surface" (Franklin et al. 2014, p. 863)
D	Anterior Sacrum Apex	"The most inferior and anterior point of the sacrum, at the sacral-coccyx border" (Franklin et al. 2014, p. 863)
E	Junction of the Fourth and Fifth sacral Vertebrae	"Junction of fourth and fifth sacral vertebrae" (Kurki, 2007, p.1154)
F	Maximum lateral point linea terminalis (right)	"Most lateral point on the interior of the pelvic brim" (Franklin et al. 2014, p. 863)
G	Maximum lateral point linea terminalis (left)	"Most lateral point on the interior of the pelvic brim" (Franklin et al. 2014, p. 863)
H	Ischial Spine Apex (right)	"The point on the ischial spine where the smooth arc of the greater sciatic notch ends posteriorly" (Franklin et al. 2014, p. 863)
I	Ischial Spine Apex (left)	"The point on the ischial spine where the smooth arc of the greater sciatic notch ends posteriorly" (Franklin et al. 2014, p. 863)
J	Ischial tuberosity maximum lateral point (right)	"The most medio-lateral point of the ischial tuberosity corresponding to the maximum width of the pelvic outlet" (Franklin et al. 2014, p. 863)
K	Ischial tuberosity maximum lateral point (left)	"The most medio-lateral point of the ischial tuberosity corresponding to the maximum width of the pelvic outlet" (Franklin et al. 2014, p. 863)
L	Maximum point anterior articular face (right)	"The most lateral and anterior point of the sacrum at the level of the auricular surface" (Franklin et al. 2014, p. 863)
M	Maximum point anterior articular face (left)	"The most lateral and anterior point of the sacrum at the level of the auricular surface" (Franklin et al. 2014, p. 863)
N	Foramen obturatum most inferior point (right)	Inferior obturator foramen point (Fischer & Mitteroecker 2015)
O	Foramen obturatum most inferior point (left)	Inferior obturator foramen point (Fischer & Mitteroecker 2015)
P	Superior iliac spine (right)	"Point at the anterior superior iliac spine" (Franklin et al. 2014, p. 863)
Q	Superior iliac spine (left)	"Point at the anterior superior iliac spine" (Franklin et al. 2014, p. 863)

R	Pubic symphysis most lateral point (right)	Most medio-lateral point of the right pubic bone at the pubic symphysis, from a ventral view (Becker et al. 2010)
S	Pubic symphysis most lateral point (left)	Most medio-lateral point of the left pubic bone at the pubic symphysis, from a ventral view (Becker et al. 2010)
T	Ileopectineal eminence (left)	“The iliopubic (or iliopectineal) eminence marks the point of union of the ilium and the pubis just lateral to the arcuate line” (White et al. 2012, p. 232)

Figure 11- Cranial landmarks

3D renderings of cranial bones with the landmarks described in Table 1 placed in red on the surface from lateral anterior and posterior views.

Figure 12- Pelvic landmarks



Pelvic landmarks (Table 2) placed in red on a 3D renderings of pelvic bones in ventral and dorsal views.

3.2.2.1 Intra observer error

3D models of pelvis and crania from 10 individuals were randomly chosen to test for intraobserver repeatability one year after, by placing landmarks again and comparing the pelvimetry and craniometry measurements by the Bland & Altman test (1986).

3.2.3. Pelvic features scoring

The criteria for assessing the presence and the scores of all pelvic features on the 3D models' surfaces are described in Table 3.

Table 3- Pelvic features scores

Pelvic Feature:	Scores:
Preauricular Sulcus (0/1)	0- Absent trait, 1- present trait.
Preauricular Extension or Notch (0/1)	0- Absent trait, 1- present trait.
Extended Pubic Tubercle (0/1)	0- Absent trait, 1- present trait.
Dorsal Pubic Pits (0/1)	0- Absent trait, 1- present trait.
Marginal Osteophytes at the Sacroiliac Joint (0/1)	0- Absent trait, 1- present trait.

3.2.4. Traditional Morphometrics

Pelvimetry and craniometry measurements were obtained directly by the calculation of the Euclidean distance between landmarks (in millimeters). The measurements taken from crania and pelvises are described on Tables 4 and 5.

Table 4- Craniometry

Measurement	LMs	Description
Coronal Plane		
Glabellum-occipital length (GOL)	A-B	The distance between the glabella and the opisthocranion.

Nasio-occipital lenght (NOL)	C-B	The distance between the nasion and the opisthocranion
Basion-bregma height (BBH)	D-E	The distance between the basion e bregma.
Sagittal Plane		
Maximum cranial breadth (XCB)	F-G	The distance between the two euryon points.
Bizygomatic breadth (ZYB)	H-I	the maximum horizontal distance between the zygion points.

Table 5- Pelvimetry

Measurement	LMs	Description
Anteroposterior diameters:		
Inlet	A-B	Sacral promontory to dorsomedial superior pubic symphysis
Midplane	C-E	From junction of fourth and fifth sacral vertebrae to dorsomedial inferior pubic symphysis
Outlet	C-D	From the tip of the sacrum to dorsomedial inferior pubic symphysis
Transversal diameters:		
Inlet	F-G	Maximum distance between linae terminales
Bispinous	H-I	Distance between ischial spines
Outlet	J-K	Distance between ischial tuberosities
Sacrum:		
Breadth	L-M	Maximum ventral distance between sacro-iliac
Length	A-D	Straight distance across ventral surface of sacrum where sacrum meets apex of auricular surface of ilium when pelvis is articulated
Angle	BÂD	Angle at the promontorium between the anteroposterior diameter of the inlet and the sacral length

Pubic Symphysis:		
Pubic-Symphysis Length	B-C	Maximum distance between superior and inferior points of the pubic symphysis
Pubic Symphysis Breadth	R-S	Maximum distance of the pubic symphysis gap
Other:		
Subpubic Angle	Ĉ	Angle formed by the inferior pubic symphysis and the ischiopubic ramus on either side
Biiliac Diameter	P-Q	Distance between anterior superior iliac spines
Oblique diameter of the inlet	L-T	From the right sacroiliac joint to the left iliopectineal eminence

3.2.5. Geometric Morphometrics

For all geometric morphometric analyses, a GPA (General Procrustes Analysis) was previously performed for cranial and pelvic landmark data separately, with Slicermorph extension for 3D Slicer 4.11 (Rolfe et al. 2020). Then, the principal components (PCs) of shape coordinates were calculated for pelvis and head, separately, in the whole sample and for each sex.

3.2.6. Statistical Analyses

3.2.6.1. For pelvic features

The frequency of each feature (Preauricular Sulcus, Extended pubic tubercle, Dorsal pubic pits, Marginal Osteophytes at the Sacroiliac Joint, Preauricular Extension or Notch) was compared between sub-groups of age (20-40 years, 40-60 years, and >60 years) and sex (male, female) through chi-square independence test (using R stats package). A “sum of features” was also calculated by summing the total of features found in each pelvis.

3.2.6.2. For traditional morphometrics

Normality tests were performed for all variables (the measurements described in Tables 4 and 5) via Shapiro-Wilk's test. Then, these variables were compared by sex via T-test or Mann-Whitney, depending on the normality, using dplyr r package (Wickham et al. 2015).

3.2.6.3. For geometric morphometrics

As most part of the morphological variation in a sample is encompassed by the first two principal components, they were calculated for pelvis and head in the whole sample and in each sex separately to help understand how the variation in shape was distributed across the principal components. A 3D source mesh of pelvic bones was warped across the first 2 principal components to give a visual reference of the extreme variation points in the PC chart using Slicermorph (Rolfe et al. 2020).

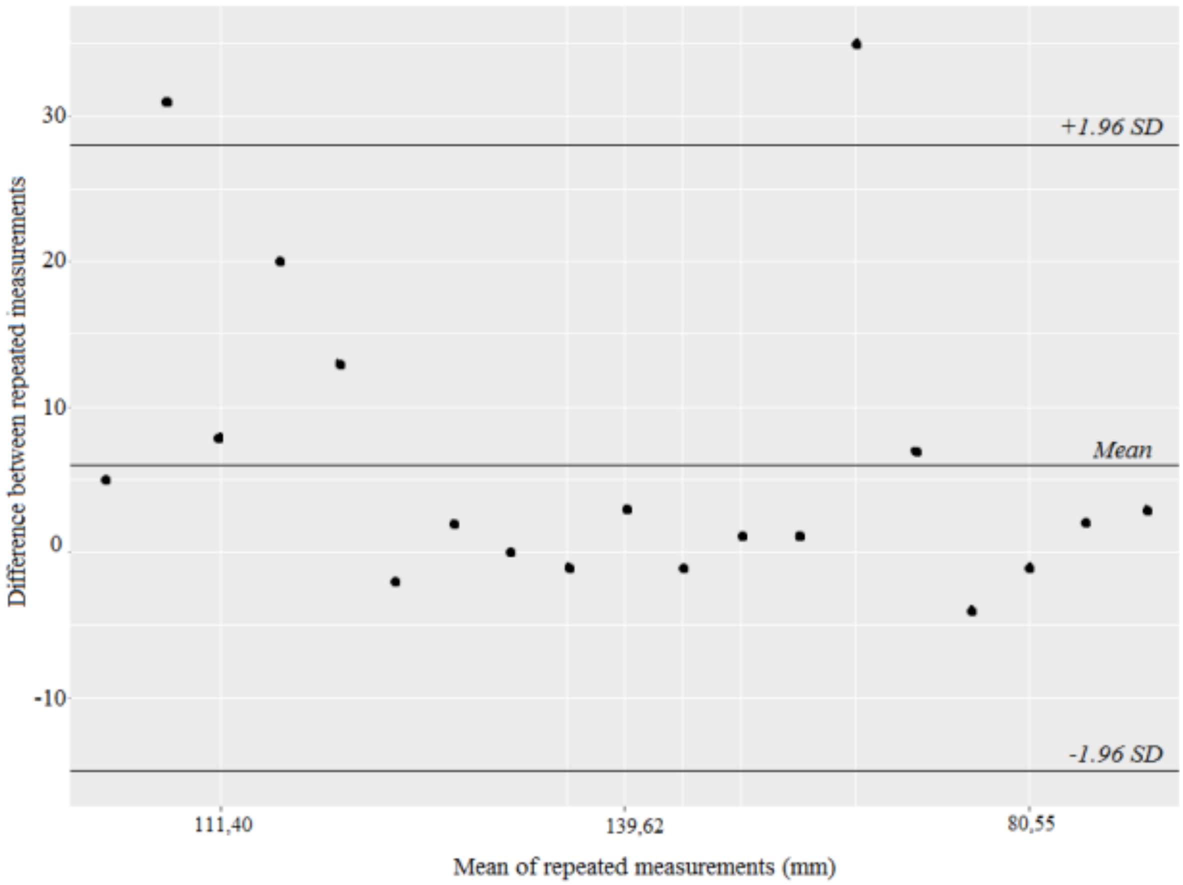
To understand and quantify the possible contribution of independent variables to the variation in shape, Partial Least Squares and Anova/Procrustes tests were performed using R package Geomorph (Adams & Otárola- Castillo 2013). These variables included: sex, body mass, stature, BMI and head centroid size. For the continuous variables (body mass, BMI, stature and head centroid size), class intervals were calculated by Sturges rule to better illustrate the distribution of these variables in PC charts. The possible covariation between head and pelvis shape was assessed through a partial least squares test between head and pelvis' landmarks.

4. RESULTS

4.1. Intra observer error

The differences between first and repeated measurements of 10% of the sample were not significant for all individuals except one (nº 916), Figure 13 shows the difference between repeated measurements for this case. The statistically significant result found between the trials is probably due to the two measurements above the confidence interval, that are represented in Figure 13 as two black dots above the standard deviation line.

Figure 13- Bland-Altman plot (nº 916)



Results of the Bland-Altman repeatability analysis for individual number 916.

4.2. Pelvic features

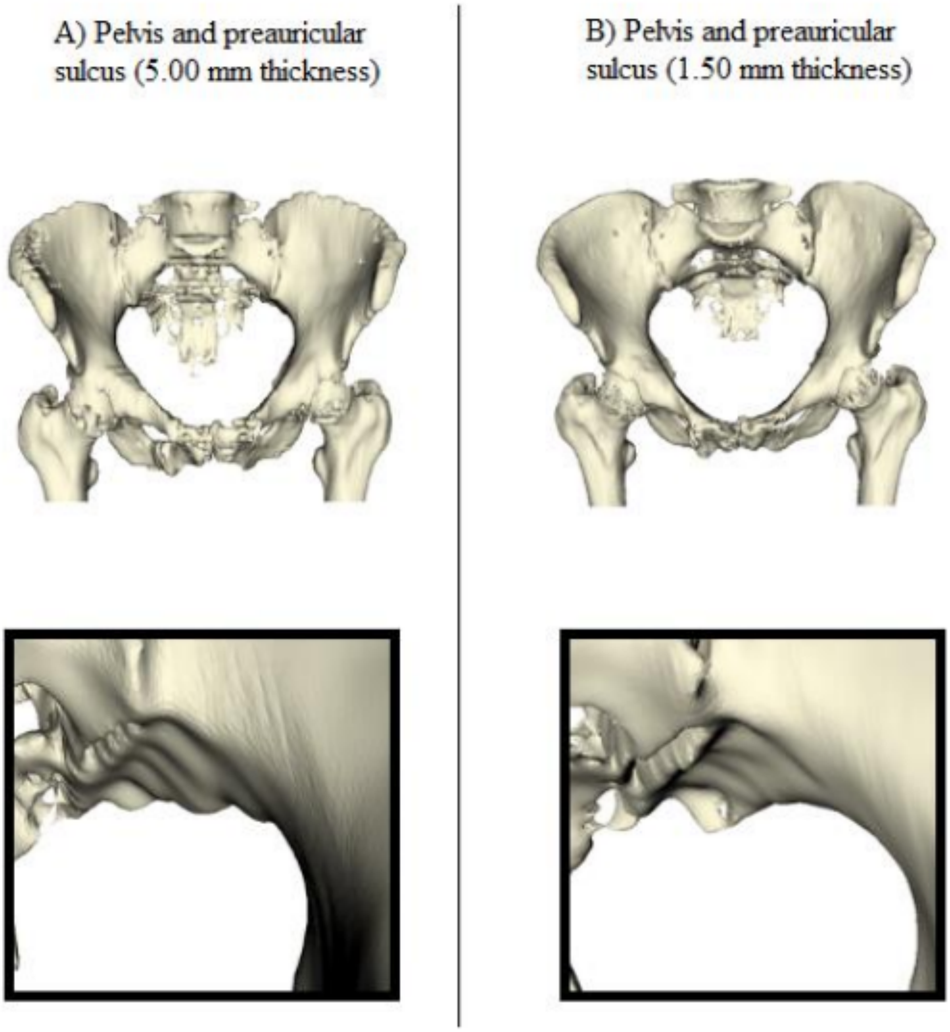
Except for the sacral preauricular extension and sacral preauricular notch, that could not be found in the sample, all other features could be well identified in the 3D models (preauricular sulcus, extended pubic tubercle, and dorsal pubic pits).

