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Secular Change of the Modern Human Bony Pelvis: Examining Morphology in the United States using Metrics and Geometric Morphometry

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To the Graduate Council:

I am submitting herewith a dissertation written by Kathryn R.D. Driscoll entitled "Secular Change of the Modern Human Bony Pelvis: Examining Morphology in the United States using Metrics and Geometric Morphometry." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

Richard L. Jantz, Major Professor

We have read this dissertation and recommend its acceptance:

Andrew Kramer, Murray K. Marks, Dawn P. Coe

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Dissertation Presented for
the Doctorate of Philosophy
Degree
The University of Tennessee, Knoxville

Kathryn Driscoll
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Abstract

The human bony pelvis has evolved into its current form through competing selective forces. Bipedalism and parturition of large headed babies resulted in a form that is a complex compromise. While the morphology of the human pelvis has been extensively studied, the changes that have occurred since the adoption of the modern form, the secular changes that continue to alter the size and shape of the pelvis, have not received nearly as much attention. This research aims to examine the changes that have altered the morphology of the human bony pelvic girdle of individuals in the United States born between 1840 and1981.

Secular changes in the human skeleton have been documented. Improvements in nutrition, decreased disease load, exogamy, activity, climate, and other factors have led to unprecedented growth in stature and weight. The size and shape of the pelvic canal, os coxa, and bi-iliac breadth were all examined in this study. Coordinate data from males and females, blacks and whites were digitized. Calculated inter-landmark data was analyzed using traditional metric methods and the coordinate data was analyzed using 3D geometric morphometrics.

After separating the samples into cohorts by sex and ancestry, results indicate that there is secular change occurring in the modern human bony pelvis. Changes in shape are significant across the groups while only white males exhibit increases in size. The dimensions of the pelvic canal have changed over time. The birth canal is becoming more rounded with the inlet anteroposterior diameter and the outlet transverse diameter becoming longer. These diameters, once limiters, are believed to have led to an adoption of the rotational birth method practiced by modern humans. In addition, the bowl of the pelvis is becoming less flared.

Childhood improvements in nutrition and decreases in strenuous activity may be the cause of the dimension changes in the bony pelvis. The similar changes across both sexes and ancestries indicate a similar environmental cause. However, it is likely a combination of factors that are difficult to tease apart. Whether the increases continue remains to be determined.

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Chapter 1

Introduction

The formation of the shape of the modern human pelvis is under constant debate in the anthropological community. The evolution of the form found in bipedal humans has been explored for over a century. While the argument continues to rage on regarding when, why, and how modern humans inherited their current morphology, the secular change occurring within *Homo sapiens* has been less explored. This is especially true when examining the changes occurring in the modern human pelvis over the last century. For this dissertation, the changes that have occurred in the bony pelvis of modern humans living in the United States and born within the last 140 years were examined. While change in pelvic morphology of modern humans have been previously studied (Delprete 2006), individuals born in the last century were not included in these works. This study explores the changes that have occurred in the pelvis of individuals born between the 1840 and 1983.

In contrast to long-term evolutionary change, secular change is the change that occurs over a relatively short period of time. Pelvic morphology has been found to be influenced by environmental, genetic, nutritional, and activity factors. The United States is a unique environment; it is a melting pot, the “land of opportunity,” the “land of plenty,” and these characteristics lend themselves to altering the human form. Isolated cultural groups migrated to America and increased their gene pool by intermarrying and interbreeding with “outsiders”. Improved nutrition has been correlated with increased stature, while poor diets can negatively affect skeletal elements such as the pelvis (Angel

1976). In the United States, we are in a state of over nutrition, and this is causing a stabilizing of stature and a ceasing of skeletal "improvements". Human activity has also changed in the last two centuries. Farming and walking have largely been replaced by office work and driving. North Americans continue to become obese and sedentary. The results of each of these changing factors on the modern human bony pelvis are the focus for this study.

Evolution of the pelvis

It is widely acknowledged that bipedalism is a defining human attribute (Jablonski and Chaplin 1993; Lovejoy 2005; Mednick 1955; Rodman and McHenry 1980; Tardieu 1999; Tardieu and Trinkaus 1994; Ward 2002; Wheeler 1991). The broadly accepted hypothesis posits that the erect posture adopted by the genus *Homo* and their closest ancestors required a change in morphology from that of an apelike, quadrupedal stance. This change included a narrowing of the hips to stabilize the legs under the trunk. In addition to locomotor pressure, encephalization followed bipedalism in altering the shape of the pelvis. Encephalization added an additional selective pressure on bipedal female hip morphology due to the need to birth larger-brained neonates. These two pressures, bipedalism and the need to birth large headed babies, have helped to form the modern shape of the human hip.

The functional morphology of the human pelvis is proposed as a compromise between locomotion and parturition (Walrath 1997). While bipedal locomotion primarily altered the shape of the pelvis into an efficient walking machine, encephalization secondarily demanded a reorganization of the bipedal human pelvis for birth. This compromise resulted in a less efficient locomotor form, which differed from bipedal human ancestors such as the Australopithecines who birthed smaller-brained infants (Abitbol 1987; Lovejoy 1988). To remain bipedal and successfully birth babies with larger crania, the human pelvis had to expand in an anterior-posterior dimension. This expansion was possible without "compromising either hip biomechanical or thermoregulatory restraints" (Ruff 1995). The pelvis in genus *Homo* could not become wider from medial to lateral, which would cause the legs to "splay" and disrupt the equilibrium of the joint (Fischman 1994; Ruff 1995). For females to birth larger-headed infants, both the structure of the birth canal as well as the mode of birth changed from the ancestral form (Berge et al. 1984; Rosenberg and Trevathan 1995; Rosenberg 1992; Stewart 1984; Trevathan 1996). These competing pressures created what is commonly known as the "obstetric dilemma" (Washburn 1960).

There has been much debate and research on the evolution of the human pelvis (Lovejoy 1988; Rosenberg and Trevathan 1995; Rosenberg and Travathan 2001; Ruff 1995; Tague and Lovejoy 1986). However, less has been presented on the recent secular change that continues to alter the form of the bony pelvis. While bipedalism and parturition are two forces that have affected the morphology of the human pelvis, their contribution to the pelvic form represents a compromise between two different biological forces: walking erect and the successful birthing of large brained neonates.

For modern human females, technological advances such as cesarean sections may be shifting the balance between these competing selective forces. According to the World Health Organization, between 1996 and 2005, Cesarean section procedures increased 46% to make up 30.2% of all births in the United States. In this research project, the result of this medical intervention on the shape and size of the birth canal will be included among the possible confounding factors that led to secular change in the North American pelvis.

In the next chapter, there is an extensive literature review. Because the human pelvic girdle is such a unique and defining characteristic of modern people, it is necessary to understand the current form through an examination of its growth and development and an exploration of pelvic evolutionary changes, modern human skeletal secular changes, and factors that affect the growth and development of the pelvis. Each of these was considered when the samples and measurements were chosen and in the design of this research.

Chapter 2

Literature Review

Pelvic Anatomy: skeletal development of the pelvic girdle

In order to understand the structure of the modern human bony pelvis, the growth and development of the skeletal structure will be described in the following sections.

In humans, the pelvic girdle bridges the trunk of the body and the lower limbs. The pelvic girdle is made up of three elements: the os coxae, the sacrum, and the coccyx. The wedge shaped sacrum makes up part of the inferior portion of the vertebral column as well as the posterior portion of the pelvic girdle. Os coxae, or hip bones, articulate with the sacrum on the left and right side at the sacro-iliac joint, and the coccyx articulates with the sacrum as a vestigial tailbone. The pelvic girdle represents the fulcrum for movement, including bipedal locomotion and erect posture. For the human skeleton to remain upright, multiple massive muscle groups attach to the bones of the pelvic girdle for stabilization and mobility; this musculature is further described in other sections of this paper. The pelvic girdle provides the supporting structure for these muscles and represents a morphology that is a compromise between form and function. The girdle also encases and protects internal organs (Baker et al. 2005). In the following section, the development of the bones that compose the pelvic girdle will be discussed. The complexity of pelvic development will help to illustrate how growth of the human bony pelvis can be altered by secular changes.

Fetal Development: general

In skeletal development of the pelvis, the ossification of the bones follows a complex process that begins with formation of mesenchymal primordium in the gestating fetus. Ossification can commence from mesenchymal tissue through either an endochondral or an intramembranous pathway. In the initial formation of the pelvic girdle, ossification occurs through an endochondral pathway: a cartilaginous template is formed prior to ossification. Chondrification centers develop in the mesenchyme tissues that form a cartilaginous anlage. Ossification centers then form within the anlage, and this cartilage template is replaced by a bone. This process drives intra-uterine development. The formation of the pelvis follows this pathway.

Lower limb buds appear around day 28 of gestation; these buds are made up of small masses of proliferating mesenchymal cells bordered by ectoderm (Scheuer and Black 2000). Mesenchymal primordium of the lower limbs is apparent in the fetal skeleton by the fifth gestational week (Fazekas and Kosa 1978). However, the nerve pathways of the lower limbs form first. These pathways dictate the formation and placement of pelvic mesenchyme and future cartilaginous anlage (templates made of cartilage); the obturator, femoral and sciatic nerves are in place by days 34-36 (Scheuer and Black 2000). This primordium in the hip region spreads in a proximal and distal direction through three processes following the nerves: the upper iliac, lower anterior pubic, and lower posterior sciatic (or ischial) (Fazekas and Kosa 1978). These three processes correspond to the three bones (the ilium, ischium and pubis) that will fuse to form the adult os coxae. The sciatic/ischial and pubic mesenchymal masses meet ventrally to fuse around the obturator nerve and to form the obturator foramen (Fazekas and Kosa 1978; Scheuer and Black 2000). By intra-uterine day 36-38, the iliac process extends dorsally toward the vertebral mesenchymal primordium and fuses with the costal process of the upper sacral vertebrae (Fazekas and Kosa 1978; Scheuer and Black 2000). By the sixth fetal week, sacro-iliac joint between the sacrum and the ilia begins to form; this joint is complete by week 18 (Scheuer and Black 2000). Finally, by end of the third lunar month, the two pubic processes will meet at the midline to form the pubic symphysis.

Fetal Development: os coxae

Once the mesenchymal cells have differentiated into the early pelvic structures, chondrification of the hip begins in the embryo in the form of plate-like processes that begin by enclosing the acetabulum (Scheuer and Black 2000). Chondrification begins around the sixth week of intra-uterine development in the iliac region of the acetabulum. By eight weeks, the chondrification sites for the pubis and ischium are developed and separated by the obturator nerve (Scheuer and Black 2000). The three chondrification centers meet by the end of the second intra-uterine month. These centers fuse to form a shallow acetabulum; the ischium and the ilium fuse earlier than the paired pubic masses (Scheuer and Black 2000). The cartilaginous pelvis is approximately complete by the beginning of the third intra-uterine month (Scheuer and Black 2000).

The cartilaginous anlage begins to ossify with the appearance of ossification centers in the region of the acetabulum; this process is similar to the chondrification process. As with chondrification, the ilium is the first in the process. By month two or three, the ilium begins to ossify. The center of the ilium in the vicinity of the acetabulum and sciatic notch begins to ossify at the end of the second month; by week nine, ossification spreads cranially and covers the iliac wing (Scheuer and Black 2000). By the fourth intra-uterine month, the ilial contribution to the acetabulum and the posterior inferior iliac spines are discernable (Schwartz 2007). The ossification process occurs in a “fanlike radiating” manner of laying down bone (Scheuer and Black 2000). The ilium is recognizable by the fourth or fifth fetal month. The inferior ischial body achieves its adult bony shape between the third and fifth prenatal month. Between intra-uterine months four and six, the superior pubic ramus unifies and ossifies; it resembles the ischium at this point in development (Schwartz 2007). The pubis is the last center to appear; it is also the smallest and most delicate of the pelvic elements (Scheuer and Black 2000).

Fetal Development: sacrum and coccyx

Sacral ossification is complex, and because of this, there is some disagreement as to the process. However, the generally accepted sequence for ossification will be discussed in this section. The sacrum develops from approximately 21 separate primary ossification centers (Scheuer and Black 2000). These centers can be divided into three groups: centra (bodies), neural arches, and sacral alae (Baker et al. 2005). Each sacral element has three primary centers that are characteristic of all vertebra− one for centra and two for each side of the neural arch (Baker et al. 2005). In addition, the first three sacral elements have additional ossification centers that form the ala and the articular surface for the hip bones (Baker et al. 2005).

Ossification of the sacra occurs from the superior to the inferior; the centra of the first and second sacral vertebra ossify around the third intra uterine month. By the fourth month, the third and four sacral centra exhibit ossification as do the neural arches of the first, second, and third sacral vertebra. This pattern continues down the sacrum. The centers for the alae, or wings, of the sacrum are the last to appear (Baker et al. 2005). All primary ossification centers are generally present at birth (Scheuer and Black 2000).

The coccyx is formed from three to five rudimentary, tapering vertebral segments (Schwartz 2007) . Research regarding the ossification of the coccyx is lacking. It is generally believed that each coccygeal element arises from one ossification center that forms the body of the vertebral segment; however, the first coccygeal vertebra may also have separate growth centers for the cornua that articulate with the sacrum (Baker et al. 2005; Scheuer and Black 2000). The first center will appear in the superior segment by the end of fetal development of in infancy (Baker et al. 2005; Scheuer and Black 2000).

Birth and continuing pelvic development: os coxae

At birth, the ilium, ischium, and pubis that make up the os coxae remain separate bones. The three primary ossification centers are easily identifiable and contribute to the formation of the acetabulum which is a shallow cup at birth (Scheuer and Black 2000). The bones are connected by a Y-shaped triradiate cartilage at the floor of the acetabulum (Fazekas and Kosa 1978; Schwartz 2007). During the first few years after birth, the morphology of the three bones changes little, but they exhibit rapid growth during the first three months after birth (Scheuer and Black 2000). This growth slows by age three and continues to slow until puberty when secondary sexually related growth occurs. Growth changes also coincide with dimorphic changes during this developmental stage.

Primary ossification centers of the ischium and the pubis are the first to fuse. While the timing is variable, fusion generally occurs between age five and eight (Scheuer and Black 2000; Schwartz 2007). This fusion between the pubis and the ischium occurs at the inferior ramus while the superior ramus of the pubis fuses with the ilium. In humans and apes, the pubic bone articulate, but they do not fuse. This non-fusion maintains the potential for movement that may be necessary in childbirth (Scheuer and Black 2000).

Between the ages of nine and twelve, ossification begins in the triradiate cartilage of the acetabulum (Schwartz 2007). Fusion occurs first between the pubis and ilium, followed by ossification between the ilium and the pubis, and finally, the pubis and ischium fuse (Schwartz 2007). Unification of the acetabulum occurs between age 14 and 16, but it may finish as late as 18 years. The ossification of the acetabular cartilage occurs comparatively early and limits continued growth in the pelvis (Scheuer and Black 2004). Later alteration in pelvic shape and size occur at epiphyses away from the acetabulum such as at the iliac crest, pubic symphyses, and caudal end of the ischium. Fusion in these secondary centers proceeds as follows: anterior inferior iliac spine, iliac crest, ischial tuberosity, and pubic symphysis (Scheuer and Black 2004). Fusion in these regions begins around puberty and commences in the twenties. The form of the pubic symphyses continues to alter into adulthood with the symphyseal rim and ventral rampart complete by age 35. The joints in these areas of extended growth have proven to be useful in estimating of age at death in adults and sexual differentiation; they exhibit longer periods of growth related changes.

Birth and continuing pelvic development: sacrum and coccyx

While the ossification of the sacrum is debated, there is more consensus regarding the fusion of the sacrum (Schwartz 2007). At birth, the sacrum consists of 21 separate elements representing the 21 different primary ossification centers. Neural arches fuse to alar elements and then to the centra. Between the ages of two and five years, the neural arches and the alae fuse together in the first three sacral vertebra; this is followed by fusion to the centra (Baker et al. 2005). Fusion of the fourth and fifth vertebra occurs between ages two and five. By six or seven years, the sacrum consists of five unfused segments (Baker et al. 2005). The laminae of each neural arch continue to grow toward each other to form the spinous process that fuses between age seven and fifteen (Baker et al. 2005). A sacral hiatus occurs when there is a lack of fusion of the arches (Schwartz 2007).

During puberty, secondary ossification centers or epiphyses appear in the sacrum. These new growth centers form on the superior and inferior aspects of the centra (forming annular rings), at the lateral plate for the auricular surface with the ilium, and two narrow strips form for the lateral margins (Baker et al. 2005). Secondary ossification begins at the lateral portions of the annular ring around the age of twelve years with the fourth and fifth sacral vertebra (Baker et al. 2005; Scheuer and Black 2000). Fusion of the inter-vertebral annular rings occurs caudocranially or in a direction from inferior to superior. This fusion is opposite to the development of the primary ossification centers. The epiphyses for the auricular surface and the lateral margins appear by age 16 and fuse in the late teens (Baker et al. 2005). By age 20, each of the sacral elements is united laterally at the annular rings; however, space remains between the centra of the upper elements until the later twenties. Each of the segments is fused in adults and forms the characteristic wedge-shaped, tapered morphology.

While the ossification center of the first vertebra of the coccyx will appear in the superior segment by the end of fetal development or in infancy, the inferior segments develop between age three and puberty (Baker et al. 2005). The center for the second vertebra will occur between age three and six, the third will form around age 10, and the final ossification center (s) will appear around puberty (Fazekas and Kosa 1978; Scheuer and Black 2000). Prior to reaching their final adult form following puberty, the coccygeal bodies appear to be “nondescript ovoids” (Baker et al. 2005).

The post-pubertal form of the coccyx will generally consist of four or five fused coccygeal vertebrae that form the rudimentary tail (Scheuer and Black 2000). The most superior, first segment will usually retain remnants of transverse processes and articular facets in the form of cornua (Scheuer and Black 2000). The superior facet of the first coccygeal segment articulates with the inferior of the sacrum and can fuse during adulthood. Fusion between the sacrum and coccyx is more common in males (Scheuer and Black 2000).

Evolution of Bipedalism

Bipedalism preceded all human attributes. While this is in agreement, the why and how humans became bipedal is more contentious. In this section, the argument surrounding the development of bipedalism will be outlined. This in conjunction with the previous section discussing the growth of the human bony pelvis will allow for a better understanding of why the pelvis exhibits its current form and why it continues to change.

Why bipedalism evolved

Most researchers agree that bipedalism evolved in some form by three to four million years ago. Several different hypotheses have been presented for why early human ancestors stood up and began walking upright. Each of the following hypotheses presents selective advantages or energy cost benefits for the altered form of locomotion. Darwin (1874) offered the earliest proposal; he believed that hunting necessitated the shift in locomotion. Survival of the fittest favored the superior brains and bodies of early man. Hunting required strength, power, and superiority and was believed to be male dominated. Free hands were needed to dominate the world around (Darwin 1874). Other carrying hypotheses also fixated on this idea that human ancestors became bipedal to free their hands for other purposes. For instance, Washburn (1960) suggested that the hands were needed to hold tools and weapons. This hypothesis suggests that tools antedate bipedalism; tools led to the "whole trend of evolution" because they altered natural selection and changed the structure of early man (Washburn 1960). These ideas return to those of Darwin: tool use was both the cause and the effect of bipedal locomotion (Washburn 1960). Washburn has been challenged in his belief that tools antedate the development of "man." While bipedalism originated three to four million years ago, tools only date to 1.8 to 2.5 million years ago (Rodman and McHenry 1980). In addition, meat consumption is also preceded by bipedalism (Wheeler 1991).

Food and provisioning are two additional carrying hypotheses. Terrestrial bipedalism corresponds with the environmental changes occurring in Africa during the same time period (Jablonski and Chaplin 1993). Increases in savanna grasslands and the need to allocate food in and between trees led to a need for efficient locomotion (Lovejoy 1981; 1993). Provisioning led to divisions of labor as well as monogamy in an effort to increase energy efficiency (Lovejoy 1981; 1993).   Jolly (1970) and Hunt (1994) used primate models to explain the origin of bipedalism. Jolly offered baboon feeding habits as analogous to early humans. Baboons adapted to small object feeding in the savanna grasslands. The shift to grass and seeds as dietary staples led to a successful subsistence in an environment that was changing. Learning small motor skills was a precursor to terrestrial behavior in baboons, and Jolly (1970) offered this as an explanation for the development of bipedalism in early hominids. Hunt (1994) used chimpanzee feeding as an analogy for the behavior of early bipeds. Chimps stand in trees to reach food and to move from branch to branch. Hunt suggested that this is similar to the behavior that would have been present in early human ancestors.

