

# Bony Pelvic Canal Size and Shape in Relation to Body Proportionality in Humans

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**KEY WORDS** obstetric selection; pelvis; ecogeographic variation; body proportions; morphometric analysis

**ABSTRACT** Obstetric selection acts on the female pelvic canal to accommodate the human neonate and contributes to pelvic sexual dimorphism. There is a complex relationship between selection for obstetric sufficiency and for overall body size in humans. The relationship between selective pressures may differ among populations of different body sizes and proportions, as pelvic canal dimensions vary among populations. Size and shape of the pelvic canal in relation to body size and shape were examined using nine skeletal samples (total female  $n = 57$ ; male  $n = 84$ ) from diverse geographical regions. Pelvic, vertebral, and lower limb bone measurements were collected. Principal component analyses demonstrate pelvic canal size and shape differences among the samples. Male multivariate variance in pelvic shape is greater than female variance for North

and South Africans. High-latitude samples have larger and broader bodies, and pelvic canals of larger size and, among females, relatively broader medio-lateral dimensions relative to low-latitude samples, which tend to display relatively expanded inlet antero-posterior (A-P) and posterior canal dimensions. Differences in canal shape exist among samples that are not associated with latitude or body size, suggesting independence of some canal shape characteristics from body size and shape. The South Africans are distinctive with very narrow bodies and small pelvic inlets relative to an elongated lower canal in A-P and posterior lengths. Variation in pelvic canal geometry among populations is consistent with a high degree of evolvability in the human pelvis. *Am J Phys Anthropol* 151:88–101, 2013. © 2013 Wiley Periodicals, Inc.

Human childbirth is typically described as being unique owing to the relative size and “twisted” nature of the pelvic canal, and the relatively large neonate with respect of maternal canal dimensions (Rosenberg and Trevathan, 2002; Wittman and Wall, 2007). These features contribute to the difficult nature of human childbirth, and the risk of maternal or neonatal death or injury. Childbirth may be a significant selective event, and this obstetric selection is assumed to be responsible for sexual dimorphism of the pelvis, wherein the pelvic canal is relatively (for body size), and often absolutely, larger in human females compared to males, the opposite pattern to sexual dimorphism in overall body size (Schultz, 1949; Leutenegger, 1974; Wood and Chamberlain, 1986; Ridley, 1995; Kurki, 2007, 2011a). Others have argued that this dimorphism is the result of different allometric growth trajectories of females and males (Schultz, 1949; Tague, 2005; but see Kurki, 2011a).

The difficult childbirth of humans and the associated pelvic dimorphisms have been posited to result from obstetric demands conflicting with constraints on the morphology and size of the pelvis relating to the biomechanics of bipedalism (Berge et al., 1984; Rosenberg, 1992; Ruff, 1995) and thermoregulatory factors (Ruff, 1995, 2010; Weaver and Hublin, 2009). This “obstetric dilemma” (Washburn, 1960) has recently been questioned on biomechanical (Warrener, 2011; but see Whitcome et al., 2012) and energetic grounds (Dunsworth et al., 2012). Grabowski (2012) demonstrates that compared to those of other apes, the pelvic canal in humans is less integrated with other pelvic traits, ensuring that twice the amount of variation in the canal is available for selection to act on. Humans have a greater ability to respond to selection acting on the pelvis, and obstetric

traits have greater independence in their evolvability (Grabowski, 2012). Although these findings do not address which selective factors have acted on the hominin pelvis, they do suggest that human pelvic canal shape may be able to respond effectively to maintain obstetric sufficiency in the face of changes in body proportionality. Thus, pelvic geometry may vary significantly among populations subject to differing climatic and demographic selective pressures on body shape or size.

The purpose of this article is to examine the relationships between pelvic size and shape and body size and shape. Human body size and shape (proportionality) generally conform to ecogeographic expectations. That is, populations in colder climates tend to have larger body mass, broader bi-iliac breadths, and relatively foreshortened limbs (Ruff, 1994; Holliday, 1997; Holliday and

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Hilton, 2010). Small maternal body size, both stature and mass, has been implicated as a causal factor in difficult childbirth (Prasad and Al-Taher, 2002; Sheiner et al., 2005; Rozenholc et al., 2007). Although maternal and neonatal body size are related, in that larger mothers tend to give birth to larger neonates, many factors have been shown to influence this relationship including environmental exposures, paternal stature and body mass, maternal weight gain during pregnancy, maternal birthweight, and thermal stress (Wells, 2002; Wells and Cole, 2002; Emanuel et al., 2004; Demerath et al., 2007; Griffiths et al., 2007; Horta et al., 2009; Salmasi et al., 2010; Stulp et al., 2011). Phenotypic plasticity may further exacerbate the obstetric dilemma (Wells et al., 2012). The relationship between body size and bony pelvic capacity has been examined, with varying results. Femoral head size has shown a positive relationship with midplane medio-lateral (M-L) breadth in some studies (Walrath and Glantz, 1996), but not all (Tague, 2000); contradictory relationships between midplane breadth and femoral length were also found. Rosenberg (1988) demonstrated differential relationships between acetabulo-symphyseal length and body size in populations of varying body proportions (e.g., femoral length and head size). This implies that the disparity in the body size–midplane breadth relationships may be owing to the use of different samples, as well as methodological differences.

The complexity of the relationships among pelvic and body size attributes suggests that an examination of pelvic geometry using a population-comparison approach may be more informative. Kurki (2011b) showed that *across* populations, canal breadths of females are isometrically related to bi-iliac breadth and body mass (but not stature), whereas inlet antero-posterior (A-P) length is not related to body size. Canal A-P may be free to vary to protect overall pelvic canal size independent of body size. Kurki (2007) found that in the Later Stone Age foragers of southern Africa, characterized by low body mass and narrow bi-iliac breadth, pelvic canal size in females is not reduced in concert with body size in comparison with larger-bodied European females. Instead, pelvic canal shape differs with expansion of the lower canal in A-P and posterior dimensions to accommodate a narrow body. It is therefore problematic to equate small body size with a small pelvic canal. How then do human populations vary in pelvic geometry and capacity, and what factors influence this variation? Do other small-bodied populations share a similar pelvic shape to these South Africans? What influence does body shape, as reflected in body breadth, stature, body mass, and skeletal trunk height (STH) have on pelvic capacity and shape? These questions are addressed here through an examination of pelvic and body size and shape variation among nine human populations from diverse geographic regions. The intent is to examine how pelvic geometry and capacity may vary with body size and shape variation.

Our knowledge of the evolution of the hominin pelvis and childbirth process has increased significantly in recent years through discoveries of fossil hominin pelvic remains (Brown et al., 2004; Rosenberg et al., 2006; Simpson et al., 2008; Lovejoy et al., 2009; Kibii et al., 2011), and virtual reconstructions of fossil pelves and hominin childbirth (Ponce de Leon et al., 2008; Weaver and Hublin, 2009; DeSilva, 2011). Detailed understandings of the variation in pelvic geometry among human populations and the factors that produce this variation

have much to contribute to this discussion. The recognition of this variation in human pelvic geometry is of importance, given the persistence of typological approaches to obstetric risk assessment deriving from studies dating to the first half of the 20th Century (e.g., Caldwell and Moloy, 1938; Greulich and Thoms, 1938), and a mechanistic approach to childbirth in modern clinical practice (e.g., Cunningham and Williams, 2005; Gibbs et al., 2008; see also Walrath, 2003).

## MATERIALS AND METHODS

The samples used in this study are predominantly from archaeological contexts; therefore, sex was estimated from osteological features. Standard nonmetric pelvic characteristics (ventral arc, subpubic concavity, ischiopubic ramus ridge, subpubic angle, and greater sciatic notch) and when available, cranial characteristics (supraorbital margin, mastoid process, nuchal crest, prominence at glabella, and mental eminence) were used to assess sex (Buikstra and Ubelaker, 1994). The preponderance of features indicating female or male was taken in the assigning of sex to individual skeletons who presented with both female and male features. Error rates in sex assessment of 6.8% for pelvic features and 3% for pelvic and cranial features combined have been previously reported (Meindl et al., 1985). Only adult skeletons were included (i.e., with epiphyses of the iliac crest and ischial tuberosity showing some fusion).