4.2.1. Appearance of pelvic features in 3D models

4.2.1.1. Effect of slice thickness on texture and pelvic features identification

All the CTs in the sample had visualizations available for reconstructions of the raw material with 1.5 mm and 5.0 mm slice thicknesses. In order to check if pelvic features could be adequately identified in 3D renderings, what was the minimal possible resolution of the CTs that allowed their identification, and how the resolution affects the overall texture of the 3D models, both the reconstructions with 5.0 and 1.5 mm were used to create 3D models that could be used in a comparison. Figures 14, 15 and 16 show the visual difference between the overall appearance of the pelvic 3D model and their pelvic features (preauricular sulcus, extended pubic tubercle and dorsal pubic pits, respectively). For the ambiguous appearance of the pelvic features in 5.00 mm slices, all further analyzes were performed on 3D models reconstructed from 1.5 mm slice thickness material.

Figure 14- Effect of slice thickness on the preauricular sulcus texture

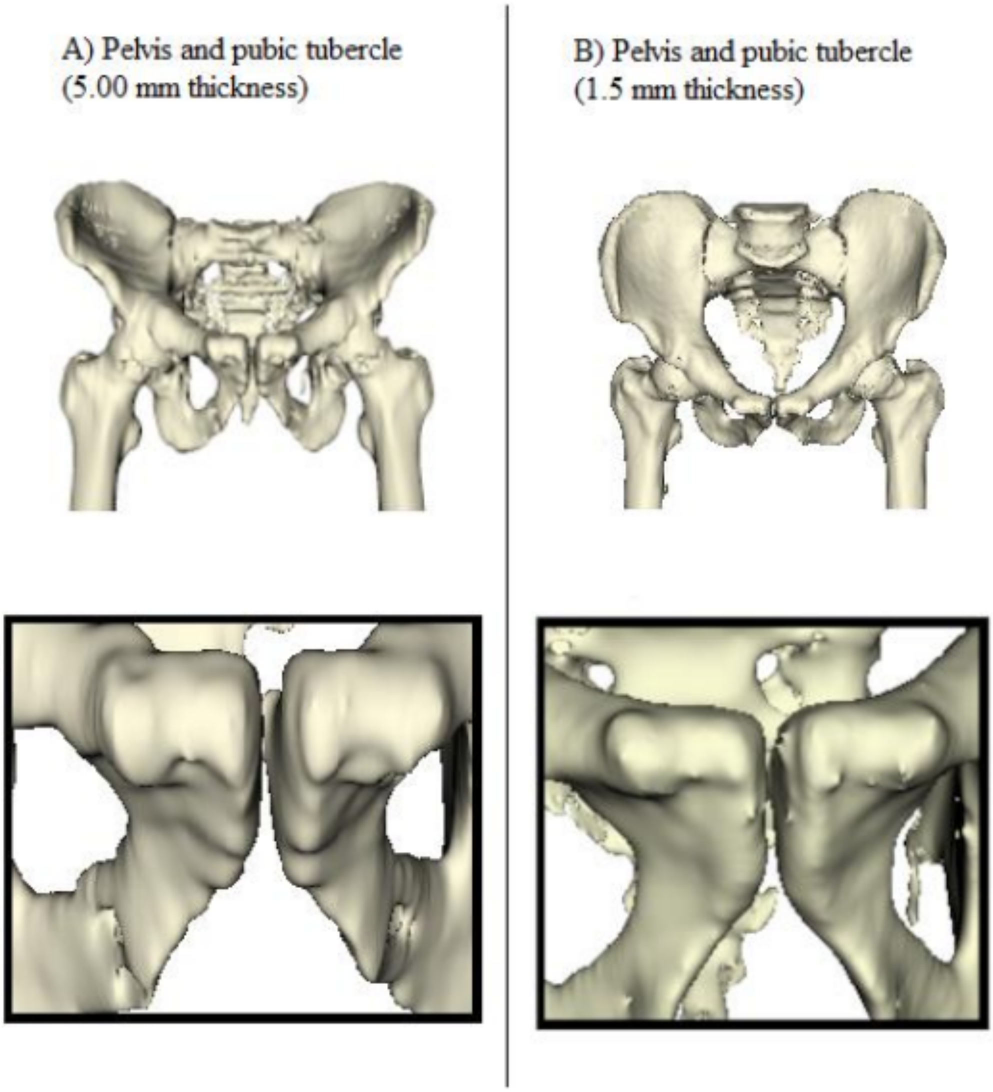


A) Pelvis and preauricular sulcus (5.00 mm thickness)

B) Pelvis and preauricular sulcus (1.50 mm thickness)

3D appearance of the prearuicular sulcus and the complete pelvis, obtained from the same raw data. A) Reconstructed with 5.0 mm slice thickness. B) Reconstructed with 1.5 mm slice thickness.

Figure 15- Effect of slice thickness on the extended pubic tubercle texture

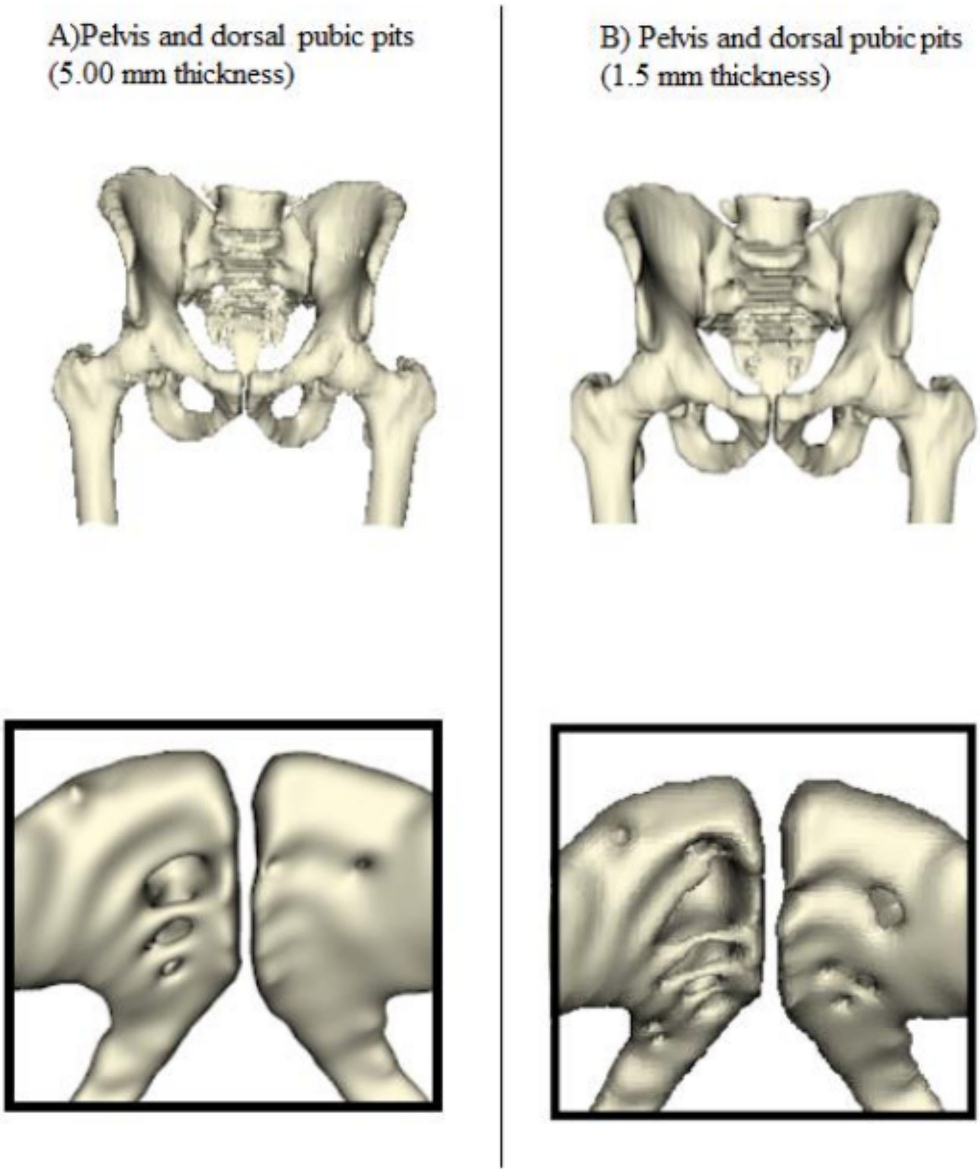


A) Pelvis and pubic tubercle (5.00 mm thickness)

B) Pelvis and pubic tubercle (1.5 mm thickness)

3D appearance of the extended pubic tubercle and the complete pelvis, obtained from the same raw data. A) Reconstructed with 5.0 mm slice thickness. B) Reconstructed with 1.5 mm slice thickness.

Figure 16- Effect of slice thickness on dorsal pubic pits texture



A)Pelvis and dorsal pubic pits (5.00 mm thickness)

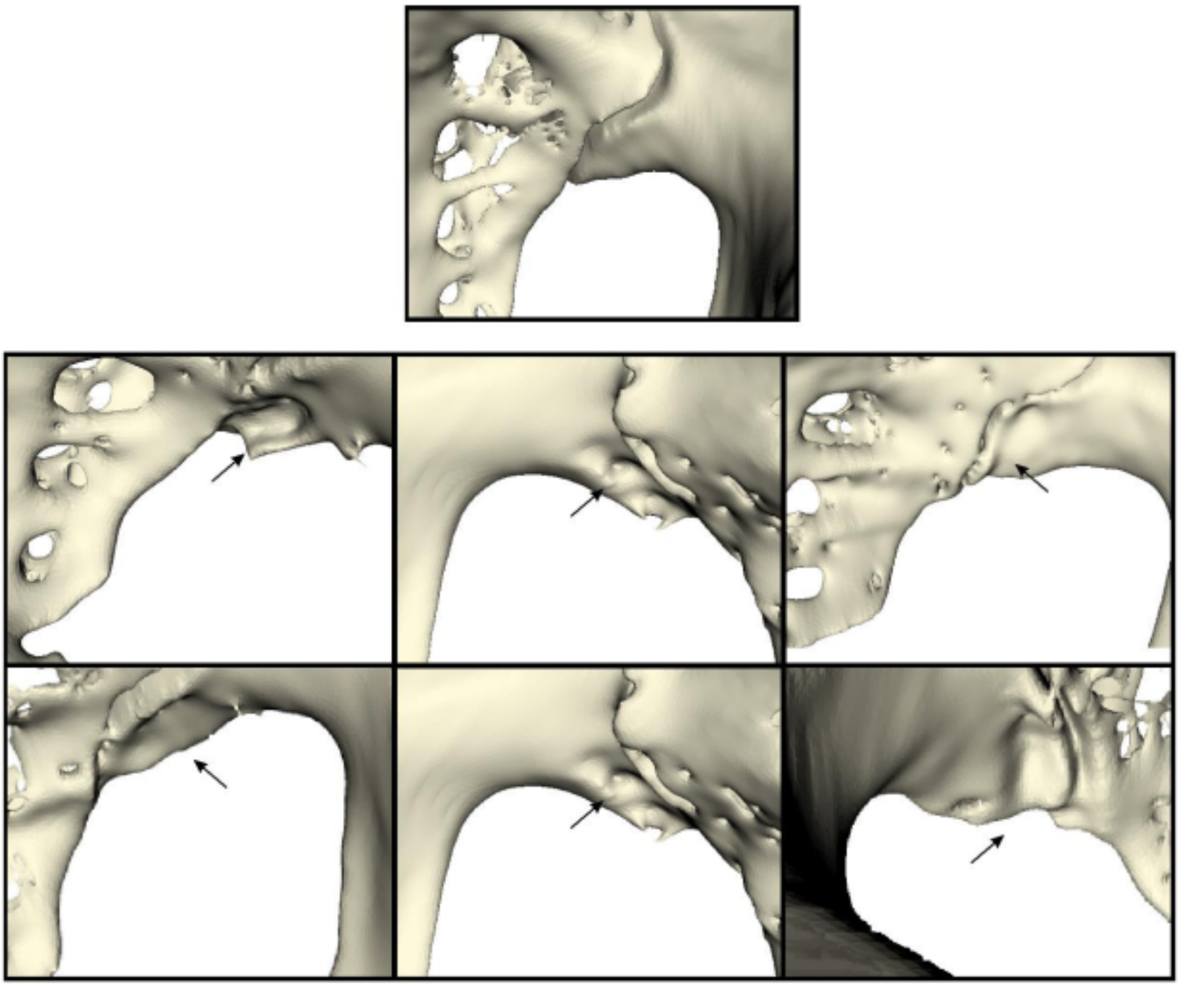
B) Pelvis and dorsal pubic pits (1.5 mm thickness)

3D appearance of the dorsal pubic pits and the complete pelvis, obtained from the same raw data. A) Reconstructed with 5.0 mm slice thickness. B) Reconstructed with 1.5 mm slice thickness.

