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# Metric Variation in the Human Sacrum: Costal Process Length Among Black and White South Africans

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METRIC VARIATION IN THE HUMAN SACRUM: COSTAL PROCESS  
LENGTH AMONG BLACK AND WHITE SOUTH AFRICANS

A Thesis

Submitted to the Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
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in

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by  
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## **ABSTRACT**

Considerable attention has been given to the measureable differences that exist between different human populations in the size and shape of the pelvis, with Africans having a narrower pelvis than Europeans. By collecting data on sacral breadth from a South African skeletal population, this study (1) tests the hypothesis that African blacks possess a narrower sacrum, and by inference pelvis, than whites and (2) considers whether the size variation between blacks and whites is due to nutritional, historical and social differences, to a genetic basis related to climatic adaptation, or to both. White South Africans were found to possess a significantly wider sacrum and longer costal processes for S1 than black South Africans. Two possible interpretations of the results were addressed, size variation is due to: (1) nutritional differences related to socioeconomic status, or (2) climatic adaptation based on thermoregulatory principles.

## CHAPTER 1: INTRODUCTION

Multiple studies have demonstrated that whites possess significantly larger pelvic dimensions than blacks (Patriquin et al. 2005, 2002; İşcan 1983, 1981). Within a North American population, İşcan (1983) reported whites as having larger measurements than blacks for bi-iliac breadth (maximum distance between the iliac crests), transverse breadth (maximum distance between the arcuate lines of the pelvic inlet), and anteroposterior height (conjugate diameter) of the pelvis. In a similar study as İşcan's (1983) conducted with a South African population, Patriquin et al. (2002) reported whites as being larger than blacks for all measurements studied, such as iliac breadth, total height of the os coxa, and acetabulum diameter. Population specific differences between black and white South African populations and black and white North American populations are most readily observable in the cranium and mandible (İşcan and Steyn 1999). To some extent, the shape of the skull may influence the shape of the pelvis, as the skull must pass through the pelvis during birth (Fischer and Mitteroecker 2015). It has been hypothesized that the pelvis of black and white South Africans will therefore also possess population specific traits (Patriquin et al. 2002). Interestingly, despite metric variation between black and whites in North America and South Africa, the accuracy of ancestry identification due to size differences influenced by the overall build and robusticity of an individual for both studies is similar. Accuracy was recorded as 83% for North American males, 83% for North American females, 88% for South African males, and 85% for South African females.

North American whites are also reported to have a wider sacrum than blacks (Tague 2007; Flander 1978). Tague (2007) found that whites are significantly larger than blacks in both sexes for measurements such as: diameter between the costal processes for S1, costal process length for S1, relative costal process length for S1, and transverse diameter and circumference of the pelvic inlet. Comparisons between males and females showed that for both blacks and



whites, males were significantly larger than females for the anteroposterior and transverse diameter of the bodies for S1. Females were significantly larger than males for costal process length of S1, relative costal process length for S1, and transverse diameter and circumference of the pelvic inlet. The sexes did not differ significantly for the diameter between the costal processes for S1.

Nutrition is recognized as having discernible influences on human growth and development (Tobias 1985; Tanner et al. 1982). Nutritional influences may directly impact skeletal proportions and shape. Poor nutrition often results in stunted growth, whereas better living conditions and diet are associated with increases in stature (Ruff 1994; Tanner et al. 1982). The shape of the pelvic inlet is affected by dietary quality during an individual's period of growth and development (Angel et al. 1987; Kelly and Angel 1987). Kelly and Angel (1987) demonstrated that inadequate nutrition changes the pelvic brim index (relationship of the anterior-posterior distance to the transverse diameter), resulting in the anterior-posterior dimension being shortened. Variation between blacks and whites in the size and shape of certain dimensions of the pelvis, such as the inlet, and presence of asymmetry may therefore be the result of nutritional differences.

Despite the existence of secular variation in size due to nutrition, long term adaptation to climate based on thermoregulatory principles may also provide an explanation for why whites possess larger pelvic measurements than blacks. The pelvis helps determine overall body proportion as well as surface area-to-mass ratio which assists in heat loss through the body's surface. Therefore, body temperature regulation is affected by the width of the pelvis (Gruss and Schmitt 2015). Body mass is well documented as being distributed clinally in modern human populations (Holliday and Hilton 2010; Ruff 2002, 1994; Holliday 1997a). Ruff (1991)

demonstrated that bi-iliac breadth displays the strongest relationship to climate of any whole body dimension. For the sacrum, McHenry (1992) observed a positive association between body mass and the product of the anteroposterior and transverse diameters (i.e., area) for the superior aspect of the first sacral vertebra.

Size and shape variation between blacks and whites may be inferred to be a result of a thermoregulatory adaptation, that is, Bergmann's Rule. Bergmann's Rule is an ecogeographic principle which states that within a polytypic species broadly distributed over a wide geographic range, larger bodied populations will be found in colder environments, and smaller bodied populations will be found in warmer environments (Ruff 1993). Heat production is proportional to body mass and heat dissipation is proportional to exposed body surface area. In thermoregulatory terms, in order to maintain a stable body temperature in hot environments, efficient heat dispersion through sweat evaporation at the body surface is facilitated in small bodied individuals by a large surface-to-volume ratio (Betti 2014). As an adaptation to maintain internal body temperature in cold environments, larger bodied individuals will have a higher ratio of heat production to heat dissipation than smaller bodied individuals (Ruff 1994). As opposed to secular trends in nutritional status, morphological adaptations to climate would have needed to occur over a significantly longer period of time, possibly tens of thousands of years (Holliday 1997a). Multiple studies have demonstrated that pelvic breadth and shape differ according to climatic conditions, with populations in higher-latitudinal regions possessing relatively wider pelves than populations in tropical regions (Kurki 2013; Weaver 2002; Holliday 1997b; Ruff 1994). Sacral breadth is strongly correlated with the transverse diameter of the false pelvis and bi-iliac breadth (Tague 1992). Variation in size and shape of the sacrum may therefore

reflect long term climatic adaptation, with whites representing higher-latitudinal populations and blacks representing more tropical populations.

The human sacrum has also been shown to exhibit sexual dimorphism. Tague (2007) and Flander (1978) observed that for the sacrum of North American blacks and whites of both sexes, curved length and maximum depth along the ventral surface, anterior and transverse diameter of the body of the first vertebrae (S1), and the costal process of S1 are sexually dimorphic. Males were significantly larger than females for almost all measurements. However, the costal process of S1 is unique in that females were longer than males (Tague 2007). Because the costal process of S1 contributes to the transverse diameter and circumference of the pelvic inlet, the costal process is most likely under selection for obstetrical sufficiency of the pelvis (Tague 2007). The magnitude of the index of sexual dimorphism (computed as, female mean(100)/male mean) for the costal process of S1 shows that this feature is one of the most highly dimorphic measures of the pelvis (Tague 2007). Traditionally, pubic length has been hailed as one of the best traits for sex determination, as females are always absolutely or relatively larger than males (Garvin 2012; Patriquin et al. 2005, 2002). However, Tague (2007) demonstrated that the costal process length of S1 displays a higher index of sexual dimorphism than for pubic length, potentially making it a better morphology for sex determination. This study considers whether blacks and whites differ in sacral breadth in samples from South Africa. As the sacrum contributes to the size and shape of the pelvic inlet, midplane, and outlet, results may explain why blacks and whites differ in pelvic breadth.

