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Reconsidering the Obstetrical Dilemma: Correlations Between Head and Pelvic Size

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**RECONSIDERING THE OBSTETRIC DILEMMA:
CORRELATIONS BETWEEN HEAD AND PELVIC SIZE**

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Arts

in

The Department of Geography and Anthropology

by
Kelsey Catrice Fox
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Abstract

The Obstetrical Dilemma (OD) theory has become canon in biological anthropology. The OD posits that i] dystocia results from bipedal mothers and encephalized infants, ii] contrasting selection for bipedality and obstetrics hinders locomotive efficiency, and iii] the contradicting requirement of the fetus being small enough to pass through the birth canal yet being cognitively advanced enough to cling to its mother after birth. Females, theoretically, exhibit deficient gait efficiency for the sake of successful childbirth. An obstetric advantage theory has been posited where taller individuals with a larger head size have larger pelves. If the distance between the acetabulae increases as an obstetric advantage, it would be necessary for there to be a concomitant increase in femoral neck length to maintain equivalent locomotor efficiency. This study tests that individuals with larger cranial circumferences have wider pelves and, in turn, longer femoral neck lengths.

The cranium, pelvis, and femur of a modern sample of 100 individuals were assessed (49 females and 51 males) at the Sam Houston State University's Applied Anatomical Research Center. Cranial circumference encompassed the widest points of the cranium. Pelvic and femoral metrics include anteroposterior diameters of the pelvic inlet, midplane, and outlet as well as the transverse diameter of the pelvic inlet, bi-iliac diameter, bi-acetabular diameter, femoral head circumference, and femoral length. Three variables were computed: i] pelvic inlet shape, ii] lateral iliac flare, and iii] skeletal effective mechanical advantage.

Results show statistically significant correlations between cranial circumference and the anteroposterior diameters of the pelvic inlet and midplane for females as well as bi-iliac diameter and lateral iliac flare for males. No significant difference was found in pelvic inlet shape for either sex in this sample; nor was there a significant correlation in either sex between femoral length, a correlate of stature, and pelvic inlet shape. There was no significant association among cranial circumference and pelvic inlet shape nor femoral neck length. The proposed hypothesis fails to be supported. Results also show no convincing evidence of significant deficient locomotive ability for females, as theorized by the OD.

Chapter 1. Introduction

The shape of the human pelvis has evolutionary, cultural, and genetic implications. The multitude of evolutionary morphological changes observed in the pelvis include laterally rotated iliac blades, longer pubic symphyses, a broader birth canal in the anteroposterior plane, and more robust and projecting iliac spines (Lovejoy et al. 1973, Simpson et al. 2008). Most of these changes in pelvic morphology are theorized to aid bipedality via natural selection. Theories on bipedality assume morphological pelvic change results from function and, consequently, selection. Hominin pelvic evolution developed from a complex, diverse pattern of natural selection and many, but not all, pelvic traits hypothesized to relate functionally to bipedalism evolved directly from natural selection (Grabowski and Roseman 2015, Sharma 2002). The pelvis also has a vital role in reproduction. For this reason, the human pelvis is markedly sexually dimorphic due to differing reproductive roles for females and males. The female pelvis is broad and shallow while the male pelvis is narrow and deep. Bony sex differences are salient enough to be a major factor in sex identification for bioarcheologists and forensic anthropologists.

The sex specific morphological differences between females and males address different selective pressures. Washburn (1960), likely inspired by the dystocia related theories of Schultz (1949) and Krogman (1951), termed these varying pressures an 'Obstetrical Dilemma'. The Obstetrical Dilemma (OD) resulted from human brains increasing in size over time, including that of the newborn, but the preceding adaptation of bipedalism prevented female birth canals from expanding. Allegedly, these conflicting

actions led to a tight fit between the fetus and birth canal, which is evident in cases of cephalopelvic disproportion, and the fetus' delivery at an earlier stage of development than that of apes (i.e., secondary altriciality) (Dunsworth 2018, Washburn 1960). Females, theoretically, had to compromise gait efficiency in order to increase the likelihood of successful childbirth. Henceforth, a narrow pelvis, as seen in males, is hypothesized to increase locomotor efficiency while a wide pelvis increases the capability of the birth canal at the expense of locomotor efficiency (Warrener et al. 2015). Critics of the OD reject that male pelvic shape is comparatively more optimal for bipedalism and insist females are as evolutionarily equipped for efficient bipedalism as well as bearing children. The associations among Washburn's trifurcated tenets of the OD (i.e. i] dangerous and difficult human childbirth results from the conflicting phenomenon of encephalized infants passing through the pelvis of a bipedally-adapted mother, ii] contrasting selection for bipedality and obstetrics limits locomotive efficiency in females, and iii] contrasting selection on infants for altriciality for obstetrical success versus precociality for the sake of clinging to the mother) have yet to be fully substantiated via empirical data and yet remain supported by anthropologists.

The size and shape of the pelvis are crucial in understanding the OD. Pelvic morphology is influenced by genetics and environment (e.g. nutrition, health, and latitude; Vraneš and Radoš 2014). Female pelvic size is influenced not only by genotype but also by nutrition and health. For example, Vraneš and Radoš (2014) documented an increase in external pelvic dimensions in Croatian women from the

1992-1994 period to the 2007-2009 period but noted no pelvic increase from the 1985-1986 period to the 1992-1994 period. Stress, nutrition, and reduced accessibility to healthcare prior to and during the Croatian Homeland War (1991-1995) likely caused stunting in pelvic growth. Further evidence of population specific pelvic variation is exemplified by Kurki and Decrausaz's (2016) study where they used multivariate analyses and found female canal shape variability was population specific while male pelvic variability was not. Consequently, the pelvis is influenced by a multitude of factors which results in population specific trends between the sexes.