Pelvic, long bone, and vertebral osteometric data were collected on nine skeletal samples representing diverse body size and shape characteristics and geographic regions (Table 1). The measurements collected quantify the size and shape of the pelvic canal, femoral and tibial lengths, femoral head size, and STH (Table 2 and Fig. 1). STH was calculated by summing the dorsal vertebral heights of the thoracic and lumbar vertebrae and ventral sacral length (Franciscus and Holliday, 1992; Holliday, 1997). Measurements on the articulated pelvis were taken with the left and right hip bones and sacrum articulated anatomically and bound together firmly with adhesive tape and elastic bands to prevent the bone slipping during measurement. No attempt was made to account for the cartilage components of the pubic symphysis and sacroiliac joints that would be present in the living individual. Sample sizes vary for the study variables owing to the variation in preservation conditions; not every skeleton preserved the necessary skeletal elements free of damage to enable the recording of each measurement. Missing measurements were not estimated, except in the case of missing vertebral elements necessary for the calculation of STH. Following Holliday (1997), for skeletons with incomplete vertebral columns STH was estimated using regression formula generated from a sample composed of all skeletons with complete vertebral columns (except those with extra thoracic or lumbar vertebrae). Kurki et al. (2008) found that using a mixed population sample for the generation of estimation formulae, versus a population-specific sample, had minimal effect on the estimation errors for STH. The percentage of individuals in each sample with missing vertebral elements ranges from 0 to 56% for the females and 29 to 50% for the males (Supporting Information Table S1). The regression formula and estimation error information (SEE and %SEE) for each combination of missing vertebral elements are provided in Supporting Information Table S2. SEE and %SEE for the estimation

TABLE 1. Details of skeletal samples included in this study

Sample	Date	Latitude	Female <i>n</i>	Male <i>n</i>	Institution <sup>a</sup>
African Pygmy	20th Century	2°S	6	6	IRSN, MdH, UG
Andaman Islands	Ca. 1860–1900	12°S	3	5	AMNH, DC, NHM
Philippines	19th Century	13°S	6	4	MdH
North Africa	2000 BC–AD 550	25°N	9	15	AMNH, DC, UCOP
Australia	19th Century	27°S	6	8	MdH, NHM, UG
South Africa	240–5370 BP ( <sup>14</sup> C) <sup>b</sup>	34°S	9	10	ALM, IMCT, NMB, UCT
Tierra del Fuego	Ca. 1880	53°S	6	11	MAE, MdH, UR
Denmark	Medieval	56°N	3	7	UCOP
Inuit	AD 800–1900	65°N	9	18	AMNH, CMC

<sup>a</sup> ALM, Albany Museum; AMNH, American Museum of Natural History; CMC, Canadian Museum of Civilization; MdH, Musée de l'Homme; DC, Duckworth Collection, University of Cambridge; IMCT, Iziko Museums of Cape Town; IRSN, Institut Royal des Sciences Naturelles de Belgique; MAE, Museo di Antropologia e Etnologia, Università degli Studi di Firenze; NHM, Natural History Museum; NMB, National Museum, Bloemfontein; UCOP, University of Copenhagen; UCT, University of Cape Town; UG, University of Geneva; UR, Museo de Antropologia, Università di Roma.

<sup>b</sup> Uncalibrated radiocarbon dates.

TABLE 2. Descriptions of measurements used in this study<sup>a</sup> (see also Fig. 1)

Measurement	Description
Femoral maximum length	Maximum length of the femur
Femoral bicondylar length	Physiological length of the femur, measured with condyles flat to stationary end of osteometric board
Tibial length	Maximum length including the spines, measured to the lateral condyle
Femoral head diameter	Maximum diameter of the femoral head
Dorsal vertebral height	Maximum height of the dorsal aspect of the vertebral body at the midline
Sacral ventral length	Straight distance on ventral side from sacral promontory to tip of S5
Bi-iliac Breadth	Maximum distance across the right and left iliac blades
Inlet A-P	Sacral promontory to dorsomedial superior pubis (A, Fig. 1)
Inlet M-L	Maximum distance between linea terminalis (B)
Inlet posterior	Curved length of linea terminalis from INML to apex of auricular surface (C)
Inlet anterior	Curved length of linea terminalis from INML to dorsomedial superior pubis (D)
Midplane A-P	From junction of 4th and 5th sacral vertebrae to dorsomedial inferior pubis (E)
Midplane M-L	Between ischial spines (F)
Midplane posterior	S4–S5 junction to ischial spine (G)
Midplane anterior	Ischial spine to dorsomedial inferior pubis (H)
Outlet A-P	Apex of fifth sacral vertebrae to dorsomedial inferior pubis (I)
Outlet M-L	Distance between inner margins of transverse ridge of ischial tuberosities (J)
Outlet posterior	Apex of S5 to transverse ridge of ischial tuberosity (K)
Outlet anterior	Transverse ridge of ischial tuberosity to dorsomedial inferior pubis (K)
Canal depth	Apex of auricular surface to transverse ridge of ischial tuberosity (M)

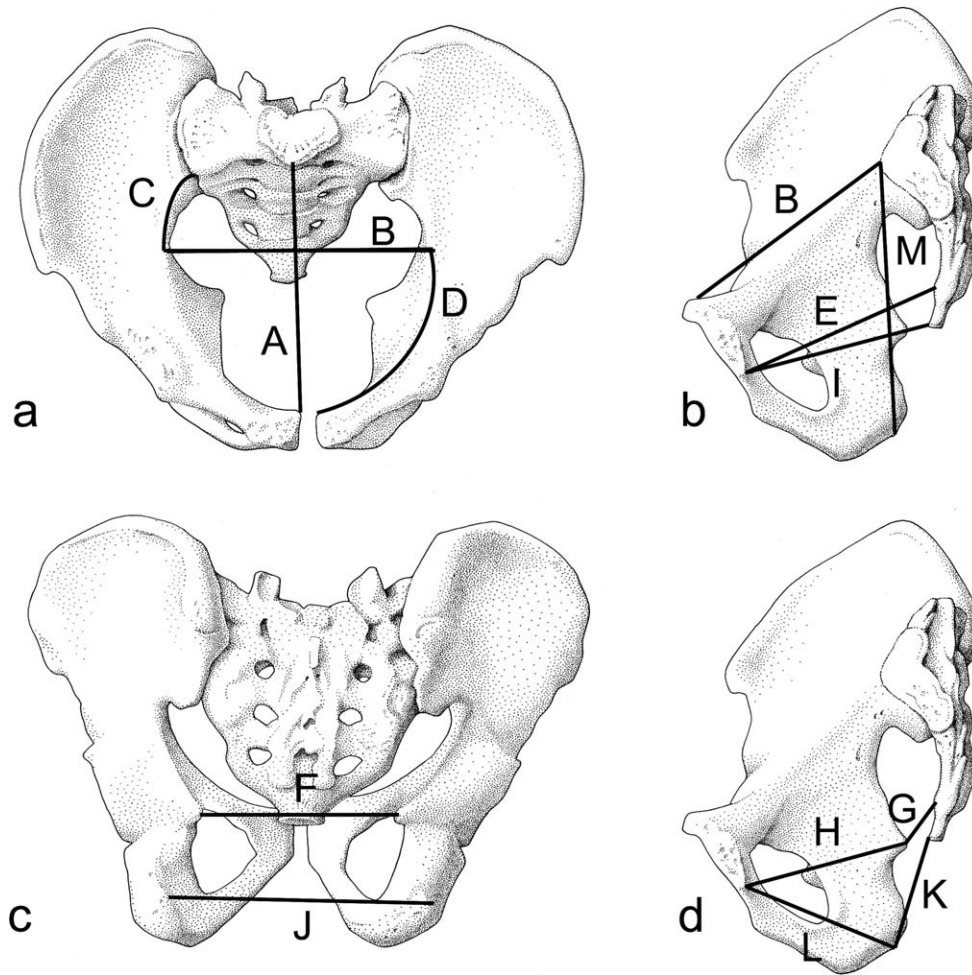
<sup>a</sup> Measurement definitions are from Tague (1989), Franciscus and Holliday (1992), and Buikstra and Ubelaker (1994).

formula range from 0.82 or 0.19% (T3 missing) to 8.20 or 1.86% (sacrum + T7 missing). Estimation of STH when the sacrum is missing results in the highest estimation error levels.

Body size is represented by reconstructed stature and body mass, and by bi-iliac breadth as a proxy for body breadth and STH as a proxy for trunk length (as a portion of overall stature). Stature was estimated using appropriate regression formula (Supporting Information Table S3) from the literature for each sample. All stature formula utilized femoral and tibial lengths, with two exceptions: 1) Allbrook's (1961) formula uses only tibial length and 2) Genoves' (1967) formula for Mexican Hispanics uses only femoral length. Some individuals in the North African (females, 1 out of 20; males, 3 out of 28) and Danish (females, 3 out of 10; males, 1 out of 9) samples are missing tibia; femora-only formula were used in these cases. A comparison (results not shown) of statures reconstructed using the tibia + femur and the femur-

only formula for these samples indicates no significant difference in the statures reconstructed from each formula. Body mass was calculated following Auerbach and Ruff (2004) using the average of three femoral head diameter<sup>1</sup> formulae (Ruff et al., 1991; McHenry, 1992; Grine et al., 1995) for all except the small-bodied samples—the Andaman Islands, African Pygmy, Philippine, and South African samples—for which only McHenry's (1992) formula was used (Supporting Information Table S3). Body mass can also be calculated based on the “morphometric” approach using stature and bi-iliac breadth (Ruff et al., 2005). Kurki et al. (2010) found that

Maximum femoral head diameter is used in this study for the estimation of body mass; however, different measures have been used by different authors. For example, Auerbach and Ruff (2004) used the antero-posterior diameter, whereas Ruff et al. (1991) used the supero-inferior diameter. As the femoral head is a globular structure, there is minimal difference among these measures.