## CHAPTER 2: MATERIALS AND METHODS

Three hundred ninety three individuals from the Pretoria Bone Collection were used for this study: 98 white males, 100 white females, 100 black males, and 95 black females. Access to the Pretoria Bone Collection was granted by Professor Erica L'Abbé. Established in 1987, the Pretoria Bone Collection is primarily cadaver based and is part of the Department of Anatomy at the University of Pretoria in South Africa. Records provided by the University of Pretoria were used for information on sex, ancestry, and ages at death. The ages at death among all individuals ranged from 22 to 94. No age limit was chosen for this study, despite some arthritic or osteophytic growth in older individuals. White South Africans are of European descent, primarily from the Netherlands, Great Britain, Germany, Portugal, and France. Black South Africans are from multiple different tribes and ethnic groups. Osteological differences have not been great enough to warrant separation among them (Patriquin et al. 2005, 2002).

For this study, instrumental measurements taken were as follows (Figure 1): maximum anteroposterior diameter of the superior body of S1, L3, and L5 (Fig. 1a,b, A-B); maximum transverse diameter of the superior body of S1, L3, and L5 (Fig. 1a,b, C-D); maximum diameter between the costal processes of S1, L3, and L5 (Fig 1a,b, E-F); and femur length. The left and right costal process of S1 (Fig. 1a, E-C; D-F), L3 and L5 (Fig. 1b, E-G; H-F) were measured to observe asymmetry. L3 and L5 were measured to test if they display similar degrees of sexual dimorphism as described in Tague's 2007 study, with L3 being sexually dimorphic and L5 being sexually monomorphic.

Four variables were also computed:

(1) calculated costal process length = (maximum diameter between costal processes - maximum transverse diameter of the body) / 2,

(2) relative costal process length =  $(2 \text{ (costal process length)} / \text{maximum diameter}) \times 100\%$  between costal processes,

(3) difference between left and right costal process length =  $[(\text{left value} - \text{right value}) / ((\text{left value} + \text{right value}) / 2)] \times 100\%$ , and

(4) measurement precision:  $[(\text{original measurement} - \text{repeat measurement}) / \text{original measurement}] \times 100\%$

Individual left and right costal process length for S1 differs from the calculated costal process length formula (Formula 1). Therefore the two measurements may give different values.

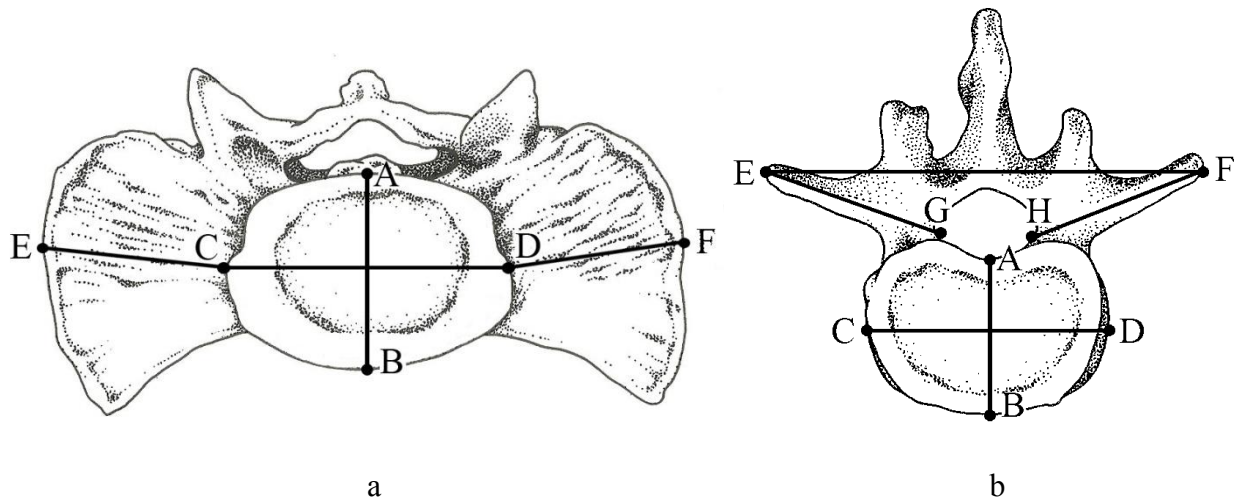


Figure 1. Measurements of Sacral and Lumbar Vertebrae. Superior view of first sacral vertebra (a) and lumbar vertebra (b). Drawing by author.

Sliding calipers were used to take linear measurements which were recorded to the nearest 0.1 mm. Left femur length was measured to the nearest mm with an osteometric board. If the left femur was not present, the right femur was used if available. The number of vertebrae (sacral, lumbar, thoracic, and cervical) were recorded as well as number of ribs present. Tague (2007) only selected individuals for research if they possessed the modal number of vertebrae for the cervical (7), thoracic (12), lumbar (5), and sacral segments (5) of the vertebral column. This

study did not follow this restriction as many individuals were missing vertebral elements, but the number of vertebrae was documented as sacralization of a lumbar or coccygeal vertebra has been demonstrated to affect measurements of the sacrum (Tague 2011, 2009).

Statistical analysis was conducted through SSPS and included Student's *t*-test, paired *t*-test, and sign test. Fifteen individuals (Table 1) were remeasured weeks after the original measurements were taken to determine intraobserver measurement precision. Measurement precision ranged from 96% to 99%.

Table 1. Intraobserver Measurement Precision, n=15.

Variable	<i>r</i>
S1 Body Transverse Diameter	98%
S1 Body Anterior Posterior	99%
S1 Maximum Diameter	99%
S1 Left Costal Process	96%
S1 Right Costal Process	97%
L5 Body Transverse Diameter	99%
L5 Body Anterior Posterior	99%
L5 Maximum Diameter	99%
L5 Left Costal Process	99%
L5 Right Costal Process	98%
L3 Body Transverse Diameter	99%
L3 Body Anterior Posterior	99%
L3 Maximum Diameter	99%
L3 Left Costal Process	97%
L3 Right Costal Process	98%

## CHAPTER 3: RESULTS

Tables 2 and 3 present summary statistics of study variables among white males, white females, black males and black females. *t*-test results (Table 4) demonstrate significant differences between black and white males and between black and white females. Whites are significantly larger than blacks in both sexes for 11 of 25 variables: transverse diameter of the body for L5 and L3; anteroposterior diameter of the body for L3; maximum diameter between the costal processes for S1 and L5; calculated costal process length for S1; left and right costal processes for S1 and L5; and femur length. White males are significantly larger than black males, but white and black females are not significantly different, for the five variables: anteroposterior diameter of the body for L5; calculated costal process length for L5; left costal process length for L3; and relative costal process length for S1 and L5. White females are significantly larger than black females, but white and black males are not significantly different, for two variables: transverse and anteroposterior diameter of the body for S1. Blacks do not possess any significantly larger measurements than whites. Both groups are not significantly different for six variables: maximum diameter between the costal processes for L3; right costal process length for L3; relative costal process length for L3; and costal process difference for S1, L5, and L3.