Heritability studies affirm positive correlations of mother's head size with her pelvic size and infant's head size (Sharma 2002, Smit et al. 2010). Covariation among head size, pelvic inlet shape, as well as stature is argued to have evolved as an obstetric advantage to ease the tight fit of childbirth (Fischer and Mitteroecker 2015). If females are evolutionarily equipped with a wider pelvis based on craniometric heritability, this has implications on pelvic biomechanics and energy expenditure. A larger bi-iliac diameter and smaller bi-acetabular diameter are linked to efficient bipedal locomotion (Lovejoy 2005, Rosenberg 1988). If bi-acetabular diameter increases as an obstetric advantage, an increase in femoral neck length should develop concomitantly to maintain equivalent locomotor efficiency. A larger bi-acetabular diameter increases the required muscle force in maintaining equilibrium of the pelvis during the single support phase of stride, but that increase in muscle force can be countered by a corresponding increase in femoral neck length (Ruff 1995). This study tests the

hypothesis that individuals with larger cranial circumferences have wider pelves, specifically larger bi-acetabular diameters, and, in turn, longer femoral necks.

Chapter 2. The Human Pelvis

2.1. Mechanics of Locomotion

Variables important in understanding postural stability and the mechanics of bipedal gait are ground reaction force (GRF), distance between center of body mass and hip joint (R), distance between hip joint and hip abductor muscles (r), and the force of hip abductor muscles (F_m) (Fig. 1). Ground reaction force refers to body weight and the opposite, yet equal force exerted by the ground on the body. During normal, striding bipedal gait, humans balance their center of gravity on a single supporting limb. Gravity acts to draw the body's center of mass downward and causes the pelvis to tilt toward the unsupported side, while pelvic musculature exerts an opposing force on the pelvis to counter pelvic tilt. Newtonian principles can be applied to predict hip abductor muscular force required for stabilization of the hip during single leg stance (Saunders et al. 1953, Warrener 2011). When an individual is supported on one leg during walking, pelvic stability requires that $(GRF \times R) = (r \times F_m)$. Stabilization of the pelvis during the single leg stance while walking is the most widely used model in hip biomechanics (Warrener 2011).

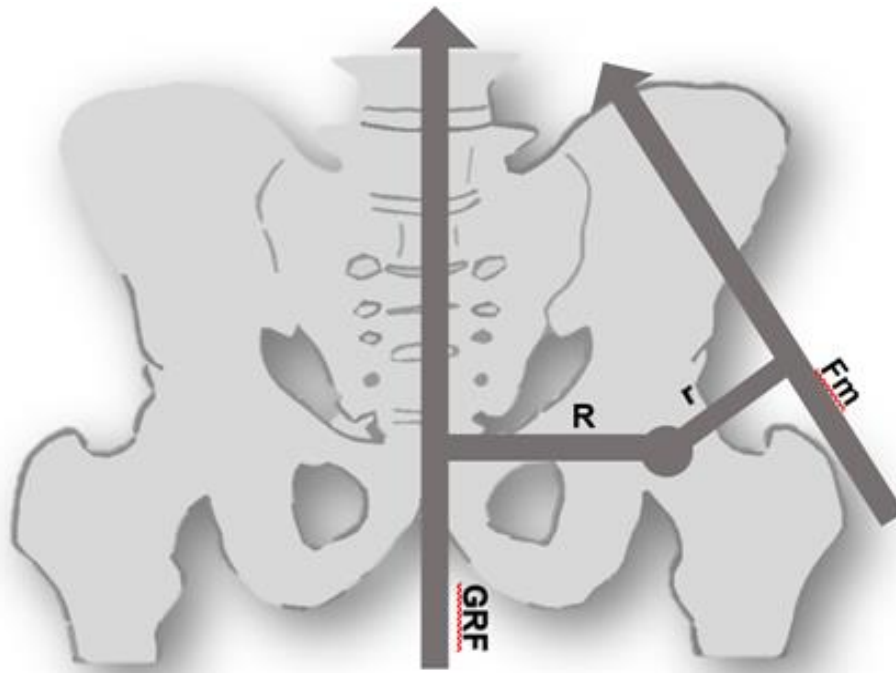


Figure 1. Free body diagram of the pelvis. GRF = ground reaction force; R = distance between center of body mass and hip joint; r = distance between hip joint and hip abductor muscles; Fm= force of hip abductor muscles.

The ratio of the muscle arm (r) and the GRF moment arm (R) is also known as the effective mechanical advantage (EMA). Changes in EMA affect the muscle force required during normal walking and running. Smaller EMAs indicate an increased demand on active muscles and increased metabolic rates. The evolutionary adapted widened hips of females mean a greater bi-acetabular diameter, which correspondingly suggests reduced EMA, increased muscle force, and consequently increased metabolic rate (Kipp et al. 2018, Warrener 2011). EMA can be determined statically and dynamically. Warrener et al. (2015) calculated both static and dynamic EMA in males and females; results based on biomechanical statics yielded a significant difference

between the sexes while results based on biomechanical dynamics between the sexes were slight and significant. Dynamic changes in R (i.e., GRF may be positioned closer to the hip joint) during locomotion may modify the expected relationship between hip morphology and muscle mechanics (Warrener 2011).