In contrast to feeding strategies, Wheeler (1991) focused on thermoregulation as a cause for adoption of habitual bipedalism. Bipedalism evolved as a physiological rather than a behavioral response; standing reduced the surface area directly exposed to the sun (Wheeler 1991). Erect posture also increased the air flow around the body and decreased overall body temperature. These factors enabled early bipeds to have freedom from shade, and they were able to search for food longer (Wheeler 1991). Additionally, bipeds needed less food and water to maintain activity—there was an energy benefit to adopting bipedality.

While the precise causes and factors leading to the shift in locomotion of early hominids may never be known, it is likely a mosaic of factors. This is the stance held by Harcourt-Smith and Aiello (2004) who contend that when considering the considerable locomotor diversity, there cannot simply be one origin of bipedalism.

How bipedalism evolved: focusing on Australopithecus

The discussion surrounding the adoption of habitual bipedalism and the evolution of the modern human gait is full of controversy. While early human ancestors such as the recently discovered *Ardipithecus ramidus* exhibited characteristics of some type of bipedalism (Lovejoy et al. 2009), the debate surrounding the early bipedal gait and development of the modern human gait can be largely be divided into two camps. The debate centers on the australopithecines. *Australopithecus* is the genus that preceded the genus *Homo* in the human evolution. Whether *Australopithecus* walked upright is not contested; rather, the debate surrounds how and why the australopiths walked. In this section, the argument surrounding the gait of the australopiths will be outlined. Again, this will provide a background necessary to understand the evolution of the modern body pelvis.

The argument that surrounds the australopithecines revolves around the presence of phylogenetic baggage. The “baggage hypothesis” was introduced by McHenry in 1986 to explain a reorganization on the hindlimb where there is a retention in fossils of primitive-like features that have no bearing on locomotion; these features are believed to be in the process of being evolved out . *Australopithecus* exhibited pelvic morphology that indicated a shift toward bipedalism. However, while the pelvis is inarguably bipedal, the australopiths also maintain primitive upper limbs that indicate a possible dependence on trees. The role of these characteristics as phylogenetic baggage splits the debate regarding the gait of the australopiths into two camps: mixed strategy (erect posture with climbing tendencies) versus modern gaits with no dependence on trees.

One of the earliest arguments regarding the gait of *Australopithecus* was championed by Mednick (1955). Mednick contended that the australopiths were transitional bipeds. Their pelves exhibited the widening, shortening, and bending back of the ilium characteristic in modern humans, but they lacked a well developed iliac tubercle and pillar necessary for balance (Mednick 1955). The extended lower limb lacked stabilization and had greater flexibility that allowed arboreality to be retained (Berge 1994). Prost (1980) agreed that the australopiths had the capacity to be bipedal on the ground, but they also exhibited characteristics of quadrupedal, vertical climbers. Their morphology was similar to quadrupedal monkeys with hips that were less capable of crossing arboreal gaps (MacLatchy 1996). The altered pelvic morphology and the maintenance of primitive climbing features suggest that the australopiths practiced a different form of bipedalism than modern humans. Stern and Susman (1983) suggest a bent-knee-bent-hip (BKBH) posture as an early gait pattern. The australopiths had ape-like hands, and their knees and hips were compatible with climbing; in order for a modern gait to be possible, the ape-like features would have been phylogenetic baggage for 1.5 million years – this was excessive holdover (Stern and Susman 1983). Richmond and colleagues agree that 1.5 million years was an unreasonable lag time for phylogenetic baggage (Richmond et al. 2001). They contend that australopiths maintained climbing features consistent with knuckle walking. The shift to a unique bipedal gait likely resulted because of food acquisition (Richmond et al. 2001).

Food acquisition has been the focus of other researchers examining the features of *Australopithecus*. Hunt (1994) and Stanford (2006) used chimpanzee feeding practice as an analogy for australopith bipedal behavior . Hunt argued that australopithecines used a synthesis of arboreal arm hanging and terrestrial bipedalism to harvest food. This form of bipedalism was fully evolved and a unique adaptation unlike any other species (Hunt 1994). Stanford (2006) observed that 96% of chimpanzee bipedalism was related to foraging; bipedalism was postural rather than locomotor. The fluid quadrupedal-to-bipedal stance observed in chimps may have also been practiced by australopiths. Stanford (2006) suggested that the behavioral plasticity and arboreality of early hominids should not be underestimated.

Abitbol (1995) and Sylvester (2006b) each suggested that the australopithecines practiced a new form of bipedalism . Abitbol contended that australopiths had a different erect posture that was intermediate and non humanlike. Sylvester suggested a decoupling of the shoulder and the hip; the hindlimbs and forelimbs became independent with respect to locomotion. Hominids were terrestrial and suspensory, which was a combination not available to quadrupeds; the australopiths entered a new niche (Sylvester 2006a; 2006b).

Each of the above arguments favors a mixed strategy for australopithecine locomotion. The other side of the debate contends that *Australopithecus* practiced a striding bipedalism similar to that practiced by modern humans. Lovejoy and colleagues (1973) challenged Mednick and argued that the australopithecines do exhibit significant iliac thickening. The differences between *Australopithecus* and *Homo* were due solely to encephalization rather than locomotion. Lovejoy and coworkers (1973) suggested that the early hominids were even more efficient bipeds than modern humans because of the form of the bony pelvis and muscle placement in australopiths. The australopith hip grew out of a compromise between locomotion, viscera and support without having to compromise for parturition (1988; Tague and Lovejoy 1986). While Lovejoy challenged Mednick's views; McHenry took issue with Prost. McHenry (1982) argued that the hindlimbs of australopiths were completely reorganized and the forelimbs showed no sign of quadrupedal propping. He also contended that the postcrania of *Australopithecus* is identical to *Homo*; this indicated that the relationship was not evolutionary (McHenry 1982). As stated above, McHenry (1986) also championed the "baggage hypothesis," which argued that primitive traits were retained without function; they were present due to a common ancestor not due to use.

The early ontogeny of the valgus knee has also been used to suggest the early development in hominid history of the modern forelimb morphology (Tardieu and Trinkaus 1994). According to Tardieu (1999), australopiths exhibited a valgus knee. This would have made arboreality hazardous (Lovejoy 2007). The bent-knee-bent-hip argument presented by mixed strategists was also challenged. Crompton and colleagues (1998) argued that BKBH bipedality was not mechanically effective and increased body heat; this was a serious disadvantage . For australopiths to have adopted a BKBH gait, a substantial selective advantage would have been needed to offset the energy cost (Wang et al. 2003).

Ward (2002) finds the evidence inconclusive. Bipedality was at least practiced by *Australopithecus* for standing, feeding and walking short distances. The arboreal behavior is less definite. According to Ward (2002), the lag time for the retention of the primitive morphology seems too long. This makes for a good summation of the evidence.

Bipedalism: Comparative pelvic anatomy

Bipedalism required a shift in morphology. The pelvic girdle rearranged to accommodate the increased stress and strain due to weight distribution. Muscle function changed when humans adopted an erect posture, and these muscles placed different requirements on the supporting bony structure. This section will briefly outline the major muscular and skeletal changes that were necessary with the adoption of bipedal locomotion.

Bipedal musculature

While apes are able to stand erect, the action requires a great amount of energy. For bipedalism to be adopted habitually by humans, the movements associated with erect movement necessitated reorganization in musculature. This shift is especially evident in the gluteal muscles. The function of the gluteal muscles changed drastically with the adoption of erect posture and bipedal locomotion. Three muscles make up the gluteal complex: the maximus, minimus, and medius. In apes, the gluteal muscles are propulsive. Their main function is to propel the primate forward in quadrupedal movement. In humans, bipedal locomotion and erect stature required the gluteal muscles to maintain stability and to balance the trunk over the pelvis. The gluteals prevent hips from collapsing forward by stabilizing the trunk over the hips especially during running and climbing.

The anterior gluteals, the medius and minimus, attach on the ilium, and in bipeds, are on the front and side of hip bones. These muscles connect the ilium with the top of the femur and contract to maintain balance when walking. The gluteus maximus that runs along the back of the femur keeps the pelvis from tipping forward during movement. These muscular changes required a corresponding reorganization of the skeleton. This shift is especially evident in the hips.

In addition to the gluteals, the iliopsoas, hamstrings, quadriceps, and the plantar flexors also shifted in form and function. The iliopsoas flexes the femur and starts the leg lift and swing. Hamstrings act to flex the knee joint and stop the leg swing so that a bipedal human can plant the foot. The quadriceps and the plantar flexors (calves) are the main propelling muscles in humans; these muscles propel the body forward. Apes, specifically chimpanzees, cannot extend fully at the hips of the knees due to muscle and skeletal restrictions; the musculature shift in humans removed these restrictions.

Bipedal skeletal morphology

The human bony pelvis is made up of the same elements as the great ape bony pelvis, but the structure of the individual elements changed. This change is most evident in the ilium. While the primate ilium is tall and narrow, the human ilium is short and broad. The human pelvis has a bowl shape that is not evident in other primates. This shape changed the center of gravity for humans; muscular flexion was no longer necessary to stand erect. The torso could rest on the bowl of the pelvis. This, again, decreased the energy required needed for standing. For apes, the center of gravity is above and in front of the hips; for apes to stand, constant muscle contraction was necessary to maintain the stance. Muscle attachment sites changed with the shift in bipedalism.

The acetabulocristal buttress is a bar that develops on the gluteal surface of the ilia; it causes this surface to face backward and laterally (Scheuer and Black 2000). This bar develops in response to the stress imposed by muscles of bipedalism and erect posture. The buttress prevents the bone from buckling under the stress (Scheuer and Black 2000). This bony thickening over the acetabulum also known as the iliac pillar is only present in humans.

The shortening and broadening of the ilium also resulted in bringing the acetabulum and the sacro-iliac joint closer together in human. This shift increased balance, but it also narrowed the birth canal. Changes in the birth canal are described in depth in other portions of this work and will not be discussed here. At birth, the human sacro-iliac joint resembles a quadruped (Scheuer and Black 2000). While the joint is formed by the seventh fetal month, its form changes after birth. At birth, the joint is straight and parallel with the vertebral column. The joint curves with the development of locomotion and an erect posture (Scheuer and Black 2000). Erect posture also alters the shape of the sacrum. As the central axis of the pelvic girdle, the superior sacral vertebrae are wider to transfer body weight with the vertebra decreasing in size. The promontory on the first sacral vertebra is forced down and forward to distribute the body weight

(Scheuer and Black 2000). The sacro-iliac surface area also greatly increases from 1.5 square centimeters at birth to seven square centimeters at puberty to 17.5 square centimeters in adulthood (Scheuer and Black 2000).

Bipedal body weight distribution

In humans, the pelvic girdle distributes body weight to make bipedal locomotion possible. The body weight is initially concentrated on the apex of the sacrum and transmitted through the sacro-iliac joint to the acetabulum and finally to the femoral head (Scheuer and Black 2000). The compressive and shearing forces due to body weight are displaced by the transferral of weight through the auricular surface and the acetabulum. The curvature of the vertebral column also represents an adaptation for body weight distribution in bipeds. The sacra of humans less than four fetal months are straight; the natural concavity develops later (Scheuer and Black 2000). In humans, the body weight falls anterior to the sacro-iliac joint which results in a rotator force on the sacrum (Scheuer and Black 2000). The sacrum tilts backward and the promontory shifts forward causing a curvature in the lower spine. This shift also alters the pelvic inlet shape (Scheuer and Black 2000).

Encephalization and Birth

The human pelvis was placed on its current trajectory with the shift in locomotion to bipedalism. Bipedalism changed the shape and purpose of the hominid pelvis. Walking with an erect posture required the reorganization of musculature and skeletal structures. Hypotheses regarding why and how early humans became bipedal were discussed in previous sections. In this section, an additional selection pressure on the shape of the pelvis will be addressed. Encephalization, the increase in the relative brain size, required the bony pelvis to evolve once again. The process of encephalization in human ancestors and the evolution of the birthing process will be discussed in the following sections. This, in addition to bipedalism, will outline the major causes of the evolution of the human bony pelvis.

Evolution of relative brain size

There is a debate over both tempo and mode of brain evolution in the genus *Homo*. While several researchers argue that the increase in the size of the brain was a gradual, linear process (Conroy et al. 2000; Henneberg 1998; Lestrel and Read 1973; Rightmire 2004), the majority point to a dramatic increase approximately two million years ago with the emergence of the genus *Homo* (Aiello and Wheeler 1995; Blumenberg et al. 1983; Falk 1991; McHenry and Coffing 2000). The latter theory will be the focus of this section. Along with thermoregulation, metabolism, and ontogeny/life history, several other hypotheses will be discussed in relation to this increase.

Vrba (1996) argued that the change in brain size grew out of a paleoecological change. Early *Homo* had a different foraging area and fit into a new niche in the ecosystem. Their ability to walk bipedally increased their success in meat accrual as well as expanding their foraging range. In contrast, Blumenberg and colleagues (1983) argued that while the increase in brain size was maintained through a shift in diet and behavior, the initial shift toward increase was a stochastic event – a non-determined molecular event that was later selected for in the genus *Homo*. This theory, as non-committal as it appears, coincides with that provided by Falk (1991). Falk developed the "radiator hypothesis". Emissary veins and foramina formed at the surface of the brain which helped to circulate blood deep in the brain to the surface to be cooled and then back into the brain. Since the brain is a metabolic monopolizer and can heat up, this hypothesis helped explain how the brain could keep expanding without adding either a huge energy requirement or overheating.

The brain requires a large amount of energy even when an individual is at rest. In order for the brain to increase in size, a greater amount of energy (nutrients) is needed to be available for use. Leonard and Robertson (1992; 1997) focused on the bioenergetics of the brain – the transfer and utilization of energy. The brain uses glucose for energy; the foraging of early *Homo* must have changed. While an increase in protein is largely provided as cause for brain expansion (increase in hunting and meat consumption), the diet needed to include a variety of other foods. The diet of early *Homo* was not simply one of *Australopithecus* with the addition of meat.

Aiello and Wheeler (1995) also focused on the need to maintain a constant metabolic rate, and they developed the "expensive tissue hypothesis." This theory posits that the increase in protein and higher grades of food available to mobile, intelligent, resourceful early *Homo* enabled the gut to decrease in size (required less processing→ same argument can be made for teeth). The gut and the brain are expensive tissues – they require a large amount of energy to function and grow. With the decrease in gut size, the brain was able to utilize the extra energy and expand. While this hypothesis explains the ability of the brain to continue its size increase ("prime releaser" on size constraints), it is not provided as a “prime mover” or initial reason for brain growth (Aiello and Wells 2002; Aiello and Wheeler 1995). Aiello and Wheeler suggest that terrestrially and bipedalism are the initial reasons for brain growth (neuron rearrangement, need to develop mental maps of areas). Wheeler (1991) further theorized that thermodynamics also led to bipedalism; an erect posture enabled *Homo* to be further from the intense heat of the ground as well as to limit the surface area of the body to direct sunlight which helped to increase the time and space that *Homo* could forage .

Henneberg argued that cultural development was the cause for brain size increase (1998). Tool use, hunting, and cooperation enabled early *Homo* to shift their diet which in turn caused brain expansion. A change in diet was also the focus of Wrangham’s tuber theory (Pennisi 1999). Wrangham theorized that early *Homo* cooked (via lightning) tubers approximately 1.9 million years ago. This was a more metabolically beneficial resource than meat and provided the energy necessary to support a brain increase. In addition, tubers needed to be protected and this protection led to a social system that is reminiscent of Lovejoy’s provisioning hypothesis (1981; 1993).

In 1982, Martin based his argument for increased brain growth on maternal energy flow (Lewin 1982). This energy flow was the key constraint in brain evolution. With stability and the nature of nutrients becoming available to early *Homo*, newborns were able to reap the benefits and bigger brains could develop. Aiello and Wells (2002) also looked to ontology as an explanation for continued brain size increase. Better nutrition enabled a decreased birth interval, greater body size, shift in organ requirements and slower childhood growth (as opposed to chimpanzee youth growth). This slower growth, and in turn, change in energy requirements, ensued as an offset to the increased infant and adolescent growth cost.

Leonard and Robertson (1992) used bioenergetics to explain changes in ontogeny as related to increased brain size. A child under five uses 40-85% of his/her resting metabolism to maintain the brain. In an effort to limit this high energy requirement, a new growth pattern emerged as a consequence.

The increase in brain size has been long touted as one of the characteristics of the genus *Homo*. In addition to absolute size differences, encephalization quotients have been calculated that also indicate that the relative growth of the brain (in relation to body size) made dramatic increases (Conroy et al. 2000). The reorganization of the early *Homo* brain has also been examined. In 1983, Holloway claimed to have identified cortical sulcul pattern differences in the brain prior to the advent of bipedalism indicating that the reorganization preceded locomotor changes and size increases followed the shift to bipedalism. Falk (1991) in turn argued that sulcul differences were not visible until after the shift to bipedalism and encephalization. McHenry and Coffing (2000) indicated that the frontal lobes in early *Homo* differ from early species of *Australopithecus*.

The increase of the brain in early *Homo* and with the subsequent evolution of *Homo* is drastic. Theories for this shift range from the unknown to behavior and diet to metabolism and growth change. Likely, it is a combination of many of the above that has allowed such an increase to initially occur and continue in the modern species.

Evolution of birth

The drastic increase in the relative brain size of *Homo* necessitated an adjustment to the pelvic morphology as well as a shift in the birthing mechanism and behavior of human ancestors. The functional morphology of the pelvis is a compromise between locomotion and parturition (Walrath 1997). While the evolution of bipedal locomotion primarily altered the shape of the pelvis into an efficient walking machine, encephalization secondarily demanded a reorganization of the bipedal human pelvis for birth. This compromise resulted in a less efficient locomotor form which differed from bipedal human ancestors such as the Australopithecines who birthed smaller brained infants (Abitbol 1987; Lovejoy 1988). In order to remain bipedal and successfully birth babies with larger crania, the human pelvis had to expand in an anterior-posterior dimension. This expansion was possible without "compromising either hip biomechanical or thermoregulatory restraints" (Ruff 1995). The genus *Homo* could not become wider from side-to-side (medial to lateral), this would cause the legs to "splay" and disrupt the equilibrium of the joint (Fischman 1994; Ruff 1995).   For females to birth larger headed infants, both the structure of the birth canal as well as the mode of birth changed from the ancestral form (Berge et al. 1984; Rosenberg and Trevathan 1995; Rosenberg 1992; Stewart 1984; Trevathan 1996). These competing pressures created what is commonly known as the "obstetric dilemma" (Washburn 1960).

Birth in humans is both difficult and complex. Obstetrically, there are three important planes present in the pelvis: the pelvic inlet, midplane and outlet (see figure 1 and 2 below). The human neonate has to pass through these three apertures during the birthing process (Greene and Sibley 1986). In humans, each of these openings is widest in a different dimension, and this results in the modern rotational birthing process. The pelvic inlet, the most superior opening or the "brim" of the pelvis, has it longest dimension transversely. The human neonate enters the inlet head first with its longest cranial axis in line with the widest dimension of the inlet. The neonates must then rotate in the midplane, the plane with the least dimension, in order to enter the pelvic outlet. The outlet, the most inferior opening of the pelvis, is widest in an anterior-posterior dimension. The neonate also emerges facing away from the mother in an increased effort to pass through the canal with the greatest ease. In addition to head rotation, the shoulders of the neonate human must rotate in order to successfully pass through the birth canal (Trevathan and Rosenberg 2000).

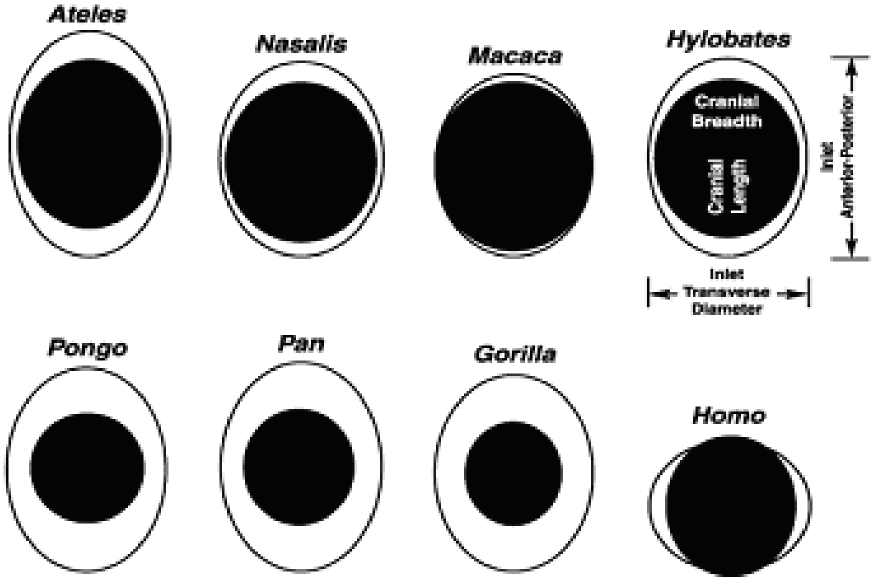

Figure 1: Relationship between size of maternal pelvic outlet and neonatal head in primate species. Modified from Rosenberg and Trevathan (2007).