For both blacks and whites, males are significantly larger than females for 13 variables: transverse diameter of the body for S1, L5, and L3; anteroposterior diameter of the body for S1, L5, and L3; maximum diameter between the costal processes for L5 and L3; left and right costal processes for L5 and L3, and femur length. Black females are significantly larger than black males for two variables: calculated costal process length for S1 and relative costal process length for S1. White females do not possess any significantly larger measurements than white males.

Table 2. Comparison of Study Variables for White Males (WM) and White Females (WF).

Variable	WM <i>n</i>	WM Mean (sd)	WF <i>n</i>	WF Mean (sd)	White Range
S1 Body Transverse Diameter (mm)	98	58.3(6.6)	100	55.3(6.9)	44-78
S1 Body Anterior Posterior (mm)	98	35.1(3.4)	100	31.4(2.6)	26-45
S1 Maximum Diameter (mm)	98	119.0(7.6)	100	116.7(7.0)	89-150
S1 Left Costal Process (mm)	98	40.9(5.3)	100	42.1(6.4)	24-62
S1 Right Costal Process (mm)	98	41.3(6.6)	100	43.1(6.3)	28-69
S1 Costal Process Length (mm) (calc)	98	30.4(3.9)	100	30.8(4.3)	18-40
S1 Relative Costal Process Length (%) (calc)	98	51.0(5.2)	100	52.7(5.7)	34-64%
S1 Costal Process Difference (%) (calc)	98	6.6(5.9)	100	7.7(9.1)	0-70%
L5 Body Transverse Diameter (mm)	95	58.3(5.9)	94	53.6(5.2)	42-77
L5 Body Anterior Posterior (mm)	95	38.1(3.9)	94	34.0(2.7)	28-49
L5 Maximum Diameter (mm)	95	94.5(8.6)	94	87.5(9.4)	52-118
L5 Left Costal Process (mm)	95	34.0(4.1)	94	31.7(5.0)	19-56
L5 Right Costal Process (mm)	95	34.4(4.6)	94	30.8(4.8)	16-44
L5 Costal Process Length (mm) (calc)	95	18.1(4.5)	94	17.0(4.8)	1-33
L5 Relative Costal Process Length (%) (calc)	95	37.9(7.2)	94	38.1(8.5)	4-58%
L5 Costal Process Difference (%) (calc)	95	2.7(3.2)	94	2.8(3.0)	0-10%
L3 Body Transverse Diameter (mm)	90	53.8(5.5)	87	47.7(4.5)	40-73
L3 Body Anterior Posterior (mm)	90	37.7(3.5)	87	33.9(3.0)	28-45
L3 Maximum Diameter (mm)	90	89.8(11.7)	87	80.4(9.6)	58-118
L3 Left Costal Process (mm)	90	35.9(6.4)	87	31.8(5.4)	16-50
L3 Right Costal Process (mm)	90	34.7(7.0)	87	30.6(5.7)	16-47
L3 Costal Process Length (mm) (calc)	90	18.0(5.9)	87	16.3(5.2)	2-32
L3 Relative Costal Process Length (%) (calc)	90	39.2(9.9)	87	40.0(9.0)	5-55%
L3 Costal Process Difference (%) (calc)	90	2.1(3.0)	87	2.1(3.2)	0-10%
Femur Length (mm)	98	472.1(25.4)	99	442.1(21.0)	385-560



Table 3. Comparison of Study Variables for Black Males (BM) and Black Females (BF).

Variable	BM <i>n</i>	BM Mean (sd)	BF <i>n</i>	BF Mean (sd)	Black Range
S1 Body Transverse Diameter (mm)	100	56.4(6.4)	96	50.8(6.2)	34-70
S1 Body Anterior Posterior (mm)	100	33.9(2.8)	96	30.3(2.7)	25-41
S1 Maximum Diameter (mm)	100	106.6(6.9)	96	106.4(6.2)	87-129
S1 Left Costal Process (mm)	100	36.2(5.4)	96	36.8(5.5)	22-60
S1 Right Costal Process (mm)	100	36.3(5.5)	96	37.0(5.5)	25-62
S1 Costal Process Length (mm) (calc)	100	25.7(6.9)	96	27.8(3.3)	15-35
S1 Relative Costal Process Length (%) (calc)	100	47.9(13.2)	96	52.3(5.3)	26-64%
S1 Costal Process Difference (%) (calc)	100	6.9(6.4)	96	6.1(6.1)	0-41%
L5 Body Transverse Diameter (mm)	95	56.1(5.6)	84	51.3(4.8)	42-73
L5 Body Anterior Posterior (mm)	95	36.6(3.3)	84	33.1(3.2)	28-47
L5 Maximum Diameter (mm)	95	87.0(7.3)	84	82.1(7.3)	60-113
L5 Left Costal Process (mm)	95	31.3(3.7)	84	29.5(4.1)	17-50
L5 Right Costal Process (mm)	95	30.8(3.7)	84	28.8(4.1)	16-40
L5 Costal Process Length (mm) (calc)	95	15.3(4.4)	84	15.4(3.9)	3-26
L5 Relative Costal Process Length (%) (calc)	95	34.8(8.4)	84	37.1(7.5)	8-54%
L5 Costal Process Difference (%) (calc)	95	3.0(3.3)	84	2.6(3.1)	0-10%
L3 Body Transverse Diameter (mm)	90	50.6(4.5)	79	45.3(4.1)	38-64
L3 Body Anterior Posterior (mm)	90	34.2(2.7)	79	30.3(2.8)	25-41
L3 Maximum Diameter (mm)	90	85.9(11.1)	79	79.7(11.5)	29-110
L3 Left Costal Process (mm)	90	34.2(5.8)	79	31.4(5.1)	15-44
L3 Right Costal Process (mm)	90	33.6(5.7)	79	31.3(5.7)	14-45
L3 Costal Process Length (mm) (calc)	90	17.8(5.3)	79	17.5(4.7)	3-30
L3 Relative Costal Process Length (%) (calc)	90	40.5(9.1)	79	42.9(7.9)	10-61%
L3 Costal Process Difference (%) (calc)	90	2.3(3.0)	79	1.9(2.6)	0-10%
Femur Length (mm)	100	455(23.8)	96	431.8(23.3)	377-511

Table 4. Results of Student's *t*-tests for Comparisons of Black Males (BM), Black Females (BF), White Males (WM) and White Females (WF) on Each Study Measure.<sup>1</sup>