4.2.1.2. Variations in the appearance of the pelvic features in 3D models

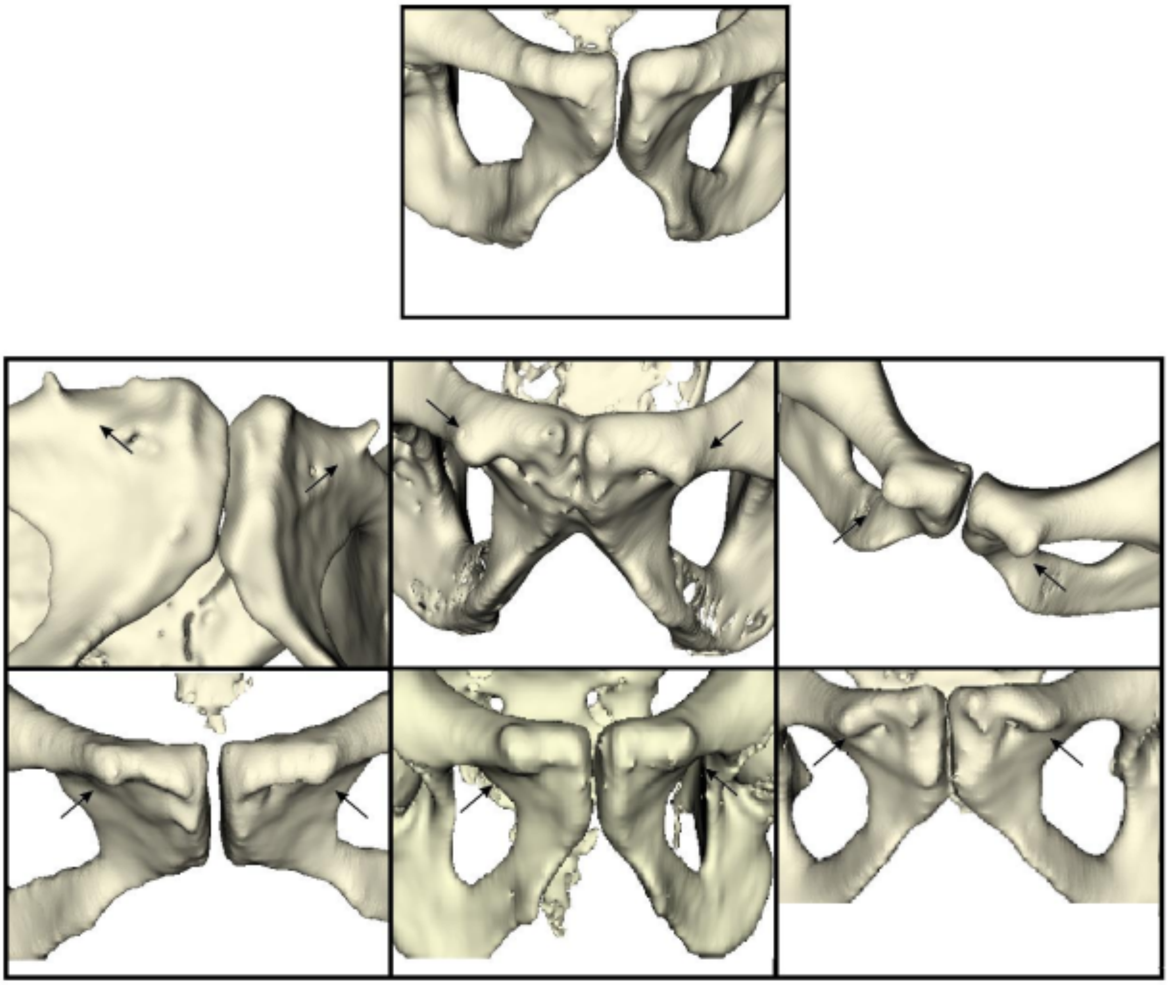
As the appearance of the features on surface models is quite different from the visual references available for dry bones, examples of the appearance of all studied found in this sample (preauricular sulcus, extended pubic tubercle and dorsal pubic pits) are illustrated in Figures 17, 18 and 19, respectively. Each figure brings 6 examples of the manifestation of the pelvic features in the 3D models, and a nonpathological form on the top, for comparison.

Figure 17- Preauricular sulci on 3D renderings



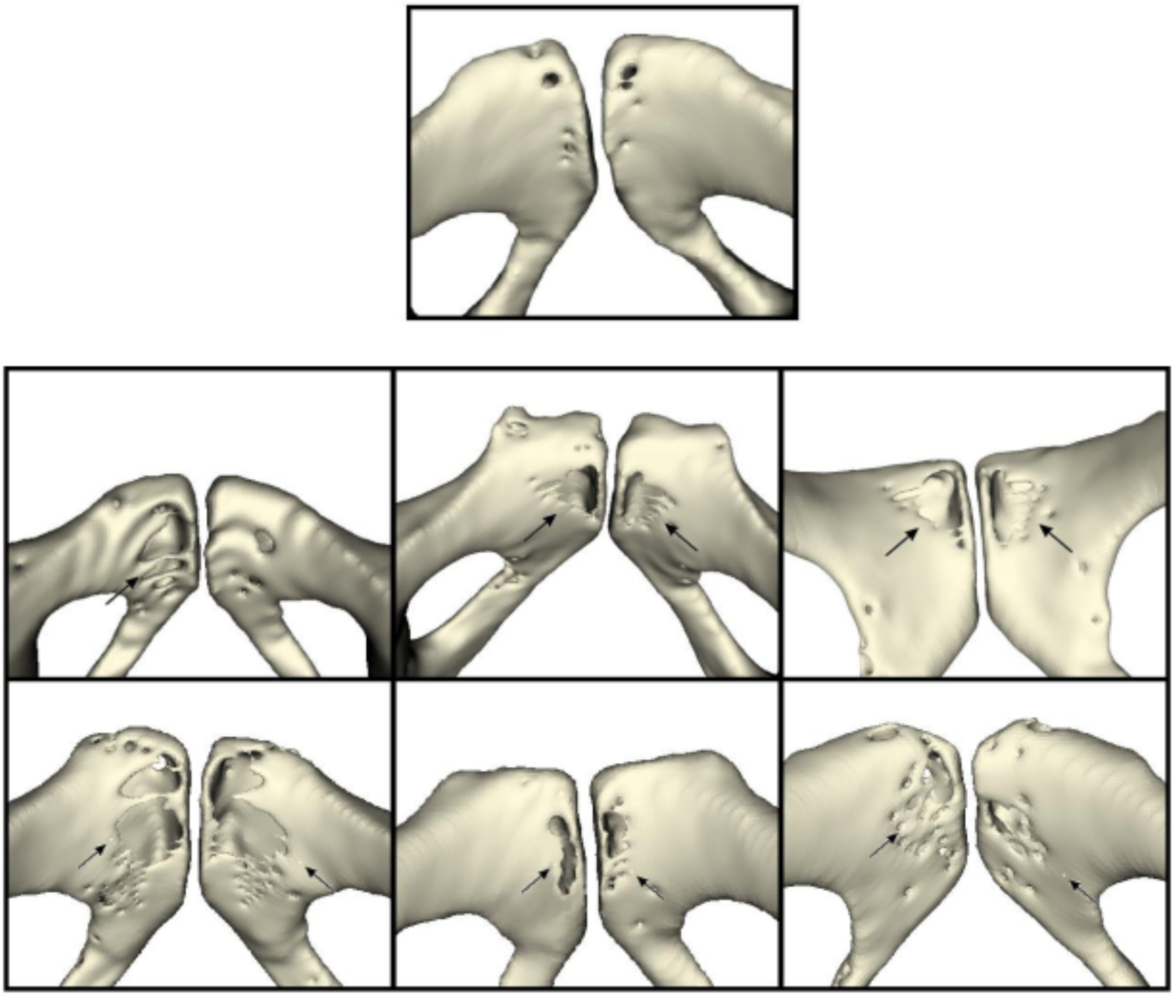
Examples of the appearance of preauricular sulci in 3D models (indicated by arrows). On the top, a screenshot of a non-pathological form.

Figure 18- Extended pubic tubercles on 3D renderings



Examples of the appearance of extended pubic tubercles in 3D models (indicated by arrows). On the top, a screenshot of a non-pathological form

Figure 19- Dorsal pubic pits on 3D renderings



Examples of the appearance of dorsal pubic pits in 3D models (indicated by arrows). On the top, a screenshot of a non-pathological form

4.2.2. Statistical analyses for pelvic features

The occurrence of each pelvic feature was checked in the pelvic 3D models and assessed as present or absent, and the frequency of the features compared by chi-square between subgroups of age and sex. From the 98 individuals available for the following analyses, 6 were excluded from the comparison between age groups because they lacked accurate information about age. None of the features showed significant associations with sex or age groups, they also showed no trend towards women or old people having more features, as expected by some of the hypotheses tested in this study.

4.2.2.1. Preauricular Sulcus occurrence according to sex and age

The statistical analysis (Pearson's chi–square test) revealed no significant association between sex and the occurrence of the preauricular sulcus (X-squared = 0.39668, df = 1, p-value = 0.5288) (Table 6), and also no significant association between age and the occurrence of the preauricular sulcus (X-squared = 1.8806, df = 2, p-value = 0.3905) (Table 7).

Table 6 - Occurrence of preauricular sulcus by sex

	Female	Male
0- absence	41 (91.1%)	51 (96,2%)
1- presence	4 (8.2%)	2 (3,8%)

Table 7 - Occurrence of preauricular sulcus by age

	20-40	40-60	>60
0- absence	9 (90%)	39 (97,5%)	38 (90,5%)
1- presence	1 (10%)	1 (2,5%)	4 (9,5%)

4.2.2.2. Extended Pubic Tubercle occurrence according to sex and age

Surprisingly, men and individuals between 20 and 40 years old have shown the highest proportion of the occurrence of this feature (45,3% and 70% respectively), but none of the differences were statistically significant according to the Pearson's chi–square test.

Chi-square values for the comparison between men and women: X-squared = 2.8724, df = 1, p-value = 0.09011 (Table 8). Chi-square values for the comparison between age groups: X-squared = 5.402, df = 2, p-value = 0.06714 (Table 9).

Table 8 - Occurrence of the extended pubic tubercle by sex

	Female	Male
0- absence	33 (73,3%)	29 (54,7%)
1- presence	12 (26,7%)	24 (45,3%)

Table 9 - Occurrence of the extended pubic tubercle by age

	20-40	40-60	>60
0- absence	3 (30,0%)	26 (65,0%)	29 (69,1%)
1- presence	7 (70,0%)	14 (35,0%)	13 (30,9%)

4.2.2.3. Dorsal Pubic Pits occurrence according to sex and age

No statistically significant difference was found between age groups or between men and women for the occurrence of dorsal pubic pits, according to the Pearson's chi–square test. Chi-square values for the comparison between men and women: X-squared = 0.39024, df = 1, p-value = 0.5322 (Table 10). Chi-square values for the comparison between age groups: X-squared = 2.0024, df = 2, p-value = 0.3674 (Table 11).

Table 10 - Occurrence of dorsal pubic pits by sex

	Female	Male
0- absence	41 (91,1%)	45 (84,9%)
1- presence	4 (8,9%)	8 (15,1%)

Table 11 - Occurrence of dorsal pubic pits by age

	20-40	40-60	>60
0- absence	10 (100%)	34 (85,0%)	44 (88,5%)
1- presence	0	6 (15,0%)	6 (11,5%)

4.2.2.4. Sum of features according to sex and age

The statistical analysis (Pearson's chi–square test) revealed no significant association between age or sex and the total sum of features per individual. Chi-square values for the comparison between men and women: X-squared = X-squared = 3.1391, df = 2, p-value = 0.2081 (Table 12). Chi-square values for the comparison between age groups: X-squared = 3.2972, df = 4, p-value = 0.5094 (Table 13).

Table 12 - Sum of features by sex

Number of features	Female	Male
0	29 (64,5%)	24 (46,2%)
1 feature	14 (31,1%)	23 (44,2%)
2 features	2 (4,4%)	5 (9,6%)

Table 13 - Sum of features by age

Number of features	20-40	40-60	>60
0	3 (30%)	21 (52,5%)	24 (57,1%)
1 feature	6 (60%)	17 (42,5%)	14 (33,3%)
2 features	1 (10%)	2 (5%)	4 (9,5%)

4.3. Traditional morphometrics

All measurements were tested for normality by Shapiro-Wilk's test, with the sub-pubic angle being the only variable without normal distribution in the pelvimetry. All measurements at the sagittal plane in the craniometrics were non normally distributed. For these non-normal variables, subgroups were compared by Mann-Whitney tests.