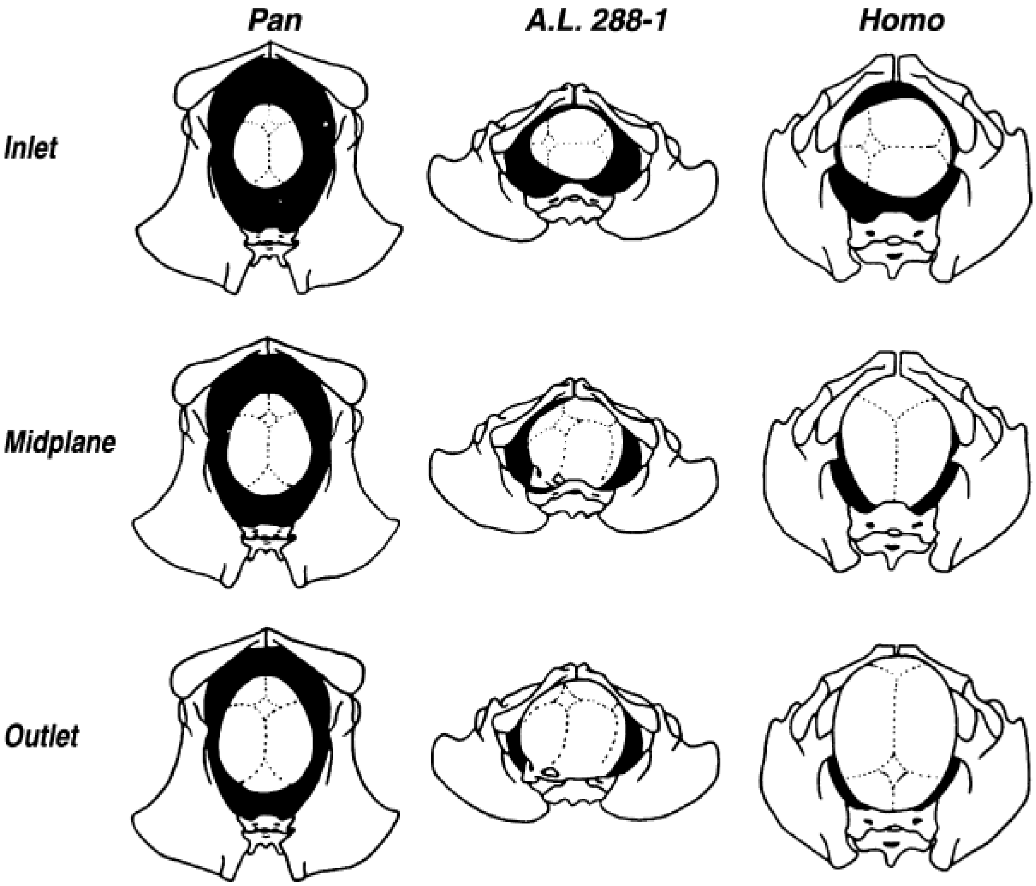

Figure 2: Birth mechanism for in chimpanzees, Australopithecines and humans. Modified from Tague and Lovejoy (1986).

While human ancestors enjoyed a less strenuous, solitary process in birthing smaller brained neonates through larger birth canals, birth in *Homo sapiens* altered social behavior (Rosenberg and Trevathan 1995; Rosenberg and Travathan 2001; Trevathan 1996). Once rotational birth became a human characteristic, it had been suggested that natural selection favored assistance for the birthing process to compensate for the bipedal pelvis, larger brained neonates and neonates emerging facing away from the mother (Rosenberg and Travathan 2001). Humans are the only species who practice social births; the twisted birth canal requires a different mechanism, and "obligate midwifery" increased the survival of the mother and the neonate (Rosenberg and Trevathan 1995). Natural selection brought about this behavior change (Trevathan 1996).

Along with midwives, the widening of the birth canal is an obvious selective force for successful parturition (Schultz 1949). While the human birth process continues to be complex, technological advances have increased the survival of mothers and neonates. Rather than depending on a sufficiently wide birth canal, many women are able to survive child birth through cultural adaptation. This may be a factor in the secular change of the human bony pelvis.

Secular Change

In addition to the evolutionary changes that altered the ancestral pelvic form into that of the modern human morphology, there continue to be factors that lead to short term, generational changes. These types of changes are known as secular changes or secular trends. In the following sections, the secular changes that have occurred in the skeleton over the last four hundred years will be discussed to illustrate how short term change can alter morphology.

Secular change since the Colonial period: changes over the past 400 years

The change in American skeletal structure over the past 400 years has been significant. The American environment has provided an arena for unique research; it is an environment that was novel to the human species. The "melting pot" make-up of human ancestry and culture as well as the abundance of resources led to a change in the human constitution. Researchers such as Boas, Angel, Meadows Jantz and Jantz are just a few of the scholars who have examined how the human skeleton responds to the American environment. Both Native American populations and those who migrated later to the Americas have experienced secular change. For the purpose of this dissertation, secular changes that occur in the bony pelvis within the United States are the focus; however, in order to grasp how the skeleton can change over a relatively short period of time, the skeletal changes that have occurred in the United States since the Colonial Period will be discussed in the following sections.

With the shift from hunting/gathering to agriculture, Native Americans were suffering from a negative trend when the Europeans "discovered" America (Steckel et al. 2002). This change of diet and mobility as well as endogamy affected both the size and shape of the skeleton. Steckel and Prince (2001) and Komlos (2003) examined the equestrian tribes of North America in the nineteenth century. These groups, Crow and Cheyenne, enjoyed a low population density in relation to their main food source (Buffalo). This resulted in a nutritional benefit, and they exhibited a tall stature - perhaps the tallest in the world during the 19th century. During a time when other Native peoples were turning to agriculture, these tribes were nomadic. While sedentary peoples were challenged with increased disease due to population density pressure and dependence on limited regional resources, the equestrian tribes were more successful. This exemplifies the effect that shifting from hunter/gather to agricultural lifestyles can exhibit in a population.

In 1983, Jantz and Willey examined the temporal and geographic patterning of head height among native peoples in the Plains. They found that head height was the most important indicator of inter-populational difference, and that the lowering of the cranial vault appeared to be a trend in the Plains. This change in shape was attributed to gene flow. Owsley joined Jantz in an examination of the Arikara in 1984. This study researched the secular change in long bone proportions in this native population from 1600-1800s. Earlier sites were characterized by long femora and short tibiae compared to later sites. The proximal limbs increased faster than the distal limbs, and the lower limbs outpaced the upper limbs.

Angel (1976) examined changes that occurred in the US since the colonial period in blacks and whites. His study included pre-colonial US, colonial US, modern US, and old world skeletal samples. Angel determined that overall health of those in the United States improved over the last 400 years. There has been an increase in longevity and a decrease in juvenile death. In addition, Angel (1982) noted changes in the cranial base height (measurement taken between basion and bregma) and the pelvic inlet that coincided with nutrition. Each of these skeletal characteristics grows from cartilage as a child, and this involves growing against gravity. When nutrition is lacking (child suffers from rickets, lack of protein), these growing bones are affected. The cranial base is flatter and the inlet is reduced in an A-P dimension (Angel 1982). Over this time period, skull size increased as a result of vault height which is a reflection of improved, increased cranial base height. There was also a deepening of the true pelvis-another indicator of improved conditions. The face also became more linearized and an increase in overbites resulted. Teeth were also affected by changes in diet during this period- this was a negative secular trend.

Jantz and Meadows Jantz have provided evidence for secular change since the 1800s in Americans. They examined both cranial and postcranial size and shape differences that have occurred over time (Jantz 1996; Jantz 2001; Jantz and Meadows Jantz 2000; Meadows Jantz and Jantz 1999). Their results indicate that vault height and bone length respond in parallel ways to environmental forces. There has been an increase in vault height over time (also determined by Angel as discussed above), and the vault has generally become longer and narrower. The length of the crania has been correlated with stature; increases in cranial length coincide with increases in stature- an indication of improved conditions. The Meadows Jantz and Jantz studies (1996; 1999) determined that shape (the size of a bone in relation to the size of other bones) change has been greater than the size change in long bones. Long bones have increased in length (white males exhibit positive secular change in each of the six long bones while black females are the most stable) and allometry. The Jantz corroboration (1999) also determined that males have a larger secular increase than females, and whites exceed blacks in changes. Overall, there has been less change in the face over this time period as compared with changes in the vault.

Perhaps the most well known study of the effect of the American environment was presented by Boas (1911). Boas' work will be covered in a separate section because of its ground-breaking importance; however, it is necessary to mention it here in the discussion of American skeletal changes. Boas claimed that the American environment could change the head form of children of immigrants. While the above has indicated that several cranial changes have occurred in Americans over the last 400 years, there is no claim or indication that these changes are converging into an American types- there is more of a parallel movement.

While the skeletal changes in blacks and whites largely indicate improved living conditions and success, this is a simplistic view. Genetics, industrialization, social inequality and population structure are a few of the factors that can and will continue to modify these effects. Secular change can be either positive or negative. Since the early 1900's, changes in most Americans indicate a positive trend; however, as Komlos (2007) has indicated, there is a cessation of secular change in height in the US. The interaction between genes and environment continues to change. Humans have the greatest ability of all animals to control their environment, but there is a limit to this success.

Boas and cranial plasticity

In 1910, Boas teamed up with the Immigration Commission to study the effect of the American environment on immigrants. He determined that there was a significant change in the head form of children of immigrants; there was American assimilation. Boas focused on the two extreme cases of change in his study: Sicilians and Hebrews. In each of these groups, he found that there was a difference in head type between the immigrant parents and the US born children. Sicilian children had round heads while their parents were more long-headed; in contrast, Hebrew children were long-headed compared to their parents. These findings were controversial. Until this point, genetics were thought to determine the head shape, and essentialist typologies were developed to differentiate between ancestral groups. Boas's findings challenged the racialist approach of the day and called into question the use of cranial morphology in the identification of peoples by "race".

While Boas's finding have been quoted and re-quoted as gospel since the early 1900s, they have also been a serious impediment to the study of craniometrics and populations. Studies of environmental effects and secular change have indicated that there are cranial measurements that are effected by nutrition and climate (cranial base, cranial length); however, there are limits to this effect as well as a lack of convergence between ancestral groups of people. In terms of understanding the plasticity of the human head form, the camp is still divided.

Hulse was a student of Earnest Albert Hooten. He examined how immigration and exogamy affected the morphology of Swiss immigrants. Hulse (1962) found that population structure influences cranial morphology, an idea which Boas had also considered as a possible cause of change in the United States. Exogamy coincides (obviously) with immigration and this makes interpretation based completely on environmental conditions difficult. Stature and head length were characteristics that were most obviously affected- an indication of better health and nutrition.

After nearly 100 years of using Boas as the pillar of plasticity, his findings have been reanalyzed. While Boas claimed that there were drastic differences between immigrant and US born, current research indicates otherwise. Sparks and Jantz (2002) used Boas's data and subject them to more vigorous and modern statistical analyses. They determined that Boas's claims were not based on statistical significance. Sparks and Jantz noted that there were shifts in measurements between the groups, and while most of the measurements were significant, they were not drastic differences. There was also no indication that the American environment could produce an American type. Long-headed populations were still long-headed while those groups characterized by shorter-heads maintained their shortness. When examining the cranial index by age (breadth/length x100), Jantz also noted that the plasticity observed in Sicilians actually occurred in Europe. In addition, the pattern of changes that were experienced by the Hebrews and Sicilians differed. In Sicilians, the CI was altered because of a shortened cranial length while Hebrew change in both dimensions. As discussed above, Hulse (1962) indicated that an increase in cranial length corresponds to better nutrition and health. This indicates that the Sicilians actually experienced a poor environment in the US in relation to Sicily.

In contrast, Gravlee and colleagues (2003a; 2003b) reanalyzed Boas's data but supported his findings. Cranial morphology was significantly changed through interaction with the American environment. However, while Gravlee and colleagues noted significant differences, these differences were also less than drastic. While there were changes in the cranial index, the ethnic differences far outpaced the immigration differences. Gravlee also failed to support a convergence to an American type.

Where do we stand? In 2003, Armelagos and VanGerven alleged that cranial index could change by a magnitude of a race in one generation continuing in the tradition of Boas. Many physical anthropologists continue to rail against the use of cranial morphology to identify ancestral groups of people. However, others have succeeded in showing that the plasticity of the human head form cannot erase genetic variation. Klepinger (2001) examined the use of historical stature estimation on current populations. She found that secular trends in stature (which are paralleled by cranial secular trends) are overshadowed by non secular populational variation. Relethford (2004) also determined that the underlying patterns of population structure could not be erased or obscured by plasticity. He referred to plasticity as “noise” when looking for underlying differences between groups. There is a neutral model of quantitative variation. Relethford also briefly comments that Boas claims of plasticity are small in magnitude. Holloway presented several questions regarding Boas’s findings that coincide with many problems addressed by Sparks and Jantz (2002). These included Boas’s apparent lack of usual statistical vigor and apparent support for environmental determinism which was a departure for Boas.

Racism was and continues to be a challenge for physical anthropology. Boas’s study indicated that the use of racial typology was inappropriate and that immigrants could assimilate in the culture and make-up of the United States. While he was known for his statistical vigor and research design, both were lacking in his study of immigrant children, and he makes some acknowledgement of this. Boas debunked a myth that was not a myth, but his effort was for the betterment of those who wanted to belong to the “melting pot”.

The use of cranial morphology to identify ancestral groups has been supported through research. While certain dimensions are affected by environment and nutrition, others remain tied to genetics. Convergence to an American type has yet to be supported. Through populational and temporal studies, effects can be differentiated and the use of craniometrics can be appropriately used to help identify population characteristics.

Secular change: Europe versus the United States

Many different explanations have been given as causes of positive secular change. Nutritional improvements (fruits, protein, amount of food), public infrastructure (water, sewage, health care access), and breakdown of isolates (immigration, assortative mating, improved travel) have all been suggested as reasons for improvement of health and a decrease in morbidity and mortality. Malnutrition and disease, which are interrelated with socioeconomic status and level of health care, also affect the rates of growth and maturation (Roche 1979).

The United States, Europe, and other first world countries enjoyed surges in growth, exemplified by stature, over the past 50 years. These secular changes in height in the US have ceased, while in Europe, they continue to march upward. Historical differences, populational change and geography, public infrastructure, environmental effects, dietary and locomotor behavior are offered as possible explanations for the differences in secular experience between these two regions.

Europe and the United States are both first world regions. Each has gone through industrialization, enjoy technological advances and have an abundance of resources (or the ability to get them). Historically, the United States has participated in two World Wars and many smaller wars while suffering few attacks on US soil. In contrast, Europe suffered numerous major attacks which affected both infrastructure and population demography. This is one possible reason for continued increases in Europe; while the US was able to maintain positive growth, Europe is still in the midst of catch-up or recovery growth.

The geographical areas of the two regions greatly differ. While the US has free movement between its states, Europe's movement between countries is more constrained. This difference affects gene flow. The breakdowns of isolates, exogamy, and immigration each have a positive effect on secular change. While these are tenets that define the melting pot of the United States, there is a decrease in their occurrence in the latter twentieth century. One area of immigration that has increased in the US is that of "Hispanic" populations. Historically, these groups are smaller in stature. Their inclusion into the US population has also likely altered the increase.

Komlos and Lauderdale (2007) determined that population density is strongly and negatively correlated with height. Higher population density leads to lower heights. The population density in the US exceeds that in Europe. The majority of US citizens live in cities. Komlos and Lauderdale indicate that the lag in the US behind Europe is largely a city phenomenon. Individuals living in the suburbs or moderately sized towns actually have the best mix of benefits with access and availability to medical care with few negatives.

Public infrastructure is affected by population density as well as by political and social choice. According to Bock and Sykes (1989), height in the US is a result of greater growth in the first two years of life. Ghosh and Bandyopadhyay (2005) found that lower leg length is a sensitive indicator to malnutrition in children as well. These studies indicate that stature is largely dependent on adequate (or better) prenatal and child care. While Europe has socialized medical and childcare, the US is sadly lacking both. While there are some social programs in place to benefit the lower socioeconomic groups in the US, they are often complicated to access.

The continued secular increase in weight in the US is indicative of chronic over-nutrition. While stature continues to increase in Europe, the US has ceased getting taller and continues to get wider. Food that is poor in nutritional value is easily attained while more beneficial fare can be harder and more costly to attain. Hot dogs cost less than pork chops; chips cost less than peppers, and milk cost twice as much as soda pop. Portion sizes vary drastically between Europe and the US. In the US, we eat poorly, and we eat more.

Locomotor trends differ between the two regions, and this affects growth. While public transportation is available in both regions, its accessibility and use differ. In the US, cars are king. The cost of fuel favors the US- this is actually a detriment to the health of the population. Sidewalks are absent in many cities in the US; returning to Komlos and Lauderdale (2007), this supports the theory that cities are the main areas of stature lag. Locomotor trends as well as population density and industrialization have all contributed to increased pollution in the US- especially in the cities. Pollution will also have an effect on the health and stature of the population (Roche 1979).

The decrease in physical activity has also affected the shape of individuals. While the US has reduced the amount of physical education in schools (only one state requires four years of high school physical education- Illinois), children in Sweden have marked increases in physical fitness between 2000-2006 (Raustorp and Ludvigsson 2007). The health of children affects the height of adults.

Several possible reasons have been given for the cessation of secular increase in height in America, specifically the United States. Komlos (2003) specifically focused on population density while Roche (1979) indicated that pollution could reverse secular change. It is also possible that the US has hit the “genetic ceiling”. While the environment is able to modify the effects of growth, genetics constrains the response. This would place the cause in the realm of gene flow. Likely, it is a combination of environmental and genetic factors.

Factors affecting the growth/formation of the pelvis

Throughout the introduction and the literature review, factors that alter the form of the human bony pelvis have been briefly mentioned. Because this research is focusing on changes in the modern pelvic girdle, several of these factors will be highlighted in the following section because their effects on the growth and formation of the current morphology are of interest. While these factors are separated into subheadings, it must be noted that each factor interacts in known and unknown ways with the others. Secular and evolutionary changes occur because of interactions between innumerable and oft amorphous factors. It is a challenge to tease out a few of the effects from the mix.

Genetic Factors

Groups of formally isolated peoples funneled through Ellis Island prior to settling in the United States. Many came from small populations that continually drew from limited gene pools. Research has shown that upon entering the United States, isolated peoples benefited from an increased genetic stock. Exogamy resulted in greater marriage distance and genetic outbreeding which led to increased stature (Dubrova et al. 1995) The size and shape of the pelvis has also been shown to have some genetic component. Abitbol reported that the gynecoid or “normal” female pelvis was displayed when a female was not exposed to strenuous adolescent work and acquired erect posture at the usual age because shape is genetically determined as a result of obstetric demands (1996). Angel (1976) found that the offspring of exogamous American Swiss and Italian matings were taller than endogamous offspring; he determined that mixture followed then by improvements in diet, disease-control and living conditions should all act to increase size.

Skeletal breadth tends to have higher heritability than weight, circumference, and skinfolds; soft-tissue traits are more easily altered by the changing nutritional environment of individuals (Cameron 2002). A greater proportion of variance in soft tissue is explained by environment than in than skeletal tissues which respond less quickly to changes in nutritional status. The heritability of bi-iliac breadth has been determined to be between 0.34 (India) and 0.73 (Belgium) (Cameron 2002).

Stature

Most industrialized countries have revealed a trend toward increasing growth and development in children and greater adult stature in the last 100-150 years (Dubrova et al. 1995). Maternal stature has been positively correlated with pelvic size, and obstetricians regard maternal stature as “an anthropometric correlate of her reproductive efficiency” (Tague 2000). Taller women suffer from fewer cephalopelvic complications including cesarean sections, stillbirths, and perinatal mortality, indicative of a larger pelvic outlet and inlet. However, not all dimensions are uniformly affected by maternal size. Transverse diameter of the outlet, the posterior space of the inlet, subpubic angle, and angulation of the sacrum are generally independent of non-pelvic measures of size suggesting that the selection for obstetric sufficiency is independent of selection for larger body size (Tague 2000). Western women are generally taller than women in less developed areas, and this is also exemplified in the ability to birth larger babies vaginally (Abitbol et al. 1997).