Variable	BM vs. WM	<i>p</i>	BF vs. WF	<i>p</i>	BM vs. BF	<i>p</i>	WM vs. WF	<i>p</i>
S1 Body Transverse Diameter	ns	.303	WF	<.001	BM	<.001	WM	.010
S1 Body Anterior Posterior	ns	.099	WF	.004	BM	<.001	WM	<.001
S1 Maximum Diameter	WM	<.001	WF	<.001	ns	1.00	ns	.121
S1 Left Costal Process	WM	<.001	WF	<.001	ns	1.00	ns	.740
S1 Right Costal Process	WM	<.001	WF	<.001	ns	1.00	ns	.221
S1 Costal Process Length (calc)	WM	<.001	WF	<.001	BF	.014	ns	1.00
S1 Relative Costal Process Length (calc)	WM	.050	ns	1.00	BF	.001	ns	1.00
S1 Costal Process Difference (calc)	ns	1.00	ns	.728	ns	1.00	ns	1.00
L5 Body Transverse Diameter	WM	.028	WF	.021	BM	<.001	WM	<.001
L5 Body Anterior Posterior	WM	.008	ns	.403	BM	<.001	WM	<.001
L5 Maximum Diameter	WM	.001	WF	<.001	BM	.001	WM	<.001
L5 Left Costal Process	WM	<.001	WF	.005	BM	.040	WM	.001
L5 Right Costal Process	WM	<.001	WF	.016	BM	.011	WM	<.001
L5 Costal Process Length (calc)	WM	<.001	ns	.127	ns	1.00	ns	.436
L5 Relative Costal Process Length (calc)	WM	.041	ns	1.00	ns	.303	ns	1.00
L5 Costal Process Difference (calc)	ns	.999	ns	1.00	ns	1.00	ns	1.00
L3 Body Transverse Diameter	WM	<.001	WF	.006	BM	<.001	WM	<.001
L3 Body Anterior Posterior	WM	<.001	WF	<.001	BM	<.001	WM	<.001
L3 Maximum Diameter	ns	.104	ns	1.00	BM	.002	WM	<.001
L3 Left Costal Process	WM	.040	ns	1.00	BM	.040	WM	.001
L3 Right Costal Process	ns	1.00	ns	1.00	BM	.011	WM	<.001
L3 Costal Process Length (calc)	ns	1.00	ns	1.00	ns	1.00	ns	.228
L3 Relative Costal Process Length (calc)	ns	1.00	ns	1.00	ns	.529	ns	1.00
L3 Costal Process Difference (calc)	ns	1.00	ns	1.00	ns	1.00	ns	1.00
Femur Length	WM	<.001	WF	.014	BM	<.001	MW	<.001

<sup>1</sup>ns = not significant

The sexes for both black and whites are not significantly different for 10 variables: maximum diameter between the costal processes for S1; calculated costal process length for L5 and L3; left and right costal processes for S1; relative costal process length for L5 and L3; and costal process difference for S1, L5, and L3.

Table 5 and 6 present results of paired *t*-tests comparing bilateral measurements within all four samples. There is no significant asymmetry between left and right costal processes of S1, L5, and L3 in black males, black females, and white males. Only white females are found to possess significant asymmetry between the left and right costal processes of S1, L5, and L3. Sign tests (Table 7) are used to test for directionality of asymmetry for left and right costal process measurements across the four samples. No significant directional asymmetry is found between the left and right costal processes for males and females.

Table 5. Paired Student's *t*-tests of Right and Left Costal Process Measurements between Black Males (BM) and Black Females (BF).

Variable	BM <i>n</i>	BM Mean (sd)	<i>t</i> ( <i>p</i> )	BF <i>n</i>	BF Mean (sd)	<i>t</i> ( <i>p</i> )
S1 Costal Process			-.37(.71)			-.51(.61)
Left	100	36.2(5.4)		96	36.8(5.2)	
Right	100	36.3(5.5)		96	37.0(5.5)	
L5 Costal Process			1.16(.25)			1.7(.09)
Left	95	31.3(3.7)		84	29.5(4.1)	
Right	95	30.8(3.7)		84	28.8(4.1)	
L3 Costal Process			1.08(.28)			
Left	90	34.8(5.8)		79	31.4(5.1)	.21(.83)
Right	90	33.6(5.7)		79	31.3(5.7)	

Table 6. Paired Student's *t*-tests of Right and Left Costal Process Measurements between White Males (WM) and White Females (WF).<sup>1</sup>

Variable	WM <i>n</i>	WM Mean (sd)	<i>t</i> ( <i>p</i> )	WF <i>n</i>	WF Mean (sd)	<i>t</i> ( <i>p</i> )
S1 Costal Process			-1.15(.25)			- 2.11(.04)*
Left	98	40.9(5.3)		100	42.1(6.4)	
Right	98	41.3(6.6)		100	43.1(6.3)	
L5 Costal Process			-1.07(.29)			2.16(.03)*
Left	95	34.0(4.1)		94	31.7(5.0)	
Right	95	34.4(4.6)		94	30.8(4.8)	
L3 Costal Process			1.7(.09)			2.03(.05)*
Left	90	35.9(6.4)		87	31.8(5.4)	
Right	90	34.7(7.0)		87	30.6(5.7)	

<sup>1</sup>\* = significant

Table 7. Sign Tests of Asymmetry for Right and Left Costal Process Measurements across Multiple Subgroups.

Variable	White Females <i>n</i>	<i>z</i> ( <i>p</i> )	All Males <i>n</i>	<i>z</i> ( <i>p</i> )	All Females <i>n</i>	<i>z</i> ( <i>p</i> )
S1 Costal Process (# Larger)		-.158 (.114)		-.227 (.820)		-1.503 (.133)
Left	37		85		78	
Right	53		89		99	
Ties	10		24		19	
L5 Transverse Process (# Larger)		-.327 (.743)		-.236 (.814)		-1.692 (.091)
Left	44		73		88	
Right	40		89		66	
Ties	10		28		24	
L3 Transverse Process (# Larger)		-1.778 (.075)		-1.640 (.101)		-1.572 (.116)
Left	49		93		83	
Right	32		71		63	
Ties	6		16		20	

## CHAPTER 4: DISCUSSION

### 4.1. Size Variation

Results of this study demonstrate that white South Africans possess a significantly wider sacrum than black South Africans. This study shows that whites of both sexes are larger than blacks in maximum diameter between the costal processes for S1 (sacral width) and L5, calculated costal process length for S1, left and right costal processes for S1 and L5, transverse diameter of the body for L5 and L3, anteroposterior diameter of the body for L3, and femur length (Table 4). Tague (2007) reported that North American whites possess a significantly longer relative costal process of S1 than North American blacks. This study, however, found only white males were larger than black males while no significant difference was found between white females and black females.

Sacral breadth at S1 is comprised of breadth of the body of S1 and length of the costal processes of S1. This study found that white females were larger than black females in the transverse diameter of the body for S1. Tague (2007) demonstrated that the costal process of S1 contributes to the transverse diameter of the pelvic inlet by separating the ilia. By inference, South African whites are likely to have a wider pelvic inlet than South African blacks. Two possible interpretations, nutritional differences and climatic adaptation, are addressed. Size variation may be a result of nutritional differences related to socioeconomic status. Alternatively, size variation may be a result of climatic adaptation based on thermoregulatory principles, namely Bergmann's Rule.

## **4.2. Reasons for Variation in Size**

### **4.2.1. Variation in Size Due to Nutritional Differences**

The Pretoria Bone Collection is a relatively recent collection, founded in 1987 (L'Abbé and Steyn 2012). The skeletal material from the Pretoria Bone Collection is completely cadaver based. The individuals within the collection are either unclaimed or donated cadavers given to the anatomy department at the University of Pretoria (Patriquin et al. 2005, 2003, 2002). The National Health Act 2003 passed in South Africa states that public hospitals may send unclaimed remains to medical institutions for the purposes of medical instruction and research (L'Abbé and Steyn 2012). The majority of black males in the Pretoria Bone Collection were acquired from local hospitals after no relatives claimed the remains (L'Abbé and Steyn 2012). Many of these black males were migrant laborers of low socioeconomic status from rural areas seeking work in larger cities. Limited communication with family still living in rural areas often leads to deaths going unnoticed or funeral costs deemed too high (L'Abbé et al. 2005). However, donated material primarily consists of white individuals of European descent, often over the age of 60 (L'Abbé and Steyn 2012; L'Abbé et al. 2005; Dayal et al. 2009).