**Fig. 1.** Measurements of the pelvis (see Table 2 for descriptions). (a) Superior view of pelvis, (b) and (d) medial view of hip bone with sacrum, and (c) posterior view of pelvis. A: inlet A-P; B: inlet M-L; C: inlet posterior; D: inlet anterior; E: midplane A-P; F: midplane M-L; G: midplane posterior; H: midplane anterior; I: outlet A-P; J: outlet M-L; K: outlet posterior; L: outlet anterior; and M: canal depth.

for the narrow-bodied Later Stone Age foragers of South Africa body mass calculated from femoral head size often displays large disagreements with those based on the stature/bi-iliac breadth (see also the African Pygmy sample in Auerbach and Ruff, 2004), and that the latter method tends to produce less biologically viable body masses for this population. They suggested that at the small end of the human body size range, McHenry's (1992) femoral head formula is the most reliable method. For consistency, all body mass estimates are based on the femoral head formulae.

Body shape was examined with a particular focus on relative bi-iliac breadth as the previous studies have shown a clear relationship between body breadth and aspects of pelvic canal size (Tague, 2000; Weaver, 2003; Kurki, 2007). Indices representative of body breadth relative to trunk length (bi-iliac breadth/STH  $\times$  100), to stature (bi-iliac breadth/stature  $\times$  100), and to body mass (bi-iliac breadth/body mass  $\times$  100) were calculated. Pearson's correlation coefficients were used to examine the relationships between latitude and the body size variables and indices to discern relationships between body shape and climate that may be associated with pelvic size or shape. Latitude was used as a proxy for annual

temperature differences among the samples, and was taken as the latitude at or near the middle of the geographic distribution of each sample; each skeleton in a sample was assigned the same latitude value. For ease of the discussion of the results, the samples were arbitrarily divided into low-, mid-, and high-latitude groups at 0–20, 21–40, and 41+ degrees latitude, respectively.

To examine pelvic canal size and shape variation in multivariate space, principal component analysis (PCA) of the canal variables was conducted. All canal measurements (inlet, midplane, and outlet A-P, M-L, posterior and anterior, and canal depth) were isometrically size-adjusted by dividing each measurement by the geometric mean (GM) of all measurements in the variable set:  $Y_i = X_i/GM$ ; or for natural log-transformed variables:  $\log Y_i = \log X_i - \log GM$  (Mosimann and James, 1979; Darroch and Mosimann, 1985; Jungers et al., 1995). "Log-size" variables are therefore the natural log-transformed versions of the original variables, whereas "log-shape" variables are the natural log-transformed, size-adjusted variables. These log-size and log-shape variables were used in PCA, based on the covariance matrices. As shape differences among the samples were the targets of these analyses, variation due to sexual dimorphism was

excluded by conducting separate sex analyses. Relationships between principal components and stature, body mass, bi-iliac breadth, and STH were examined through Pearson's correlation coefficients. The first component (PC1) of the log-size analysis is typically representative of overall size and therefore provides an indication of general pelvic canal size. Pelvic canal size relative to body size in each sample was examined through indices: log-size PC1/bi-iliac breadth  $\times$  100; log-size PC1/STH  $\times$  100; log-size PC1/stature  $\times$  100; and log-size PC1/body mass  $\times$  100.

Differences in the levels of diversity in pelvic shape between females and males of each sample were investigated using the *F*-statistic method for multivariate variance (Wills et al., 1994; Fleagle et al., 2010). A weighted PC score for the log-shape analysis was calculated for each individual in the sample across all of the principal components in the analysis relative to each component's eigenvalue:  $\sum PC_x e_x + PC_{x+1} e_{x+1} + \dots + PC_{x+n} e_{x+n}$  where PC is the principal component score for *x* component and *e* is the component eigenvalue. All 13 principal components were included in the calculation of weighted PC score ( $x = 1, n = 12$ ). The coefficients used to calculate the weighted PC scores are derived from the separate female and male PCAs and the amount of sample variance and the morphology represented by each PC differ between the sexes. As PC scores are on the same scale as the original variables (Joliffe, 2002) the outcomes of these analyses are comparable for the total morphospace (all 13 components). The equality of variances between the females and the males in each sample was examined using an *F*-test.

## RESULTS

### Body size and shape

The variation in body sizes and shapes among the samples as well as within the samples are apparent in the sample descriptive statistics (Table 3, Supporting Information Fig. S1). In cases of small samples, size inter-

pretations should be made with caution. In general, the distributions of body size and shape with latitude follow ecogeographic expectations (e.g., Eveleth and Tanner, 1976; Ruff, 1994; Holliday, 1997; Holliday and Hilton, 2010). All of the body size variables for both sexes, except stature for the females, are positively correlated with latitude (Table 4). The three low-latitude samples (African Pygmy, Andaman Islands, and Philippines) tend to display the smallest body sizes in terms of bi-iliac breadth, skeletal trunk length, stature, and body mass. The three high-latitude samples (Terra del Fuego, Denmark, and Inuit) display the broadest and heaviest bodies, and are among the largest for stature (except the Fuegians) and trunk length. The three mid-latitude samples vary in components of body size. The North Africans and Australians lie in the middle of the samples for bi-iliac breadth, trunk length, and body mass, but they are tall relative to most other samples. The South Africans are more distinctive. The male South Africans are

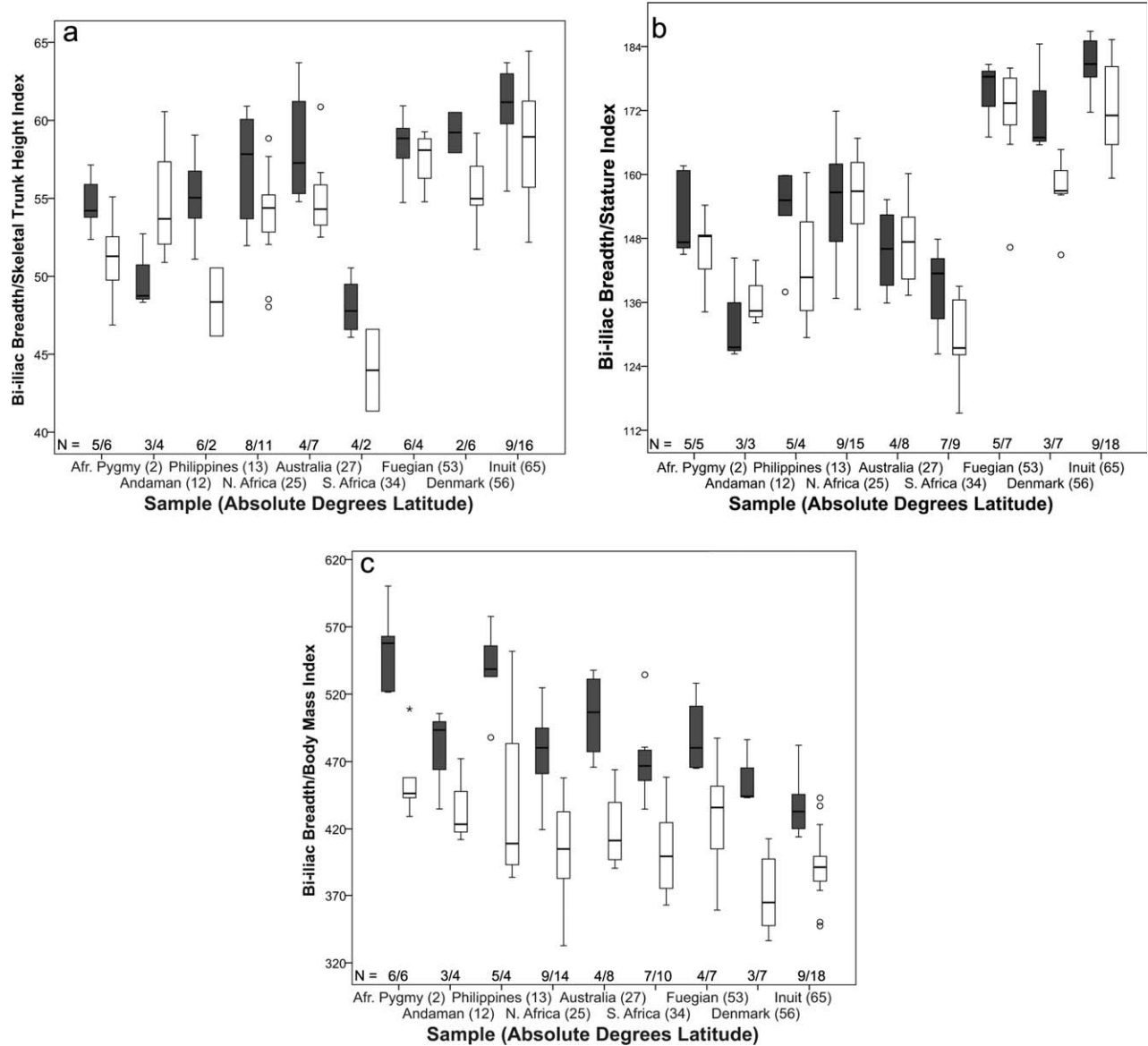
TABLE 4. Pearson correlation coefficients<sup>a</sup> of body size variables and indices with latitude (absolute degrees from equator)

	<i>n</i>	<i>r</i>	<i>P</i> -value
<i>Females</i>			
Bi-iliac breadth	57	0.72	<0.001
STH	47	0.56	<0.001
Stature	50	0.06	0.658
Body mass	50	0.86	<0.001
Bi-iliac breadth/STH	47	0.52	<0.001
Bi-iliac breadth/stature	50	0.70	<0.001
Bi-iliac breadth/body mass	50	-0.68	<0.001
<i>Males</i>			
Bi-iliac breadth	84	0.68	<0.001
STH	58	0.58	<0.001
Stature	76	0.28	0.016
Body mass	78	0.70	<0.001
Bi-iliac breadth/STH	58	0.63	<0.001
Bi-iliac breadth/stature	76	0.59	<0.001
Bi-iliac Breadth/Body Mass	78	-0.41	<0.001

<sup>a</sup>Significant correlations ( $P < 0.05$ ) are indicated in italics.