Sex

Men and women have hips that serve different functions. While both sexes developed bony pelves that enabled them to walk upright, only females required pelvic outlets that were sufficient to pass a large brained neonate. This fundamental difference results in the sexually dimorphic characteristics that are manifest in the human os coxa and sacra. Female os coxae are more shallow, broader, and less acutely flared with a rectangular pubis and longer ischiopubic ramus (Shipman et al. 1985). The inferior pubic ramus of females is concave with a subpubic angle that is usually greater than 90 degrees. Males exhibit a more triangular pubis, convex inferior pubic ramus, and a subpubic angle of approximately 60 degrees (Shipman et al. 1985). The acetabulum is smaller and shallower in females while the auricular surface is more raised. Females usually have a wider sciatic notch that may approach 90 degrees.

The difference in structure is largely attributed to the need for females to bear large headed babies; a broad pelvis with large pelvic inlet and outlet is necessary for birthing (Shipman et al. 1985). However, in order to be efficient bipedally, a narrow pelvis that places hip joints closer together minimizes the side-to-side displacement of the body during walking and maximizes mechanical efficiency. Thus, there needs to be a compromise; human infants are less mature at birth and the female pelvic structure is less bipedally efficient (Shipman et al. 1985).

Ancestry

While stature and sex may add obvious variation to the human pelvic form, ancestry also plays a role in the shape of the pelvis. Differences in musculature between blacks and whites have been shown to alter the formation of bone in individuals. Both size and shape differ in the os coxa between blacks and whites (Synstelien 2001). There is a greater distance in white individuals between the anterior superior and inferior iliac spines, the anterior superior spine and point ilioauricular, a greater depth of the iliac fossa and lesser depth of the notch between the anterior superior and inferior iliac spines when compared to blacks. Synstelien (2001) also found that there was a significant mean increase in white males for 14 of 19 variables measured over blacks.

Environmental Factors

Altitude and climate also affect the final form of the adult human pelvis. Two well known and often cited “rules” regarding ecological effects on the skeleton are credited to Bergmann (1847) and Allen (1877). Bergmann's rule states that "races of warm blooded vertebrates from cooler climates tend to be larger than races of the same species from warmer climates" (Mayr 1956) while Allen’s rule focuses on limb lengths and extremity proportions. In 2002, Ruff determined that the dimorphism present in modern humans exists as a gradation along latitudinal climates. Geography and climate altered the shape and size of the human form; however, Ruff warned that a genetic component also exists.

Katzmarzyk and Leonard (1998) corroborated the findings of Bergmann, Allen, and Ruff. They also found that secular trends in body size do not appear to be equal across populations of different climatic zones; there is an increase in body mass that appears to be disproportionately larger in tropical regions. The impact of acculturation and lifestyle change and the associated improvements in health care and nutrition disproportionally affect developing world pops of the tropics and subtropics (Katzmarzyk and Leonard 1998). Genetics as well as nutrition were found to have moderated the influence of climatic factors (Katzmarzyk and Leonard 1998).

Nutritional Factors

The shape of the pelvis has been shown to be effected by fetal and childhood nutrition. Nicholson (1945) found that a period of malnutrition, like the war of 1914-1918, may have led to the low length of the conjugate diameter in England. In contrast, rural populations in England escaped the effects of malnutrition of war and exhibited a half inch higher diameter. This may have occurred because of malnutrition during early years of weight bearing. Nicholson also found a correlation between the length of conjugate diameter and stature with a one centimeter above average diameter corresponding to a stature that is seven centimeters taller than average. Angel (1976) determined that the pelvic inlet responds to levels of childhood suboptimal nutrition caused by war or lower socioeconomic class with a reduced AP diameter and pelvic index; he found significant changes from the colonial to modern pelvic index. Rickets also alters the obstetric success of females by decreasing the inlet AP diameter; nutritional deficiencies distort growth at cartilage joints inhibiting bone formation such as the AP arch of pelvis (Angel 1982; Kaltreider 1951). According to Weyl (1977), diet (especially meat consumption), a shortage of food, climatic change, and dysentery will all effect the pelvic inlet.

Mothers born and raised in third world countries are, on average, shorter, have less weight, have narrower pelvic dimensions, and give birth to smaller babies than women born in United States (Abitbol et al. 1997). This could be due to a low-protein diet and inadequate prenatal care. Mothers born outside of the United States but who eat a high-protein diet and have adequate health care after migrating to the United States as adults give birth to relatively large newborns (Abitbol et al. 1997). Marked cephalopelvic disproportion and severe dystocia which frequently leads to cesarean section births occurs in these migrant women (Abitbol et al. 1997). Good nutrition during infancy, childhood, and adolescence will contribute to high stature in adulthood with adequate pelvic dimensions for women, and nutrition with an emphasis on more protein can increase fetal weight by 25% while minimum to moderate prenatal care (high-protein diet, iron, calcium, vitamins) can see fetal weight increase up to 50% as compared to no care (Abitbol et al. 1997).

Activity Factors

Becoming bipedal ultimately set about the evolution of the hominid pelvis. Walking upright required an alteration in the form of the os coxae and the sacrum.

Walking continues to alter the form of the pelvis. Children, specifically females, who walk at an earlier age have been shown to have a different pelvic shape that those who walk after 14 months of age (Abitbol 1996). Early walkers exhibit a platypelloid shape which is transversely wide and narrow anteroposteriorly. In contrast, later walkers develop a form that is narrow transversely and wide anteroposteriorly, a shape referred to as anthropoid. Strenuous activity prior to adulthood has also been shown to effect the adult shape of the pelvis leading to a more triangular pelvic inlet or android shape (Abitbol 1996). Additionally, early pregnancy will distort the primary shape of the female pelvis (Abitbol 1987).

Other Factors

In addition to the factors discussed above, technology and culture need to be explored whenever humans are studied. Culture often dictates the activity performed by males and females. Divisions of labor between males and females has been linked to difference in the pelvic form (Ruff 1987). Pelvic dimorphism is accentuated when cultures allow different activities, and dimorphism is often less accentuated when there was little or no gender differentiation in terms of physical activity (Abitbol 1996). Increases in body size, shape, rates of maturation, and changes in body compositions of children are also associated with changes in child-labor practices, family size, household size (Roche 1979).

Technological advances are also adding to the factors that can alter the form of the human bony pelvis. As discussed earlier, between 1996 and 2005, Cesarean section procedures increased 46% to make up 30.2% of all births in the United States. Its effect on the shape and size of the pelvic canal is not completely known. In Germany, technology has been linked to a decrease in the female dimensions of the birth canal over the last 80 years (Lehmann et al. 1992; Wischnik et al. 1992).

Chapter 3

Hypotheses and Samples

Having covered the background necessary to understand the growth and development of the modern human pelvis, this chapter will outline the hypotheses driving this research and the samples used in this study.

Ultimately, this is a project focusing on secular change. As such, differences that occur over a relatively short time will be examined. Changes in the dimensions of the pelvic planes in addition to the height and breadth of the pelvis are of primary importance. Size and shape differences are both of interest.

Hypotheses

Improvements in nutrition and general health have been shown to lead to increased stature and physical size. To determine if the same trends are altering the pelvic girdle, overall size changes in inter-landmark distances will be examined. In addition, the femoral head of each individual will be measured to test for changes in body size (Delprete 2006; McHenry 1986). The mean femoral head diameter will be used, if necessary, to remove size as a primary difference and to focus on shape. While size will be examined, if left un-controlled, shape differences could be missed.

Body & Pelvis Size

Increases in stature and overall body size have been shown to occur over time in this study sample. As discussed in the literature review, individuals in the United States have benefited from improved conditions, and until very recently, as a group, they have experienced unprecedented increases in stature. A coinciding increase in the mean femoral head diameter is expected to occur in each of the ancestral groups dependent on birth cohort. In concert, os coxa height and breadth, and overall pelvic breadth are also expected to increase due to improved nutrition and environment. Additionally, analyses using 3D morphometrics produce centroid sizes for each individual that will enable overall pelvic size to be compared across cohorts, and these results that will be examined in addition to those found using traditional metrics.

Pelvic canal shape

With improved nutrition, the pelvic inlet should mirror the secular change in stature. An increase in the anteroposterior dimension of the inlet through time is expected to occur within the samples measured. Additionally, as nutrition has improved, activity has decreased. With this decrease in activity, specifically strenuous activity of children, the number of individuals with android shaped pelvic inlet (triangular) is expected to decrease. Principal component scores produced through the rotation, translation, and scaling of Procrustes Analyses will illuminate changes occurring in shape between the cohorts.

Lehmann, Wischnik, and colleagues found that the female pelvis in Germany has become less favorable for birthing and more bipedally efficient over the last 80 years (Lehmann et al. 1992; Wischnik et al. 1992). Increased use of technology, such as cesarean intervention, may also be altering the shape of the pelvic canal. If this is the case, there should also be a decrease in the sexual dimorphism among the samples. There should be a shift by females to a more masculine, bipedally more efficient, form.

Samples

Three skeletal collections were used in this study. The Hamann-Todd Human Osteological Collection housed at the Cleveland Museum of Natural History in Cleveland, Ohio, the Robert J. Terry Anatomical Skeletal Collection curated at the Smithsonian National Museum of Natural History, and the William M. Bass Donated Skeletal Collection maintained by the Anthropology Department of the University of Tennessee, Knoxville. These collections were chosen for a variety of reasons. First and foremost, these invaluable skeletons represent individuals living in the United States between 1822 and the present. The United States is a unique combination of novel environment and melting pot. Since each of the individuals used in this study died in the US, each was subjected to the conditions that coincide with living in this environment. This is not to say that each group was exposed to identical environments. Each collection represents different facets found within the country, and those differences will be highlighted and tested for to determine which factors result in shifts in morphology between the samples.

Prior to beginning this research, birth cohorts were devised to break up the available population into generational groups born within 28 year intervals. This interval length was chosen based on cross-cultural genealogical research and precedence (Delprete 2006; Fenner 2005). These birth cohorts will be used when comparing groups for secular change. Samples from each collection were chosen from generated lists of cohorts including only adults with recorded birth years. Individuals with missing or damaged pelvic elements were not used nor were individuals with pathologies. In order to maximize the total possible individuals within a cohort, the birth years that were used when partitioning the skeletal populations into samples are listed in the table below. Also the sample sizes used from each collection are included in Table 1.

Table 1: Cohort birth years and sample breakdown

Cohort	**Birth Years**	**Collection**	**Sample Demography**
1	1842-1869	Todd	20BF, 20WF, 20BM, 20WM
		Terry	19BF, 20WF, 19BM, 20WM
2	1870-1897	Todd	20BF, 20WF, 20BM, 20WM
		Terry	20BF, 20WF, 20BM, 18WM
3	1898-1925	Todd	20BF, 11WF, 20BM, 20WM
		Terry	20BF, 23WF, 20BM, 14WM
		Bass	1 BF, 19WF, 4BM, 20WM
4	1926-1953	Bass	3BF, 30WF, 11BM, 30WM
5	1954-1981	Bass	1BF, 12WF, 11BM, 30WM

Hamann-Todd

The Hamann-Todd Human Osteological Collection is currently the largest collection of modern human skeleton with documentation that exists in the world. This collection was started by Carl A. Hamann while professor of anatomy at the medical school at Western Reserve University in Cleveland, Ohio, from 1893-1912. Skeletons were collected from cadavers after dissection. In 1912, Hamann became dean of the medical school and supported incoming anatomy professor Thomas Wingate Todd in enlarging the collection until Todd's death in 1938. In 1968, over 3000 human skeleton were moved to the Cleveland Museum of Natural History where they are currently. This collection is composed of individuals born between 1835 and 1913, age 0 to 105 with many coming from a lower socioeconomic background. For this study, adult males and females of black and white ancestry were used.

In an effort to collect an evenly distributed sample, the goal was to digitize and measure 20 individuals per birth cohort per ancestry (black and white) and sex. In the Hamann-Todd collection, this protocol was attainable except for white females in the more recent birth cohort (1898-1925). In the collection, there were only 11 skeletons that fit the research criteria.

Terry

Robert J. Terry began collecting skeletons for research in 1898; however, his early efforts were riddled with element loss and commingling. During his tenure at Washington University Medical School in St. Louis, Missouri, from 1921 to 1946, Terry amassed the majority of the specimen current housed in the Smithsonian National

Museum of Natural History in Washington DC. Mildred Trotter, Terry's successor at Washington University, added to the collection and is responsible for evening out the demographic distribution of the skeletal population. Trotter aimed to add younger individuals, especially white females, to the anatomical collection, and she continued this work until her retirement in 1964. The collection was donated to the Smithsonian Institution in 1967.

The Robert J. Terry Anatomical Skeletal Collection has 1728 individual in the collection with documented demography (Hunt and Albanese 2005). Prior to the Willed Body Law of Missouri in 1955-56, the majority of cadavers used in dissection were predominantly unclaimed bodies or individuals who were signed over by family members. After the passage of the law, signed releases were required prior to use. This shift in protocol changed the socioeconomic make up of the collection; those collected prior to 1955 had lower incomes and many died during the depression while those after 1955 were largely from the middle to upper socioeconomic class.

Again, as with the Hamann-Todd collection, an effort was made to collect an evenly distributed sample of the Terry Collection and to digitize and measure 20 individuals per birth cohort per ancestry (black and white) and sex. In the Terry collection, the limiting group was the white males born between 1898 and 1925; only 14 skeletons fit the criteria. However, there were additional white females in this birth cohort, and three additional specimens were measured in an effort to compensate for the lack in the Hamann-Todd sample.

Bass

The William M. Bass Donated Skeletal Collection housed in the Anthropology Department of the University of Tennessee, Knoxville, is the only one out of these three collections still growing. Rather than being made up of dissected cadaveric donations, the Bass collection is made up of skeletons collected from donated bodies that have decomposed at the William M. Bass Anthropological Research Facility. Over 60% of those in the collection were donated by family members. Most of the remaining 40% come from self (pre) donors or medical examiner (unclaimed) donors.

Bass started the collection in 1981 while a professor at the university, and at the time of sample measurement, there were 750 skeletons. Twenty-three states and two countries are represented by skeletons in the collection with ages ranging from 0 to 101. The majority of the collection is made up of white males, and while the demography of this collection is certainly skewed, the utility of the Bass Donated Collection is high. This collection is the largest collection of documented skeletal material from people born during the modern industrial era. As discussed previously, the environment of the United States has changed drastically over the last century and having research materials that represent the population currently inhabiting the country is essential to understanding the current state of the modern skeleton in addition to illuminating incidence of secular change.

While the sampling protocol of 20 individuals per birth year cohort was the benchmark for the Bass Donated Collection, this approach was altered. For cohort 3 that was to overlap with the Terry and Todd collections (1898-1925), the measurement sample goal was, again, 20 individuals. This was only possible for the white males and females; there, currently, are not that many black individuals born within this time period contained in the collection. In the Bass Collection, black males and females are underrepresented. As many individuals that fit the testing criteria were measured in these cases. For cohort 4 and cohort 5, the sample size goal was increased to 30 since the Bass Collection was the sole contributor in these birth cohorts. However, again, sample availability became an issue. In addition to the black males and females, white females in the most recent birth cohort (1954-1981) were limited.

Chapter 4

Measurements and Methods

This chapter will cover the measurements chosen for collection, the method used for data collection, and the statistical approaches used in the data analysis. To determine the pertinent measurements that should be taken to determine secular changes in the human pelvis, an understanding of the organization of the pelvis is essential, and the regions of the pelvis as well as the historic definitions of pelvic shapes present in humans will be introduced below. Additionally, measurements were chosen in order to be comparable to previous studies, and those measurements will also be discussed in this chapter.

For measurement collection, digitizing was chosen for a number of reasons. Digitizing the pelvis enabled a large number of data points to be collected in a relatively short time, and it reduced the need to record a point multiple times. Also, the points are automatically stored in the computer which removes translation error. The specific technique used to digitize the pelvic girdle will be outlined following the discussion of data point selection.

Measurements

Pelvic regions

The pelvic girdle is made up of two regions: the greater (false) pelvis and the lesser (true) pelvis. The pelvic inlet, or the brim, divides these two regions. The false pelvis, which is the anatomically superior region, houses the abdominal viscera and is bound by the abdominal wall anteriorly, the iliac fossa laterally, and the fifth lumbar vertebra ventrally (Scheuer and Black 2000). The brim that separates the regions is formed by the promontory and alae of the sacrum posteriorly, the iliopectineal lines laterally, and the pubic crest and symphysis anteriorly. The true pelvis, the inferior pelvic region, protects the urinary bladder, the rectum, and internal genitalia. The posterior wall of the true pelvis is formed by the sacrum and the coccyx. Anteriorly, a shorter wall is formed by the pubic symphysis and the body of the pubis. The lateral walls of the true pelvis is made up of the inner aspect of the os coxae, the obturator fascia, and the muscles that cover the obturator foramen (Scheuer and Black 2000).

The most posterior opening of the pelvis is the pelvic outlet. This space, which is diamond shaped, is bound by the coccyx, ischial tuberosities, and the sacrotuberous ligaments laterally, and the pubic symphysis anteriorly (Scheuer and Black 2000). Obstetrically, this posterior opening and the pelvic inlet, which divides the pelvic regions, are most important. Their shape and size alter efficacy of locomotion and birthing. The inlet and outlet as well as the pelvic midplane will be the main areas of measurement concentration in the current study.

Historical pelvic shapes

The shape of the pelvis and the pelvic canal has been of interest for millennia. Females have a more shallow, broader, and less acutely flared shape with a deeper and longer ischiopubic ramus (Shipman et al. 1985). The pubis is more rectangular in females while the pubis is triangular in males. Males also have a more convex inferior pubic ramus and small subpubic angle while females exhibit greater sciatic notches and larger subpubic angles – each of these characteristics contributed to the more rounded, open canal found in females (Shipman et al. 1985). Prior to the current modern era, birthing success was dependent upon the ability for the mother to pass an infant through the birth canal, and the dimorphic differences were evolutionarily necessary. Generally, there are four classifications used to describe pelvic canal shape. The names of these four types vary, but the characteristics are consistent. For purposes here, the terminology will include the following four types: anthropoid, android, gynecoid, and, platypelloid (Caldwell and Moloy 1938; Greulich and Thoms 1938; Shipman et al. 1985). Classification is based on the difference between the anteroposterior diameter and the transverse diameter of the pelvic inlet. Turner (1885) developed the pelvic index to quantify canal shape. The Turner Index or Pelvic Index is the anteroposterior diameter of the inlet times 100 then divided by the maximum transverse diameter. According to the Turner classification, pelves with an index greater than 95 are designated as dolichopellic (anthropoid); those with an index of from 90 to 94.9 are mesatipellic (gynecoid); and those whose index is less than 90 are platypellic (platypelloid) (Turner 1885). Turner did not define a range for the android pelvis.

An anthropoid pelvis has an oval inlet with its long axis in the A-P dimension and a narrower transverse diameter. This shape resembles the inlet shape of higher, non-human primates. Human males are more often anthropoid. Android inlets are small and heart shaped. The ischial spines are prominent and the pelvic arch is narrow in android pelves; the inlet is wider posteriorly than anteriorly; it more common in males. The most common shape is the gynecoid inlet. This shape is rounded and found in approximately half of all females. Gynecoid inlets are round, slightly wider transversely with dull ischial spines, and have a wider pubic arch; birth is better facilitated in women with gynecoid inlets. Finally, the platypelloid shape is transversely broad and narrow anteroposteriorly; this is the most uncommon shape in humans. To complicate matters, mixed morphology also exists in pelvic canal shape in which the morphology anterior to the transverse diameter differs from that to the posterior. Examples of the four main types are shown in Figure 3.

To further quantify the pelvic shape, Delprete subtracted the inlet transverse diameter from the inlet AP diameter (2006). She defined pelvic shape in the following way: values less than -30 were platypelloid; android pelves were between -30 and -10; pelves between -10 and 0 were gynecoid; those with pelvic canals with values greater than 0 were anthropoid (Delprete 2006). This shape index will be used in the current study.