Energy efficiency is a primary factor in the evolution of the human hip. Compared to animals of similar mass (such as ostriches and reindeer), the net energy cost of running and walking in humans is similar or lower (Rubenson et al. 2007). Pontzer et al. (2009) estimate early hominins experienced greater locomotor costs compared to modern humans based on the authors' locomotor cost model. The body's center of gravity during normal, striding gait follows a smooth undulating, sinusoidal curve of low amplitude in the plane of progression, thereby conserving energy. Saunders et al.'s (1953) determinants of gait (pelvic rotations, pelvic tilt, foot and knee mechanisms, and lateral displacement of the pelvis) follow the least energetic path. Morphological changes of the pelvis have been thought to be the effects of natural selection, but Grabowski and Roseman (2015) conclude pelvic evolution is more complex than that. Whereas there may be a mosaic of selection pressure on a suite of pelvic traits, there may be broader change among pelvic traits not directly subject to selection due to correlated responses. For example, bi-acetabular breadth increased considerably from the A.L. 288-1 (*Australopithecus afarensis*) pelvis to the SH Pelvis 1 (*Homo heidelbergensis*) yet decreased considerably from SH Pelvis 1 to the modern human

pelvis. Grabowski and Roseman (2015) argue that this change was not due to strong selective pressure but to a correlated response to selective change in bi-iliac breadth.

The position of the hip abductor muscles' insertion site affects hip biomechanics and gait by controlling motion of the femur relative to the hip. The greater trochanter of the femur is the insertion point for hip abductor muscles: gluteus minimus and gluteus medius. These two gluteal muscles along with the tensor fascia lata function integratively to control pelvic tilt during single leg support in walking and running (Warrener 2011). This study extrapolates on the aforementioned pelvic stabilization equation ($GRF \times R = F_m \times r$) and defines "R" as half of the bi-acetabular diameter and "r" as the femoral neck length to approximate static measurements. Based on the static model, hip abductor muscle force is a result of GRF and EMA. The skeletal EMA (ratio of femoral neck length and half the bi-acetabular diameter) measurements discussed here are interpreted as an estimate of locomotive economy. If larger cranial sizes correlate to larger pelvic dimensions, in general, one could postulate "r" would be larger as well for the sake of continued locomotive efficiency.

2.2. Reconsidering the Obstetrical Dilemma

Washburn (1960) presented the OD with the following interdependent presumptions: i] traumatic human childbirths are to be expected due to encephalized infants being birthed by bipedally-adapted mothers, ii] a sufficiently wide birth canal hinders locomotive efficiency, and iii] contradicting requirement of the fetus being small enough to pass through the birth canal yet be cognitively advanced enough to cling to

its mother after birth. Infant altriciality is a consequence of the limited size of the female pelvis. The OD has become canon in biological anthropology, evolution, medicine, anatomy, and beyond. Harvey Karp, a pediatrician and founder of the “Happiest Baby” enterprise, uses OD thinking when he advises parents to treat infants like fetuses because human infants are born too early (Karp 2018). Beyond academia, OD thinking is demonstrated in the lyrics of Father John Misty’s 2017 “Pure Comedy” album:

The comedy of man starts like this:
Our brains are way too big for our mother’s hips
So, nature, she devised this alternative:
We emerge half-formed and hope whoever greets us on the other end
Is kind enough
To fill us in
And, babies, that’s pretty much how it’s been ever since.

OD logic is persuasive, and it addresses parturition difficulty commonsensically. Critical reviews of the OD have been done in recent decades and are summarized here. The first tenet defines the OD as the result of encephalization and bipedal adaptation; but when did this conflict occur? By DeSilva’s (2011) estimation, *Australopithecus afarensis* and *Au. africanus* had slightly larger neonates for their body size, compared to chimpanzee values. However, specimens included in DeSilva’s work are not from mother-infant dyads. Kibii et al.’s (2011) assessment of *Au. sediba* (dating to approximately 2-1.8 million years ago) revealed shared features with *Homo* including more vertically oriented and sigmoid shaped iliac blades, greater robusticity of the iliac body, sinusoidal anterior iliac borders, shortened ischia, and more superiorly oriented pubic rami. These traits appear although fossil evidence of *Au. sediba* adults shows a

smaller cranial capacity compared to earlier hominins, indicating that these pelvic anatomies did not manifest out of obstetrical necessity. *Au. sediba* may have adapted morphological traits which are suggestive of birthing encephalized infants before large-brained infants occurred, meaning the capacity to birth large or large-brained infants developed before large or large-brained infants did. Our primate cousins, chimpanzees, would experience the same scenario if neonates were to become more encephalized or larger, overall, at birth because chimpanzee pelvic morphologies are capacious enough to handle even larger infants (Dunsworth and Eccleston 2015). Also, a tight fit through the birth canal is not reserved for modern *Homo*. Other primates experience tight fits between infants and the birth canal such as *Ateles*, *Hylobates*, *Macaca*, and *Nasalis* (Rosenberg and Trevathan 1995).