4.3.1. Pelvimetrics

All the diameters of the true pelvis were significantly greater in women. Other measurements in the true pelvis were also significantly greater in women (oblique diameter and subpubic angle), which is something remarkable in the human skeleton, where greater dimensions are normally found among men. All values of means (or medians) by sex for all the pelvimetry measurements, and also the significance value of the comparisons by sex can be found in Table 14.

Table 14 - Pelvimetrics

Measurement	Results
True Pelvis- Anteroposterior Diameters	
Inlet	Mean value for women: 119.44 mm Mean value for men: 112.56 mm p= 0.002
Midplane	Mean value for women: 129.87 mm Mean value for men: 122.34 mm p= 5.936e-05
Outlet	Mean value for women: 113.91 mm Mean value for men: 107.82 mm p= 0.0007
True Pelvis- Transversal Diameters	
Inlet	Mean value for women: 128.40 mm Mean value for men: 120.44 mm p= 6.549e-06
Outlet	Mean value for women: 125.78 mm Mean value for men: 107.88 mm p= 1.188e-1
Bispinous	Mean value for women: 107.53 mm Mean value for men: 92.32 mm p= 6.833e-12
True Pelvis- Other	
Oblique Diameter	Mean value for women: 127.89 mm Mean value for men: 118.91 mm p= 0.0006
Sacral Length	Mean value for women: 114.20 mm Mean value for men: 116.42 mm p= 0.40

Sacral Breadth	Mean value for women: 106.41 mm Mean value for men: 104.92 mm p= 0.26
Pubic Symphysis Length	Mean value for women: 34.43 mm Mean value for men: 37.11 mm p= 0.0054
Pubic Symphysis Breadth	Mean value for women: 5.57 mm Mean value for men: 5.61 mm p= 0.89
Subpubic Angle	Median value for women: 82.9 mm Median value for men: 66.2 mm p= 1.732e-12
Sacral Angle	Mean value for women: 69.88 mm Mean value for men: 69.95 mm p= 0.95
False Pelvis	
Biiliac Diameter	Mean value for women: 225.94 mm Mean value for men: 230.49 mm p= 0.2088

4.3.2. Craniometrics

All the measurements of the craniometric analysis were significantly greater in men. All values of means (or medians) by sex for all the craniometric measurements, and also the significance value of the comparisons by sex can be found in Table 15.

Table 15 - Craniometrics

Measurement	Results
Sagittal Plane	
GOL	Median value for women: 174.0 mm Median value for men: 179.0 mm p= 0.0005
NOL	Median value for women: 174.0 mm Median value for men: 179.0 mm p= 0.003
BBH	Median value for women: 130.0 mm

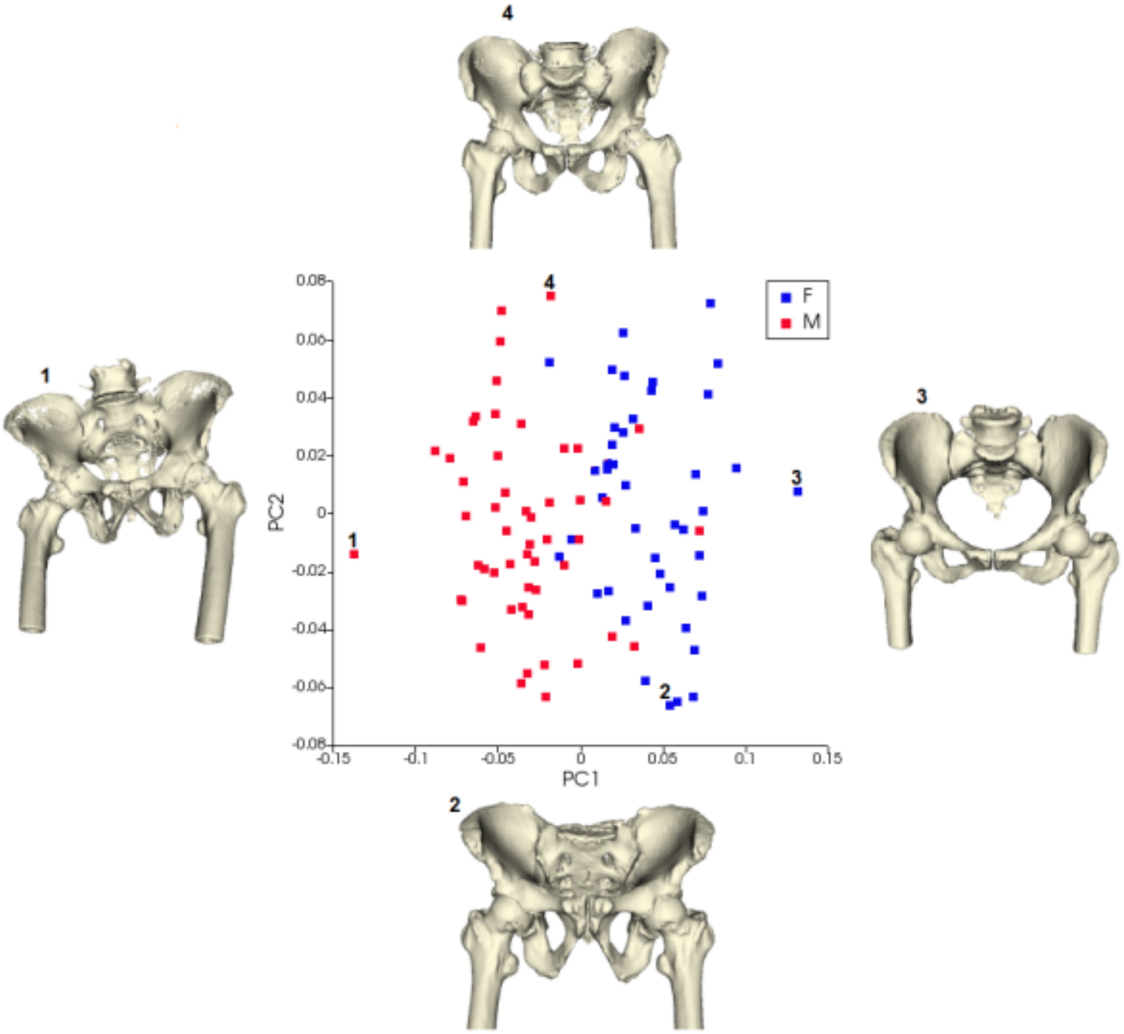
	Median value for men: 134.0 mm p= 0.004
Coronal Plane	
XCB	Mean value for women: 135.14 mm Mean value for men: 138.29 mm p= 0.00146
ZYB	Mean value for women: 121.81 mm Mean value for men: 130.85 mm p= 7.893e-13

4.4. Geometric morphometrics

4.4.1. Principal components of pelvis

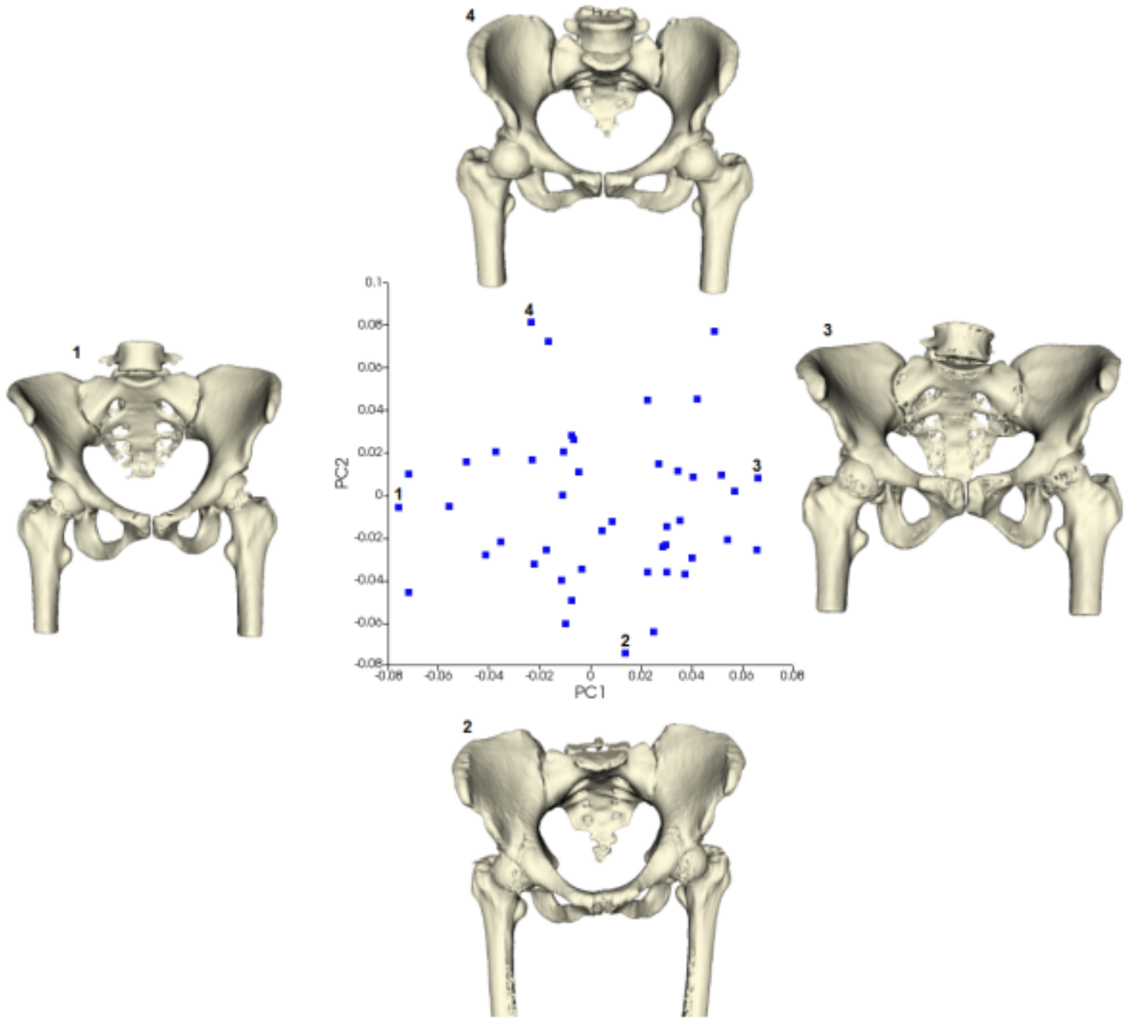
In Figure 20, all individuals in the sample are plotted around the first two principal components of pelvis shape. The first principal component contributes with 24,8% of the variance and clearly separate the sample by sex, the second principal component contributes with 12,3% of the variance. In Figure 21, only the women in the sample are plotted around the first two principal components of pelvis shape, calculated with their coordinates of pelvis shape. The first principal component contributes with 18.6% of the variance and the second contributes with 15.6%. The 3D model warped in Figure 22 shows the expected shape of a pelvis in the extreme points of the first principal component, calculated for the whole sample (Figure 22-a) and for women, separately (Figure 22-b). These figures exhibit a pronounced variation in the shape of the true pelvis across the first principal component, when the complete sample is considered (Figure 22-a), and a more discrete variation in the relative position of the posterior and anterior parts of the bony pelvis across the first principal calculated for women (Figure 22-b).

Figure 20- Principal components of pelvis shape (complete sample)



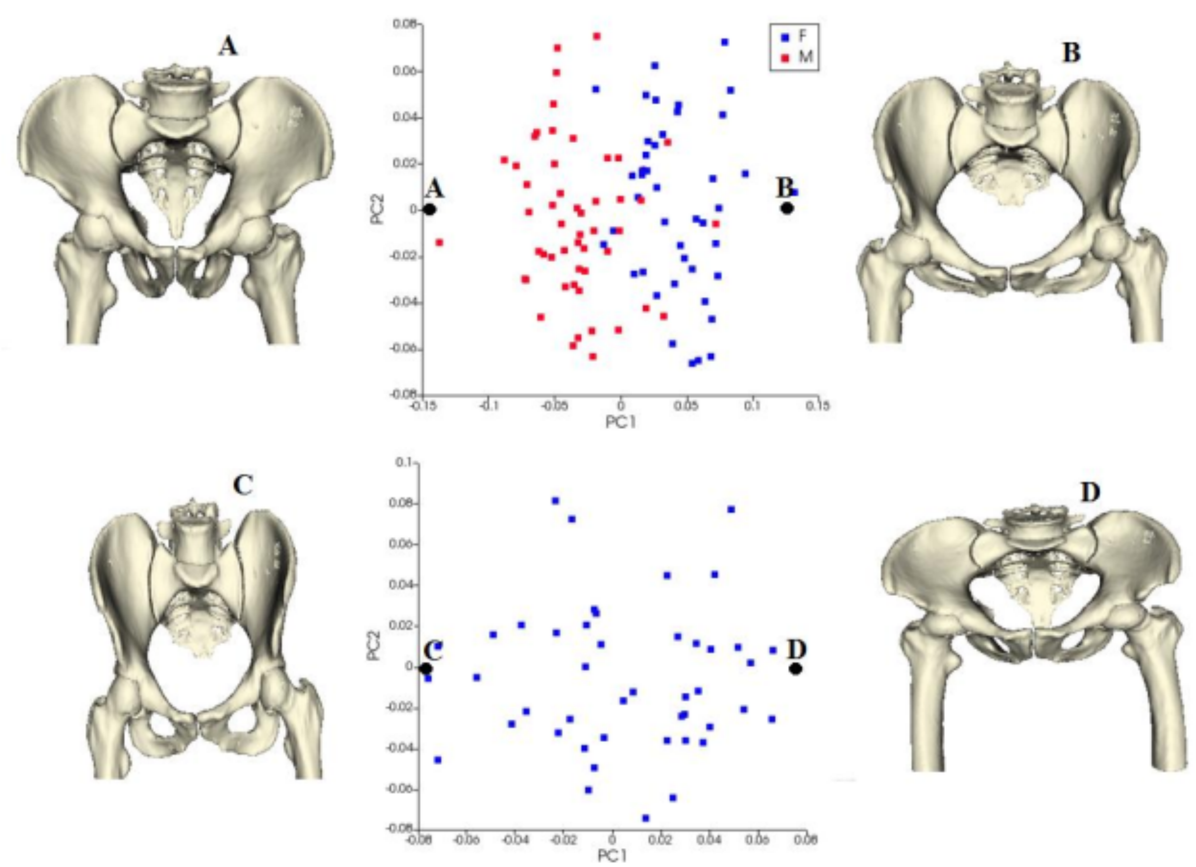
Distribution of the sample across the first and second principal components of pelvis shape. Female individuals in blue and male in red. A screenshot of the 3D rendering of the bony pelvis of the four individuals in the most extreme points of the distribution was taken and placed around the chart.