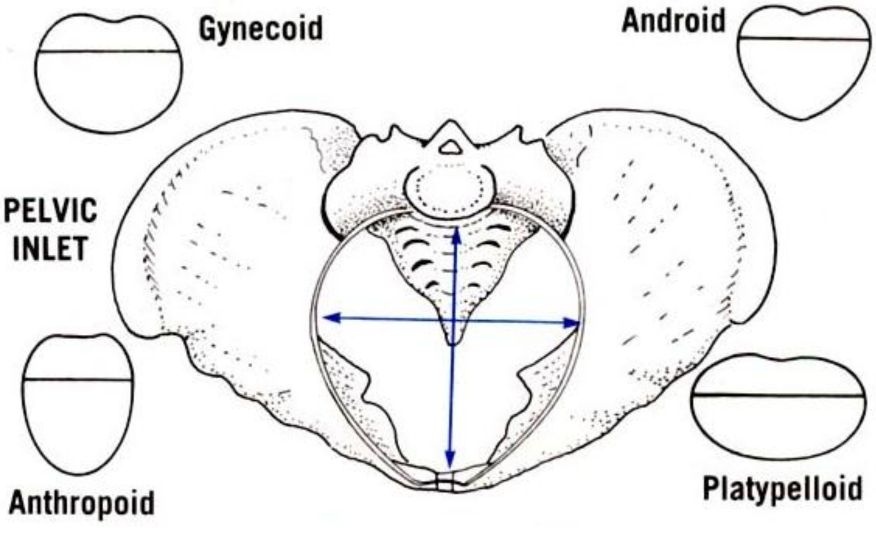

Figure 3: Cranial view of the pelvis showing the anteroposterior (conjugate) and transverse diameters of the inlet (modified from Ronan O'Rahilly 2009).

Measurement Selection

After taking into account the hypotheses driving this research, traditional measurements taken on the pelvis, previous research, and determining the number of points necessary to visualize the pelvis once plotted in the morphometrics software, 64 pertinent distances were chosen; see Table 1 for a list of measurements. In order to calculate each of these measurements, 115 points and four arcs were taken from each articulated pelvis; these points encompass the pelvic canal and all three planes, iliac flare, sacral curvature, os coxa heights and widths, angles, acetabulum, and obturator foramen; see Table 2. There are many, many more measurements taken than will be used in the present study; however, because of the ease of collection using the digitizer, additional points of interest could be recorded without adding significant time. Also, in order to create a recognizable 3D image, numerous points were needed. Those measurements not used here will be utilized in later studies that will build on the results of the present research.

When choosing skeletal landmarks for measurement, Zelditch and colleagues (2004) outline five criteria for choosing ideal landmarks; these require the landmark to be “homologous anatomical loci that do not alter their topological position relative to other landmarks, provide adequate coverage of the morphology, can be found repeatedly and reliably, and lie within the same plane.” Each of these criteria was taken into account when choosing the landmarks used in this research. The fifth criteria, for points to be most readily and reliable located, presented the greatest challenge when working with the pelvic girdle. According to Bookstein, landmarks can be classified into three groups: Type 1, Type 2, and Type 3 (Bookstein 1991). Type 1 points are those that occur at the intersection of three bones along where sutures come together. These types of points are easily located and there is relatively low inter- and intra- observer error. While Type 1 landmarks are ideal for reproducibility, unfortunately, the adult pelvic girdle lacks sutures and Type 1 landmarks. All landmarks used in this study are Type 2 landmarks. Type 2 landmarks are located at tips or ends of bony processes or are points that are the maximum or minimum points along curvatures; they are defined by local properties of the bone. While Type 2 landmarks can be problematic, they are more reliable than those points defined by Bookstein as Type 3 and the only option in the pelvis. Type 3 landmarks are extremal points that are defined by their distance away from another structure; these types of landmarks can also be defined as constructed landmarks such as a centroid.

Finally, the measurements and their associated landmarks can be found in Table 2 and illustrated in Figures 4a and 4b. For this study, the following measurements were examined to test the hypotheses: AP diameter of the inlet, midplane, and outlet; transverse diameter of the inlet, midplane, and outlet; the height and breadth of the left and right os coxa; the sacral breadth; internal and external breadth of the pelvic girdle; the femoral head diameter. These measurements are in bold in Table 2 and shown in the wireframe in Figure 4b. In addition, two measurements were calculated for this study. Turner's Index and Pelvic Inlet Shape utilized the inlet AP and transverse diameters. Turner's Pelvic Index is inlet AP diameter times 100 and then divided by the inlet transverse diameter. Pelvic Inlet Shape was calculated by subtracting the transverse diameter from the AP diameter. The range values for each pelvic type were defined above.

Table 2: Measurements and associated landmarks

Pelvis Measurement	**Landmark 1**	**Landmark 2**	**Landmark 3**
acetabulum breadth L	anteromedial point of the acetabulum L	posterior acetabulum L	
acetabulum breadth R	anteromedial point of the acetabulum R	posterior acetabulum R	
acetabulum height L	superior acetabulum point L	inferior acetabulum point L	
acetabulum height R	superior acetabulum point R	inferior acetabulum point R	
anterior inferior iliac spine breadth	AIIS L	AIIS R	
anterior iliac spine notch breadth	left anterior iliac notch	right anterior iliac notch	
anterior upper spinal breadth	ASIS L	ASIS R	
AP midplane diameter	dorsal-medial aspect of inferior pubis border, Center	4/5 sacral vert	
AP outlet diameter	DM aspect of inferior pubis border C	S5 apex	
bi-iliac breath external	cristal tubercle L	cristal tubercle R	
bi-iliac breath internal	point medial to cristal tubercle L	point medial to cristal tubercle R	
bi-iliac breadth	iliac tuberosity L	iliac tuberosity R	
canal arc L (curved)	sacral AS apex L	iliopectineal line from PS L	
canal arc R (curved)	iliopectineal line from PS R	sacral AS apex R	
depth of true pelvis L	AS apex L	inferior ischial tuberosity L	
depth of true pelvis R	AS apex R	inferior ischial tuberosity R	
iliac crest arc L (curved)	PSIS L	ASIS L	
iliac crest arc R (curved)	PSIS R	ASIS R	
inlet anterior space R	DM aspect of superior pubis border R	transverse diameter point R	
inlet AP diameter	DM aspect of superior pubis border C	ant sacral promontory	
inlet iliopubic eminence	eminence on iliopectineal line L	eminence on iliopectineal line R	
inlet posterior area R	AS apex R	transverse diameter point R	
inlet transverse diameter	transverse diameter point L	transverse diameter point R	

Table 2: Measurements and associated landmarks (continued)

Pelvis Measurement	**Landmark 1**	**Landmark 2**	**Landmark 3**
ischiopubic angle	ventral arc L	ventral arc R	
maximum pelvic breadth L	PSIS L	ASIS L	
maximum pelvic breadth R	PSIS R	ASIS R	
maximum pelvic height L	inferior ischial tuberosity L	max height iliac crest L	
maximum pelvic height R	inferior ischial tuberosity R	max height iliac crest R	
medial iliopubic eminence	central point of eminence L	central point of eminence R	
midplane anterior space L	ischial spine L	DM aspect of inferior pubis border L	
midplane anterior space R	ischial spine R	DM aspect of inferior pubis border R	
midplane posterior space L	4/5 sacral vert	ischial spine L	
midplane posterior space R	4/5 sacral vert	ischial spine R	
midplane transverse diameter	ischial spine L	ischial spine R	
minimum acetabular breadth	anteromedial point of the acetabulum L	anteromedial point of the acetabulum R	
oblique diameter L	AS apex L	transverse diameter point R	
oblique diameter R	AS apex R	transverse diameter point L	
obturator foramen max height L	superior point L	inferior point L	
obturator foramen max height R	superior point R	inferior point R	
obturator foramen max length L	medial point L	lateral point L	
obturator foramen max length R	medial point R	lateral point R	
outlet ant space (curved): ischiopubic ramus L	ischial tuberosity L	DM aspect of inferior pubis border	
outlet ant space (curved): ischiopubic ramus R	ischial tuberosity R	DM aspect of inferior pubis border	
outlet posterior space L	S5 apex	medial ischial tuberosity L	
outlet posterior space R	S5 apex	medial ischial tuberosity R	
outlet transverse diameter	medial ischial tuberosity L	medial ischial tuberosity R	

Table 2: Measurements and associated landmarks (continued)

Pelvis Measurement	**Landmark 1**	**Landmark 2**	**Landmark 3**
posterior inferior iliac spine breadth	PIIS L	PIIS R	
posterior iliac spine notch	left post iliac notch	right post iliac notch	
posterior upper spinal breadth	PSIS L	PSIS R	
promontory length	left sacral promontory	right sacral promontory	
promontory width	ant sacral promontory	post sacral promontory	
pubic tubercle width	pubic tubercle L	pubic tubercle R	
pubis length L	SM aspect of superior pubis border L	anteromedial point of the acetabulum L	
pubis length R	SM aspect of superior pubis border R	anteromedial point of the acetabulum R	
pubis symphysis height L	inferior symphysis L	superior symphysis L	
pubis symphysis height R	inferior symphysis R	superior symphysis R	
pubis symphysis width L	dorsal symphysis L	ventral symphysis L	
pubis symphysis width R	dorsal symphysis R	ventral symphysis R	
sacral arc (curve apex to apex)	sacral AS apex R	sacral AS apex L	
sacral breadth	auricular surface apex R	AS apex L	
sacral height	ant sacral promontory	S5 apex	
sciatic notch L	upper sciatic border L	deepest aspect of sciatic notch L	lower sciatic border L
sciatic notch R	upper sciatic border R	deepest aspect of sciatic notch R	lower sciatic border R
subpubic angle	inferior ischial tuberosity L	inferior ischial tuberosity R	

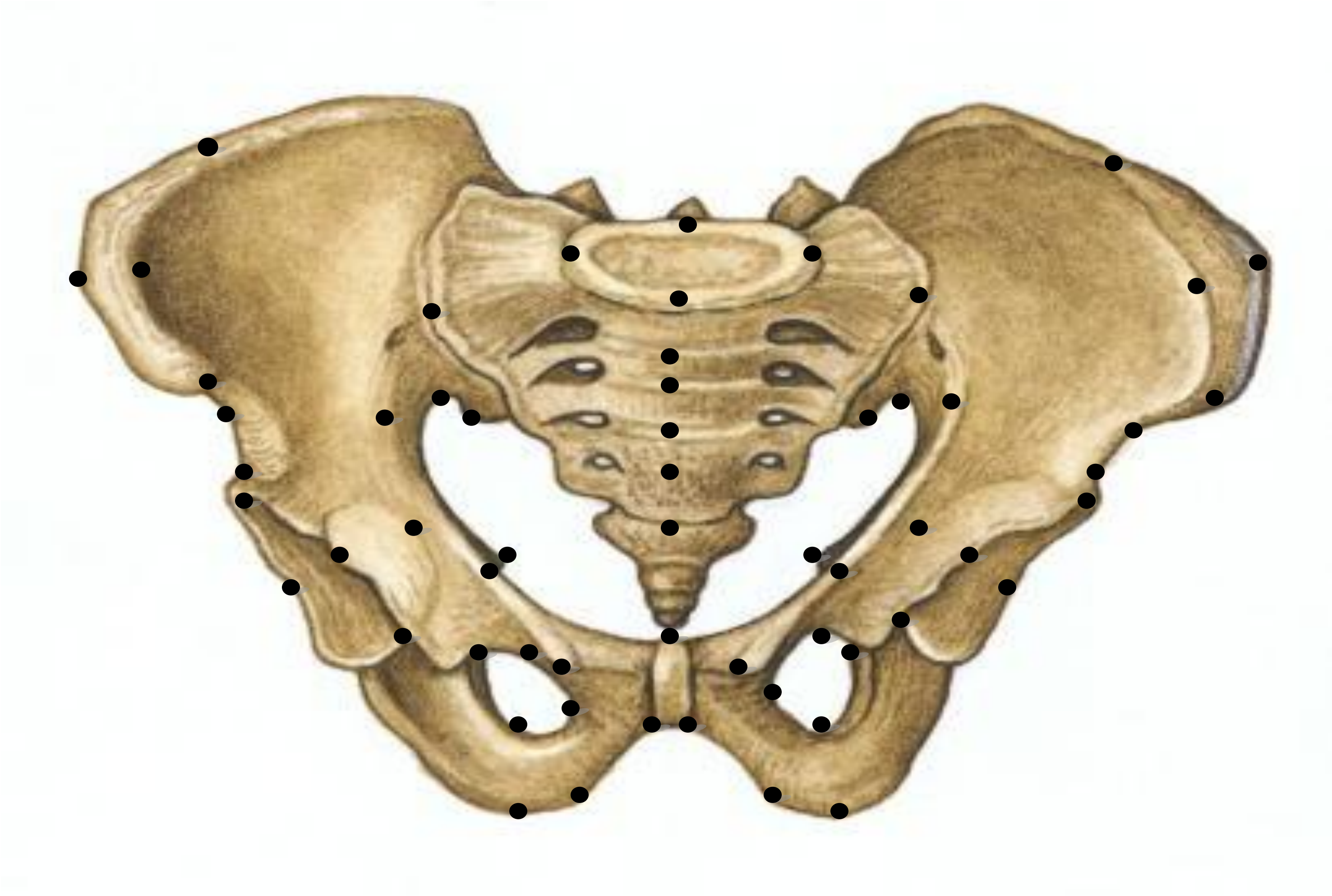

Figure 4a: Illustration of landmarks

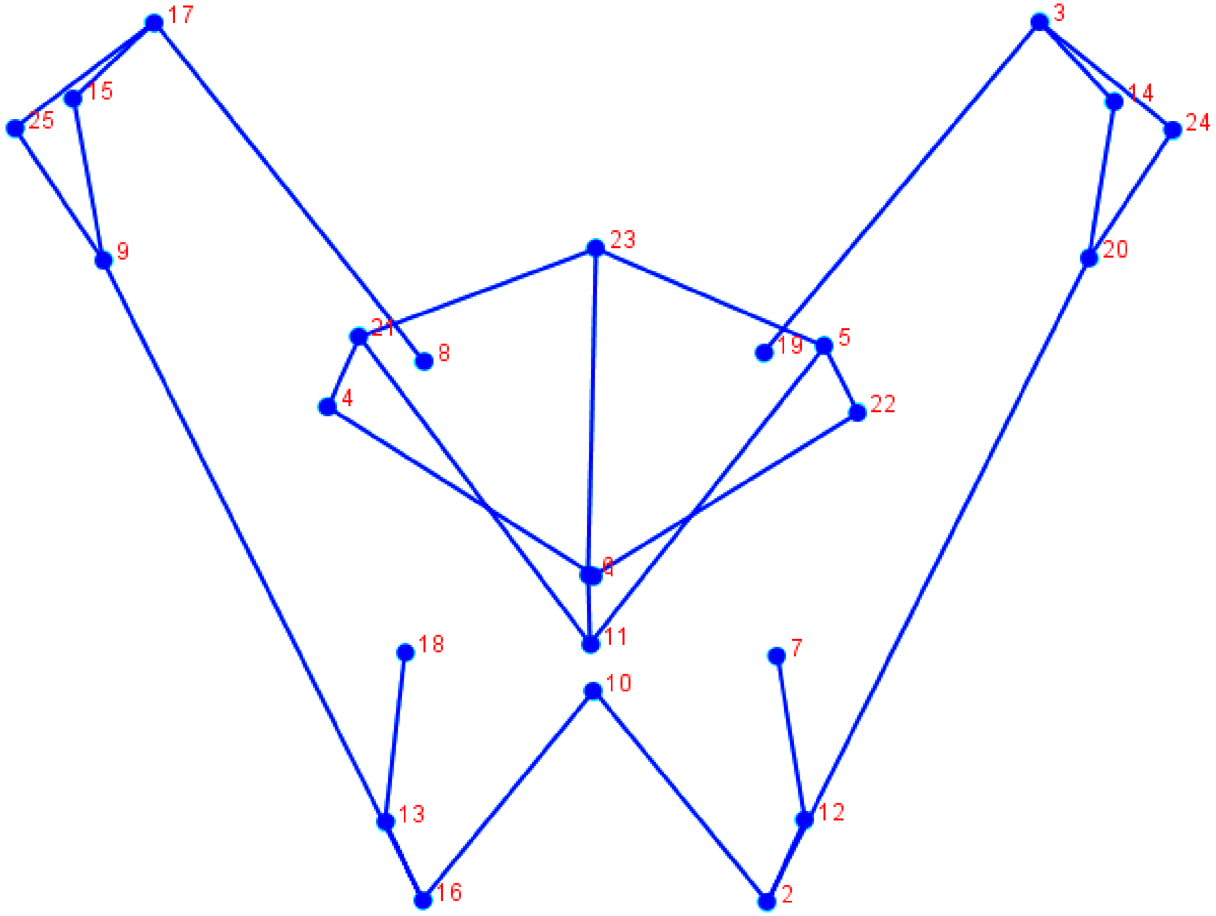

Figure 4b: Wireframe illustration of landmarks used in this research. Landmark identifications of the numbered points can be found in Table A13 in the appendix.

Methods

For each specimen, the pelvic girdle was rearticulated and the maximum femoral head diameter was measured. The left femoral head was measured to the nearest tenth of a millimeter using Mitutoyo digital calipers unless damaged; in cases of damage or missing left femora, the right femur was measured. An input tool was attached to the calipers and measurements were saved directly into an Excel spreadsheet which eliminated the chance of recorder error. The os coxae and the sacra were examined for damage and areas of fusion. Damage in landmark areas and sacra with fused coccygeal or lumbar vertebra were excluded from the sample.

Once the three bones were pulled for measurement, the maximum height and breadth of each os coxa was located using an osteometric board and marked with chalk. Additionally, once the bones were rearticulated, the maximum pelvic breadth was measured and marked. After articulation and marking, the pelvic girdle was mounted on clay pillars in preparation for digitizing with care to ensure each landmark was in reach of the arm of the 3DX microscribe digitizer. If any shifting occurred in the rearticulated girdle or of the pillars, the setup was redone.

Articulating the pelvic girdle

Prior to data collection, the three skeletal elements of the pelvic girdle needed to be rearticulated. Rubber bands of various sizes were used in this process. In order for the structure to remain stable during data collection, three to five bands were used. The technique used to rearticulate the girdle was modeled after those used by Tague in his numerous works on the pelvis, Ruff, Hager, and Delprete (Delprete 2006; Hager 1989;

Ruff 1995; Tague 1989; 1992; 1995; 2000; 2007). No compensation was made during the rearticulation for the symphyseal disc or other soft tissue that is present in living humans. This is consistent with previous studies and makes the measurements comparable to past research; it also reduces the error introduced through estimating the thickness of soft tissue.

Digitizing the pelvic girdle

After determining which measurements would be collected, the landmarks used in calculating these distances were listed. It became apparent that many of the measurements utilized the same or similar landmarks. In an effort to decrease remeasurement error, a 3DX microscribe digitizer was used to collect the data points. Using the digitizer required taking a point’s coordinates a single time; distances could then be calculated using a single recorded point rather than determining a landmark’s position multiple times. The digitizer also allowed for the collection and recording of many points in one session. When digitizing crania, 3Skull, a paradox based program written by Steve Ousley (2004), is the software used to collect the coordinates and calculate the inter-landmark distances. For this project, 3Skull was adapted to collect and calculate those landmarks of interest. In all, 115 points and four arcs were collected from each pelvic girdle.

Statistical Analyses

Once all of the pelvic girdles were digitized and the femoral heads were measured, the inter-landmark distances and femoral head measurements were imported into NCSS statistical software for analysis (Hintze 2006). The tests run and results of each statistical test will be discussed in a following section. In addition to analyzing the traditional metrics, the coordinates of each landmark were input into the 3D morphometric software freeware Morphologika2 (O'Higgins and Jones 2006) and MorphoJ (Klingenberg 2008). The process through which the geometric morphometric analyses proceeded will also be discussed below.

Initial Testing

Prior to running any statistical analyses focusing on secular change, it was necessary to determine whether similar cohorts could be pooled by sex, ancestry, and/or collection. Multivariate analyses of variance (MANOVA) were run to determine whether inter-landmark distances differed between groups based on ancestry and/or sex.

After separating the data into single sex and ancestry birth cohorts (1WF for white females in cohort one, 1BF for black females in cohort one, etc.), the groups were further separated by collection. The normality of each measurement was tested using D'Agostino Omnibus Normality test for skewness and kurtosis. When data was normal, t-tests were used to determine whether there were differences in mean of each measurement between similar cohorts of differing collections; for example, comparing the bi-iliac breadth of the 1WFs in the Hamann-Todd Collection to the 1WFs the Terry

Collection. When data was not normally distributed, the non-parametric versions of the t- test, the Wilcoxon Rank-Sum/ Mann-Whitney test, was used.

For comparisons of cohort three, which is made up of individuals from all three skeletal collections, univariate analysis of variance (ANOVA) was used to test for differences between the three collections. ANOVA tests were used to determine whether there were differences when data was normal; when data was not normally distributed, the non-parametric test, and the Kruskal Wallis test was used. T-test were run on each on pair (Terry-Todd, Bass-Terry, Bass-Todd) in those cohorts where significant differences were noted to determine which groups significantly differed; a reduced alpha of 0.015 (Bonferroni 0.05/3tests) was used in these cases.