Contrasting with the second tenet, Warrener et al. (2015) found no significant difference in females' and males' locomotive economy. They compared locomotor costs between the sexes using metabolic, kinematic, kinetic, and magnetic resonance imaging data. Their results showed slight significant differences between females' and males' anatomical EMA (based on the static biomechanical model) and locomotor EMA (defined as dynamic measurements calculated during walking and running). Differences were attributed to shorter hip abductor moment arms (r) in females compared to males and not pelvic width (Warrener et al. 2015).

The third tenet states the obstetric limitations of female pelvis alter gestation length; but compared to other primates, humans do not have an unusual gestation

length. The great apes have the longest gestation lengths of all nonhuman primates, ranging between 30-39 weeks (Dunsworth 2018). The gestation length for humans ranges between 39-42 weeks, only a few weeks longer than great apes. Dunsworth (2018) summarizes some birth-related traits unique to humans compared to other primates, including: i] longest pregnancies, ii] fattest babies (Kuzawa 1998), and iii] largest brains at birth. Also, biochemical processes determine the timing of childbirth and the degree in which mothers invest in their infants. Dunsworth et al. (2012) present the energetics of gestation and fetal growth hypothesis which posits that the end of gestation is triggered when pregnancy reaches a critical point. By the third trimester, the energetic demands of the fetus push the mother's metabolic ceiling, likely initiating labor (Dunsworth et al. 2012). The OD insists neonatal head size is constrained by the bipedally adapted pelvis, but Dunsworth et al. (2012) argue fetal growth is limited by maternal metabolism.

2.3. Evolution of Human Obstetrics

Currently, the earliest hominin ancestor exhibiting evidence of bipedality is *Sahelanthropus tchadensis* (dating to 6-7 million years ago) based on cranial morphology (Brunet et al. 2002, Zollikofer et al. 2005). *Ardipithecus ramidus* (dating to 4.4 million years ago) is the first to exhibit bipedality based on pelvic remains (Lovejoy et al. 2009). Another early representation of an adult hominin pelvis belongs to a 3.2 million-year-old female *Au. afarensis* specimen known as A.L. 288-1 (commonly referred to as Lucy). This specimen showed adaptations to bipedality but lacked

“obstetric specializations” (Simpson et al. 2008, p. 1089). Lovejoy (2005) concluded that the broad, lowered, and laterally flared ilium in A.L. 288-1 indicates hip abductors were capable of managing the single leg support phase characteristic of bipedality and the relatively long femoral neck permitted a greater EMA—exceeding that of *Homo sapiens*. A relatively longer femoral neck in *Au. afarensis* would structurally alleviate locomotive fatigue. The shape of the A.L. 288-1 pelvis implies that bipedality was the strongest influence on pelvic morphology. The pelvis’ platypelloid shape was not ideal for childbirth based on the shortened anteroposterior axes, but Tague and Lovejoy (1986, p. 250) state “with cephalic asynclitism and pelvic ligamentous relaxation, fetal descent should not have been obstructed”.

Increased encephalization began around 2.3 million years ago in *Paranthropus boisei*, approximately 2.1 million years after initial bipedal adaptations of the pelvis. With the exception of *P. boisei* and *P. robustus*, all archaic non-*Homo* hominins have a cranial capacity similar to *Pan troglodytes* (282-454 cc) (Robson and Wood 2008, Schoenemann 2013). Cranial enlargement continued in *Homo habilis* (640 cc), the earliest known species of *Homo*, circa 2.4 million years ago (Kimbel et al. 1998). By the early Pleistocene, *H. erectus* attained the largest cranial capacity (~1,200 cc) compared to that of its hominin predecessors, making it plausible that large-brained infants prompted pelvic morphological changes. This inference is supported by Simpson et al.’s (2008) assessment of an adult female *H. erectus* pelvis. They assert BSN49/P27 exhibits an obstetrical advantage based on the pelvis’ capacious similarities to modern

human female ranges. See Table 1 for summary information of early hominin cranial capacities.

Table 1. Early hominins' cranial capacities.

Taxa	Cranial Capacity (cc)	Age (mya)
<i>Sahelanthropus tchadensis</i>	~365 ¹	7.0-6.0
<i>Ardipithecus ramidus</i>	~300 ²	4.4
<i>Australopithecus afarensis</i>	400-550 ³	3.7-3.2
<i>Kenyanthropus platyops</i>	400-450 ¹	3.5-3.3
<i>Australopithecus africanus</i>	440-515 ³	3.1-2.5
<i>Australopithecus sediba</i>	~420 ³	2.0
<i>Australopithecus garhi</i>	~450 ³	2.5
<i>Paranthropus aethiopicus</i>	~410 ⁴	2.7-2.3
<i>Paranthropus boisei</i>	~513 ⁵	2.3-1.2
<i>Paranthropus robustus</i>	~530 ⁵	2.0-1.0
<i>Homo habilis</i>	~640 ⁵	2.1-1.5
<i>Homo rudolfensis</i>	650-675 ⁵	2.5-1.8
<i>Homo erectus</i>	600-1,200 ⁶	1.8-0.8
<i>Homo heidelbergensis</i>	900-1,300 ⁷	0.6-0.4
(table cont'd.)		

¹ Schoeneman (2013)

² Simpson (2013)

³ Hammond and Ward (2013)

⁴ Wood and Schroer (2013)

⁵ Schrenk (2013)

⁶ Antón (2013); *H. ergaster* is included with *H. erectus*, following the author.