The composition of the Pretoria Bone Collection is affected by socioeconomics, history, and disease pandemics. From 1948-1994, Apartheid legislation led by Afrikaner minority rule enforced racial segregation over the black majority as well as other ethnic groups (Beck 2000). Residential segregation and mass-removal of non-white South Africans ultimately led to the formation of 10 tribally based independent Bantustans or 'homelands', often in the most arid and inhospitable parts of the country (Wisner 1989). The white minority controlled proper medical care, education, agricultural land and water resources while inferior services were provided for blacks (Beck 2000). Black residents of Bantustans, predominately females, children, and the

elderly, became dependent on purchased food and remitted incomes from male migrant workers (Wisner 1989). Apartheid rule and dependence on a migrant labor system directly led to severe chronic malnutrition in black South Africans, especially among children. During the 1970's, malnutrition and severe forms of starvation such as kwashiorkor (deficiency in dietary protein) and marasmus (energy deficiency) accounted for 75% of children in KwaZulu having stunted growth (33% for the entire country) and 40% of recorded hospital deaths (Scragg and Rubidge 1978).

The first racially inclusive democratic election held in 1994 led to the victory of the African National Congress (ANC), officially ending Apartheid rule (Beck 2000). Through the Reconstruction and Development Programme, the ANC aimed to transform the country by reducing poverty afflicting the majority of the population (Aliber 2003). However, attempts by the government to reduce chronic poverty shaped by colonialism have struggled. Consistent short term projects combating poverty have not been enough to reduce the rate of unemployment over sustained periods of time which has led to a new dependence on social security grants and 'developmental welfare' rather than achieving economic self-sufficiency (Aliber 2003). South Africa today has the third most unequal economy in the world, with half the population living below the poverty line (World Health Organization 2014). Malnutrition is the second most common cause of death for children, and is prevalent among lower socioeconomic groups due to food insecurity, living conditions, and inadequate medical care (Beck 2000).

Chronic malnutrition shaped by Apartheid and modern socioeconomic conditions have increased the rate of disease. Beginning in the early 1980's, the HIV/AIDS epidemic led to a dramatic decline in life expectancy in South Africa (Aliber 2003; Beck 2000). Well known symptoms for HIV and AIDS include severe weight loss known as wasting and a weakened

immune system. In children, HIV/AIDS often leads to stunted growth and shorter stature (Center for Disease Control 2013). The most densely populated HIV/AIDS affected areas include the KwaZulu-Natal and Gauteng province (where Pretoria is located), with over half of all blacks being infected. Infection throughout the entire country is exceedingly divided by race; approximately 13.6% of blacks are HIV-positive compared to only 0.3% for whites (World Health Organization 2014). From 1900 to 1990, life expectancy for black South Africans steadily increased from approximately 37 years to 63 years. However post 1990, life expectancy sharply dropped to approximately 51 years due to HIV/AIDS (World Health Organization 2006). The HIV/AIDS epidemic resulted in larger number of young individuals (less than 50 years of age with an increase in 30-39 and 40-49 year old categories) being accessioned into the Pretoria Bone Collection (L'Abbé and Steyn 2012).

A narrower sacrum, and therefore pelvis, in South African blacks may be a reflection of nutritional deficiencies related to socioeconomic status, disease, or both. Unlike their white counterparts, blacks suffering from poor nutrition would be less likely to meet their maximum growth potential resulting in a permanent reduction to bone size and stature. However, because the direction in difference in size between black and white South Africans is similar to that of North American black and whites, the composition of other skeletal collections must be taken into account. Two North American collections repeatedly used for the study of the sacrum and pelvis include the Hamann-Todd and Terry Collections, located at the Cleveland Museum of Natural History and the National Museum of Natural History, Smithsonian Institution, respectively (Tague 2007, 1989; İşcan 1983; Flander 1978). Both collections primarily consist of individuals from the late 19th to 20th centuries donated by hospitals or morgues after no relatives came to claim them (Hunt and Albanese 2005). Within the Hamann-Todd collection, black and



white individuals are both of low socioeconomic class and questionable nutritional status (İşcan 1983). While the United States shares a history of racial segregation with South Africa, resulting in inequality between blacks and whites, the similar low socioeconomic status of individuals in the Hamann-Todd and Terry collections as well as lack of chronic malnutrition in the United States weakens the conclusion that size variation in the South African sample is strictly due to nutritional differences. Nutritional differences may, instead, simply exaggerate preexisting genetic size variation.

#### 4.2.2. Variation in Size Due to Climatic Adaptation

General body morphology among modern humans varies clinally according to theoretical expectations based on thermoregulatory principles such as Bergmann's and Allen's Rules (Gruss and Schmitt 2015; Holliday and Hilton 2010; Ruff 2002). Bergmann's Rule states that large-bodied populations of a morphologically variable species spanning a large geographic range will be found in colder parts of the range, while small-bodied populations will be found in warmer parts of the range (Ruff 1994). Under the same conditions, Allen's Rule states that populations with shorter extremities will be found in colder environments, while those with longer extremities will be found in warmer environments (Ruff 1994). Both Rules reflect a relationship between surface area (SA) and body mass (BM) where SA/BM is maximized in warmer climates to help facilitate heat loss and minimized in colder climates to help maintain internal body temperature (Betti 2014; Ruff 1991).

Ruff (1994, 1991) demonstrated that for modern humans estimation of body surface area and mass can be modeled as a cylinder. Stature estimated from long bones of the limbs, most commonly the femur, is used to represent the height of the cylinder while bi-iliac breadth of the pelvis is used to represent the breadth of the cylinder (Ruff 2002, 1994; Feldesman et al. 1990).

The calculation of surface area and mass from the 'cylindrical model' of the human body demonstrates two patterns. First, surface area to mass ratio remains constant as long as the width of the cylinder does not change. Second, change in width always produces the same change in surface area/body mass regardless of height; an increase in width produces a decrease in the ratio while a decrease in width produces an increase in the ratio (Ruff 1991). When applied to thermoregulation, these two patterns predict that populations living in similar climatic conditions will have similar body breadths regardless of stature (since a constant SA/BM ratio is still maintained) and populations living in different climatic conditions will have different body breadths (with individuals living in colder environments having absolutely wider bodies producing a smaller SA/BM ratio than individuals living in warmer environments, who have absolutely narrower bodies producing a larger SA/BM ratio; Ruff 1994).

Ruff (1991) analyzed stature and bi-iliac breadth data for 71 living human populations. All samples fell into one of four broad geographically defined groups. Sub-Saharan Africans, southeastern Asians, Europeans (mostly Western European), and northern Asian-derived (Eskimos, Aleuts, and Apaches) were used to broadly represent tropical, subtropical, cold-temperate, and subarctic to arctic climates respectively. The first pattern of the cylindrical model was observed when bi-iliac breadth was plotted against stature, demonstrating that as populations within the same climatic zone increase in stature, they also become more linear (the ratio of bi-iliac breadth to stature decreases). Regardless of sex, the tallest representatives of each climatic zone were also found to be the relatively thinnest while the shortest representatives were found to be the relatively stockiest (Ruff 1991). The second pattern of the cylindrical model was also observed in modern human populations. Systematic differences were found in absolute body breadth among populations in different climatic conditions regardless of variation in stature, with

those in colder climates having absolutely wider bodies and those in warmer climates having absolutely narrower bodies.