Traditional Metrics

After determining the appropriate pooled groups, MANOVAs were utilized to determine significant changes in inter-landmark distance between cohorts. This is appropriate since there are multiple dependent variables (inter-landmark distances) compared between multiple groups (cohorts). A significant Wilks' lambda (the multivariate p-value) indicated that there was at least one distance that significantly differs between the cohorts. Subsequent ANOVA indicated which distances were significantly different between at least two of the cohorts; a reduced alpha of 0.003 was used to assess the ANOVA p-value. This reduced values of alpha is based on the Bonferroni correction which takes the original alpha of 0.05 and divides it by the number of individual t-test that are done- in this case, there were 16 separate tests (0.05/16 =0.003). Those distances with ANOVA p-values that were significant were then compared between cohorts using a Hotellings T^2 tests (the multivariate t-test). If the Hotellings T^2 was significant, this indicated that at least one distance was significantly different between two specific cohorts; a reduced alpha depending on the number of significant distances (determined from the ANOVA) was used to evaluate the significance of the individual t-tests. When assessing the p-values of the Hotellings T^2 tests, multivariate normality does not necessarily need to be tested if the p-values for both equal and unequal covariances are similar. The Bartlett test, which is done in concert with the Hotellings T^2 tests in NCSS, will indicate whether the variances are, in fact, equal. Also, randomization was done to account for possible invalid assumptions (multivariate normality, independent samples, equal covariances). The p-values for the tests were taken from randomization using 1,000 Monte Carlo sample permutations.

Geometric Morphometrics

The use of geometric morphometric analyses with coordinate data provides a way to quantitatively analyze multi-dimensional data shape and size. Much of the software used to transform and analyze the data is freeware and easily available which enables great opportunity to expand the use of geometric morphometrics. In anthropology, the evolutionary changes that have occurred in the pelvis are of paramount interest. Using geometric morphometrics in concert with landmark coordinates on the articulated pelvis is novel in anthropology, and this section will describe the process taken in this research.

As past studies have shown, there are characteristic differences in the shape and size of the pelvis dependent on ancestry and sex (Hager 1989; LaVelle 1995; Synstelien 2001). For this reason, the coordinate data was imported in groups separated by sex and ancestry. The change due to secular change is of interest in this study, so separating the groups reduces maximizing landmark difference based on demographic differences rather than time. After getting the data in the appropriate form, the landmark coordinates needed to be arranged into a common coordinate system; this was done through a Generalized Procrustes least squares superimposition or Generalized Procrustes Analyses (GPA). GPA rotates, scales, and translates the configurations of landmarks through a least-squares method and removes all non-shape variation (Rohlf and Slice 1990). The location and orientation of each new landmark position is based on minimizing the sum of the squared distances between homologous landmarks of two configurations; with more than one configuration, each is located based on a reference specimen (Slice 2005). GPA was performed in Morphologika2 (O'Higgins and Jones 2006) and MorphoJ (Klingenberg 2008). Landmark configurations of the articulated pelves in this study are shown before and after GPA in Figure 5. Centroid size, the square root of the summed squared distance of each landmark from the centroid of the landmark reference configuration, were calculated for each specimen (Zelditch et al. 2004). The centroid sizes are uncorrelated with shape and were used in further analyses as a representation of size. Centroid sizes were examined in relation to demographic parameters to determine correlation.

The new GLS landmarks produced in GPA exist in multi-dimensional, non-Euclidean, non-linear space referred to as Kendall’s shape space (Zelditch et al. 2004). For the ease of statistical analyses, the landmarks were translated into a linear tangent space through the use of principal components analysis (PCA). Principal components are computed as linear combinations of the original variables of each specimen and represent as much of the total variance of the sample as possible. PCA was run on the generalized Procrustes landmark configurations in Morphologika2. In homologous samples, PCA estimates characteristic structures within the sample, otherwise, PCA simply reduces dimensionality for additional statistical analyses (Slice 2007). In this study of secular change, the samples are not homogenous, they consist of several birth cohorts, so the principal components created using PCA were used in multivariate analyses examining changes in shape.

Canonical variates analysis (canonical discriminant function analysis) was used on the principal components. The canonical variates produce maximize the variance between groups, so when “cohort” was used as the grouping variable, CVs were produced that separate the sample into cohorts. The morphological variation associated with significant CVs are discussed in the Results section.

In addition to testing for cohort differences using canonical variates analysis, samples were tested by collection to determine if change was based on spatial location rather than temporal difference. The Mahalanobis distance between the cohorts was also calculated. Multiple regression, MANOVA, and variable selection were all run on centroid size to test different variables’ effect on size. Death age, death type, sex, ancestry, and collection were all tested in addition to birth year for correlation with centroid size.

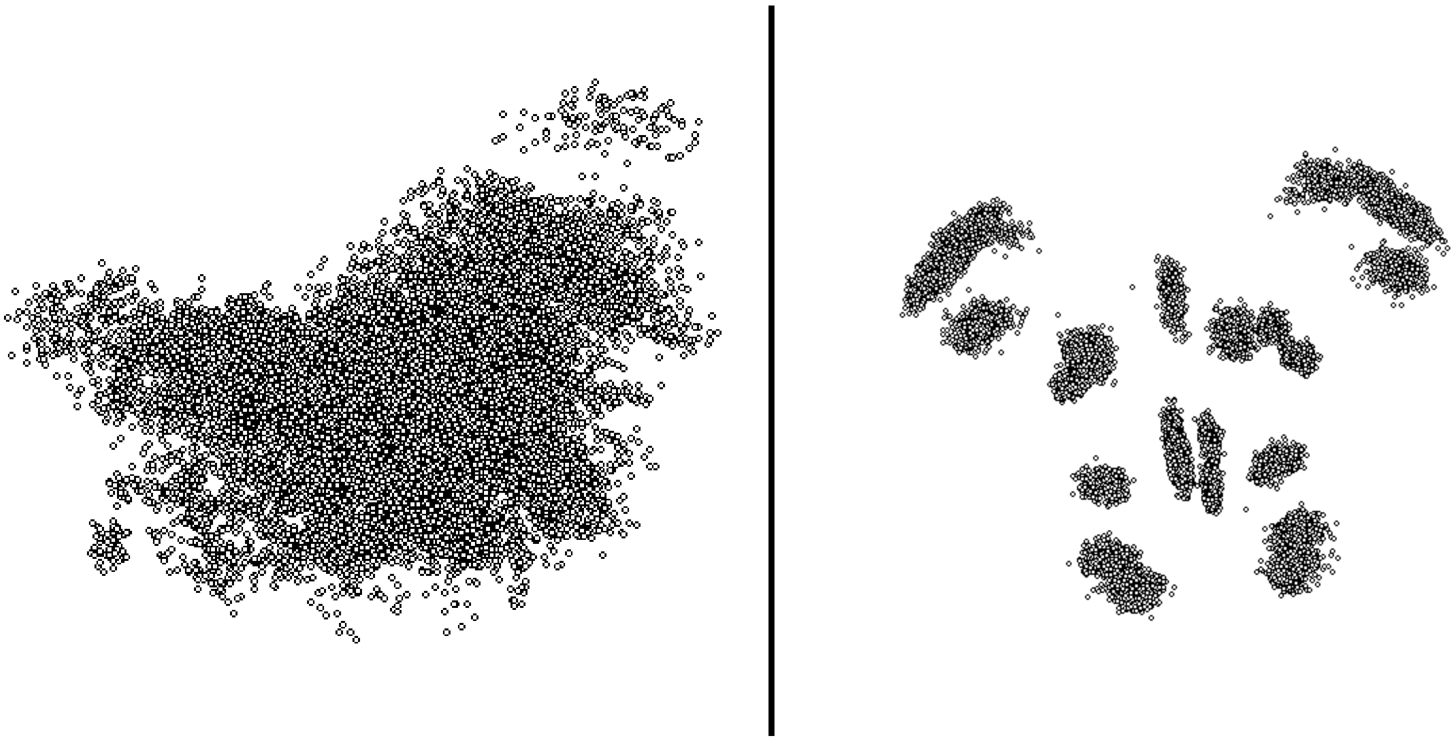

Figure 5: Landmark distribution of all individuals before and after GLS Procrustes Analysis

Chapter 5

Results

In this chapter, the results from the analyses outlined in the previous section will be discussed. Prior to testing the hypotheses, the data was analyzed for normalcy, and the samples were tested for significant differences between sex and ancestry among common birth cohorts to determine whether samples of corresponding cohorts could be combined. As has been stated, there are documented significant differences in the pelves of males and females and between those belonging to ancestral groups labeled, for the purpose of simplicity here, as “black” or “white.”

Data Analysis: Initial Testing

Initially, the femoral head was to be used to account for body size in the traditional metric analyses. After assessing the differences in sex, ancestry, and birth cohort, there were no statistical differences in the femoral head diameter among the cohorts; this is consistent with previous studies (Cridlin 2007). Additionally, because changes in size were of paramount interest in this study, accounting for body size would be counter-productive. Size differences were accounted for in the 3D geometric morphometric analyses, so rather than remove them in the traditional metric analyses, the raw distances were used.

The differences in demography were analyzed using MANOVA, and a Wilks’ Lambda of less than 0.0001 indicated that there were significant sex and ancestry differences in each of the measurements used in this study with (see Table 3). Subsequent ANOVA were assessed with a reduced alpha of 0.003 (0.05/16 tests), and nearly every inter-landmark (IL) distance indicated significant differences between the groups. It was decided to separate the groups into single sex and ancestry cohorts in order to prevent masking of secular changes by demographic differences.

Table 3: MANOVA results for sex and ancestry (significant differences denoted with italics and *)

MANOVA tests: Sex and Ancestry			
Sex		**Ancestry**	
Wilks' Lambda	*0.000**	**Wilks' Lambda**	*0.000**
IL Distance	**p-value**	**IL Distance**	**p-value**
BBE	0.0565	**BBE**	*0.000**
BBI	0.117	**BBI**	*0.000**
IAP	*0.000**	**IAP**	*0.000**
ITD	*0.000**	**ITD**	*0.000**
MAP	*0.000**	**MAP**	0.905
MTD	*0.000**	**MTD**	0.004
OAP	*0.000**	**OAP**	0.004
OTD	*0.000**	**OTD**	*0.000**
PBL	*0.000**	**PBL**	*0.000**
PBR	*0.000**	**PBR**	*0.000**
PHL	*0.000**	**PHL**	*0.000**
PHR	*0.000**	**PHR**	*0.000**
SAB	*0.000**	**SAB**	*0.000**
Femoral_Head	*0.000**	**Femoral_Head**	0.02

After separating the samples by sex and ancestry, the differences between the collections in the first three birth cohorts were examined to determine whether the samples from the different collections were similar enough to pool for further analyses. Each distance was tested for normality using the D'Agostino Omnibus Normality test for skewness and kurtosis to determine whether parametric or nonparametric tests were necessary. T-tests were then used to determine whether there were differences in the means when data was normal; when data was not normally distributed, the non-parametric test, the Wilcoxon Rank-Sum / Mann-Whitney test was used. Additionally, ANOVA was used to test for differences between the three collections in cohort 3 when the data was normal; when data was not normally distributed, the non-parametric test, the Kruskal Wallis test was used. T-tests were run on those cohorts where significant differences were noted. T-tests were run on the pairs to determine which groups significantly differed; a reduced alpha of 0.015 (Bonferroni 0.05/3tests) was used in these cases. Tables containing the results of these tests can be found in the appendix.

After examining all of the descriptive statistics, it was determined that the Terry and Hamann-Todd samples were similar enough to be combined; this differs from the results found by Delprete (2006). This may be due to her pooling the birth cohorts together under sex and ancestry groupings rather than examining the significant difference between samples within single cohorts. In the third birth cohort that includes individuals from the Terry, Hamann-Todd, and Bass collections, there are several variables that show significant differences between the samples within this birth cohort. This is especially evident in the males. Because of these significant differences, the third cohort samples will be pooled for the females while only the Terry and Todd males will be pooled. The Bass males in the third cohort will be a separate group.

Traditional Metrics

After separating the samples into sex, ancestry, and collection specific birth cohorts, MANOVAs were run on each cohort to test for differences in the inter-landmark distances. When the Wilks' lambda was significant (multivariate p-value), there was at least one distance that is different between the cohorts. The results of the separate groups tested will be discussed below.

Black Females

The black females in this study were the most stable group and exhibited the least amount of significant differences between inter-landmark distances among cohorts. The Wilks' Lambda was significant, and after adjusting the alpha to 0.003 to account for the number of separate ANOVA tests, only the calculated measurements, Turner's Pelvic Index and Pelvic Shape, were shown to be significantly different. Hotellings T^2 pairwise testing between cohorts further indicated that the differences in Turner's Pelvic Index and the Pelvic Shape were only significant between cohorts 1-3 and cohorts 2-3; however, the plots do show a positive trend in each variable over time. Significant results in the calculated measurements but not the linear measurements indicates that the secular change that is occurring, at least in the black females, is one of shape rather than size;

this will be further explored in the geometric morphometrics. The results are shown in Table 4 and Figure 6.

White Females

The white females show more significant inter-landmark distances than the black females. Again, Wilks' Lambda indicated significant differences in the samples. Like the black females, adjusted ANOVAs led to significant results in Turner's Pelvic Index and Pelvic Shape; white females were significant in cohorts 1-3 1-4, 1-5, 2-4. Additionally, the inlet AP, midplane AP, and outlet transverse diameters were significantly different among at least two cohorts; the results are shown in Table 5 and Figure 7. Each of the diameters showed increased length over time with significant increases in inlet AP between cohorts 1-3, 1-4, and 2-4. The midplane AP was significantly different between cohorts 1-4 and 1-5; the difference in the outlet transverse diameter was significant between cohorts1-4, 1-5, 2-5, and 3-5.

Black Males

The males were far more variable than the females. Like the females, the calculated measurements showed significant change. In addition, five other measurements had significant ANOVA values: external and internal bi-iliac breaths, inlet and outlet transverse diameters, and sacral breadth. While the trends in the females indicate increases in inter-landmark distances, the differences in cohorts of the males are less clear. The black males in the early Bass cohort (3b) appear to skew the plots with peak values for internal and external bi-iliac breadths, sacral breadth, and inlet transverse diameters; this could be due to the small sample size of four black males in the Bass cohort 3. Aside from the peak, these distances decrease over time. The outlet transverse diameter and the calculated measurements both increase between the cohorts. The specific cohorts with significant differences in inter-landmark distances can be found in Table 6 and Figure 8.

White Males

The white males exhibit the most variation of any of the groups with significant differences between cohorts in ten variables. In addition to the calculated Turner's Pelvic Index and Pelvic Shape measurements, the AP measurement of all three planes, the outlet transverse diameter, the external bi-iliac breadth, bilateral pelvic height, and the left pelvic breadth all showed significant differences between at least two cohorts. Like the black males, the bi-iliac breadth exhibits a peak value for the Bass 3b cohort. The inlet AP diameter and the calculated measurements showed the most constant, significant increases across the cohorts while the midplane AP diameter also showed an upward trend that was significant between the early and late cohorts. The other significant changes in distance fluctuate between the early and late cohorts with trends in cohorts 1-2-3 mirrored in cohorts 3b-4-5. The specific cohorts with significant differences in inter-landmark distances can be found in Table 7 and Figure 9.

Table 4: MANOVA results for inter-landmark distances in black females (significant differences denoted with italics and *)

Black Females	**MANOVA Analysis: Inter-landmark distance by Cohort**										
	MANOVA p-value	**Hotellings T^2 tests**									
		1v2	**1v3**	**1v4**	**1v5**	**2v3**	**2v4**	**2v5**	**3v4**	**3v5**	**4v5**
	_0.0095*_	0.046	_0.0006*_	_0.022*_	−	_0.023*_	_0.05*_	−	0.26	−	−
Inter-landmark Distance	**ANOVA p-value α=0.003**	**Individual t-tests (if Hotellings T^2 p-value is significant) α= 0.01 (0.025/ 2 distances)**									
BBE	0.029	−	−	−	−	−	−	−	−	−	−
BBI	0.051	−	−	−	−	−	−	−	−	−	−
IAP	0.006	−	−	−	−	−	−	−	−	−	−
ITD	0.035	−	−	−	−	−	−	−	−	−	−
MAP	0.13	−	−	−	−	−	−	−	−	−	−
MTD	0.2	−	−	−	−	−	−	−	−	−	−
OAP	0.14	−	−	−	−	−	−	−	−	−	−
OTD	0.07	−	−	−	−	−	−	−	−	−	−
PBL	0.64	−	−	−	−	−	−	−	−	−	−
PBR	0.07	−	−	−	−	−	−	−	−	−	−
PHL	0.03	−	−	−	−	−	−	−	−	−	−
PHR	0.035	−	−	−	−	−	−	−	−	−	−
SAB	0.06	−	−	−	−	−	−	−	−	−	−
F_H	0.17	−	−	−	−	−	−	−	−	−	−
Turner	_0.0006*_	−	_0.002*_	0.03	0.057	_0.007*_	0.057	0.074	−	0.81	0.8
Shape	_0.0008*_	−	_0.002*_	0.05	0.67	_0.0061*_	0.093	0.096	−	0.87	0.79

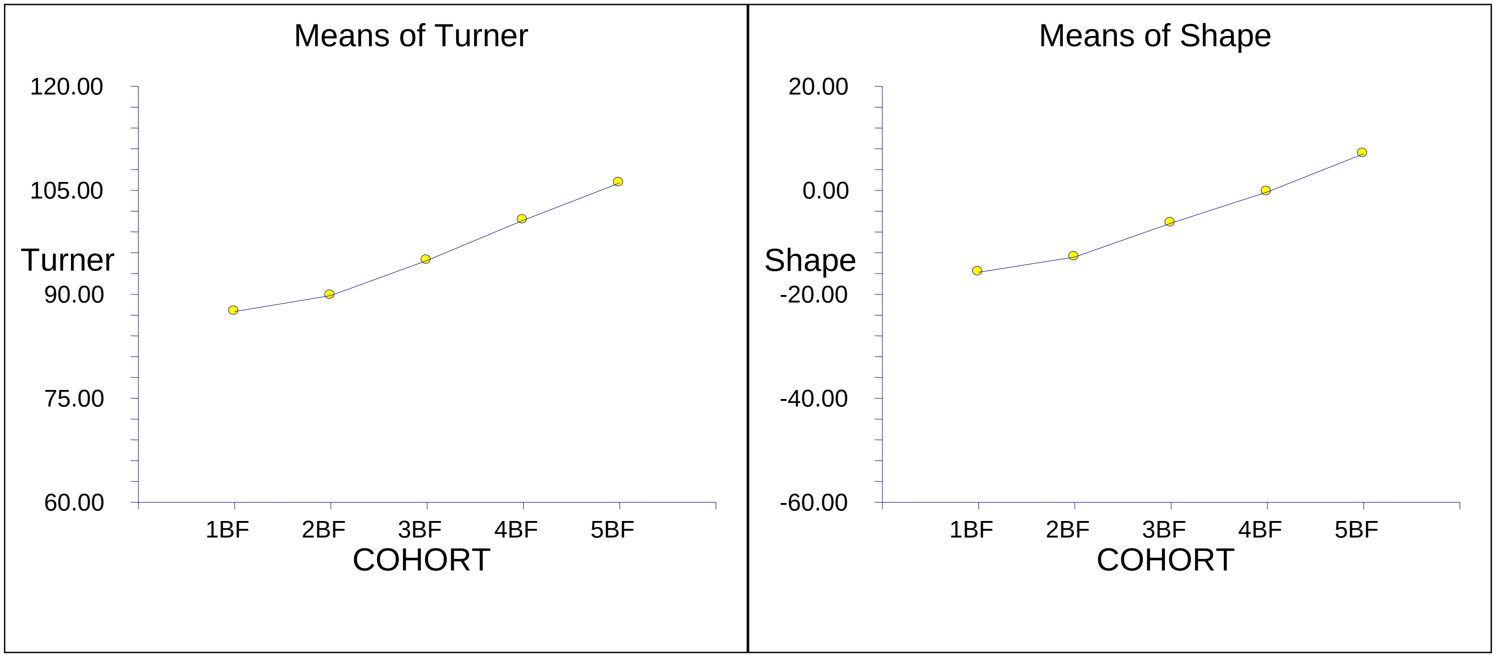

Figure 6: Plots of mean differences of significant variables in black females

Table 5: MANOVA results for inter-landmark distances in white females (significant differences denoted with italics and *)