⁷ Hublin (2013)

Taxa	Cranial Capacity (cc)	Age (mya)
<i>Homo neanderthalensis</i>	~1,520 ⁸	0.2-0.03
<i>Homo sapiens</i>	1,435 ⁹	0.19-present

2.4. Obstetric Advantage

Fischer and Mitteroecker (2015) found correlations among stature, pelvic shape, and head size indicating associated selective pressures on each variable. Their study revealed that individuals with a smaller head have a more oval pelvic inlet (larger ratio of anteroposterior diameter to transverse diameter) on average in both sexes. Taller individuals also have a more oval pelvic inlet shape compared to shorter individuals who tend to have a rounder pelvic inlet shape. Owing to the OD theory, female variability should be limited due to stabilizing selection, but Tague (1989) found no significant or systematic differences in variation of pelvic dimensions between females and males. Pelvic allometry—the association between body size (e.g. stature) and pelvic size—can explain sexual dimorphism to a certain extent. Fischer and Mitteroecker (2017) determined pelvic size is correlated with stature in both sexes, but some traits are largely non-allometric, i.e. size of the acetabulum, distance between the acetabulae, and the subpubic angle. Stature is a well-known factor associated with cephalopelvic

⁸ Harvati-Papatheodorou (2013)

⁹ Collard and Dembo (2013); estimate based on Omo II specimen.

disproportion. Shorter females are more susceptible to a difficult childbirth compared to taller females due to smaller pelvic dimensions (Stulp et al. 2011).

Explanations for childbirth difficulty are abundant and mostly involve dogma established by the OD. As the pelvis is multi-adapted to bipedality and obstetrics, the covariation among stature, pelvic dimensions, and cranial size has consequent implications on bipedality. If a larger cranium leads to a wider pelvis (interpreted as a larger bi-acetabular diameter), a longer femoral neck is necessary in order to preserve locomotor economy. To investigate the notion of an obstetric advantage, this study compares cranial circumference to pelvic and femoral variables.

Chapter 3. Materials and Methods

This study investigates correlations among cranial size, pelvic size, and femoral neck length in a recent skeletal sample from the 20th century of 49 females and 51 males housed at the Sam Houston State University's Applied Anatomical Research Center. The sample consists of individuals between the ages of 18-60 years with females having a mean age of 55.43 years and males having a mean age of 54.35 years. Three females reported no affiliated ethnicity but 5 out of the 49 females were of non-European descent (2 Asian Americans, 2 Hispanic Americans, and 1 Native American). Four males reported no affiliated ethnicity but 4 of the 51 males were of non-European descent (1 Asian American, 1 Hispanic American, and 2 African Americans). Remaining individuals were of European descent. Measurements include cranial circumference which encompassed the widest points in the sagittal and coronal planes. The pelvis was rearticulated using masking tape and rubber bands to obtain metrics. No adjustments were made for the missing symphyseal disk. Pelvic metrics included anteroposterior diameters of the pelvic inlet, midplane, and outlet, as well as a transverse diameter of the pelvic inlet, bi-iliac diameter, bi-acetabular diameter, femoral head circumference, femoral length and femoral neck length. See Table 2 for definitions of each variable. Femoral metrics were averaged when both the right and left elements were available, but if that was not possible only one side was used.

Linear measurements were taken with sliding and spreading calipers and an osteometric board, and circumferences were taken with a cloth measuring tape. Three

variables were computed: i] pelvic inlet shape defined as the ratio of the anteroposterior diameter of pelvic inlet and transverse diameter of pelvic inlet, ii] lateral iliac flare defined as the difference between bi-iliac diameter and bi-acetabular diameter, and iii] skeletal EMA defined as the ratio of the femoral neck and half of the bi-acetabular diameter. Student's t-tests and correlation coefficients were determined by SAS (Statistical Analysis Software). The t-tests were used to identify sexual dimorphism between the sexes for each variable and correlation coefficients were computed to assess the strength of association of cranial circumference with pelvic and femoral variables as well as femoral length, femoral neck length, and lateral iliac flare with pelvic variables. Instrumentally determined measurements were repeated on one individual on three occasions and intra-observer error for each variable was a mean of 1.31% with a range of 0.24% and 2.28%. Statistical significance was set at $P \leq 0.05$.

Table 2. Skeletal variables with definitions and referenced sources.

Measured Variables	Description	Reference
Bi-iliac diameter	Distance between the most lateral points of the right and left iliac tubercles.	Tague 1989
Bi-acetabular diameter	Distance between the midpoints of both acetabulae (i.e., between the midpoints of the anteroposterior and superinferior diameters of the acetabulae on their posteromedial walls).	Ruff 1995
Pelvic inlet (transverse)	Distance between the linea terminales visualized in the transverse plane and perpendicular to the anteroposterior diameter.	Adapted from Tague 1989
(table cont'd.)		