TABLE 3. Sample descriptive statistics for body size variables

	Bi-iliac Breadth (mm)		STH (mm)		Stature (cm)		Body mass (kg)	
	<i>n</i>	Mean (S.D.)	<i>n</i>	Mean (S.D.)	<i>n</i>	Mean (S.D.)	<i>n</i>	Mean (S.D.)
<i>Females</i>								
African Pygmy	6	215.3 (12.1)	5	401.0 (15.7)	5	144.2 (3.2)	6	39.0 (2.6)
Andaman Islands	3	197.7 (13.9)	3	395.7 (12.2)	3	149.0 (4.0)	3	41.5 (4.2)
Philippines	6	221.5 (7.8)	6	402.9 (28.8)	5	145.0 (4.3)	5	41.3 (3.7)
North Africa	9	242.4 (17.3)	8	426.4 (18.7)	9	156.6 (3.9)	9	51.1 (5.3)
Australia	6	241.5 (16.4)	4	409.8 (32.3)	4	163.3 (2.0)	4	47.3 (3.2)
South Africa	9	213.2 (11.1)	4	455.4 (24.1)	7	154.6 (7.2)	7	45.5 (4.1)
Terra del Fuego	6	255.0 (7.3)	6	437.1 (21.2)	5	145.7 (1.8)	4	52.6 (2.6)
Denmark	3	265.7 (20.8)	2	444.4 (35.2)	3	154.2 (7.5)	3	58.1 (5.1)
Inuit	9	270.6 (12.8)	9	444.7 (26.8)	9	150.0 (4.1)	9	62.0 (1.4)
<i>Males</i>								
African Pygmy	6	215.8 (16.7)	6	421.8 (16.8)	5	146.4 (4.5)	6	47.4 (3.5)
Andaman Islands	5	210.6 (17.6)	4	379.1 (31.4)	3	146.5 (2.3)	6	48.5 (6.0)
Philippines	4	218.0 (20.8)	2	428.8 (9.1)	4	152.6 (1.8)	4	50.7 (8.8)
North Africa	15	253.9 (10.1)	11	468.3 (28.8)	15	163.2 (7.9)	14	63.0 (7.3)
Australia	8	247.0 (8.4)	7	447.9 (21.3)	8	168.1(5.1)	8	59.2 (4.6)
South Africa	10	203.6 (16.7)	2	451.4 (41.5)	9	156.2 (5.6)	10	50.6 (4.4)
Terra del Fuego	11	265.2 (17.1)	4	476.3 (10.8)	7	155.2 (5.1)	7	62.4 (6.8)
Denmark	7	274.7 (12.8)	6	491.3 (12.5)	7	174.8 (7.1)	7	74.2 (6.1)
Inuit	18	274.0 (13.8)	16	469.3 (23.7)	18	159.1 (5.4)	18	70.0 (3.9)



**Fig. 2.** Boxplots of bi-iliac breadth indices by sample. Sample sizes provided as female *n*/male *n*. Shaded boxes: females, open boxes: males. Median value indicated by line inside of box, box extends from 25th (bottom) to 75th (top) percentiles, whiskers extend from 2.5th percentile or minimum value (bottom) to 97.5th percentile or maximum value (top), circles indicate outliers, stars indicate more extreme outliers. (a) Bi-iliac breadth/STH × 100; (b) bi-iliac breadth/stature × 100; (c) bi-iliac breadth/body mass × 100.

the narrowest-bodied group (by 7 mm), and the females are only slightly broader-bodied than the female Andaman Islanders. This translates into low body mass for both sexes. The female South Africans display the longest mean trunk length, and third tallest mean stature, though sample sizes are small. In terms of body breadth and mass, the South Africans can be grouped among the small-bodied samples of the lower latitudes, but not in terms of stature and trunk length.

The bi-iliac breadth indices are all positively (negative for bi-iliac breadth/body mass index) correlated with latitude for both sexes (Fig. 2 and Table 4). The very narrow pelvic breadths of the South African and Andaman Island samples relative to stature are apparent. Except for the latter samples, these results are consistent with thermoregulatory expectations (e.g., Ruff, 1994). Bi-iliac

breadth relative to body mass presents a more complex picture as variation in stature among the samples also contributes to body mass variation (Ruff, 1994). For the males, this index tends to decrease as latitude increases, except for the broad-bodied and short-statured Fuegians. For the females, a similar trend is apparent though more variable within each latitude grouping.

**Principal component analysis**

PCA was used to explore size and shape variation among and within the samples. Sample descriptive statistics for the pelvic variables are summarized in Supporting Information Tables S4 and S5. The principal components are multivariate axes representing linear combinations of the log-size or log-shape variables that account for the

TABLE 5. Eigenvector coefficients for principal components from the female canal variables set

	Females			Males		
	Log-size		Log-shape	Log-size		Log-shape
	PC1	PC1	PC2	PC1	PC1	PC2
<i>Inlet</i>						
A-P	0.120	-0.330	-0.217	0.140	-0.163	-0.357
M-L	0.273	0.171	-0.289	0.320	-0.030	0.076
Anterior	0.235	0.140	-0.148	0.203	0.061	-0.201
Posterior	0.248	-0.796	-0.135	0.385	-0.846	0.160
<i>Midplane</i>						
A-P	0.276	-0.038	0.369	0.225	0.126	-0.292
M-L	0.343	0.352	-0.099	0.337	0.166	0.415
Anterior	0.242	0.096	-0.013	0.226	0.014	-0.203
Posterior	0.372	0.113	0.426	0.299	0.291	0.165
<i>Outlet</i>						
A-P	0.253	-0.036	0.473	0.214	0.174	-0.289
M-L	0.315	0.236	-0.374	0.351	-0.033	0.532
Anterior	0.219	0.061	-0.212	0.241	-0.083	-0.124
Posterior	0.354	0.037	0.297	0.325	0.291	0.267
Canal depth	0.259	-0.005	-0.069	0.227	0.042	-0.146
Eigenvalue	0.073	0.029	0.190	0.103	0.040	0.190
% Total variance	51.3	40.1	26.3	54.8	44.3	20.8

highest percentages of the total sample variation. Plotting principal component scores enables the identification of sample-specific size and shape characteristics; individuals who fall near to each other in the plot share a similar shape with respect to the variables weighted on each component axis; when members of a particular sample cluster together, this indicates a general sample-specific shape. Only the first component of the log-size analyses will be discussed; subsequent components are similar to the component of the log-shape analysis (results not shown); this is common with GM size-adjusted variables (Jungers et al., 1995; Holliday, 1997; Kurki, 2007).

**Females.** The eigenvector coefficients for the principal components are listed in Table 5. The PC1 of the log-size analysis is highly correlated with size (i.e., log GM;  $r = 0.996$ ,  $P < 0.001$ ) and accounts for 51.3% of the sample variance. This component is interpreted as representing overall canal size as all variables load in a positive direction with similar eigenvector coefficients (Jungers et al., 1995). The Inuit and Fuegian females display the largest pelvic canals (Table 6 and Fig. 3), followed by the North Africans and Danes, the South Africans and Australians, and finally the low-latitude samples. Significant positive relationships are present between PC1 and bi-iliac breadth, STH, and body mass, but not stature (Table 7). An important caveat in considering the PC-body size variable correlations is that these analyses are conducted on the total sex-specific sample, the relationships within any of the samples may differ, and the larger samples (e.g., South African, North African, and Inuit) may be outweighing the smaller samples.