Figure 21 –Principal components of pelvis shape (women)



Distribution of the women of the sample across the first and second principal components of pelvis shape (calculated for women). A screenshot of the 3D rendering of the bony pelvis of the four individuals in the most extreme points of the distribution was taken and placed around the chart.

Figure 22- Models warped across the extreme points of the first principal component

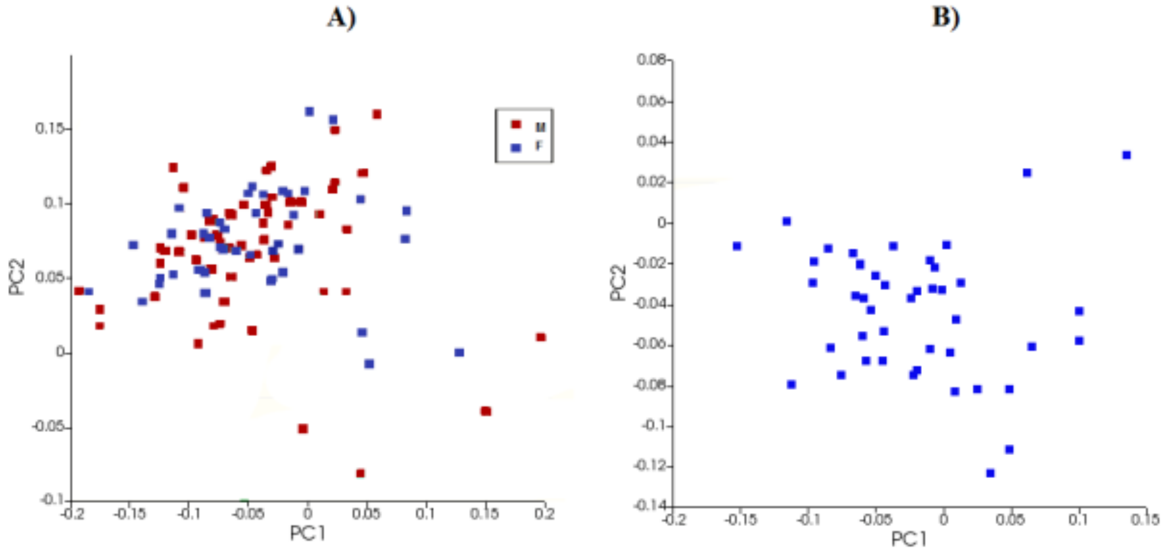


Theoretical expectations of the shape of a bony pelvis in the two extreme points of the first principal component, calculated for the whole sample (at the top) and for women (below).

4.4.2. Principal components of head

In Figure 23-a, all individuals in the sample are plotted around the first two principal components of head shape. The first principal component contributes with 43.7% of the variance, while the second principal component contributes with 19.5%. In Figure 23-b, the women in the sample are plotted around the first two principal components of head shape, calculated with coordinates of head shape of women only. The first principal component contributes with 44.5% of the variance and the second contributes with 15.7%.

Figure 23 – Principal components of head shape



A) Distribution of the individuals of the sample across the first two principal components of cranial shape, with female individuals in blue and male in red. B) Distribution of the women of the sample across the first and second principal components of cranial shape (calculated for women).

4.4.3. Co-variances between pelvic coordinates and independent variables

The results of Anova Procrustes and Partial Least squares tests, used to test for covariances between pelvis shape and other independent variables are presented in Table 16. Significant associations were found between sex, stature and head centroid size, and pelvis shape, when the complete sample was covered.

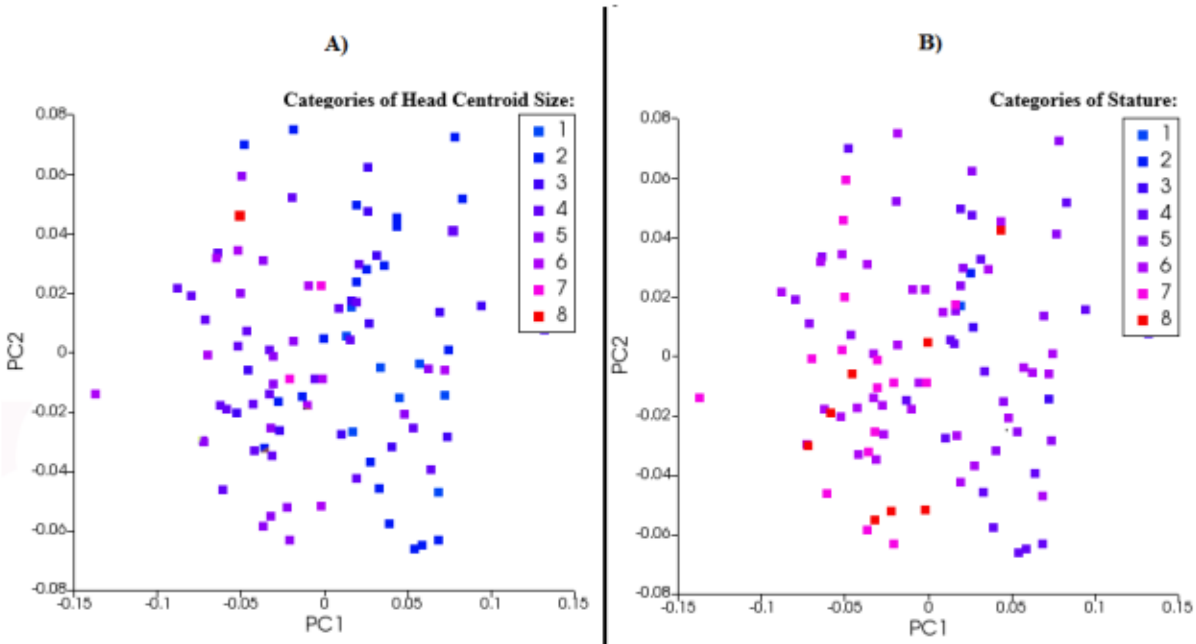
These significant co-variations, however, are possibly only a reflection of the sexual dimorphism in the sample, as shown in Figure 24.

Table 16- Partial Least Squares and Anova Procrustes tests

	Pelvis Coordinates			
	Complete Sample		Women	
Independent variables	PLS	Anova Procrustes	PLS	Anova Procrustes
Sex	r-PLS = 0.597 p = 0.001	Z =5.7326 p = 0.001		
Stature	r-PLS = 0.494	Z =2.8013 p = 0.002	r-PLS = 0.601	Z =0.89781 p = 0.186

	p = 0.008		p = 0.126	
BMI	r-PLS = 0.359 p = 0.337	Z =0.73794 p = 0.222	r-PLS = 0.592 p = 0.171	Z =0.14451 p = 0.44
Head Centroid Size	r-PLS = 0.492 p = 0.002	Z = 3.8541 p = 0.001	r-PLS = 0.502 p = 0.648	Z =-0.31776 p = 0.628
Body mass	r-PLS =0.34 p = 0.453	Z = -0.13616 p = 0.545	r-PLS = 0.583 p = 0.197	Z =0.0023314 p = 0.509

Figure 24- Principal components of pelvis shape with categories of stature and head centroid size highlighted



Categories of Head Centroid Size:

1- 223 to 228;
2- 228 to 233;
3- 233 to 238;
4- 238 to 243;
5- 243 to 248;
6- 248 to 253;
7- 253 to 258;
8- 258 to 262.

Categories of Stature:

1- 133 to 137 cm;
2- 137 to 145 cm;
3- 145 to 152 cm;
4- 152 to 160 cm;
5- 160 to 167 cm;
6- 167 to 174 cm;
7- 174 to 182 cm;
8- 182 to 189 cm.

A) Distribution of the individuals of the sample across the first two principal components of cranial shape, with categories of head centroid size highlighted in 8 different colors. B) Distribution of the individuals of the sample across the first two principal components of cranial shape, with categories of stature highlighted in 8 different colors.

4.4.4. Co-variances between pelvic and cranial coordinates

To test for covariances between pelvis and head shape, a Partial Least Square test was performed for the complete sample, showing no significant result (r-PLS: 0.384, P-value: 0.236), and also for the coordinates of head and shape of women only, also showing no significant result (r-PLS: 0.471, P-value: 0.902).

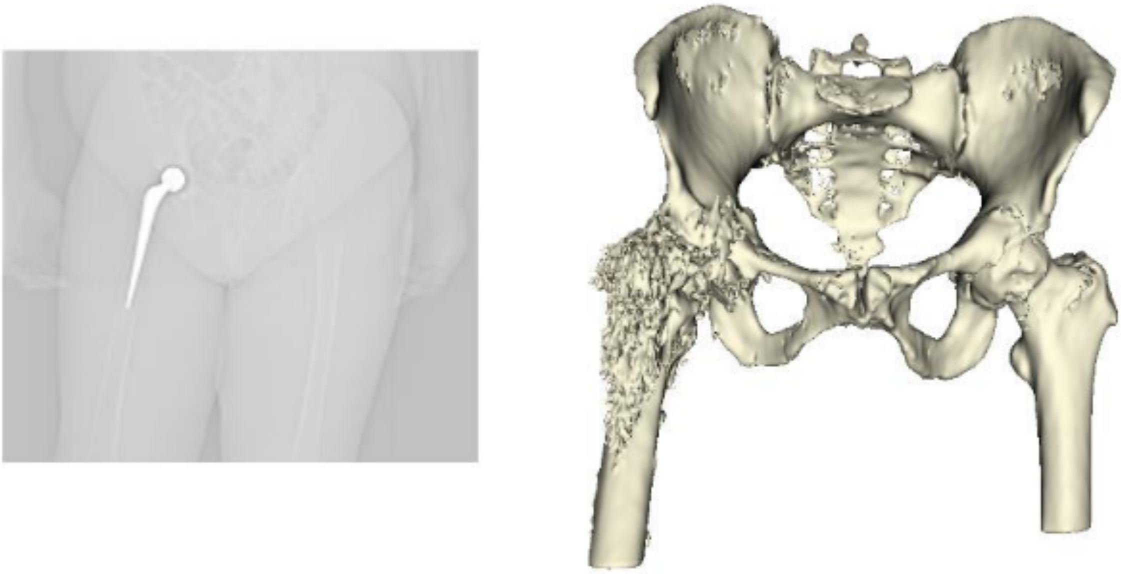
5. DISCUSSION AND CONCLUSIONS

5.1. The visibility of Pelvic Features in 3D renderings

Despite not finding neither the sacral preauricular extension or the sacral preauricular notch among the individuals of the sample, all other features assessed (preauricular sulcus, extended pubic tubercle and dorsal pubic pits) could be adequately identified in the pelvic bones of some individuals in renderings of 1.5 mm slice thickness. In 5.0 mm slice thickness, the appearance of the features was ambiguous and, therefore, the assessment of pelvic features in CTs with that resolution or less is not recommended due to the risk of misidentification.

Other factors that should be considered when looking at texture details in 3D reconstructed bones' texture, like osteological marks, are the possible limitations of the tools used for the reconstruction. In this case, the threshold tool available for 3D slicer was used to separate the bones from other tissues in the CT scans, so that, pathologies related to bone density loss (like osteoporosis) or calcification of soft tissues could have a slight effect on the shape of the models. Other problematic findings in this sample that are worth mentioning are the metal pieces attached to the bones and teeth found in some individuals, like metallic prostheses, orthodontic appliances and metallic dental restorations, because metal creates bright streaks in the image, and lead to deformities in the 3D renderings, as can be seen in figure 25. These kinds of issues must also be considered in studies that use automated landmark positioning tools, as these metal pieces may severely affect the shape of the 3D renderings, not only texture details, thus changing, as a consequence, the position of many semilandmarks.

Figure 25- Example of the artifacts created by metal pieces in CT Scans



Example of the appearance of an artifact created by the presence of a metal piece found in a CT (left) on the 3D rendering obtained from this CT (right).

5.2. The relationship between pelvic features and events of pregnancy and birth

The two hypotheses tested in this study, namely: “Hypothesis 1: The occurrence of pelvic features is positively associated with age” and; “Hypothesis 2: Pelvic features are more frequently found among women” were designed to investigate if the presence of the features could be related to events of pregnancy and birth, given the data available for the sample. As no data about parity was available, the expectation was that, if there was indeed a positive relationship between the presence of the features with birth, a trend towards older people and women showing more features could be identified. The results, however, did not match these expectations.