Ruff (1994) also conducted a similar study looking at stature and bi-iliac breadth using 56 living human populations, although samples were not limited to four specific regions and absolute latitude was used instead of four broad geographically defined groups. Results are the same as Ruff's (1991) previous study with the exception of two outliers, Polynesians and African Pygmies, highlighting that the use of latitude may sometimes be a misleading guide when assessing potential thermal stress in humans. No outliers are seen when climatic zones are used instead of latitude. Representing a tropical population in the Pacific region and generally living within 25° latitude of the equator, Polynesians are both a tall and heavy people. This outlier can be explained by understanding their traditional way of life, where long distance travel in open boats over cool waters (as low as 21°C) and in windy conditions is frequent (Houghton 1990). As an adaptation to great cold thermal stress, the combination of a large, lean body mass with vigorous exercise resulting in high heat production allowed for survival during open sea voyages. This specific body type has been in existence in the southwestern Pacific for at least 4,000 years, and the environmental conditions under which it evolved spans tens of thousands of years earlier (Houghton 1990). Difference in stature from expected results based on the cylinder model found among African Pygmies demonstrated that tropical populations may be tall or short, provided that SA/BM is kept low (Ruff 1994; Schreider 1964). Although Pygmies are short and stocky and other African populations are tall and long, both groups have similar body breadths. Difference in stature is related to humidity and openness of environment, rather than variation in temperature (Hiernaux et al. 1975). Evaporation of sweat from the skin is the primary mechanism for heat dissipation for humans living in hot environments. However, in humid

environments with little or no airflow evaporation is ineffective (Ruff 1991). In order to prevent overheating during physical activities, African Pygmies and other Pygmy populations living in hot and humid environments have adapted to limit body mass itself as a means to limit heat production (Ruff 1994). In contrast to African Pygmies, taller tropical populations inhabit relatively drier and more open environments (such as the semi-arid grasslands south of the Sahara desert) where evaporative heat loss is most effective.

Overall, absolute body breadth shows the strongest relationship to climate in modern humans and variation in body breadth has been demonstrated to be the principal driving force behind latitudinal change in body mass and SA/BM (Ruff 1993). McHenry (1992) demonstrated that body mass is positively associated with the product of the anteroposterior and transverse diameter of the superior aspect of the body of S1. Although the transverse diameter of the body of S1 is a component of sacral breadth (comprised of breadth of the body of S1 and length of the costal processes of S1), it is statistically independent from costal process length of S1 which has been directly associated with obstetric demands (Tague 2007). While white South Africans in this study possessed larger measurements on average than black South Africans, only white females possessed a significantly larger anteroposterior and transverse diameter of the body of S1 than black females. There were no significant differences between the white and black males. However, white South Africans have a significantly wider sacrum than blacks. Because there are no significant differences in the body of S1 in males, the larger sacral breadth in white males is a result of the contribution of significantly larger costal processes of S1. Costal process length of S1 contributes to the circumference of the pelvic inlet as well as the transverse diameter (Tague 1992). A wider sacrum also contributes to a greater distance between the ilia, and therefore bi-iliac breadth. Tague (1992) demonstrated that sacral breadth is strongly correlated with the

transverse diameter of the false pelvis. Bi-iliac breadth, the maximum mediolateral breadth of the pelvis, is one of the best measurements for estimating general body breadth (Ruff 1994).

As well as having a significantly wider sacrum than blacks, white South Africans of both sexes also have a longer femur. By inference, white South Africans are of taller stature than black South Africans. If white South Africans are descended from populations adapted to cold climatic conditions and black South Africans descended from populations adapted to warm climatic conditions, then the narrower sacrum and smaller stature of blacks may be a result of long term thermoregulatory adaptation.

Composition of the Pretoria Bone Collection almost entirely consists of blacks and whites. White South Africans are predominately of Western European ancestry, specifically Afrikaner and English (Patriquin et al. 2002). Europe is part of the North Temperate Zone which lies between tropic and polar regions. The four annual seasons occur in the North Temperate Zone, and temperatures range from warm to cool (Small and Cohen 1998). Afrikaners are primarily descended from Dutch immigrants who first arrived in South Africa during the 17th and 18th centuries. However, Afrikaner ancestry also includes German and French Huguenot immigrants as well as minor percentages of other European ancestries and indigenous African populations (Beck 2000). Black South Africans in the Pretoria Bone Collection are of Bantu ancestry. Unlike the Khoisan, Bantu groups were not originally indigenous to South Africa. Rather, they migrated from Central Africa to South Africa circa 500 CE (Beck 2000). Central Africa lies in the Tropical Zone which surrounds the equator and where the sun points directly overhead at least once a year. The Tropical Zone is warm to hot all year, and annual seasons do not occur (Small and Cohen 1998).

Zulu, Ndebele, Xhosa, and Swazi (Nguni) populations settled the east coast of modern day South Africa. South Africa falls in the Southern Hemisphere subtropical zone, with temperatures ranging from 32°C in the summer and 4°C in the winter in the Free State and Gauteng provinces (South African Info 2015). Tswana, Basotho, and Pedi (Sotho-Tswana) populations settled the interior Highveld, and the Shangaan-Tsonga, Venda, and Lemba populations settled the north east (Beck 2000). The most represented groups used for this study include Sotho, Zulu, and Xhosa. Despite the existence of multiple tribal and ethnic groups, there are not enough osteological differences among them to necessitate separation in analysis (Patriquin et al. 2005). South African blacks may therefore represent a population historically adapted to warm climatic conditions, while South African whites represent a population historically adapted to cold climatic conditions.

The ancestry of blacks and whites in the Hamann-Todd and Terry Collections is comparable to those of the Pretoria Bone Collection in terms of latitudinal climate. German American, Irish American, English American, and Italian American are the four largest self-reported white ancestry groups; however, certain Middle Eastern, South American, and North African groups also identify as white in the United States (United States Census 2014). The majority of North American blacks are descended from West and Central Africans who were brought to the United States as enslaved persons. Caribbean, African, Central and South American immigrants, whose ancestors were also Africans, may also identify as black (United States Census 2014). Consequently, North American blacks and whites may also represent populations historically adapted to warm and cold climatic conditions, respectively.

If size variation in the sacrum has a genetic basis as a result of climatic adaptation, both South African and North American populations should yield similar results. Short-term non-

genetic changes to nutritional variation involve changes in stature rather than body breadth. Froehlich (1970) observed secular changes in stature and bi-iliac breadth for three generations of Japanese Americans living in Hawaii. Stature significantly increased by 8% for males and 5% for females; however, there was no significant change in bi-iliac breadth. Skeletal body breadth is a more evolutionary conservative feature than stature and limb length (Ruff 1994). In order for skeletal effects on body breadth to be seen, populations would need to inhabit a climatic zone for a substantial amount of time, perhaps tens of thousands of years (Ruff 2002). Because body breadth remains constant with SA/BM, changing body mass by altering stature but not body breadth is an effective means to adapt to rapid nutritional changes while continuing to maintain a sufficient thermoregulatory adaptation to climate (Ruff 1994).