Measured Variables	Description	Reference
Pelvic inlet (anterioposterior)	Distance from the sacral promontory to dorsomedial aspect of the superior border of the pubic symphysis.	Fischer and Mitteroecker 2015
Pelvic midplane (anterioposterior)	Distance from the sacral promontory to the dorsomedial aspect of the inferior border of the pubic symphysis.	
Pelvic outlet (anterioposterior)	Distance from the apex of the 5 th sacral vertebra to the dorsomedial aspect of the inferior border of the pubis.	Tague 1989
Femoral neck length	Mediolateral distance from the most superior aspect of the femoral head to the most lateral projection of the greater trochanter.	Lovejoy et al. 1973
Femoral head circumference	Maximum circumference around the femoral head.	
Femoral length	Maximum length.	
Cranial circumference	Maximum circumference encompassing the widest points in the sagittal and coronal planes. Widest points instrumentally determined with calipers.	
Computed Variables		
Lateral iliac flare	Difference between bi-iliac and bi-acetabular diameters.	
Skeletal effective mechanical advantage	Ratio of the femoral neck length and half of the bi-acetabular diameter.	
Pelvic inlet shape	Ratio of the anteroposterior pelvic inlet diameter to transverse pelvic inlet diameter.	Fischer and Mitteroecker 2015

Chapter 4. Results

Males exhibited significantly larger dimensions than females, specifically in cranial circumference, femoral neck length, femoral head circumference, femoral length, skeletal EMA, and lateral iliac flare. Nonsignificant differences presented in the following variables: bi-iliac diameter, bi-acetabular diameter, transverse pelvic inlet, pelvic inlet shape, and anteroposterior diameters of the pelvic inlet, midplane, and outlet (Table 3). Results show statistically significant correlations between females' cranial circumference and the anteroposterior diameters of the pelvic inlet ($r = 0.425$, $P = 0.002$) and midplane ($r = 0.290$, $P = 0.043$). In males, correlation coefficients were statistically significant between cranial circumference and bi-iliac diameter ($r = 0.379$, $P = 0.006$) and lateral flare of the ilium ($r = 0.333$, $P = 0.017$). All other cranial circumference correlation coefficients were not significantly different from zero (Table 4).

Female correlation coefficients between femoral length and variables of the pelvis were significant in the following: bi-iliac diameter ($r = 0.553$, $P = <0.001$), bi-acetabular diameter ($r = 0.564$, $P = <0.001$), transverse pelvic inlet ($r = 0.460$, $P = 0.001$), and the anteroposterior diameters of the pelvic inlet ($r = 0.418$, $P = 0.004$) and midplane ($r = 0.288$, $P = 0.044$); significant correlations also appeared between femoral neck length and bi-acetabular diameter ($r = 0.316$, $P = 0.029$) as well as lateral iliac flare and transverse pelvic inlet ($r = 0.335$, $P = 0.020$). Nonsignificant correlations for females were between femoral length and the anteroposterior pelvic outlet and

pelvic inlet shape. Males exhibited significant correlations between femoral length and the same pelvic variables as females, i.e. bi-iliac diameter ($r = 0.488$, $P = <0.001$), bi-acetabular diameter ($r = 0.331$, $P = 0.018$), transverse pelvic inlet ($r = 0.454$, $P = <0.001$), and the anteroposterior diameters of the pelvic inlet ($r = 0.326$, $P = 0.020$) and midplane ($r = 0.340$, $P = 0.015$). The correlation between male lateral iliac flare and transverse pelvic inlet was $r = 0.436$ and significant, $P = 0.001$, as seen in females. Males had nonsignificant correlations for femoral length with anteroposterior pelvic outlet and pelvic inlet shape, as well as with femoral neck length and bi-acetabular diameter (Table 5).

Table 3. Summary statistics and results of t-tests between females' and males' mean values in centimeters; σ = standard deviation, ns = not significant.

Measured Variables	Females		Males		P value
	\bar{X}	σ	\bar{X}	σ	
Bi-iliac Diameter	27.258	1.689	27.360	1.744	ns
Bi-acetabular Diameter	12.900	0.777	12.269	0.664	ns
Transverse Pelvic Inlet	13.023	0.816	12.319	0.663	ns
Anteroposterior Pelvic Inlet	11.877	0.783	11.247	0.890	ns
Anteroposterior Pelvic Midplane	13.125	1.150	13.022	0.899	ns
Anteroposterior Pelvic Outlet	12.149	1.039	11.083	2.373	ns
(table cont'd.)					

Measured Variables	Females		Males		
	\bar{X}	σ	\bar{X}	σ	P value
Femoral Head Circumference	13.601	0.757	15.301	0.691	<0.001
Femoral Neck Length	4.530	0.411	4.897	0.827	<0.001
Femoral Length	43.699	2.233	47.597	2.968	<0.001
Cranial Circumference	50.452	1.458	52.952	1.327	<0.001
Computed Variables					
Lateral Iliac Flare	14.321	1.369	15.092	1.559	0.011
Skeletal Effective Mechanical Advantage	0.704	0.064	0.800	0.076	<0.001
Pelvic Inlet Shape	0.890	0.078	0.914	0.066	ns

Table 4. Correlation coefficients between females' and males' cranial circumference with pelvic and femoral variables and indices¹⁰.

Measured Variables	Females		Males	
	Correlation Coefficient (<i>r</i>)	P value	Correlation Coefficient (<i>r</i>)	P value
Bi-iliac Diameter	0.181	ns	0.379	0.006
Bi-acetabular Diameter	0.014	ns	0.208	ns
Transverse Pelvic Inlet	-0.049	ns	0.114	ns
Anteroposterior Pelvic Inlet	0.425	0.002	0.181	ns
Anteroposterior Pelvic Midplane	0.290	0.043	0.071	ns
Anteroposterior Pelvic Outlet	-0.039	ns	0.104	ns
Femoral Head Circumference	0.247	ns	0.153	ns
Femoral Neck Length	0.059	ns	0.111	ns
(table cont'd.)				