5.2.1. The relationship between pelvic features and age groups

No significant result was found in the chi-square tests loaded for each pelvic feature in isolation, or the sum of features per individual, with the age groups. Since the occurrence of these features is normally associated with weight load, as the hip joints transmit the loads from the upper side of the body to the lower limbs, a trend toward older men showing more features could also be expected for this reason, as well as considering that old people would have accumulated more features during life; however that was not the case for this sample.

Surprisingly, the youngest age group (20 to 40 years old) showed more individuals with an extended pubic tubercle than without (only 3 individuals without this feature while the other 7 had shown an extended pubic tubercle). This is consistent with the results found by Waltenberger et al (2022), however, it is not consistent with the findings of numerous studies on pelvic features, that found more features among older people (Snodgrass & Galloway 2003, Suchey et al. 1979, Maass & Friedling2016, Andersen 1986, McKern & Stewart 1957, Acsádi & Nemeskéri 1970, Rosatelli et al., 2006, Ubelaker & La Paz 2012, Waltenberger 2021).

There is a possibility that bone remodeling could explain the situation found in this case, where old people show less features, especially the extended pubic tubercle. Waltenberer et al. (2021) found that the pelvis, especially the female pelvis goes through significant shape changes during adult years (from 17 years old onwards), which means that bone remodeling does happen throughout these ages, and there is, therefore, the possibility that this remodeling could recede the appearance of the features. This hypothesis has already been proposed by Kelley (1979) and Bergfelder & Herrmann (1980). This is, however, in disagreement with the far majority of the studies carried out on pelvic features as said before.

5.2.2. The relationship between pelvic features and sex

No association was found between the manifestation of the pelvic features and the female sex. Actually, males showed more dorsal pits and extended pubic tubercles than females, in absolute numbers (Tables 8 and 10), although these differences were not statistically significant at a significance level of 5%.

Despite the common association between the manifestation of pelvic features and the female sex being the reason why these features were once associated with pregnancy and birth, results like this are not uncommon. Actually, the preauricular sulcus has some morphological variations that could not be observed here that were found to be associated with the male sex. Houghton (1974) described two variations of the preauricular sulcus, defined by him as "groove of pregnancy" and "groove of ligament", which were found to be in association with the female and the male sex, respectively. Bruzek (2002), described three different variations of the preauricular sulcus, regarding details on the sulcus floor, called paraglenoid groove, preauricular groove and piriform tubercle. Among them, only the preauricular groove would be associated with the female sex and obstetrical causes, according to him, while the others were found to be in association with high muscular activity and skeletal robusticity, and were more frequent among men.

5.3. Traditional morphometrics approach

Due to the sexual dimorphism in human species, men usually show greater dimensions in all segments of the skeleton when compared to women in traditional morphometric approaches, with the only exception of the true pelvis, which is the most sexually dimorphic part of the skeleton, and also the only part where women show greater dimensions than men (Fischer & Mitteroecker 2015, Fischer & Mitteroecker 2017, Huseynov et al 2016, Schultz 1949, Tague 1992). In this regard, the sample studied here is in total agreement with the expectation: all measurements obtained from the craniometry were significantly greater in men than women and, for the pelvimetry, all measurements obtained from the true pelvis were significantly greater in women than men. Despite the differences found from the craniometry being not very noticeable in terms of magnitude, with men's measurements being, on average, 6 millimeters greater than women's (GOL, NOL, XCB, ZYB, and BBH), when the average difference of stature is about 8 centimeters, for example, the differences were all statistically significant, according to the Mann-Whitney and T tests.

The greater dimensions obtained from the true pelvis of women in this sample are consistent with the findings of several other studies, obtained both from current and archaeological populations (Kolesova et al. 2017, Arsuaga et al. 1994, Tague 1992, Betti & Manica 2018, Sibley et al. 1992, Iscán 1983, Kurki 2007, Coleman 1969, Crespo 2015, Tague 2000). These remarkably greater dimensions in women's pelvises are traditionally interpreted as the result of birth acting as a selective force in our pelvic morphology that supposedly became more compelling with cranial expansion in the last two million years (Lovejoy et al. 1973, Tague 1992, Rosenberg & Trevathan 1995). Indeed, the anteroposterior diameters of the true pelvis have considerably enlarged in the Homo erectus, and that can be reasonably interpreted as an adaptation to the delivery of more encephalized neonates during that time, just as much as other changes in morphological features of the bony pelvis, that have happened in other moments of our evolutionary history, must have reflected other sources of selective pressures, like bipedalism (Gruss & Schmitt 2015). This point, however, is still contentious as the sexual dimorphism in the human bony pelvis is not as remarkable as the usual for a mammal species that gives birth to large neonates (Grunstra et al. 2018). Moreover, in a comparative study recently carried out by Fischer et al. (2021), our sexual dimorphism in the bony pelvis was found to be no different from that of chimpanzees, bringing into question the assumption that birth has acted as a selective pressure that pushed the human female pelvis to a relative enlargement in comparison to men's.

Interestingly, the only measurement obtained from the pelvimetry that showed no significant difference between man and women was exactly the one that was not located in the true pelvis: the bi-iliac diameter. Men's average size was even greater than women's (about 5 millimeters) for this measurement. This is particularly interesting because not only is that specific part not located in the true pelvis, and, therefore, not directly related to obstetric functions, but also because this pelvic dimension has already been found to be related to thermoregulatory functions. In a comparative study among different human populations, Ruff (1994) found an association between the average size of the bi-iliac diameter and latitude, which could be interpreted as a climatic adaptation, in terms of the capacity of the body to retain heat due to the surface/volume ratio.

5.4. Geometric morphometrics approach

Having both the results from traditional and geometric morphometrics' approaches was extremely useful for this exploratory study since we are using a sample that has never been studied before and, with these two sources of data, the information of size could be easily isolated from that of shape. In this case, the first two PCs calculated for cranial coordinates showed that the significant difference obtained from the comparisons between sexes in the craniometry was only due to size differences, as there is a complete overlap between the sexes in the cranial PC chart that is colored by sex (Figure 23a), which means that the sexes are not different in terms of cranial shape, only size. The first two PCAs calculated for pelvic coordinates, on the other hand, showed the opposite pattern, with an almost complete separation between the sexes along the first principal component, which confirms that pelvic shape is indeed sexually dimorphic (Figure 20).

The results obtained from the pelvimetry are also in accordance with the final shape observed in the pelvic model that was warped across the first principal component of pelvic coordinates, which shows what would be the expected shape of a pelvis in the two extreme points of the first principal component (Figure 22). According to the pelvimetry results, the most dimorphic dimensions were that of the true pelvis, where all diameters were significantly greater in women and, comparing these 3D models, it is clear that the major difference in shape is also located in the birth canal. While one model shows an extremely wide and roundly shaped birth canal at the extreme point that is nearer to where women are located in the chart, that of the opposite side (near to where all males are located) shows a very constricted, funnel shaped canal.

In general, female primates show greater diameters in the true pelvis, regardless of their neonate's size, with a wider pelvic inlet, greater pubic length and a wider sacra that, when combined, result in a wider birth canal (Tague 2005, Moffet 2017, Steudel 1981), but more remarkable sexual dimorphism in the true pelvis is traditionally interpreted as the result of birth acting as a selective pressure on the morphology of pelvic bones in primate species, considering that those species that give birth to the larger neonates are exactly those that show more accentuated sexual dimorphism (Moffet 2021). The human case is special in many regards, starting from the fact that our pelvis is not as sexually dimorphic as expected given the general and cranial size of our neonates (Grunstra et al. 2019, DeSilva & Lesnik 2008, Fischer et al. 2021). Besides, there were other very unique selective pressures that acted in the evolutionary history of our species shaping our pelvis in very particular ways, being bipedalism the most noticeable one (Young et al. 2022). It is noteworthy that bipedalism has not pushed our pelvis to be more efficient in terms of walking and running only, once it has also changed our bodies' center of gravity, posture, and these dramatic changes had consequences for our lumbar vertebrae, abdominal organs, pelvic muscles, and so this new body configuration imposed other constraints to the variation in pelvic morphology.

For example, nowadays, medical literature has shown associations between certain degrees of variation in pelvic morphology and increased risks of prolapse, obstructed labor, as well as locomotor and postural problems (Mitteroecker et al. 2021); hence, it is totally reasonable to suppose that natural selection might have been modeling our pelvic shape due to these other functional demands imposed by the transition to bipedalism. Moreover, several correlations between human pelvic morphology and other variables have been found, giving us clues about other possible contributions of pelvic morphology to the general functioning of the body that are less direct and obvious, like the covariations found between pelvic morphology and head size, stature, gut size, and even environmental variables, such as latitude (Arsuaga & Carretero 1994, Kurki 2013, Ruff 1994, Fischer & Mitteroecker 2015, Torres-Tamayo et al. 2018, Torres-Tamayo et al. 2020, Uy et al 2020).

Some of these correlations, however, were not found for the complete pelvis shape, but for specific measurements (for example, the bi-iliac breadth is correlated with latitude, and the inlet is correlated with stature - Ruff 1994) and these results also give us clues about the modularity patterns of bony pelvis, which are the most probable reason why so many different demands could have been accommodated by only one morphological unit. Studies on modular integration in primates' pelvis have been showing very accordant results: primates share a common and weak modular pattern that assures high evolvability to this unit, with a clearer separation between the ilium and the ischiopubic (Betti 2017, Moffet 2017, Moffet 2021, Lewton 2011, Grabowski et al. 2011). In the case of Homo sapiens, Grabowski (2011) argues that this modularity pattern is even weaker, and hypothesizes that the evolution of bipedalism would have broken it and enhanced evolvability even more.

5.5. Covariance tests

In order to explore the possibility of statistical correlations between the variation in pelvic shape and other variables, and, consequently, the possibility of some modularity between this morphological unit and other body dimensions, Partial Least Squares and Procrustes ANOVA tests were performed between the pelvic coordinates and the following variables: cranial centroid size, cranial coordinates, stature, body mass, BMI, and sex. Statistically significant results were found for sex, cranial centroid size and stature with pelvic coordinates, both for the Procrustes ANOVA and PLS tests (Table 16).

The significant result obtained for sex is very reasonable as a separation of the sample according to sex along the first principal component was very clear in the pelvic PC chart (Figure 20). The other significant results, however, must be carefully interpreted because both head centroid size and stature are highly dependent on sex, putting these covariations at risk of being spurious due to sexual dimorphism.

Stature and head centroid size, as any other data that includes size, tend to be sexually dimorphic, so, as pelvic morphology also varies along with sex, there is a great possibility that these statistically significant covariations are only reflecting the sexual dimorphism, and not a morphological integration between these parts.

5.5.1 The covariation between cranial centroid size and pelvic morphology

It is very surprising that, despite all the concerns about the high cephalopelvic proportion in humans and the extensive debates about the obstetric dilemma (Washburn 1960), so far, only one study has explored the possibility of a modular integration between our cranium and pelvis. Fischer & Mitteroecker (2015) have found a positive correlation between a rounder pelvic shape and head circumference in a sample of white Americans from the beginning of the 20th century, that brought into discussion the possibility of cephalopelvic disproportions during birth being avoided in our species due to a morphological integration between the two parts. This hypothesis, thus, had to be tested in different populations, and the sample used here was considered to be especially interesting for testing correlation or covariations hypotheses like that, due to its admixed genetic background that diminishes the possibility of finding meaningless correlations. Actually, this possibility of integration does not seem to be a new idea, as it resembles an old popular belief about birth that cephalopelvic proportions are only at risk of imbalance in mixed populations. George J. Engelmann, an American obstetrician from the 19th century who wrote the first known anthropological treatise on birthing practices where he described a series of obstetric practices and beliefs of indigenous people, clearly alludes to this belief in the following passage:

> "We can then readily account for the rapid and easy delivery of savage women who live in a natural state, and the rarity of accidents from these facts: First, they marry only their kind, and thus the proportions of the child are suited to the parts of the mother; secondly, their more healthy condition and vigorous frames; while, thirdly, from the active life they lead, head or breech presentations result. [...] People intermarry regardless of difference in race or frame of body, and the consequence is the frequent disproportion between the head of the child and the pelvis of the mother" (Engelmann, 1882, p. 9)

Indeed, our results did not show clear signs of a covariance pattern between pelvis and cranium, with no significant results found for the covariation tests between coordinates of head and cranium, and even the significant covariance found between pelvic coordinates and head centroid size cannot be interpreted as a possible protection from cephalopelvic disproportion due to other findings that put this significative result into question: the first is the sexual dimorphism found in the craniometry, with all cranial measurements varying significantly by sex; the second is probably a consequence of this sexual dimorphism that can be observed in Figure 24a, where the sample is colored by head centroid size categories in the pelvis PC chart and a slight distribution from larger to smaller cranial dimensions is visible from left to right, following the same spatial distribution of sex; the third are the results obtained from the Procrustes ANOVA and PLS tests loaded between cranial centroid size and pelvic coordinates for women only, that did not show this significant results, corroborating to the conclusion that there is no real association between pelvic shape and cranial size (Table 16).