White Females	**MANOVA Analysis: Inter-landmark distance by Cohort**										
	MANOVA p-value	**Hotellings T^2 tests**									
		1v2	**1v3**	**1v4**	**1v5**	**2v3**	**2v4**	**2v5**	**3v4**	**3v5**	**4v5**
	_0.000000*_	0.07	_0.004*_	_0.001*_	_0.001*_	0.2	_0.005*_	_0.001*_	0.17	_0.019*_	0.38
Inter-landmark Distance	**ANOVA p-value α=0.003**	**Individual t-tests (if Hotellings T^2 p-value is significant) α= 0.01 (0.05/ 5 distances)**									
BBE	0.043	−	−	−	−	−	−	−	−	−	−
BBI	0.059	−	−	−	−	−	−	−	−	−	−
IAP	_0.0005*_	−	_0.003*_	_0.001*_	0.017	−	_0.003*_	0.057	−	0.58	−
ITD	0.12	−	−	−	−	−	−	−	−	−	−
MAP	_0.027*_	−	0.5	0.21	_0.007*_	−	0.048	_0.002*_	−	0.063	−
MTD	0.11	−	−	−	−	−	−	−	−	−	−
OAP	0.13	−	−	−	−	−	−	−	−	−	−
OTD	_0.000042*_	−	0.04	_0.001*_	_0.001*_	−	0.051	_0.001*_	−	_0.003*_	−
PBL	0.56	−	−	−	−	−	−	−	−	−	−
PBR	0.72	−	−	−	−	−	−	−	−	−	−
PHL	0.38	−	−	−	−	−	−	−	−	−	−
PHR	0.46	−	−	−	−	−	−	−	−	−	−
SAB	0.017	−	−	−	−	−	−	−	−	−	−
F_H	0.31	−	−	−	−	−	−	−	−	−	−
Turner	_0.00001*_	−	_0.001*_	_0.001*_	_0.0081*_	−	_0.001*_	0.049	−	0.78	−
Shape	_0.00001*_	−	_0.001*_	_0.001*_	_0.01*_	−	_0.001*_	0.066	−	0.84	−

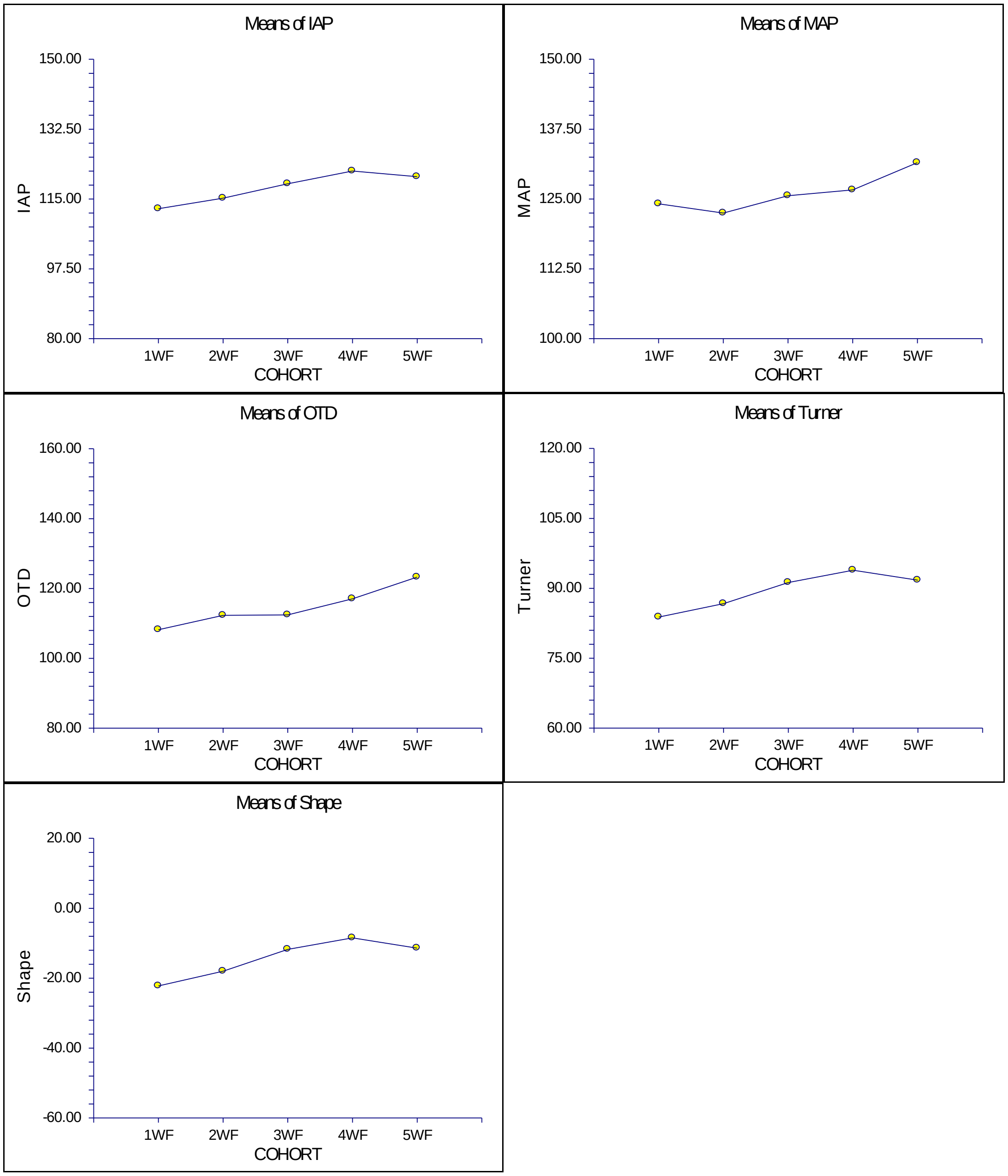

Figure 7: Plots of mean differences of significant variables in white females

Table 6: MANOVA results for inter-landmark distances in black males (significant differences denoted with italics and *)

Black Males	**MANOVA Analysis: Inter-landmark distance by Cohort**															
	MANOVA p-value	**Hotellings T^2 tests**														
		1v2	**1v3**	**1v3b**	**1v4**	**1v5**	**2v3**	**2v3b**	**2v4**	**2v5**	**3v3b**	**3v4**	**3v5**	**3bv4**	**3bv5**	**4v5**
	*0.000001**	*0.002**	*0.003**	*0.043**	*0.004**	*0.001**	0.99	*0.008**	*0.007**	*0.001**	0.014*	*0.03**	0.0009*	0.41	0.024*	0.022*
Inter-landmark Distance	**ANOVA p-value α=0.003**	**Individual t-tests (if Hotellings T^2 p-value is significant) α= 0.007 (0.05/ 7 distances)**														
BBE	*0.00004**	*0.006**	0.011	*0.002**	0.28	*0.002**	−	*0.001**	0.47	0.1	*0.001**	0.63	0.13	−	*0.001**	0.1
BBI	*0.0002**	0.62	0.1	0.04	0.086	*0.001**	−	*0.002**	0.52	*0.004**	0.008	0.64	0.013	−	*0.002**	0.067
IAP	0.049	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
ITD	*0.00081**	0.612	0.83	*0.008**	0.76	0.001*	−	*0.004**	0.55	*0.002**	0.018	0.7	*0.004**	−	*0.002**	*0.002**
MAP	0.017	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
MTD	0.11	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
OAP	0.15	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
OTD	*0.00013**	0.014	0.026	0.024	0.001	0.017	−	0.2	*0.002**	*0.34*	0.15	*0.001**	0.31	−	0.51	0.16
PBL	0.055	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
PBR	0.84	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
PHL	0.14	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
PHR	0.15	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
SAB	*0.0027**	0.97	0.9	0.025	0.18	*0.001**	−	0.034	0.15	*0.001**	0.022	0.19	*0.0008**	−	*0.001**	0.51
F_H	0.15	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Turner	*0.0009**	0.059	0.02	0.70	0.12	*0.001**	−	0.62	0.66	*0.003**	0.5	0.87	*0.0028**	−	0.032	0.068
Shape	*0.0013**	0.064	0.03	0.84	0.12	*0.001**	−	0.49	0.65	*0.003**	0.40	0.83	*0.0029**	−	0.026	0.061

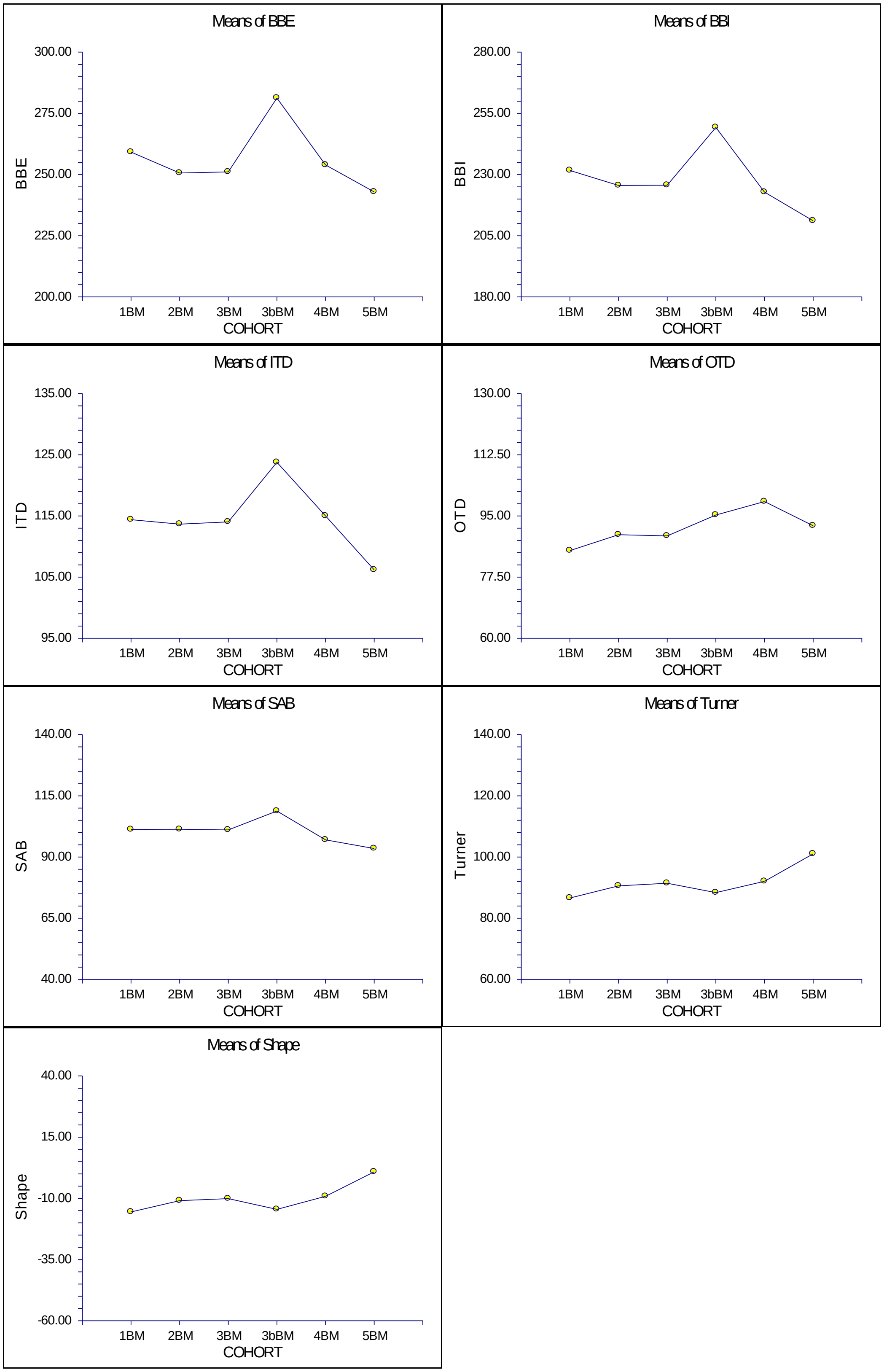

Figure 8: Plots of mean differences of significant variables in black males

Table 7: MANOVA results for inter-landmark distances in white males (significant differences denoted with italics and *)

White Males	**MANOVA Analysis: Inter-landmark distance by Cohort**															
	MANOVA p-value	**Hotellings T^2 tests**														
		1v2	**1v3**	**1v3b**	**1v4**	**1v5**	**2v3**	**2v3b**	**2v4**	**2v5**	**3v3b**	**3v4**	**3v5**	**3bv4**	**3bv5**	**4v5**
	_0.0000*_	0.08	_0.001*_	_0.001*_	_0.001*_	_0.001*_	_0.002*_	_0.037*_	_0.001*_	_0.001*_	0.03*	_0.002*_	_0.004*_	_0.022*_	_0.004*_	0.096
Inter-landmark Distance	**ANOVA p-value α=0.003**	**Individual t-tests (if Hotellings T^2 p-value is significant) α= 0.007 (0.05/ 7 distances)**														
BBE	_0.0004*_	−	0.075	0.008	0.77	0.026	0.25	_0.005*_	0.33	0.14	_0.001*_	0.042	0.74	0.01	_0.001*_	−
BBI	0.0031	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
IAP	_0.000*_	−	_0.001*_	_0.001*_	_0.001*_	_0.001*_	0.008	_0.001*_	_0.001*_	_0.001*_	0.08	_0.001*_	_0.001*_	0.013	0.11	−
ITD	0.033	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
MAP	_0.0003*_	−	0.041	0.059	_0.002*_	_0.001*_	0.03	0.059	_0.002*_	_0.003*_	0.92	0.27	0.12	0.37	0.22	−
MTD	0.19	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
OAP	_0.0019*_	−	_0.002*_	0.061	0.036	_0.005*_	0.002*	0.058	0.02	_0.007*_	0.73	0.4	0.77	0.85	0.6	−
OTD	_0.000*_	−	0.18	0.3	_0.001*_	_0.002*_	0.63	0.49	0.01	0.078	0.79	_0.006*_	0.032	_0.004*_	0.02	−
PBL	_0.0021*_	−	0.046	0.12	0.21	0.061	0.99	0.009	0.008	0.21	_0.004*_	_0.006*_	0.18	0.56	0.079	−
PBR	0.023	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
PHL	_0.00026*_	−	0.99	0.008	_0.002*_	0.13	0.41	_0.003*_	_0.001*_	0.024	0.031	0.008	0.21	0.75	0.26	−
PHR	_0.0003*_	−	0.94	0.02	_0.003*_	0.1	0.35	_0.003*_	_0.001*_	0.011	0.05	0.014	0.17	0.72	0.39	−
SAB	0.02	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
F_H	0.6	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Turner	_0.000*_	−	_0.001*_	_0.001*_	_0.001*_	_0.001*_	0.022	0.027	_0.001*_	_0.001*_	0.82	_0.002*_	_0.001*_	_0.005*_	_0.005*_	−
Shape	_0.000*_	−	_0.001*_	_0.001*_	_0.001*_	_0.001*_	0.033	0.047	_0.001*_	_0.001*_	0.92	_0.003*_	_0.001*_	_0.004*_	_0.005*_	−

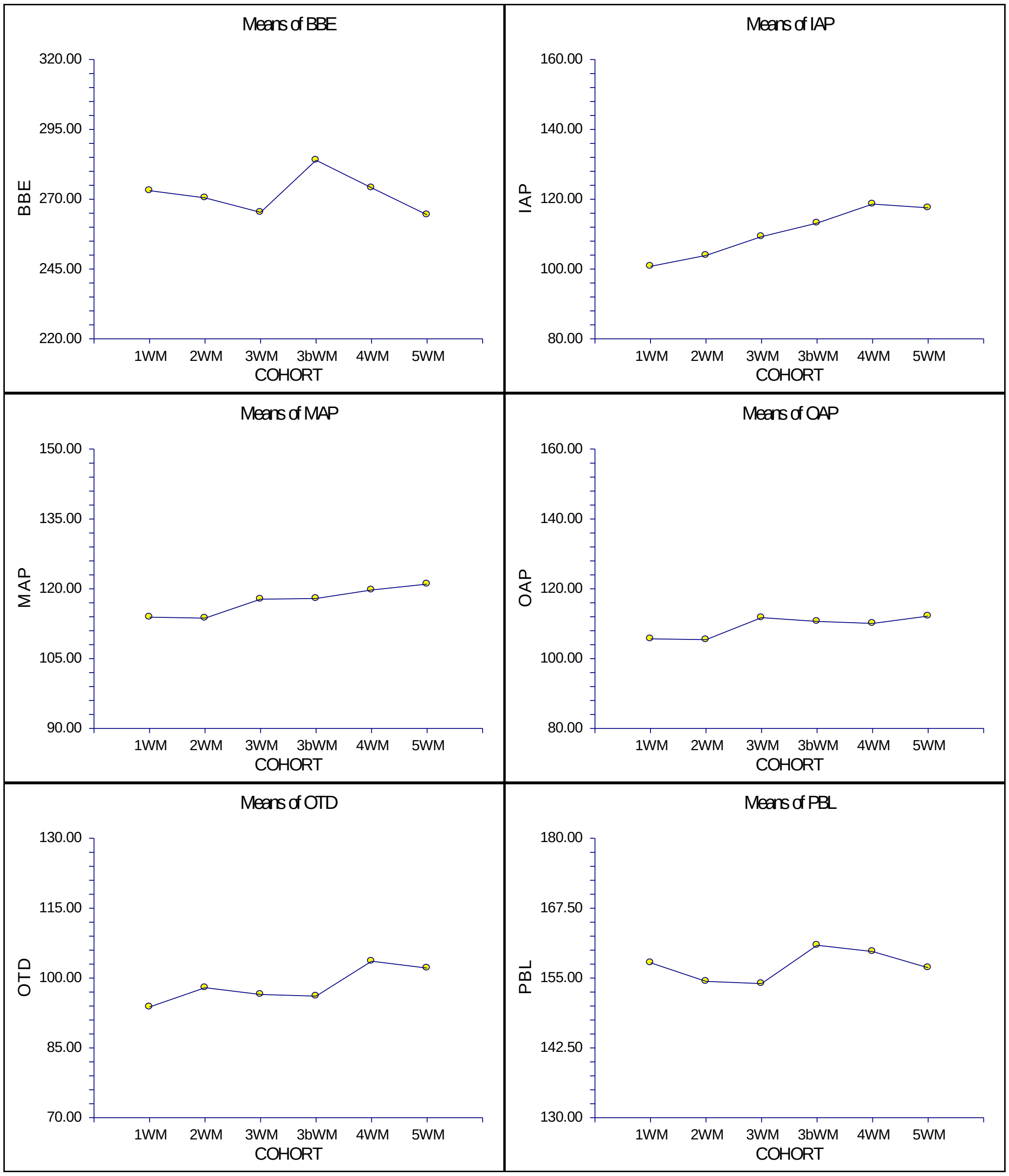

Figure 9: Plots of mean differences of significant variables in white males

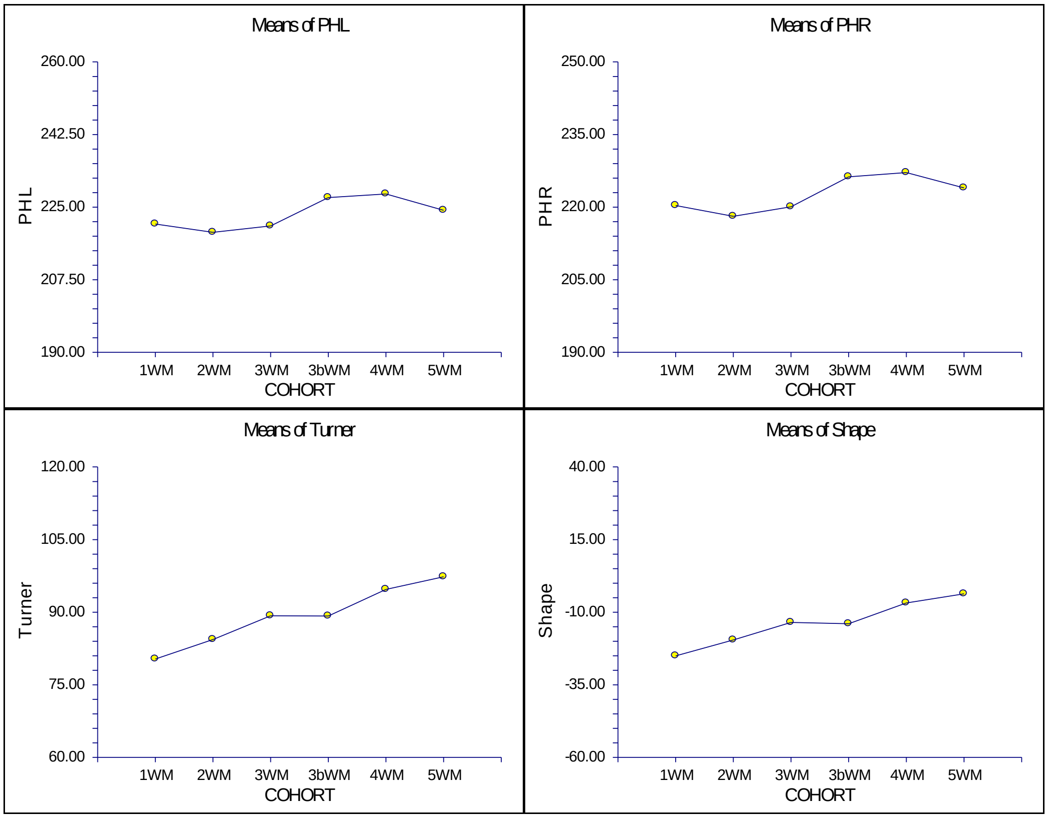

Figure 9 (cont): Plots of mean differences of significant variables in white males

Geometric Morphometrics

The groups were separated, again, by ancestry and sex, and four separate groups were run through geometric morphometric software: black females, white females, black males, and white males. The collections were pooled within the birth cohorts, and preprocessing (General Procrustes Analysis followed by Principal Components Analysis) was done in Morphologika2. Because the groups were, again, run separately, this will enable the partitioning out of the factors affecting the Principle Components (PCs) and centroid size whether collection, cohort, cause of death, year of birth, or age at death. After GPA, PCA indicated that retaining 14 principal components explained over 80% of the variation in the samples, so further analyses utilized the scores from 14 PCs. Tables 8a - 8d contains the principal components retained with their associated eigenvalues and the amount of variation each explains within the sample. The results produced by Morphologika2 were mirrored in MorphoJ. In addition to the PC scores, which were used to test for shape changes, the centroid sizes were used in further analyses of size differences.