The first principal component of the log-shape analysis accounts for 40.1% of the sample variance, and is not correlated with size ( $r = 0.111$ ,  $P = 0.410$ ). This component contrasts the M-L breadths of the midplane and outlet (inlet M-L has the third highest loading) with inlet posterior space, and to a lesser degree inlet A-P. Component two accounts for 26.3% of the sample var-

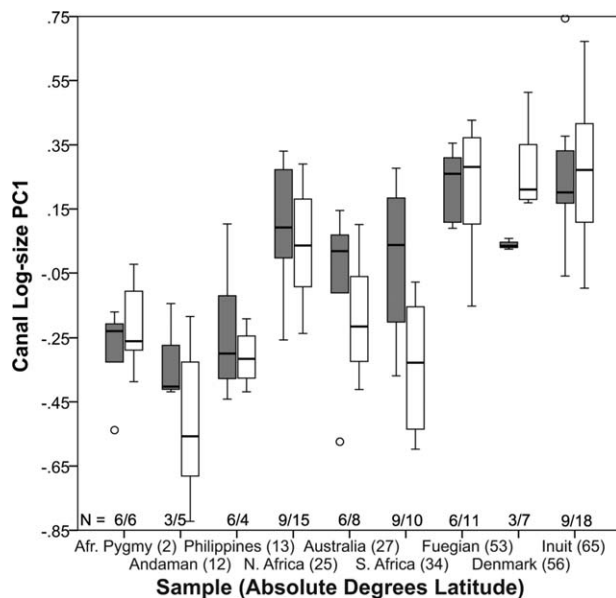


Fig. 3. Boxplot of Canal log-size PC1 by sample. Sample sizes provided as female  $n$ /male  $n$ . Shaded boxes: females, open boxes: males. Median value indicated by line inside of box, box extends from 25th (bottom) to 75th (top) percentiles, whiskers extend from 2.5th percentile or minimum value (bottom) to 97.5th percentile or maximum value (top), circles indicate outliers.

iance and is also not correlated with size ( $r = 0.131$ ,  $P = 0.330$ ). It largely contrasts midplane and outlet posterior and A-P lengths, with inlet size (A-P, M-L, anterior and posterior lengths) and outlet M-L and anterior lengths. The distributions of PC scores are visualized in two ways: 1) individual scores on PC1 and PC2 to explore clustering in morphospace (Fig. 4a); 2) sample score distributions for each PC (Fig. 5 and Table 6) for comparison of the level of morphological diversity in the samples. Significant overlap exists in the distributions of individuals along these two axes (Fig. 4a); however, some clustering is apparent. On PC1, the Inuit, Fuegian, and Danish individuals cluster at the positive end of the axis, representing relatively broad canals and short inlet posterior and A-P lengths, whereas the rest of the samples, excluding the South Africans, lie toward the negative end. On PC2, several of the samples are dispersed, but the South African, African Pygmy, and Fuegian females lie toward the positive end, representing large outlet and midplane A-P and posterior lengths with short outlet and inlet M-L, inlet A-P, and outlet anterior lengths. The North African, Australian, and Danish females lie toward the negative end, displaying the opposite morphology, and the Andaman Islands, Philippines, and Inuit lie primarily in the middle.

Log-shape PC1 shows significant positive relationships with bi-iliac breadth, STH, and body mass, but not stature (Table 7) although several of the South Africans deviate considerably from this relationship for bi-iliac breadth (Fig. 6a); despite their very narrow bodies, they typically have high scores on PC1. The Andaman Islands and Philippine females also tend to display high PC1 scores for bi-iliac breadth, in contrast to the African Pygmy females. PC2 shows a negative relationship with bi-iliac breadth (for remaining PC-body size plots, see Supporting Information Fig. S2).

TABLE 6. Sample descriptive statistics for log-size and log-shape principal components

	<i>n</i>	Log-size PC1	Log-shape PC1	Log-shape PC2
		Mean (S.D.)	Mean (S.D.)	Mean (S.D.)
<i>Females</i>				
African Pygmy	6	-0.283 (0.135)	-0.212 (0.085)	-0.012 (0.034)
Andaman Islands	3	-0.032 (0.154)	-0.048 (0.080)	-0.009 (0.119)
Philippines	6	-0.239 (0.200)	-0.024 (0.088)	-0.043 (0.124)
North Africa	9	0.091 (0.194)	-0.102 (0.114)	-0.100 (0.074)
Australia	6	-0.072 (0.260)	-0.081 (0.184)	-0.080 (0.096)
South Africa	9	-0.014 (0.237)	0.092 (0.208)	0.170 (0.137)
Terra del Fuego	6	0.230 (0.111)	0.112 (0.083)	0.054 (0.081)
Denmark	3	0.039 (0.017)	0.144 (0.108)	-0.153 (0.154)
Inuit	9	0.260 (0.224)	0.115 (0.115)	0.058 (0.083)
<i>Males</i>				
African Pygmy	6	-0.221 (0.133)	-0.111 (0.120)	0.028 (0.108)
Andaman Islands	5	-0.514 (0.260)	-0.010 (0.230)	-0.167 (0.129)
Philippines	4	-0.310 (0.094)	-0.103 (0.123)	-0.007 (0.121)
North Africa	15	0.041 (0.181)	-0.105 (0.141)	0.017 (0.120)
Australia	8	-0.189 (0.181)	-0.132 (0.166)	-0.121 (0.212)
South Africa	10	-0.340 (0.191)	0.172 (0.280)	-0.038 (0.097)
Terra del Fuego	11	0.223 (0.183)	0.010 (0.183)	0.073 (0.103)
Denmark	7	0.279 (0.130)	0.057 (0.168)	0.032 (0.167)
Inuit	18	0.279 (0.207)	0.085 (0.158)	0.042 (0.086)

TABLE 7. Pearson correlation coefficients<sup>a</sup> of principal components and body-size variables

	Bi-iliac breadth			STH			Stature			Body mass		
	<i>n</i>	<i>R</i>	<i>P</i> -value	<i>n</i>	<i>r</i>	<i>P</i> -value	<i>n</i>	<i>r</i>	<i>P</i> -value	<i>n</i>	<i>r</i>	<i>P</i> -value
<i>Females</i>												
Log-size PC1	57	<i>0.65</i>	<i>&lt;0.001</i>	47	<i>0.65</i>	<i>&lt;0.001</i>	50	0.15	0.300	50	<i>0.70</i>	<i>&lt;0.001</i>
Log-shape PC1	57	<i>0.33</i>	<i>0.012</i>	47	<i>0.47</i>	<i>0.001</i>	50	-0.22	0.133	50	<i>0.50</i>	<i>&lt;0.001</i>
Log-shape PC2	57	<i>-0.37</i>	<i>0.005</i>	47	0.17	0.266	50	-0.18	0.213	50	-0.20	0.159
<i>Males</i>												
Log-size PC1	84	<i>0.82</i>	<i>&lt;0.001</i>	58	<i>0.75</i>	<i>&lt;0.001</i>	76	<i>0.45</i>	<i>&lt;0.001</i>	78	0.74	<i>&lt;0.001</i>
Log-shape PC1	84	-0.05	0.683	58	0.08	0.550	76	-0.13	0.273	78	0.06	0.587
Log-shape PC2	84	<i>0.25</i>	<i>0.020</i>	58	<i>0.35</i>	<i>0.007</i>	76	-0.10	0.381	78	0.15	0.190

<sup>a</sup> Significant correlations ( $P < 0.05$ ) are indicated in italics.

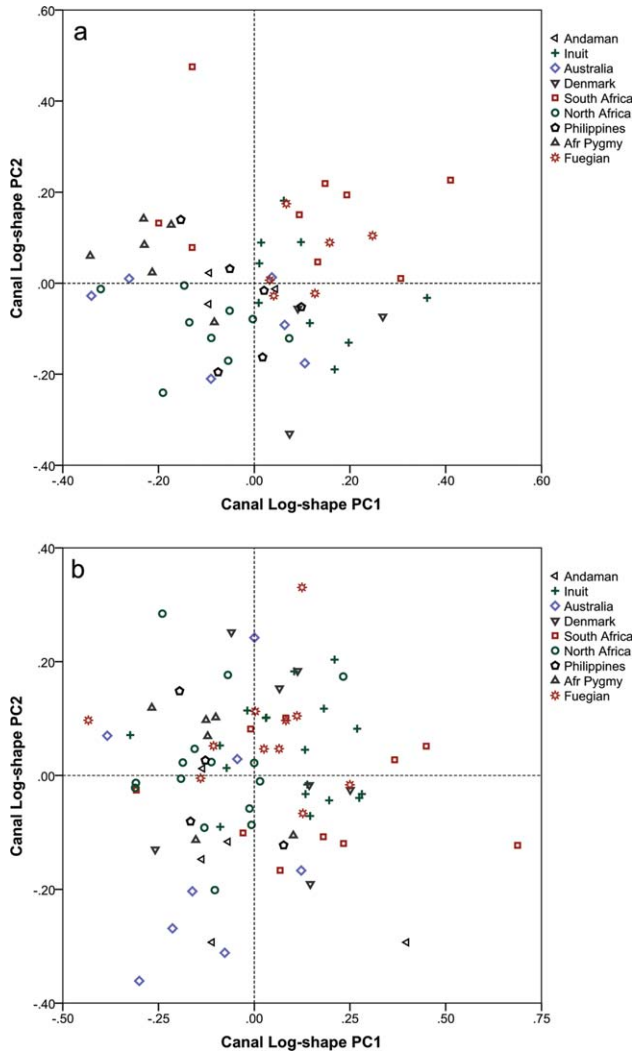
**Males.** The eigenvector coefficients for the principal components are listed in Table 5. Log-size PC1 is highly correlated with size ( $r = 0.996$ ,  $P < 0.001$ ) and accounts for 54.8% of the sample variance. This component is interpreted as representing canal size. The high-latitude samples (Inuit, Danish, and Fuegian) possess the largest canals (Table 6 and Fig. 3), followed by the North Africans, then the Australian and African Pygmy samples, whereas the Philippines, South African, and Andaman Island males are smallest. Pelvic canal size displays significant positive relationships with all body size variables (Table 7).