Comparison between South African black and whites and North American black and whites supports the interpretation that size variation in the sacrum is a result of long term adaptation to climate. Tague (2007) reports that North American whites are on average larger than blacks as well as significantly larger for certain measurements also found in this study, such as maximum diameter for S1, calculated costal process length for S1, and anteroposterior diameter of the body for L3. North American whites were also found to be larger than North American blacks for transverse diameter and circumference of the pelvic inlet. Both this study and Tague's (2007) found that whites possess a significantly wider sacrum than blacks. The wider sacrum of white South Africans and white North Americans, and by inference a wider pelvis, may be a reflection of Bergmann's rule where an increase in body mass, and consequently body breadth, results in the decrease of SA/BM as a means to maintain internal body temperature in cold environments. The narrower sacrum of black South Africans and black North Americans may reflect an increase in SA/BM which increases exposed surface area as a means to maximize

heat dissipation in warm environments. Unlike short term variation in stature due to nutrition or socioeconomic status, the wider sacrum of whites and the narrower sacrum of blacks may reveal a deeper evolutionary history, providing an explanation for the origin of metric differences found between phenotypic populations according to latitude.

### **4.3. Explanation of Results in Terms of Sexual Dimorphism**

Results demonstrate varying degrees of sexual dimorphism between black and white South Africans. This study shows that males are larger than females in transverse diameter of the body for S1, L5, and L3; anteroposterior diameters of the body for S1, L5, and L3; maximum diameter between the costal processes for L5 and L3; left and right costal processes for L5 and L3; and femur length. Black females have a significantly longer calculated costal process length of S1 than black males. Interestingly, no significant differences in the calculated costal process length of S1 for white females were found when compared to white males. These results differ from Tague (2007) who reported that both black and white North American females possess a larger calculated costal process length of S1 and relative costal process length of S1 than males. Flander (1978) demonstrated that the body of S1 is significantly wider in males than females, but males and females did not differ significantly in the breadth of the sacrum. Both Tague's (2007) and Flander's (1978) studies used material from the Terry Collection. The long costal process of S1 in females is inferred to be associated with selection for obstetrical sufficiency of the pelvis. The costal process of S1 contributes to the circumference and transverse diameter of the pelvic inlet (Tague 2007).

This study found males possess significantly larger left and right costal processes for L3 and L5 than females. However, Tague (2007) reported that among black and white North Americans the sexes were not different for L1 and L5 while males possessed a longer costal



process than females for L2 and L3. Despite these differences, both studies showed that for other vertebral measurements (such as the transverse and anteroposterior diameters of the body for L5 and L3) males were typically larger than females.

No asymmetry between the left and right costal processes of S1, L5, and L3 was found among black males, black females, and white males. No significant directional symmetry was found between the left and right costal processes of males and females. Significant asymmetry between the left and right costal processes of S1, L5, and L3 was only found in white females (Tables 5, 6). As nutritional deficiency may result in asymmetry, this result is unexpected given that white South African females likely had a higher nutritional status than black South African females (L'Abbé and Steyn 2012). One would expect that black South Africans, the group that faced chronic malnutrition, would exhibit more asymmetry than their white counterparts. Further research needs to be done to determine the cause of such significant asymmetry in white South African females.

While differential climatic adaptation has shaped population differences in body size and proportions (especially pelvic breadth) in modern humans, strong stabilizing selection acting to maintain a sufficiently spacious birth canal for parturition has preserved some obstetrical dimensions in females independent of body size. This general pattern is valid regardless of ancestry or geographical location (Betti 2014). Sexual dimorphism in the human pelvis, therefore, reflects differential selection on the two sexes (Correia et al. 2005). Though males are larger than females for some pelvic measurements, certain obstetrically relevant measurements demonstrate a reverse pattern with females larger than males, such as pubic and bi-acetabular length (Kurki 2007; Correia et al. 2005). Other traits that appear identical in size in males and females are often noticeably dimorphic when size is taken into account and different proportions

are revealed (Betti 2014). Once size has been taken into account, shape differences in the pelvis are significant and are extensively used in visual sex determination. Features of the pelvis that display sexual dimorphism in females include the shape of the auricular surface, subpubic angle, ischial tuberosity, sciatic spine, as well as width of the sciatic notch and pubic length (Kurki 2011; Steyn and Patriquin 2009; Weaver 2002; Phenice 1969). The larger costal process of S1 in females than in males also contributes to the overall capacity of the pelvic inlet (Tague 2007). Despite females possessing a larger costal process of S1, both males and females do not significantly differ from one another in breadth of the sacrum.

Although population differences in sexual dimorphism exist, they appear to be relatively minor aspects of shape variation and do not contradict the evidence for broader climatic and obstetrical patterns shared by all human populations (Kurki 2011; Steyn and Patriquin 2009). Consideration of these patterns is important because the selection of a large, obstetrically sufficient pelvis has been hypothesized to conflict with the thermoregulatory demands of a narrow pelvis in hot environments. As a result, females in small bodied populations may face more difficulties during parturition. Such a conflict which might not present itself in colder environments where a larger pelvis would be favored (Betti 2014; Kurki 2007).

#### **4.4. Overview of Sexual Dimorphism, Obstetrics, and Climatic Adaptation**

##### **4.4.1. Sexual Dimorphism and Obstetrics**

Modern humans possess a unique birth mechanism which is considerably more complicated and dangerous than in great apes (Grabowski 2013; Rosenberg and Trevathan 2002). This birth mechanism and distinctive cephalopelvic proportions in modern humans are hypothesized to be the result of evolutionary constraints imposed by selection for efficient

bipedalism and a large neonatal cranium and body size relative to maternal pelvic dimensions (Correia et al. 2005).

Bipedal locomotion is one of the primary traits distinguishing hominins from all other primates. Locomotor differences therefore result in differences in pelvic morphology. In modern humans, bipedal locomotion has favored a shorter and wider pelvis with a short and broad ilium for efficient upright walking, weight bearing posture, and visceral support (Correia et al. 2005; Lovejoy et al. 1973). The iliac blades face laterally and flare outward, producing a bowl shaped pelvis which allows the lesser gluteals to cross laterally over the hip to act as abductors and assist in bipedal walking. Quadrupedal primates, such as chimpanzees, where the center of mass is not directly placed over the foot, possess a long and narrow pelvis with a thin ilium (Lovejoy 1988). While humans of both sexes are under selection due to bipedal locomotion, in females the demands of bipedal locomotion for a relatively narrower pelvis are in contrast with selection for a spacious pelvis and wide birth canal which allow enough space for delivery of a large neonate (Rosenberg and Trevathan 2002). Competition between these two pressures would have been of significant selective importance in past populations, as an obstetrically insufficient pelvis could lead to difficulties during birth, likely resulting in the death of the neonate or mother (Kurki 2007).

The circumference of the pelvic inlet is also minimally altered due to the effects of the hormone relaxin (MacLennan 1991). Therefore, obstetrical adequacy of the inlet is ensured by lengthening one or more of its components relative to males (Tague 2007). The larger calculated costal process of S1 in black South African females relative to that of black South African males may be a reflection of this. A larger costal process of S1 in females helps contribute to the overall capacity of the pelvic inlet, such as the circumference and area, which have been

demonstrated to be some of the most important obstetric dimensions (Tague 2007; Correia et al. 2005).