5.5.2. The covariation between stature and pelvic morphology

The significant results found in the covariance tests loaded for pelvic coordinates and stature seem to follow a similar pattern of that found for the cranial centroid size and pelvic coordinates. Nonetheless, the relationship between these two variables has been explored by several studies that sought after easily identifiable predictors of birth outcomes, with many of them showing women of shorter stature to be at a higher risk of emergency c-sections or complications during birth (Bernard 1952, Zaffarini & Mitteroecker 2019, Dujardin et al. 1996, Stewart et al. 1979, Holland et al 1982, Dougherty & Jones 1988, Stulp et al. 2011, Kurki 2007). The results found here, however, seem to reflect the same pattern of variation due to sexual dimorphism found for cranial centroid size: the difference in the average stature of men and women is statistically significant (mean value for females: 161cm; mean value for males: 171 cm; $p = 0.001$); the distribution of stature categories in the PCA chart (Figure 24a) follows the spatial pattern of sexual distribution, and; the results found in the same tests when loaded for women, separately, had no significant result (Table 16).

5.6. Conclusions

Pelvic features can be fairly identified in virtual reconstructions but further research is needed to better understand their appearance in 3D surface models, especially when the images are obtained in different resolutions, or from different sources (like CT Scans, Magnetic Resonance or photogrammetry), and to what degree their virtual appearance corresponds to the features found in dry bones.

The bony pelvises of this sample follow the same pattern of sexual dimorphism found in every other human sample, with the true pelvis being the most dimorphic part and showing greater dimensions in women than men. Further research is needed to understand if correlations between pelvic shape and other body dimensions can be found in other human populations of admixed ancestry (like the Brazilian) and in more homogeneous ones.

REFERENCES:

Abitbol, M. M. (1996). The shapes of the female pelvis. Contributing factors. The Journal of Reproductive Medicine, 41(4), 242-250.

Acsádi, G., Nemeskéri, J., & Balás, K. (1970). History of human life span and mortality (pp. 113-135). Budapest: Akadémiai Kiadó.

Adams, D. C., & Otárola- Castillo, E. (2013). geomorph: an R package for the collection and analysis of geometric morphometric shape data. Methods in Ecology and Evolution, 4(4), 393-399.

Andersen, B. C. (1986). Parturition scarring as a consequence of flexible pelvic architecture (Doctoral dissertation, Theses (Dept. of Archaeology)/Simon Fraser University).

Angel, J. L. (1969). The bases of paleodemography. American Journal of Physical Anthropology, 30(3), 427-437.

Arendt, H. (2013). The human condition. University of Chicago press. (Original work published in 1958).

Arsuaga, J. L., & Carretero, J. M. (1994). Multivariate analysis of the sexual dimorphism of the hip bone in a modern human population and in early hominids. American journal of physical anthropology, 93(2), 241-257.

Becker, I., Woodley, S. J., & Stringer, M. D. (2010). The adult human pubic symphysis: a systematic review. Journal of anatomy, 217(5), 475-487.

Bergfelder, T., & Herrmann, B. (1980). Estimating fertility on the basis of birth-traumatic changes in the pubic bone. Journal of Human Evolution, 9(8), 611-613.

Bernard, R. M. (1952). The shape and size of the female pelvis. Edinburgh medical journal, 59(2), T1.

Betti, L. (2017). Human variation in pelvic shape and the effects of climate and past population history. The Anatomical Record, 300(4), 687-697.

Bland, J. M., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. The lancet, 327(8476), 307-310.

Bonmatí, A., Gómez-Olivencia, A., Arsuaga, J. L., Carretero, J. M., Gracia, A., Martínez, I., & Carbonell, E. (2010). Middle Pleistocene lower back and pelvis from an aged human individual from the Sima de los Huesos site, Spain. Proceedings of the National Academy of Sciences, 107(43), 18386-18391.

Brown, K. M. (2015). Selective pressures in the human bony pelvis: Decoupling sexual dimorphism in the anterior and posterior spaces. American Journal of Physical Anthropology, 157(3), 428-440.

Bruzek, J. (2002). A method for visual determination of sex, using the human hip bone. American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists, 117(2), 157-168.

Buikstra, J. E., & Ubelaker, D. H. (1994). Standards for data collection from human skeletal remains. Arkansas Archaeological Survey Research Series No. 44. Fayetteville: Arkansas Archaeological Survey.

Coleman, W. H. (1969). Sex differences in the growth of the human bony pelvis. American Journal of Physical Anthropology, 31(2), 125-151.

Cox, M. (2000). Assessment of parturition. Human osteology in archaeology and forensic science, 131-142.

Cox, M., & Mays, S. (Eds.). (2000). Human osteology: in archaeology and forensic science. Cambridge University Press.

Cox, M., & Scott, A. (1992). Evaluation of the obstetric significance of some pelvic characters in an 18th century British sample of known parity status. American Journal of Physical Anthropology, 89(4), 431-440.

Crespo, C., Rissech, C., Thomas, R., Juan, A., Appleby, J., & Turbon, D. (2015). Sexual dimorphism of the pelvic girdle from 3D images of a living Spanish sample from Castilla-La Mancha. Homo, 66(2), 149-157.

Cunningham, F. G., Leveno, K. J., Bloom, S. L., Spong, C. Y., & Dashe, J. S. (2014). Williams obstetrics, 24e. New York, NY, USA: Mcgraw-hill.

Decrausaz, S. L. (2014). A morphometric analysis of parturition scarring on the human pelvic bone (Doctoral dissertation, University of Victoria).

Dee, P. M. (1981). The preauricular sulcus. Radiology, 140(2), 354-354.

Derry, D. E. (1909). Note on the innominate bone as a factor in the determination of sex: with special reference to the sulcus praeauricularis. Journal of anatomy and physiology, 43(Pt 3), 266.

DeSilva, J. M. (2011). A shift toward birthing relatively large infants early in human evolution. Proceedings of the National Academy of Sciences, 108(3), 1022-1027.

DeSilva, J. M., & Lesnik, J. J. (2008). Brain size at birth throughout human evolution: a new method for estimating neonatal brain size in hominins. Journal of human evolution, 55(6), 1064-1074.

DeSilva, J. M., & Rosenberg, K. R. (2017). Anatomy, development, and function of the human pelvis. The Anatomical Record, 300:628–632

DeSilva, J. M., Laudicina, N. M., Rosenberg, K. R., & Trevathan, W. R. (2017). Neonatal shoulder width suggests a semirotational, oblique birth mechanism in Australopithecus afarensis. The Anatomical Record, 300(5), 890-899.

Dougherty, C. R. S., & Jones, A. D. (1988). Obstetric management and outcome related to maternal characteristics. American journal of obstetrics and gynecology, 158(3), 470-474.

Dujardin, B., Cutsem, R. V., & Lambrechts, T. (1996). The value of maternal height as a risk factor of dystocia: a meta-analysis. Tropical Medicine & International Health, 1(4), 510-521.

Engelmann, G. L. (1882). Labour among Primitive Peoples (St. Louis: Chambers).

Falk, D. (2012). Hominin paleoneurology: where are we now? Progress in brain research, 195, 255-272.

Fedorov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J. C., Pujol, S. & Kikinis, R. (2012). 3D Slicer as an image computing platform for the Quantitative Imaging Network. Magnetic resonance imaging, 30(9), 1323-1341.

Finlay, B. L., Darlington, R. B., & Nicastro, N. (2001). Developmental structure in brain evolution. Behavioral and Brain Sciences, 24(2), 263-278.

Fischer, B., & Mitteroecker, P. (2015). Covariation between human pelvis shape, stature, and head size alleviates the obstetric dilemma. Proceedings of the National Academy of Sciences, 112(18), 5655-5660.

Fischer, B., & Mitteroecker, P. (2017). Allometry and sexual dimorphism in the human pelvis. The Anatomical Record, 300(4), 698-705.

Fischer, B., Grunstra, N. D., Zaffarini, E., & Mitteroecker, P. (2021). Sex differences in the pelvis did not evolve de novo in modern humans. Nature Ecology & Evolution, 5(5), 625-630.

Franklin, D., Cardini, A., Flavel, A., & Marks, M. K. (2014). Morphometric analysis of pelvic sexual dimorphism in a contemporary Western Australian population. International journal of legal medicine, 128(5), 861-872.

Gould, S. J., & Lewontin, R. C. (1979). The spandrels of San Marco and the Panglossian paradigm: a critique of the adaptationist programme. Proceedings of the royal society of London. Series B. Biological Sciences, 205(1161), 581-598.

Grabowski, M. W., Polk, J. D., & Roseman, C. C. (2011). Divergent patterns of integration and reduced constraint in the human hip and the origins of bipedalism. Evolution: International Journal of Organic Evolution, 65(5), 1336-1356.

Grunstra, N. D., Zachos, F. E., Herdina, A. N., Fischer, B., Pavličev, M., & Mitteroecker, P. (2018). Humans as inverted bats: A comparative approach to the obstetric conundrum. American Journal of Human Biology, 31(2), e23227.

Gruss, L. T., & Schmitt, D. (2015). The evolution of the human pelvis: changing adaptations to bipedalism, obstetrics and thermoregulation. Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1663), 20140063.

Gruss, L. T., Wall-Scheffler, C. M., Malik, N. (2009). Infant carrying in humans: interactions between morphometric and gait parameters. American Journal of Physical Anthropology. S48 141.

Gunz, P., Neubauer, S., Falk, D., Tafforeau, P., Le Cabec, A., Smith, T. M., & Alemseged, Z. (2020). Australopithecus afarensis endocasts suggest ape-like brain organization and prolonged brain growth. Science Advances, 6(14).

Häusler, M., & Schmid, P. (1995). Comparison of the pelvis of Sts 14 and AL288-1: implications for birth and sexual dimorphism in australopithecines. Journal of human evolution, 29(4), 363-383.

Hisaw, F. L. (1929). The corpus luteum hormone. I. Experimental relaxation of the pelvic ligaments of the guinea pig. Physiological Zoology, 2(1), 59-79.

Holland, E. L., Cran, G. W., Elwood, J. H., Pinkerton, J. H. M., & Thompson, W. (1982). Associations between pelvic anatomy, height and year of birth of men and women in Belfast. Annals of human biology, 9(2), 113-120.

Holt, A. C. (1978). A re- examination of parturition scars on the human female pelvis. American journal of physical anthropology, 49(1), 91-94.

Houghton, P. (1974). The bony imprint of pregnancy. Bulletin of the New York Academy of Medicine, 51(5), 655.

Huseynov, A., Zollikofer, C. P., Coudyzer, W., Gascho, D., Kellenberger, C., Hinzpeter, R., & de León, M. S. P. (2016). Developmental evidence for obstetric adaptation of the human female pelvis. Proceedings of the National Academy of Sciences, 113(19), 5227-5232.

Igarashi, Y., Shimizu, K., Mizutaka, S., & Kagawa, K. (2020). Pregnancy parturition scars in the preauricular area and the association with the total number of pregnancies and parturitions. American Journal of Physical Anthropology, 171(2), 260-274.

Işcan, M. Y. (1983). Assessment of race from the pelvis. American Journal of Physical Anthropology, 62(2), 205-208.

Kawada, M., Nakatsukasa, M., Nishimura, T., Kaneko, A., & Morimoto, N. (2020). Covariation of fetal skull and maternal pelvis during the perinatal period in rhesus macaques and evolution of childbirth in primates. Proceedings of the National Academy of Sciences, 117(35), 21251-21257.

Kelley, M. A. (1979). Parturition and pelvic changes. American Journal of Physical Anthropology, 51(4), 541-545.

Kolesova, O., Kolesovs, A., & Vetra, J. (2017). Age-related trends of lesser pelvic architecture in females and males: a computed tomography pelvimetry study. Anatomy & Cell Biology, 50(4), 265-274.

Krogman, W. M. (1951). The scars of human evolution. Scientific American, 185(6), 54-57.

Kurki, H. K. (2007). Protection of obstetric dimensions in a small-bodied human sample. American Journal of Physical Anthropology, 133(4), 1152-1165.

Kurki, H. K. (2013). Bony pelvic canal size and shape in relation to body proportionality in humans. American Journal of Physical Anthropology, 151(1), 88-101.

Laudicina, N. M., Rodriguez, F., & DeSilva, J. M. (2019). Reconstructing birth in Australopithecus sediba. PloS one, 14(9), e0221871.

Leakey, M. D., & Hay, R. L. (1979). Pliocene footprints in the Laetolil Beds at Laetoli, northern Tanzania. Nature, 278(5702), 317-323.

Lewton, K. L. (2012). Evolvability of the primate pelvic girdle. Evolutionary Biology, 39(1), 126-139.

Lopreno, G. P., Santos, F., & Bruzek, J. (2021). Is the preauricular groove, as defined by, an indicator of parity? A test using the SIMON identified skeletal collection (Vaud, Switzerland). Anthropologischer Anzeiger; Bericht Uber die Biologisch-anthropologische Literatur.

Lovejoy, C. O. (1988). Evolution of human walking. Scientific American, 259(5), 118-125.

Lovejoy, C. O. (2009). Reexamining human origins in light of Ardipithecus ramidus. science, 326(5949), 74-74e8.

Lovejoy, C. O., Heiple, K. G., & Burstein, A. H. (1973). The gait of Australopithecus. American Journal of Physical Anthropology, 38(3), 757-779.

Lovejoy, C. O., Suwa, G., Spurlock, L., Asfaw, B., & White, T. D. (2009). The pelvis and femur of Ardipithecus ramidus: the emergence of upright walking. science, 326(5949), 71-71e6.

Maass, P. (2012). The bony pelvis scars of parturition and factors influencing their manifestation (Master's thesis, University of Cape Town).