The first principal component of the log-shape analysis accounts for 44.3% of the sample variance and is not correlated with size ( $r = -0.062$ ,  $P = 0.574$ ). The posterior aspect of the canal is the main area of shape contrast on this component as inlet posterior length is contrasted with the posterior lengths of the midplane and outlet, and outlet A-P and midplane M-L. The second component accounts for 20.8% of sample variance and is correlated with size ( $r = 0.449$ ,  $P < 0.001$ ). This component predominantly contrasts M-L dimensions of the midplane and outlet, plus outlet posterior length, with the A-P, and anterior dimensions of all three planes. Sample statistics for each component are given in Table 6. There is little in the way of clear clustering of individuals in

samples for these two components (Fig. 4b) though some patterns emerge: the high-latitude samples tend to lie toward the positive end of PC1, as do the widely dispersed South Africans; and the Andaman Islander and Australian males tend toward the negative end of PC2. PC1 is not correlated with any of the body size variables (Table 7), whereas PC2 displays significant positive correlations with bi-iliac breadth and STH.

**Between sexes pelvic shape diversity.** Levels of pelvic shape diversity (i.e., variation) were compared between females and males of the samples using an *F*-test for equality of variances in the multivariate variance of the total model morphospace (variance represented by all 13 components). Samples with four or fewer individuals in one of the sexes (African Pygmy, Andaman Islands, and Denmark) were excluded from the analysis. Sample sizes for the remaining comparisons are relatively small, reducing the ability to detect true differences in variance between the sexes. For the South and North African samples, male variance in weighted PC score is significantly larger than in the females (Table 8). Within-sample shape diversity in the first two log-shape components is also shown in Figure 5. The lower within-sample variability for females of the

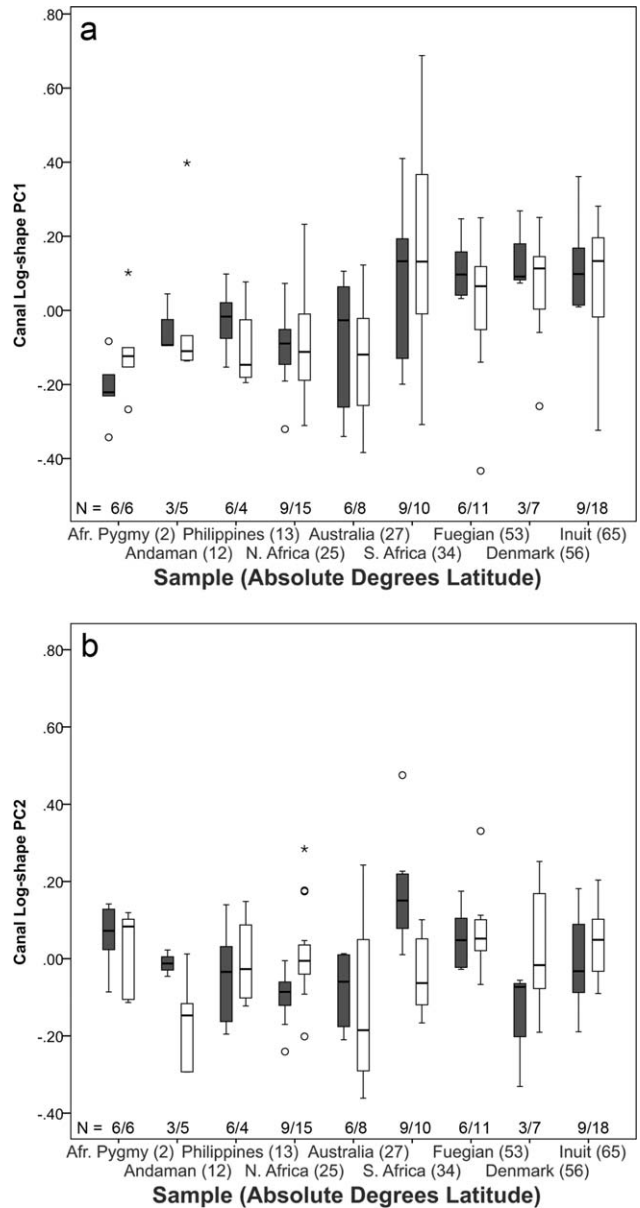




**Fig. 4.** Plot of individual component scores for Canal log-shape PC1 and PC2. (a) Females and (b) males.

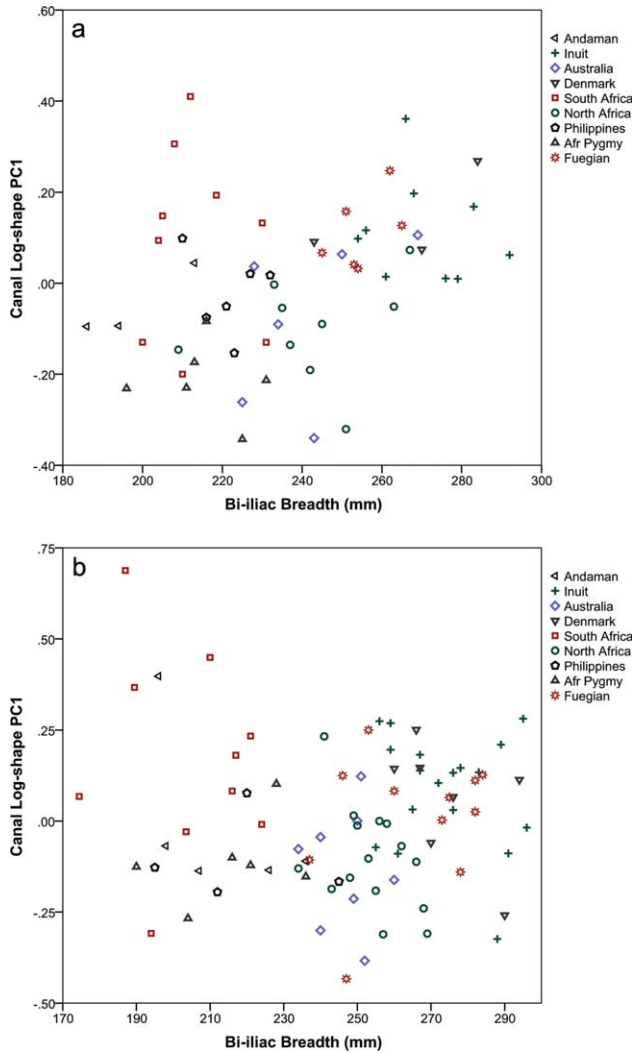
South and North African, Australian, Inuit, and Danish samples for one or both of these components is evident. Caution must be taken in comparing the sexes in these figures as the components incorporate similar but different levels of total model variation for each sex (see above). The greater degree of overlap among the male samples relative to that seen among the female samples is also apparent.

**Relative pelvic canal size.** For the females, the general patterns in the log PC1/body size indices (Fig. 7) are similar for all four body size variables: the higher latitude samples tend to have relatively large pelvic canals for their body size, though the Fuegian females are comparatively small. The low-latitude groups all have relatively small pelvic canals. Of the mid-latitude female samples, the Australians have the relatively smallest canals, whereas the North and South Africans are more similar to the high-latitude samples. The males display similar patterns to the females across the samples although some contrasts are exaggerated. Unlike the females, the Andaman Islander males display very small



**Fig. 5.** Boxplot of Canal log-shape PC1 and PC2 scores. Sample sizes provided as female *n*/male *n*. Shaded boxes: females, open boxes: males. The amount of complete model variance accounted for by each component differs between the sexes; female and male shape variance in each sample cannot be directly compared on these figures. Median value indicated by line inside of box, box extends from 25th (bottom) to 75th (top) percentiles, whiskers extend from 2.5th percentile or minimum value (bottom) to 97.5th percentile or maximum value (top), circles indicate outliers. (a) PC1 and (b) PC2.

pelvic canals for body size. The small size of the Andaman Islander sample warrants caution in interpretation. The South African males also possess relatively small pelvic canals for their body size, a pattern also not seen in the females. Again, South Africans STH sample size is small. This extremely small pelvic canal of the South African males is consistent with Kurki's (2007) study. As the scores for the females and males derive from separate analyses, the differences between the sexes in PC1



**Fig. 6.** Plot of individual scores for Canal log-shape PC1 and bi-iliac breadth. (a) Females and (b) males.

score distributions should not be interpreted as indicative of levels of sexual dimorphism.