¹⁰ ns = not significant.

Computed Variables	Females		Males	
	Correlation Coefficient (<i>r</i>)	P value	Correlation Coefficient (<i>r</i>)	P value
Lateral Iliac Flare	0.012	ns	0.333	0.017
Skeletal Effective Mechanical Advantage	-0.095	ns	-0.096	ns
Pelvic Inlet Shape	0.067	ns	0.110	ns

Table 5. Correlation coefficients among femoral and pelvio-metric variables as well as indices for females and males¹¹.

Variables		Females		Males	
		Correlation Coefficient (<i>r</i>)	P Value	Correlation Coefficient (<i>r</i>)	P Value
Femoral Length	Bi-iliac Diameter	0.553	<0.001	0.488	<0.001
	Bi-acetabular Diameter	0.564	<0.001	0.331	0.018
	Transverse Pelvic Inlet	0.460	0.001	0.454	<0.001
	Anteroposterior Pelvic Inlet	0.418	0.004	0.326	0.020
	Anteroposterior Pelvic Midplane	0.288	0.044	0.340	0.015
	Anteroposterior Pelvic Outlet	0.139	ns	0.130	ns
	Pelvic Inlet Shape	-0.203	ns	0.100	ns
Femoral Neck Length	Bi-acetabular Diameter	0.316	0.029	0.263	ns
(table cont'd.)					

¹¹ ns = not significant.

		Females		Males	
Variables		Correlation Coefficient (<i>r</i>)	P value	Correlation Coefficient (<i>r</i>)	P value
Lateral Iliac Flare	Transverse Pelvic Inlet	0.335	0.020	0.436	0.001

Chapter 5. Discussion

Fischer and Mitteroecker (2015) showed a positive correlation among pelvic shape, head size, and stature in both sexes. This study shows statistically significant correlations between cranial circumference and the anterioposterior diameter of the pelvic inlet and midplane for females as well as bi-iliac diameter and lateral flare of the ilium for males. Pelvic inlet shape was not significantly different between the sexes, unlike the results discussed by Fischer and Mitteroecker (2015). Results of this study also differed from Fischer and Mitteroecker (2015) when relating pelvic inlet shape to stature and pelvic inlet shape to cranial circumference. No significant correlation presented in either sex between pelvic inlet shape and femoral length (as a skeletal correlate of stature) nor pelvic inlet shape and cranial circumference.

This study tested whether individuals with a larger cranial circumference possessed larger pelves, specifically wider bi-acetabular diameter, and correspondingly longer femoral necks. While the anterioposterior diameters of the pelvic inlet and midplane of the pelvis are significantly, positively correlated with cranial circumference in females, there was no concomitant association between cranial circumference and pelvic inlet shape nor femoral neck length. Therefore, the proposed hypothesis fails to be supported based on the results for this sample.

The lack of sex differences in bi-iliac diameter, bi-acetabular diameter, transverse pelvic inlet, and anterioposterior diameters of the pelvic inlet, midplane, and outlet could be a result of selection on female pelvic canal size and variance affecting males via

genetic correlation (Kurki and Decrausaz 2016). After the onset of menopause in females, pelvic morphology becomes more masculine due to the decreased concentration of estrogen. According to Huseynov et al. (2016), females and males experience similar developmental trajectories in the pelvis before puberty and after age 40. Femoral length correlations with pelvio-metrics in Table 5 further exemplify this point as the mean female age is 55.43 years and both sexes have significant correlations in similar variables. Nonsignificant sexual dimorphism in these variables (bi-iliac diameter, bi-acetabular diameter, transverse pelvic inlet, and anterioposterior diameters of the pelvic inlet, midplane, and outlet) is documented for some populations - but significant differences are also reported (Brown 2015, Kurki 2013a, Tague 1992, Warrener et al. 2015). Bi-iliac diameter can be larger in males or females, depending on the population (Kurki 2013a). Differing results among populations for pelvic sexual dimorphism could be due to populational differences in sexual dimorphism in femoral length (or, more generally, in body size). For example, this study, Tague (2000), and Kurki (2013b) report a significant, positive association between femoral length and anterioposterior diameter of the pelvic inlet in both females and males. Therefore, the greater magnitude of sexual dimorphism in femoral length, with males larger than females, the lesser the magnitude of sexual dimorphism in the anterioposterior diameter of the pelvic inlet. Correspondingly, Tague (2000) reported significant, positive correlations between femoral head diameter and bi-iliac diameter, transverse diameter of the pelvic inlet, and anterioposterior diameters of the pelvic midplane and outlet. As with the anterioposterior

diameter of the pelvic inlet, the greater the magnitude of sexual dimorphism in femoral head diameter (or circumference, this study), with males larger than females, the lesser the sexual dimorphism in pelvio-metrics. Another explanation for the absence of pelvic sexual dimorphism seen in this study is that the hormone relaxin, which is secreted during pregnancy, permits malleability in pelvic dimensions during childbirth, converting an obstetrically insufficient pelvis into one apt for parturition (Tague 1992).