#### 4.4.2. Sexual Dimorphism and Climatic Adaptation

Within a given population, taller and larger bodied women have been demonstrated to possess larger pelvic canals than shorter and smaller bodied women (Kurki 2011; Rosenberg 1992). In modern populations, small bodied women of shorter stature are at a higher risk for cephalo-pelvic disproportion (Sheiner et al. 2005; Prasad and Al-Taher 2002; Witter et al. 1995). Cephalo-pelvic disproportion is caused by a discrepancy between the size of the mother's birth canal and neonatal cranium, often resulting in surgical intervention. In pre-modern populations, cephalo-pelvic disproportion could have resulted in the death or injury of the mother or neonate (Toh-adam et al. 2011; Kurki 2007). Maternal and neonatal size are related; however, pre-pregnancy weight and weight gain during pregnancy are more directly related to neonatal size. Small women, therefore, do not necessarily give birth to small neonates (Pickett et al. 2000; Flegal et al. 1993). The small body size of black South African females as a result of climatic adaptation may place this population at a higher risk for developing problems during birth. As costal process length is correlated with circumference and transverse diameter of the pelvic inlet, the significantly smaller calculated costal process length of S1 and instrumentally determined left and right costal process length of S1 in black South African females implies that they possess a smaller pelvic inlet than white South African females. However, lateral flare of the ilia is also known to contribute to pelvic inlet breadth.

Variations in the relationships between obstetric pelvic size variables and body size variables highlight the complex relationship between selection for an obstetrically sufficient pelvis and for overall body size (Kurki 2011). Kurki (2007) proposes that selective forces acting

on pelvic size and overall body size may be independent from one another to ensure adequate pelvic capacity in small-bodied populations. Certain pelvic dimensions have been found to be highly sexually dimorphic and obstetrically important independent of body size, such as the posterior space of the inlet, transverse diameter of the outlet, subpubic angle, and sacral angle (Tague 2000). Independent selection between these pressures would mean that small bodied women would not necessarily have small pelves (Kurki 2007). However, other obstetrically important dimensions such as the circumferences and areas of the inlet, midplane, and outlet are moderately correlated with body size (Tague 2000). Therefore, these findings suggest that in small-bodied populations females would have absolutely smaller dimensions than females in large-bodied populations (Kurki 2007; Rosenberg and Trevathan 2002). Tague (2000) also shows that femoral head diameter and clavicular length are positively correlated with pelvic capacity in females. Femoral length, used as an estimate for stature, shows limited association with pelvic capacity, suggesting that body mass is more important than stature when predicting pelvic capacity among females.

If small neonates were at a disadvantage for survival, larger neonatal size relative to maternal size has been proposed to be a beneficial adaptation (Pickett et al. 2000; Flegal et al. 1993). As weight gain during pregnancy largely determines neonatal size rather than maternal body size, adaptive allometric modeling of the pelvis may mitigate potential difficulty that would arise from variation in the amount of weight gain during pregnancy. This would allow for neonates in a smaller-bodied population to be larger relative to maternal size (compared to this relationship in larger-bodied populations), which could be important if small neonates were at a disadvantage for survival (Kurki 2007). However, small-bodied populations still possess a higher risk for cephalo-pelvic disproportion. Due to the smaller body size of black South African

females, this population is likely at greater risk for obstetric difficulties such as cephalo-pelvic disproportion than large-bodied white South-African females.

#### **4.5 Overview of Asymmetry**

Dental and skeletal asymmetry research has been used as a way to estimate the level of developmental stability in multiple organisms (Albert and Greene 1999). Developmental stability is the capability of an organism to grow and mature to its phenotypic potential under a variety of environmental conditions (Møller 1997). Among humans, environmental stress (such as nutritional and climatic influence on growth and development) has been demonstrated to affect asymmetry by disrupting developmental stability and may result in differential rates on either side of the median plane (Little et al. 2002; Albert and Greene 1999).

Biomechanical stress acting upon the skeleton also may affect asymmetry as the skeleton can undergo remodeling in response to mechanical force (Trinkaus 1978). There are two common types of asymmetry: fluctuating and directional. Fluctuating asymmetry does not favor one side of the body over the other and is strongly linked with genetic regulation. Directional asymmetry reflects environmental influences and favors one side of the body consistently over the other (Little et al. 2002; Albert and Greene 1999). Asymmetry in the post-cranial skeleton is also affiliated with congenital anomalies such as birth defects or long term disabilities. Consideration of asymmetry for S1, L5, and L3 in modern human populations is important because it may negatively impact efficient bipedalism, obstetrics, or both.

As females are under selective pressure for an obstetrically sufficient pelvis, this may result in symmetry being favored over asymmetry. Stress that disrupts the bilateral symmetry of the sacrum may in turn influence the pelvis, resulting in an obstetrically insufficient pelvis risking the lives of both mother and infant. Interestingly, only white females possessed

significant asymmetry among the costal processes of S1, L5, and L3 (Table 6). Asymmetry among the costal processes of S1, L5, and L3 was not found among black males, black females, or white males. Asymmetry is unexpected in white females due to the socioeconomic disparity between black and white South African populations. As discussed earlier, white South Africans in the Pretoria Bone Collection are of a higher socioeconomic standing than black South Africans. Because asymmetry is predominately influenced by environmental stress, asymmetry would be expected to be found in black South Africans rather than white South Africans given that they are under more socioeconomic and nutritional stresses that may disrupt developmental stability.

Asymmetry in white females may therefore have a genetic basis, reflecting a higher risk for pathology such as scoliosis. Scoliosis has been shown to be more prevalent in females than males as well as in white populations than black (Palastanga et al. 1998). If asymmetry in the length of the costal process of S1 alters the dimensions of the birth canal, it could also place white females at a higher risk for complications during childbirth. In its most extreme form, asymmetry may lead to an obliquely contracted pelvis called Naegele's pelvis (Williams 1929). The direct cause of asymmetry in the sacrum of white South African females, however, requires further study.

## CHAPTER 5: CONCLUSION

This study shows that black South Africans possess a narrower sacrum than white South Africans. Two interpretations were addressed. Size variation may have been a result of nutritional differences related to socioeconomic status or climatic adaptation based on thermoregulatory principles such as Bergmann's rule. Comparisons of the sacrum between South African and North American blacks and whites did not support the interpretation that size variation is strictly due to nutritional differences. While the United States shares a history of racial segregation with South Africa resulting in inequality between blacks and whites, shared socioeconomic status of black and white individuals in North American collections and a lack of chronic malnutrition in the United States as opposed to South Africa weakens the conclusion that size variation is strictly due to nutritional differences. However, these comparisons did support the interpretation that size variation in the sacrum is the result of long term adaptation to climate.

White South Africans also possessed significantly larger costal processes than black South Africans. The calculated costal process of S1 in black South African females was unique in that it was found to be significantly larger than black South African males. The sexually dimorphic costal process of S1 is under obstetric selective pressure and is known to contribute to the circumference and transverse of the pelvic inlet (Tague 2007). As black South Africans possess a narrower sacral breadth, this small-bodied population may face a higher risk for difficulties during birth such as cephalopelvic disproportion. Because this study supports the interpretation that size variation in the sacrum is due to long term adaptation to climate, the narrow sacrum of black South Africans may reflect the conflict between obstetric and thermoregulatory demands in a hot environment. White South Africans, who possess a larger sacral breadth, would not face the same challenge.



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