**DISCUSSION**

Given the variation in relationships between pelvic dimensions and body size demonstrated in previous studies (Walrath and Glantz, 1996; Rosenberg, 1988; Tague, 2000; Kurki, 2007), the expectation in this study was that samples with similar body shapes, in terms of stature, body mass, body breadth, and trunk length, would display similarly shaped pelvic canals. Four of the samples can be considered relatively small-bodied—African Pygmy, Andaman Islands, Philippines, and South African—although with variable aspects reflecting their small size (i.e., short stature for the African Pygmy and Philippines samples, narrow body breadth, and small body mass for the Andaman Islands and South African). The Australians and North Africans are tall and narrow-bodied, whereas the remaining samples are broader with greater body mass and variable statures. There is a complex pattern of bi-iliac breadth for body mass. The broad bodies relative to body mass for the low-latitude, small-bodied African Pygmy and Phil-

**TABLE 8.** Sample variances for multivariate<sup>a</sup> variance and *F*-test for equality of variances between the sexes

	Females		Males		<i>F</i>	<i>P</i> -value <sup>c</sup>
	<i>n</i>	Variance <sup>b</sup>	<i>n</i>	Variance <sup>b</sup>		
African Pygmy	6	$6.97 \times 10^{-6}$	6	$1.77 \times 10^{-5}$	2.54	0.329
Andaman Islands <sup>d</sup>	3	$6.39 \times 10^{-6}$	5	$6.95 \times 10^{-5}$		
Philippines <sup>d</sup>	6	$3.22 \times 10^{-6}$	4	$1.68 \times 10^{-5}$		
North Africa	9	$9.41 \times 10^{-6}$	15	$4.72 \times 10^{-5}$	<i>5.01</i>	<i>0.028</i>
Australia	6	$2.42 \times 10^{-5}$	8	$7.14 \times 10^{-5}$	2.96	0.251
South Africa	9	$3.22 \times 10^{-5}$	10	$1.41 \times 10^{-4}$	<i>4.39</i>	<i>0.049</i>
Terra del Fuego	6	$1.40 \times 10^{-5}$	11	$5.47 \times 10^{-5}$	3.91	0.146
Denmark <sup>d</sup>	3	$3.70 \times 10^{-5}$	7	$5.84 \times 10^{-5}$		
Inuit	9	$1.36 \times 10^{-5}$	18	$4.95 \times 10^{-5}$	3.64	0.069

<sup>a</sup> Multivariate variance represents the sum of the variances of all principal components in the model, each component variance weighted by its eigenvalue, and is calculated for each individual in the sample as:  $\sum PC_x \times e_x + PC_{x+1} \times e_{x+1} + \dots + PC_{x+n} \times e_{x+n}$  where PC is the component score, *e* is the eigenvalue. All 13 components are included in this calculation (*x* = 1, *n* = 12).

<sup>b</sup> Variance statistic (standard deviation squared) of multivariate variance for sample.

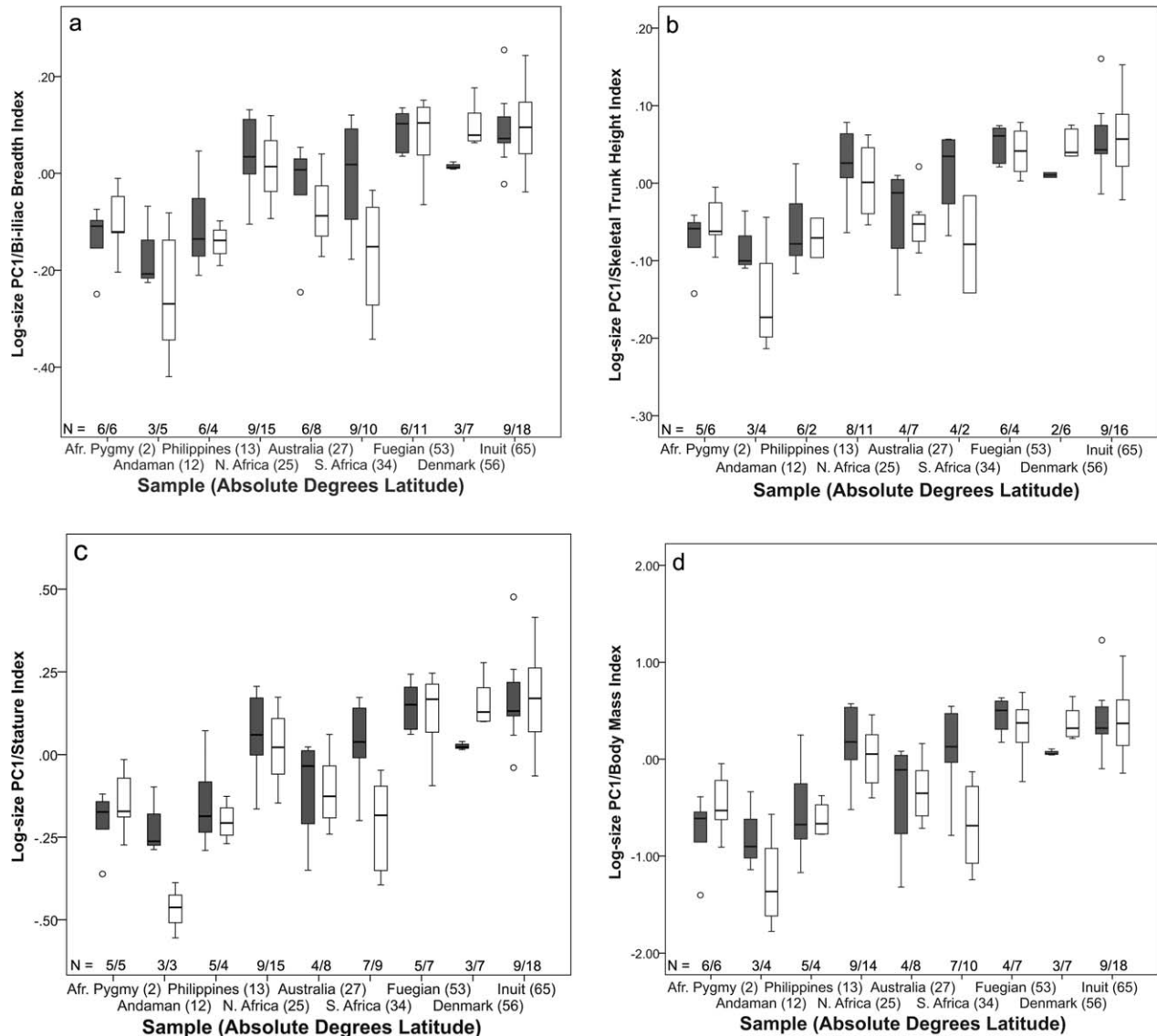
<sup>c</sup> Significant results (*P* < 0.05) are indicated in italics.

<sup>d</sup> Samples with four or fewer individuals were considered too small for the *F*-test. Mean and standard deviation are provided for comparative purposes.

ippines samples are consistent with Ruff's (1994) cylindrical model of thermoregulation. The Andaman Islands females and both sexes of the South Africans do not conform to expectations, displaying narrow bodies with lower body mass than expected for latitude (see also Kurki et al., 2008).

Pelvic canal size (log-size PC1) is larger in the larger-bodied samples for both sexes, although not stature in the females; taller women do not possess larger canals. Previous studies have produced similar results for stature (Tague, 2000; Kurki, 2007). It is apparent that larger-bodied populations also, in general, possess larger pelvic canals relative to body size. More specifically, it is the wider-bodied high-latitude samples that possess relatively large pelvic canals compared to lower latitude groups. The North and South African females, however, are not consistent with this trend, highlighting the variability in relative canal size. Although PC1 of the log-size analysis for both the females and the males is interpreted as representing overall canal size, lower canal M-L and posterior lengths present larger coefficients on this component (Table 5), such that "size" in this case is more heavily weighted toward these aspects. The greater body breadths of the high-latitude samples may unduly influence their higher component scores. In light of the strong relationship between the body (bi-iliac) breadth and the M-L dimensions of the pelvic canal planes (Tague, 2000; Weaver, 2003; Kurki, 2007, 2011b), the relatively large pelvic canal of the narrow-bodied South African females is unexpected, particularly in comparison with the equally narrow-bodied (but shorter statured) Andaman Island females. Instead of possessing wide pelvic canals, the South African females possess expanded A-P and posterior lengths of the midplane and outlet.