As discussed above, individuals with longer femora (and, by inference, taller stature) exhibit larger dimensions in specific pelvic variables. Table 5 shows femoral length is significantly, positively correlated to similar pelvio-metric variables between the sexes (bi-iliac diameter, bi-acetabular diameter, transverse pelvic inlet, and the anteroposterior diameter of the pelvic inlet and midplane). Furthermore, the anteroposterior aspects of the pelvic inlet and midplane positively correlate to cranial circumference in females. Understanding this relationship among stature, cranium and the pelvis begins with describing the rotation of the fetus through the birth canal. Tague (2000) explains that fetal rotation places the back of the head toward the anterior portion of the pelvic cavity. If the anterior portion of the pelvic midplane is constrained in dimension, fetal rotation reverses the back of the fetus' head toward the posterior. During childbirth, the fetus rotates approximately 45-90 degrees at the midplane. The posterior portion of the pelvic cavity requires substantial space for fetal decent (Tague 2000). Hormonal relaxation of ligaments enlarges the anteroposterior pelvic outlet by approximately 10-20% and the transverse pelvic outlet by only 5-7% (Russell 1969). In

short, stature and cranial circumference significantly influence the anteroposterior plane of the pelvic inlet and midplane in females, variables important for fetal descent through the canal.

A logical assumption is that as one pelvic variable increased in breadth, the entire pelvis would increase overall. If this were to occur, selection for bipedalism would necessitate some accommodating changes to alleviate the energetic strain of a large ground reaction force moment arm (interpreted as 'R' or half of the bi-acetabular diameter) similar to what is described by Ruff's (1995) biomechanical analysis of early hominins. He noticed *H. erectus* specimens had relatively large bi-acetabular diameters and femoral neck lengths compared to other hominins. Increasing bi-acetabular breadth along with the femoral neck length maintains gluteal abductor and hip joint forces at more "normal" levels (i.e. energetically efficient levels) (Ruff 1995, p. 527). A significant correlation between (female) bi-acetabular diameter and femoral neck is documented in this study. According to Kurki and Decrausaz (2016), obstetric selection may conserve shape variability by expanding the canal in some dimensions and reducing in other dimensions. This evolutionary adaptation explains the lack of concomitant correlation among female cranial circumference, bi-acetabular diameter, and femoral neck length, making an obstetrically advantaged pelvis simultaneously accommodating to bipedalism.

For males, cranial circumference correlates to elements tailored to efficient locomotion (bi-iliac diameter and lateral iliac flare). The ilium serves as the origin of the

lesser gluteal muscles (medius and minimus), while the greater trochanter of the femur serves as the insertion area for the same muscles. Individuals with a more flared ilium have these muscles farther from the acetabulum than a less flared pelvis (Lovejoy et al. 1973). Increased bi-iliac diameter increases the hip's muscle moment arm which counters torque created by body mass and larger bi-acetabular distance when combined with gluteal muscle force (Ruff 1995). This tailoring to bipedalism also has some obstetric significance. Lateral iliac flare positively correlates to increased pelvic inlet diameter in the transverse plane (Tague and Lovejoy 1986). Results in Table 5 support this relationship for both sexes.

Obstetric selection implies a potential stabilizing effect on the pelvic inlet, yet Kurki (2013b) found the opposite to be true. Specifically, Kurki (2013b) observed no significant difference in variation in the noncanal pelvis between the sexes but the pelvic canal was more variable compared to the noncanal pelvis in both sexes. Also, pelvic canal shape variability in females was more interrelated than males, specifically each female pelvis-metric displayed a high coefficient of variation compared to males (Kurki 2013b). While under the influence of diverse selective pressures, the human pelvis retains a significant degree of morphological plasticity. A morphologically variable pelvis digresses from the basic dogma of the OD.

The assumption underlying this study is that the female pelvis is less adapted to bipedalism compared to the male pelvis due to obstetric adaptations. However, there was no statistically significant difference between females and males for bi-iliac

diameter or bi-acetabular diameter indicating skeletal EMA in females is not compromised by obstetrics. As the position of gluteal abductor muscles is dependent on bi-iliac and bi-acetabular diameters, the nonsignificant sex difference in these variables refutes the OD assertion of deficient female locomotor economy. It is possible males are subject to just as high selective pressures as females.

Contrastingly, males exhibited a significantly greater skeletal EMA and lateral iliac flare than females. Longer femoral necks in males than females determined the significant difference seen in skeletal EMA, a result consistent with Warrener et al.'s 2015 study. A more mechanically efficient EMA is seen in males due to general body size (i.e. larger femoral neck lengths), although the significant difference between the sexes in femoral neck length and, consequently, EMA was not great enough to influence overall locomotor economy (Warrener et al. 2015). The larger lateral iliac flare seen in males is also explained by general body size. In this sample, average bi-iliac diameter is larger in males and average bi-acetabular diameter is larger in females comparatively, but no statistically significant difference presented between the sexes in these two variables. However, other studies have reported statistically significant differences in these variables (Warrener et al. 2015). Obstetric and bipedal adaptations effect overall pelvio-metrics, yet there is a differential response to selective pressures (also described by Brown 2015). This differential response results in a lower lateral iliac flare in females.

Pelvic shape is known to be a result of numerous selective pressures. Washburn (1960) explained these pressures through a priori assumptions when he proposed the OD. Differing selective pressures manifested differing modes of adaptation to bipedalism and obstetrics much like the mosaic Grabowski and Roseman (2015) discussed. The results in this study show no convincing evidence of significant deficient locomotive ability for females. Furthermore, the correlation between the anteroposterior pelvic dimensions with cranial circumference in females without corresponding sexual dimorphism in pelvic dimensions reiterates the assertion that females are equally adapted to bipedalism as males.

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