Maass, P., & Friedling, L. J. (2016). Scars of parturition? Influences beyond parity. International Journal of Osteoarchaeology, 26(1), 121-131.

McFadden, C., & Oxenham, M. F. (2018). Sex, parity, and scars: A meta-analytic review. Journal of forensic sciences, 63(1), 201-206.

McKern, T. W., & Stewart, T. D. (1957). Skeletal age changes in young American males: analysed from the standpoint of age identification. Headquarters, Quartermaster Research & Development Command.

Mitteroecker, P., Huttegger, S. M., Fischer, B., & Pavlicev, M. (2016). Cliff-edge model of obstetric selection in humans. Proceedings of the National Academy of Sciences, 113(51), 14680-14685.

Mitteroecker, P., Grunstra, N. D., Stansfield, E., Waltenberger, L., & Fischer, B. (2021). Did population differences in human pelvic form evolve by drift or selection? Bulletins et mémoires de la *Société d'Anthropologie de Paris*, 33(33 (1)).

Moffett, E. A. (2017). Dimorphism in the size and shape of the birth canal across anthropoid primates. The Anatomical Record, 300(5), 870-889.

Moffett, E. A. (2021). Sexual dimorphism in the size and shape of the non- obstetric pelvis across anthropoids. American Journal of Physical Anthropology, 176(3), 402-421.

Pany- Kucera, D., Spannagl- Steiner, M., Argeny, S., Maurer- Gesek, B., Weninger, W. J., & Rebay- Salisbury, K. (2019). Sacral preauricular extensions, notches, and corresponding iliac changes: New terms and the proposal of a recording system. International Journal of Osteoarchaeology, 29(6), 1013-1021.

Pany-Kucera, D., Spannagl-Steiner, M., Maurer-Gesek, B., Weninger, W. J., & Rebay-Salisbury, K. (2021). Sacral preauricular extensions and notches as parts of a 'Pelvic Pattern'may provide information on past pregnancies and parturitions. Anthropologischer Anzeiger; Bericht uber die biologisch-anthropologische Literatur.

Pany- Kucera, D., Spannagl- Steiner, M., Desideri, J., & Rebay- Salisbury, K. (2022). Indicators of motherhood? Sacral preauricular extensions and notches in identified skeletal collections. International Journal of Osteoarchaeology, 32(1), 64-74.

Praxmarer, E. (2019). The Bony Pelvis: Macroscopic Analysis of the Frequency and Morphology of the so-called Scars of Parturition and their Relationship with Sex, Age, Body Mass and Pelvic Dimensions. Master's thesis, Universitat Wien, Wien.

Praxmarer, E. M., Tutkuviene, J., & Kirchengast, S. (2020). Metric and morphological analysis of pelvic scars in a historical sample from Lithuania: Associations with sex, age, body size and pelvic dimensions. International Journal of Osteoarchaeology, 30(5), 629-641.

Pavličev, M., Romero, R., & Mitteroecker, P. (2019). Evolution of the human pelvis and obstructed labor: new explanations of an old obstetrical dilemma. American journal of obstetrics and gynecology, 222(1), 3-16.

Porto, A., Rolfe, S., & Maga, A. M. (2020). ALPACA: a fast and accurate approach for automated landmarking of three-dimensional biological structures. bioRxiv.

Rak, Y. (1991). Lucy's pelvic anatomy: its role in bipedal gait. Journal of Human Evolution, 20(4), 283-290.

Rebay-Salisbury, K., Pany-Kucera, D., Spannagl-Steiner, M., Kanz, F., Galeta, P., Teschler-Nicola, M., & Salisbury, R. B. (2018). Motherhood at early bronze age Unterhautzenthal, lower Austria. Archaeologia Austriaca, 102, 71-134.

Reyes, L. D., & Sherwood, C. C. (2015). Neuroscience and human brain evolution. In Human Paleoneurology (pp. 11-37). Springer, Cham.

Rolfe, S., Pieper, S., Porto, A., Diamond, K., Winchester, J., Shan, S. & Maga, A. M. (2020). SlicerMorph: An open and extensible platform to retrieve, visualize and analyze 3D morphology. bioRxiv.

Rosatelli, A. L., Agur, A. M., & Chhaya, S. (2006). Anatomy of the interosseous region of the sacroiliac joint. Journal of Orthopaedic & Sports Physical Therapy, 36(4), 200-208.

Rosenberg, K. R. (1992). The evolution of modern human childbirth. American Journal of Physical Anthropology, 35(S15), 89-124.

Rosenberg, K. R., De Leon, M. P., Zune, L., & Zollikofer, C. (2010). The evolution of rotational birth: inferences from a three-dimensional virtual reconstruction of the pelvic girdle of Jinniushan. American Journal of Physical Anthropology.

Rosenberg, K., & Trevathan, W. (1995). Bipedalism and human birth: The obstetrical dilemma revisited. Evolutionary Anthropology: Issues, News, and Reviews, 4(5), 161-168.

Rosenberg, K., & Trevathan, W. (2002). Birth, obstetrics and human evolution. BJOG: An International Journal of Obstetrics & Gynaecology, 109(11), 1199-1206.

Ruff, C. (2010). Body size and body shape in early hominins–implications of the Gona pelvis. Journal of Human Evolution, 58(2), 166-178.

Ruff, C. B. (1991). Climate and body shape in hominid evolution. Journal of Human Evolution, 21(2), 81-105.

Ruff, C. B. (1994). Morphological adaptation to climate in modern and fossil hominids. American journal of physical anthropology, 37(S19), 65-107.

Schemmer, D., White, P. G., & Friedman, L. (1995). Radiology of the paraglenoid sulcus. Skeletal radiology, 24(3), 205-209.

Schultz, A. H. (1949). Sex differences in the pelves of primates. American Journal of Physical Anthropology, 7(3), 401-424.

Sibley, L. M., Armelagos, G. J., & Van Gerven, D. P. (1992). Obstetric dimensions of the true pelvis in a medieval population from Sudanese Nubia. American Journal of Physical Anthropology, 89(4), 421-430.

Simpson, S. W., Quade, J., Levin, N. E., Butler, R., Dupont-Nivet, G., Everett, M., & Semaw, S. (2008). A female Homo erectus pelvis from Gona, Ethiopia. Science, 322(5904), 1089-1092.

Snodgrass, J. J., & Galloway, A. (2003). Utility of dorsal pits and pubic tubercle height in parity assessment. Journal of Forensic Sciences, 48(6), 1226-1230.

Spring, D. B., Lovejoy, C. O., Bender, G. N., & Duerr, M. (1989). The radiographic preauricular groove: Its non- relationship to past parity. American Journal of Physical Anthropology, 79(2), 247-252.

Stansfield, E., Fischer, B., Grunstra, N. D., Pouca, M. V., & Mitteroecker, P. (2021). The evolution of pelvic canal shape and rotational birth in humans. BMC biology, 19(1), 1-11.

Steinetz, B., Lasano, S., De Haas van Dorsser, F., Glickman, S., Bergfelt, D., Santymire, R., & Swanson, W. (2009). Relaxin Concentrations in Serum and Urine of Endangered and Crazy Mixed- Up Species: New Methods, Uses, and Findings. Annals of the New York Academy of Sciences, 1160(1), 179-185.

Stern Jr, J. T. (2000). Climbing to the top: a personal memoir of Australopithecus afarensis. Evolutionary Anthropology: Issues, News, and Reviews: Issues, News, and Reviews, 9(3), 113-133.

Steudel, K. (1981). Sexual dimorphism and allometry in primate ossa coxae. American Journal of Physical Anthropology, 55(2), 209-215.

Stewart, T.D. (Ed.). (1970). Personal Identification in Mass Disasters: Report of a Seminar Held in Washington, DC, 9-11 December 1968, by Arrangement Between the Support Services of the Dept. of the Army and the Smithsonian Institution. TD Stewart, Editor. Smithsonian Institution.

Stewart, K.S., Cowan, D.B., & Philpott, R. (1979). Pelvic dimensions and the outcome of trial labour in Shona and Zulu primigravidas. South African Medical Journal, 55(21), 847-851.

Stulp, G., Verhulst, S., Pollet, T. V., Nettle, D., & Buunk, A. P. (2011). Parental height differences predict the need for an emergency caesarean section. PloS one, 6(6), e20497.

Suarez-Kurtz, G. (2005). Pharmacogenomics in admixed populations. Trends in pharmacological sciences, 26(4), 196-201.

Suchey, J. M., Wiseley, D. V., Green, R. F., & Noguchi, T. T. (1979). Analysis of dorsal pitting in the os pubis in an extensive sample of modern American females. American Journal of Physical Anthropology, 51(4), 517-539.

Tague, R. G. (1992). Sexual dimorphism in the human bony pelvis, with a consideration of the Neandertal pelvis from Kebara Cave, Israel. American Journal of Physical Anthropology, 88(1), 1-21.

Tague, R. G. (2000). Do big females have big pelves?. American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists, 112(3), 377-393.

Tague, R. G. (2005). Big-bodied males help us recognize that females have big pelves. American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists, 127(4), 392-405.

Tague, R. G., & Lovejoy, C. O. (1986). The obstetric pelvis of AL 288-1 (Lucy). Journal of Human Evolution, 15(4), 237-255.

Tague, R. G., & Lovejoy, C. O. (1998). AL 288-1—Lucy or Lucifer: gender confusion in the Pliocene. Journal of Human Evolution, 35(1), 75-94.

Torres-Tamayo, N., García-Martínez, D., Nalla, S., Barash, A., Williams, S. A., Blanco-Pérez, E., & Bastir, M. (2018). The torso integration hypothesis revisited in Homo sapiens: Contributions to the understanding of hominin body shape evolution. American journal of physical anthropology, 167(4), 777-790.

Torres-Tamayo, N., Martelli, S., Schlager, S., García-Martínez, D., Sanchis-Gimeno, J. A., Mata-Escolano, F., & Bastir, M. (2020). Assessing thoraco-pelvic covariation in Homo sapiens and Pan troglodytes: A 3D geometric morphometric approach. American journal of physical anthropology, 173(3), 514-534

Trevathan, W., & Rosenberg, K. (2000). The shoulders follow the head: postcranial constraints on human childbirth. Journal of human evolution, 39(6), 583-586.

Ubelaker, D. H., & De La Paz, J. S. (2012). Skeletal indicators of pregnancy and parturition: a historical review. Journal of forensic sciences, 57(4), 866-872.

Uy, J., Hawks, J., & VanSickle, C. (2020). Sexual dimorphism of the relationship between the gut and pelvis in humans. American Journal of Physical Anthropology, 173(1), 130-140.

Wall-Scheffler, C. M. (2012). Energetics, locomotion, and female reproduction: implications for human evolution. Annual review of anthropology, 41, 71-85.

Wall- Scheffler, C. M., Geiger, K., & Steudel- Numbers, K. L. (2007). Infant carrying: the role of increased locomotory costs in early tool development. American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists, 133(2), 841-846.

Waltenberger, L., Pany-Kucera, D., Rebay-Salisbury, K., & Mitteroecker, P. (2021). The association of parturition scars and pelvic shape: A geometric morphometric study. American journal of physical anthropology, 174(3), 519-531.

Waltenberger, L., Rebay-Salisbury, K., & Mitteroecker, P. (2021). Age dependent changes in pelvic shape during adulthood. Homo.(accepted).

Waltenberger, L., Rebay-Salisbury, K., & Mitteroecker, P. (2022). Are parturition scars truly signs of birth? The estimation of parity in a well-documented modern sample. International Journal of Osteoarchaeology.

Warrener, A. G. (2017). Hominin hip biomechanics: changing perspectives. The Anatomical Record, 300(5), 932-945.

Warrener, A. G., Lewton, K. L., Pontzer, H., & Lieberman, D. E. (2015). A wider pelvis does not increase locomotor cost in humans, with implications for the evolution of childbirth. PloS one, 10(3), e0118903.

Washburn, S. L. (1960). Tools and human evolution. Scientific American, 203(3), 62-75.

Wells, C. (1975). Ancient obstetric hazards and female mortality. Bulletin of the New York Academy of Medicine, 51(11), 1235.

Wells, J. C., DeSilva, J. M., & Stock, J. T. (2012). The obstetric dilemma: an ancient game of Russian roulette, or a variable dilemma sensitive to ecology? American journal of physical anthropology, 149(S55), 40-71.

Wells, J. C., Pomeroy, E., & Stock, J. T. (2021). Evolution of lactase persistence: Turbo-charging adaptation in growth under the selective pressure of maternal mortality? Frontiers in Physiology, 1344.

Wickham, H., Francois, R., Henry, L., & Müller, K. (2015). dplyr: A grammar of data manipulation. R package version 0.4, 3, p156.

White, T. D., Black, M. T., & Folkens, P. A. (2011). Human osteology. Academic press.

Young, M., Richard, D., Grabowski, M., Auerbach, B. M., de Bakker, B. S., Hagoort, J., & Capellini, T. D. (2022). The developmental impacts of natural selection on human pelvic morphology. Science advances, 8(33).

Zaffarini, E., & Mitteroecker, P. (2019). Secular changes in body height predict global rates of caesarean section. Proceedings of the Royal Society B, 286(1896), 20182425.

Zelditch, M. L., Swiderski, D. L., & Sheets, H. D. (2012). Geometric morphometrics for biologists: a primer. academic press.

Zollikofer, C. P., de León, M. S. P., Lieberman, D. E., Guy, F., Pilbeam, D., Likius, A., Brunet, M. (2005). Virtual cranial reconstruction of Sahelanthropus tchadensis. Nature, 434(7034), 755-759.