In terms of pelvic canal shape, while the expectation that canal shape is more similar among samples with



**Fig. 7.** Boxplot of Canal log-size/body size indices. Sample sizes provided as female *n*/male *n*. Shaded boxes: females, open boxes: males. Median value indicated by line inside of box, box extends from 25th (bottom) to 75th (top) percentiles, whiskers extend from 2.5th percentile or minimum value (bottom) to 97.5th percentile or maximum value (top), circles indicate outliers. (a) Log-size PC1/bi-iliac breadth  $\times 100$ ; (b) log-size PC1/STH  $\times 100$ ; (c) log-size PC1/stature  $\times 100$ ; and (d) log-size PC1/body mass  $\times 100$ .

similar body shapes is largely supported by these analyses, some interesting exceptions are apparent. Compared to the males, the females provide clearer clustering among the samples for canal shape along the first two shape components (Fig. 4), and lower within-sample dispersions (Fig. 5 and Table 8). For the females, there is a general contrast in broad (M-L) midplane and outlet and short (A-P) inlet in high-latitude samples versus narrow and long in mid- and low-latitude samples that is driven by differences in body size, most appreciably body mass, but also trunk length and bi-iliac breadth. The South Africans do not fall neatly into this pattern, as the females, and to a lesser extent the males, display pelvic canals that are particularly elongated in the A-P and posterior dimensions of the midplane and outlet, though with small inlet planes overall, and narrow outlet breadths. Relative to bi-iliac breadth, this shape (log-shape PC2) is unique to the South Africans (Fig. 6). The

African Pygmy and Fuegian females overlap to a degree with the South Africans for this shape component. All three of these samples are small-bodied though they differ considerably in body breadth characteristics. Body size and shape do not appear to exert much influence on this component of canal shape. In comparison, the males of each sample cluster together less clearly although only for the South and North African samples are the differences between male and female multivariate variances significant; small sample sizes may also limit the ability to detect significant differences. These results suggest that male pelvic canal shape may be freer to vary in relative dimensions than in females, supporting the contention that it is the action of obstetric-related selective factors that affect female canal shape. Still, the unique shape of the South African female canal is mirrored to some degree in the males, potentially as a result of correlated response to selection acting on the females (Lande, 1980).

The contrast in inlet A-P relative to midplane and outlet A-P (and posterior length) evidenced in log-shape PC2 implies that it is the orientation of the sacrum with respect to the hip bones that may be enabling the A-P expansion of the lower planes. With a large sacral angle the lower sacral vertebrae are displaced further from the pubic bone, and the midplane and outlet are expanded in the A-P and posterior canal lengths (as the posterior canal is measured to the ischial spine and ischial tuberosity, respectively). Meanwhile, the anterior aspect of the first sacral vertebrae, the sacral promontory, is rotated forward into the canal, effectively shortening inlet A-P. The alternative is that the pubic bone is rotated upward by lengthening the inferior pubic ramus and shortening the superior pubic ramus, effectively extending the lower plane A-P dimensions (measured to the posterior–inferior pubic symphysis), and shortening inlet A-P (measured to the posterior–superior pubic symphysis). In both cases, to expand the posterior lengths of the lower planes the ischial spines and tuberosities would also be pulled forward or everted away from the sacrum. It is noteworthy that Kurki (2005) did not find significant differences in sacral angle among South African, European-American, and Portuguese samples, suggesting the latter explanation may be more likely.

Although one may have anticipated that the greatest contrasts in canal shape would be between the largest and the smallest bodied samples, perhaps more specifically between the broad-bodied and narrow-bodied samples, some significant shape contrasts were also found among the small-bodied samples. These results suggest that although body size and shape, particularly body breadth, influence pelvic canal size and shape, some aspects of pelvic geometry are independent of overall body shape. The South Africans appear to stand out in aspects of both body size and shape and pelvic canal size and shape, with canal shape being driven by a small inlet. The basic assumption is that a sufficient obstetric canal, in size and shape, is “normal” in human populations of varying body shapes and sizes. If we assume that the pelvic sizes and shapes found in these analyses represent “normal” sizes and shapes for the populations represented here, then these results help to explain the various stature “thresholds” for increased risk of difficult childbirth, including cephalo-pelvic disproportion, found in various populations, which have ranged for example from 140 cm in New Zealand (McGuinness and Trivedi, 1999) to 160 cm for “white” women in the United Kingdom (Prasad and Al-Taher, 2002). Significant variation exists among populations in pelvic size and shape. Further, the smaller pelvic canal of the low-latitude samples may facilitate smaller neonatal size under thermal stress (Wells, 2002; Wells and Cole, 2002).

In addition, as this study and others (Tague, 2000; Kurki, 2005, 2007) have shown, stature displays a weaker relationship to pelvic capacity than other aspects of body size. If one considers the potential for different routes to small body size—via compromised growth or via selection for small body size or early cessation of growth—then the issue is not whether all small women are at risk, but why they are small. When growth is compromised in the individual owing to poor health or nutrition during childhood, overall skeletal size and proportionality may be affected (Bogin and Varela-Silva, 2003; Frisancho, 2007; Stinson, 2012), including pelvic capacity. However, if small adult body size is the end result of normal growth (Migliano et al., 2007; Stock and Migliano, 2009; Pfeiffer and Har-

ington, 2011), then one might expect pelvic capacity to be protected through allometric growth trajectories (Kurki, 2007). The small-bodied samples in this study are assumed to represent the latter case. Although this contention is difficult to ascertain, for the South Africans small body size has been maintained in the population for thousands of years (e.g., Pfeiffer and Sealy, 2006), whereas for the African Pygmy population small size has been shown to be have a genetic basis (e.g., Bozzola et al., 2009). The reduction of growth in response to poor environments may be the basis for the clinical preconception that small women are at risk (see also Kurki, 2011b). Variation in shape of the pelvic canal among populations, as demonstrated in this study, makes it problematic to characterize a single or standard mechanism of childbirth, also known as the “cardinal movements,” in terms of a standard orientation of the fetus as it passes through the canal. Consider the expansion of the posterior space of the inlet in female samples that lie toward the negative end of log-shape PC1. An expanded inlet posterior length suggests that a position of “occiput posterior,” where the fetal occiput aligns with the posterior of the inlet may be a more common orientation in these populations. This orientation is considered a “malposition,” whereas the “occiput anterior” is reportedly “normal” (Walrath, 2003; Cunningham and Williams, 2005). Although rotation of the fetus is a consistent feature, fetal orientation at each canal plane is dependent on canal geometry (Walrath, 2003).

This study did not account for the possible effect of phylogenetic relationships among the sample populations though the samples derive from diverse geographical locations at low, middle, and high latitude. Betti et al. (2012) found that within-population variation in pelvic measurements (bi-iliac breadth, maximum iliac blade length, and maximum acetabular height) is consistent with a neutral demographic signal and an out-of-Africa expansion model. This suggests that phylogenetic history, genetic drift, and selective pressures (e.g., thermoregulation and obstetrics) all play a role in determining geographic patterns in pelvic shape variation. Pelvic variation present in a population for selection to act on may be diminished owing to repeated bottlenecks with population expansion. Small sample sizes preclude similar phylogenetic analyses of the sample data presented here.

## CONCLUSIONS

This study examined the relationships between pelvic size and shape and body size and shape among nine human skeletal samples. The results illustrate that pelvic canal size and morphology vary among populations, largely in conjunction with body size and shape, particularly body breadth. Higher latitude populations tend to be broader-bodied and heavier, and to display larger and relatively broader midplane and outlet canal planes. Lower latitude populations are narrower-bodied with lower body mass, and display narrower midplane and outlet levels, expanded instead in the A-P dimensions. Pelvic canal shapes also vary independently of body shape attributes. Among the females, the South Africans possess pelvic canals with small inlet planes, short outlet breadths, and anterior lengths, but expanded A-P and posterior canal lengths of the outlet and midplane. The African Pygmy and Fuegian females tend to display a similar morphology. All three samples are considered small-bodied but in different ways. The South Africans are very narrow-bodied with low body mass but are not

specifically short in stature, the African Pygmy females are short with low body mass but relatively broad bodies, and the Fuegians are short but broad-bodied and heavy. The opposite pelvic morphology tends to be displayed among the North Africans and Australians, both tall and relatively narrow-bodied, and the Danes, who are tall, broad, and heavy. Male within-sample multivariate variance in pelvic morphology appears to be higher than for the females though only for the North and South Africans are these differences significant. The male samples also cluster less distinctly in log-shape PC1 and PC2 morphospace compared with the females.

The results of this study support the contention that just as human populations vary in body size and shape characteristics, they also vary in pelvic canal geometry, but not in a consistent manner. That is, some aspects of pelvic morphology vary independently of body size and shape, weakening the applicability of typological approaches to the assessment of obstetric risk and birth mechanics across populations. Further, this variation in human pelvic geometry has implications for our understandings of the evolution of hominin childbirth. The high degree of evolvability in the human pelvis, as demonstrated by Grabowski (2012), has enabled the generation of diverse pelvic geometries among and within human populations. Caution should be taken in generalizing from fragmentary hominin pelvic remains to complete pelvic morphologies as relationships within the canal and with body size and shape are shown here to vary. The relationships among pelvic shape variation, locomotion, and energetics are areas for future study (Wall-Scheffler, 2012).

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