Canonical discriminant analysis through canonical variates analysis was used to determine whether shape difference exists between birth cohort groups using the first 14 PC scores. The canonical variates were then plotted. In addition, distance matrices show the differences between the cohorts of each group. The results for each sample group are described in the following sections.

Tables 8 a-d: Principal Components retained for analyses

a) Black Females

Black Females	eigenvalue	percentage of total variance explained	cumulative variance explained
PC 1	0.0017	21.89668	21.89668
PC 2	0.001109	14.28148	36.17817
PC 3	0.000576	7.420575	43.59874
PC 4	0.000504	6.491402	50.09014
PC 5	0.000467	6.014315	56.10446
PC 6	0.000364	4.689333	60.79379
PC 7	0.000336	4.334345	65.12814
PC 8	0.000302	3.890841	69.01898
PC 9	0.000233	3.000992	72.01997
PC 10	0.000213	2.744888	74.76486
PC 11	0.00019	2.448211	77.21307
PC 12	0.000165	2.127672	79.34074
PC 13	0.000152	1.953225	81.29396
PC 14	0.000135	1.743024	83.03699

b) White Females

White Females	eigenvalue	percentage of total variance explained	cumulative variance explained
PC 1	0.002303	27.10806	27.10806
PC 2	0.001593	18.75211	45.86017
PC 3	0.00064	7.534214	53.39438
PC 4	0.000562	6.61497	60.00935
PC 5	0.000387	4.553962	64.56331
PC 6	0.00037	4.356562	68.91988
PC 7	0.000307	3.613719	72.53359
PC 8	0.000246	2.897247	75.43084
PC 9	0.000213	2.505188	77.93603
PC 10	0.000186	2.186134	80.12216
PC 11	0.00016	1.887244	82.00941
PC 12	0.00014	1.647064	83.65647
PC 13	0.000122	1.434516	85.09099
PC 14	0.000112	1.321044	86.41203

c) Black Males

Black Males	eigenvalue	percentage of total variance explained	cumulative variance explained
PC 1	0.001395	19.21764	19.21764
PC 2	0.000932	12.83164	32.04928
PC 3	0.000512	7.050644	39.09993
PC 4	0.000453	6.246161	45.34609
PC 5	0.000407	5.604851	50.95094
PC 6	0.00039	5.375956	56.3269
PC 7	0.000376	5.183867	61.51076
PC 8	0.000312	4.299617	65.81038
PC 9	0.000255	3.513901	69.32428
PC 10	0.000229	3.148464	72.47275
PC 11	0.000182	2.509522	74.98227
PC 12	0.000164	2.265436	77.2477
PC 13	0.000156	2.147218	79.39492
PC 14	0.000152	2.095746	81.49067

d) White Males

White Males	eigenvalue	percentage of total variance explained	cumulative variance explained
PC 1	0.001605	22.25604	22.25604
PC 2	0.00116	16.08472	38.34076
PC 3	0.000511	7.082668	45.42343
PC 4	0.000439	6.08902	51.51245
PC 5	0.000378	5.245871	56.75832
PC 6	0.000307	4.251158	61.00948
PC 7	0.000289	4.013938	65.02342
PC 8	0.000255	3.537707	68.56112
PC 9	0.000227	3.147784	71.70891
PC 10	0.000193	2.675848	74.38475
PC 11	0.00017	2.364355	76.74911
PC 12	0.000154	2.1325	78.88161
PC 13	0.000125	1.737469	80.61908
PC 14	0.000111	1.539796	82.15887

Shape: Black Females

Canonical variate analysis maximizes the amount of variation between groups. After running the analysis on the five birth cohorts using the first 14 PCs, the first and second canonical correlations were 0.67 and 0.42. The first two canonical variates (CVs) represented 82.5% of the variation with the first CV responsible for over 65% of the total variation. Only the eigenvalue associated with the CV1 was significant. Canonical variate plots are shown in Figure 10a and 10b and Figure 11; these plots show two different perspectives of the data, but each exhibits the same tendency. After plotting the CV1 and CV2, the cohorts were separated temporally with the cohorts aligning along the first canonical variate in order of birth year. Cohort 5 was separated from the rest of the cohorts along the CV2. Temporally, cohort 5 fell in line with cohort 3; however, this was based on a single black female in cohort 5. CV2 appears to account for variation that is present in Cohort 4 and 5, black females from the Bass Collection. Again, it needs to be noted that there are very few individuals in these cohorts compared to the earlier cohorts. The distances between the cohorts are shown in Table 9.

In order to visualize the morphological changes that are occurring along CV1, illustrations were created in MorphoJ; these illustrations correspond to the plot shown in Figure 11. The illustrations are shown in Figure 12. Landmark identifications of the numbered points can be found in Table A13 in the appendix. These illustrations illuminate the shape change that is occurring as landmarks shift. The birth canal, specifically the inlet AP diameter, is lengthening as is the outlet transverse diameter along CV1. In concert, the iliac flare is decreasing with later cohorts.

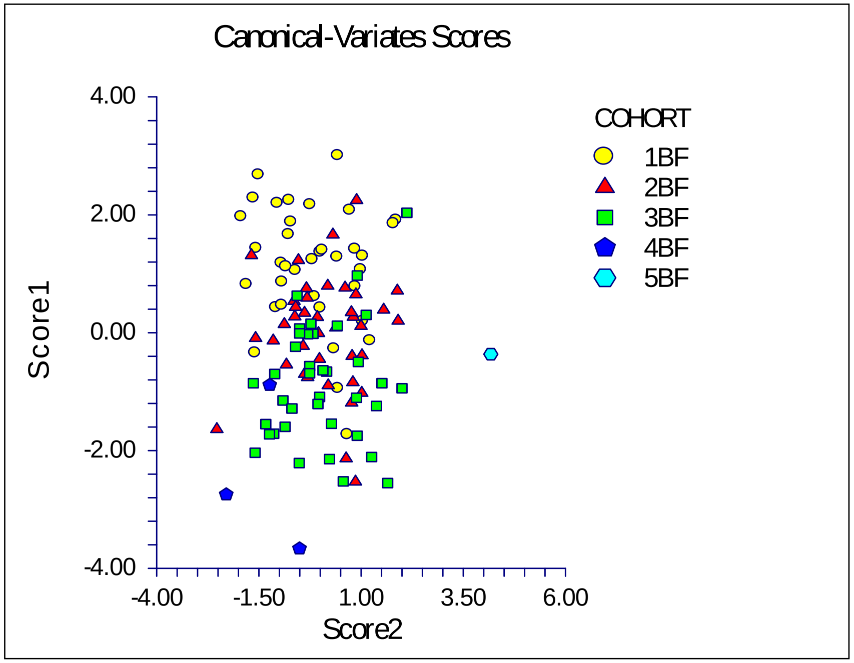

Figure 10a: Canonical plot of individual black females

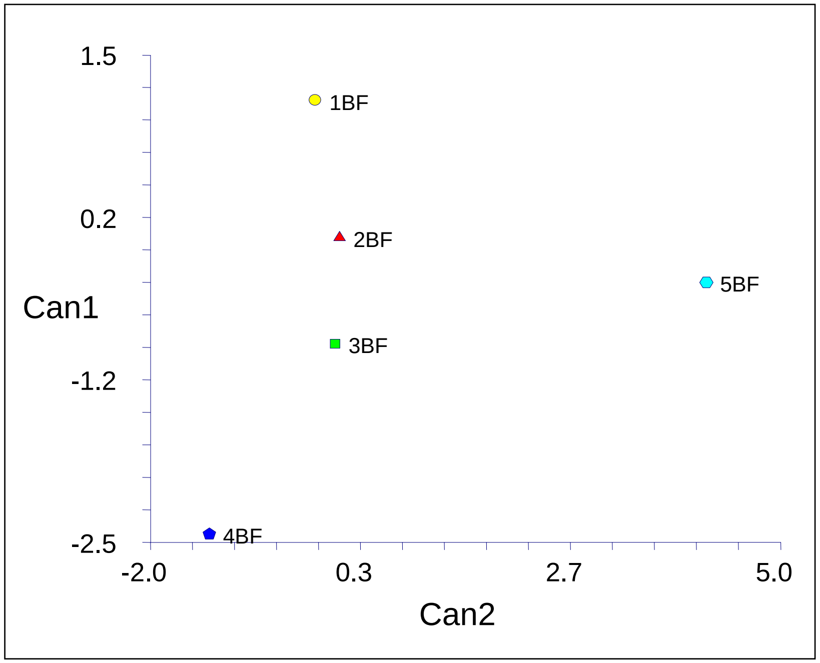

Figure 10b: Canonical plot of cohort means of black females

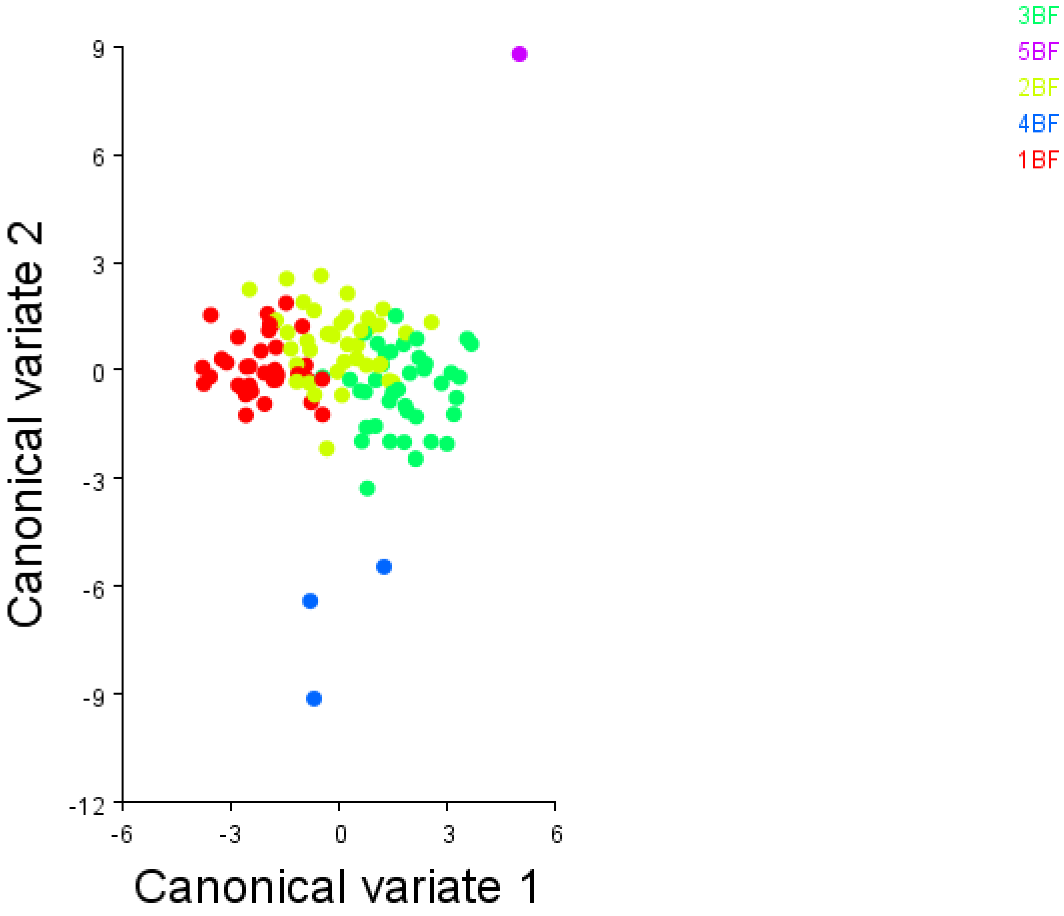

Figure 11: Canonical plot of individual black females produced in MorphoJ

Table 9: Distance matrix between black female cohorts, significance denoted by italics

Cohort	**1BF**	**2BF**	**3BF**	**4BF**
2BF	*3.2349**			
3BF	*4.0153**	*3.2864**		
4BF	*9.1047**	*8.8938**	*8.8870**	
5BF	*14.2316**	*13.1444**	*13.5818**	17.5315

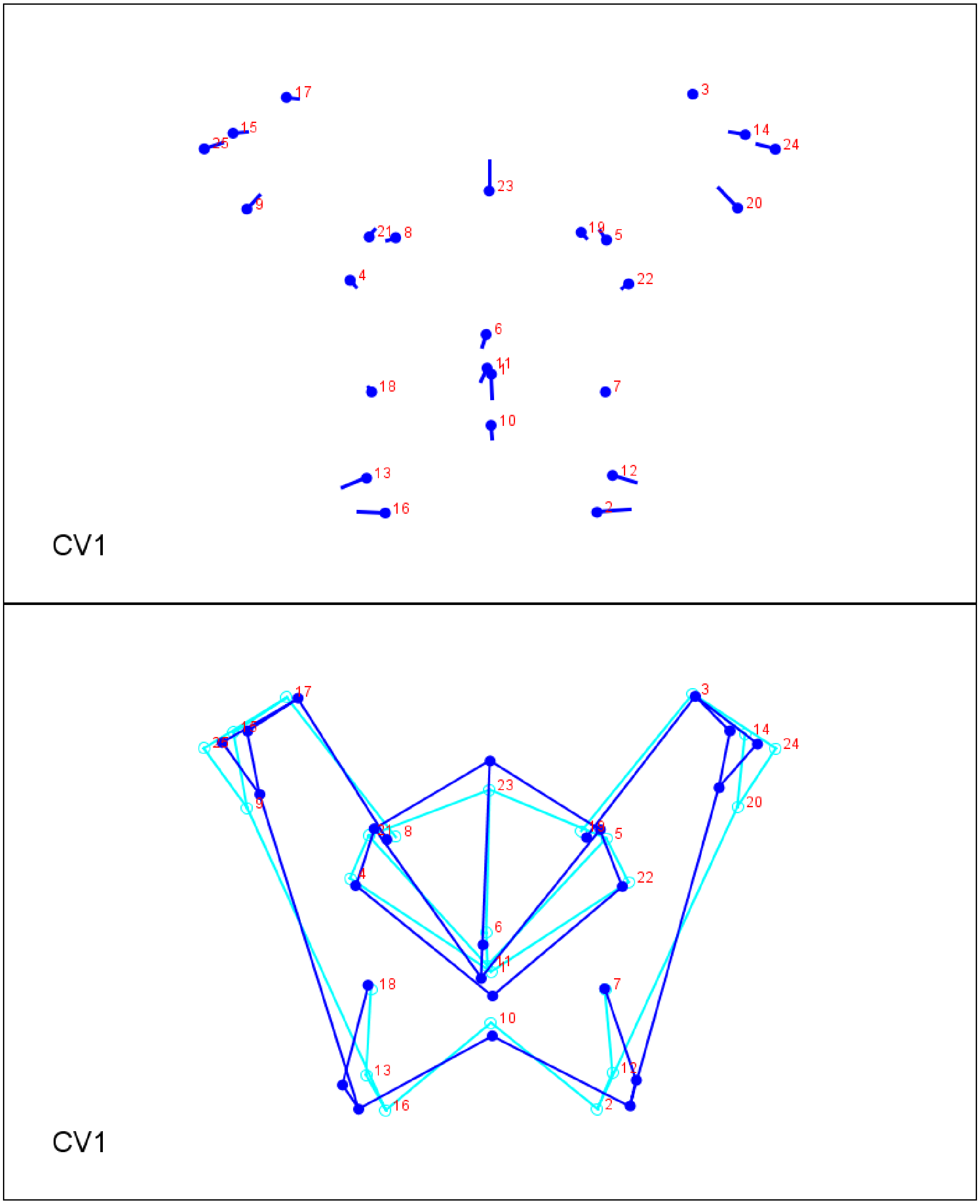

Figure 12: Landmark shifts along first canonical variate in black females. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate one (later cohorts). Landmark identifications of the numbered points can be found in Table A13 in the appendix.

Shape: White Females

The first two canonical variates were significant in the white females and account for nearly 80% of the variation between the cohorts. Canonical variate one accounted for 56.8% of the total variation with a canonical correlation of 0.58. The second canonical variate explained 22.7% of the variation and the canonical correlation is 0.41. The plots of the canonical variates are shown in Figures 13a,b, and 14. Figures 13a and 13b were produced using NCSS and depict the individual values and the mean value, respectively. Figure 14 was produced in Morphologika2. Similar to the black females, CV1 separated the cohorts temporally. Again, cohort 5 was separated from the rest of the groups on CV2, but with the white females, this CV is significant; CV2 was not significant in the black females. While the separation in the black females was based on a single individual, there are 11 white females in cohort 5. The distance matrix for the white females is shown in Table 10; there is significant distance between each of the five cohorts.

The morphological changes along CV1 and CV2 correspond to the plot shown in Figure 14 are illustrated in Figures 15 and 16. These illustrations illuminate the shape change that is occurring as landmarks shift. Like the black females, along CV1, the outlet transverse diameter is lengthening and the inlet AP diameter greater in later cohorts. The increase in the AP length was not as extreme as was found in the black females. Also along CV1, there is a decrease in bi-iliac flare as well as an expansion of the subpubic angle. In CV2, which appears to separate cohort 5, the angle of the iliac blade appears to be the most significant difference.

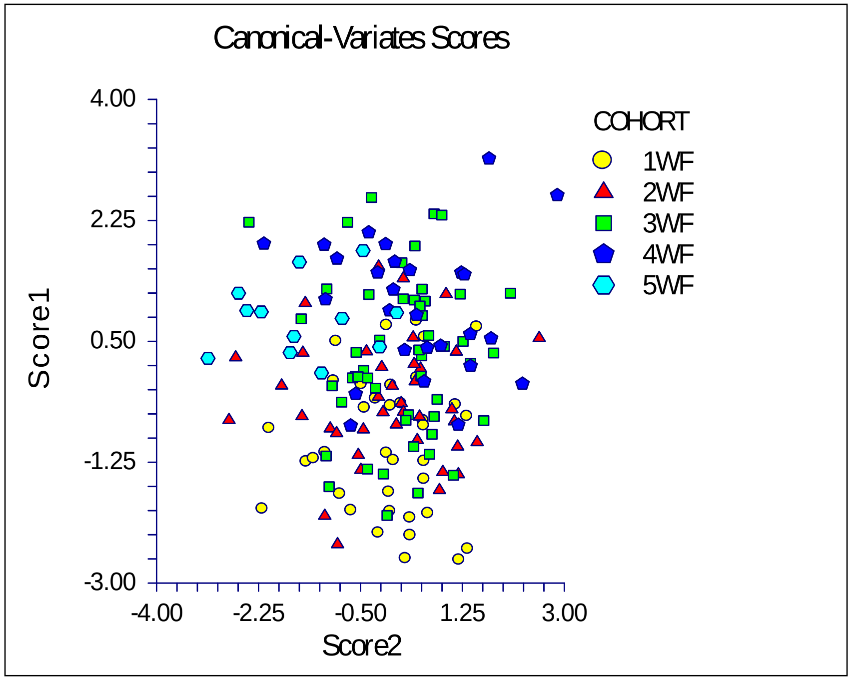

Figure 13a: Canonical plot of individual white females

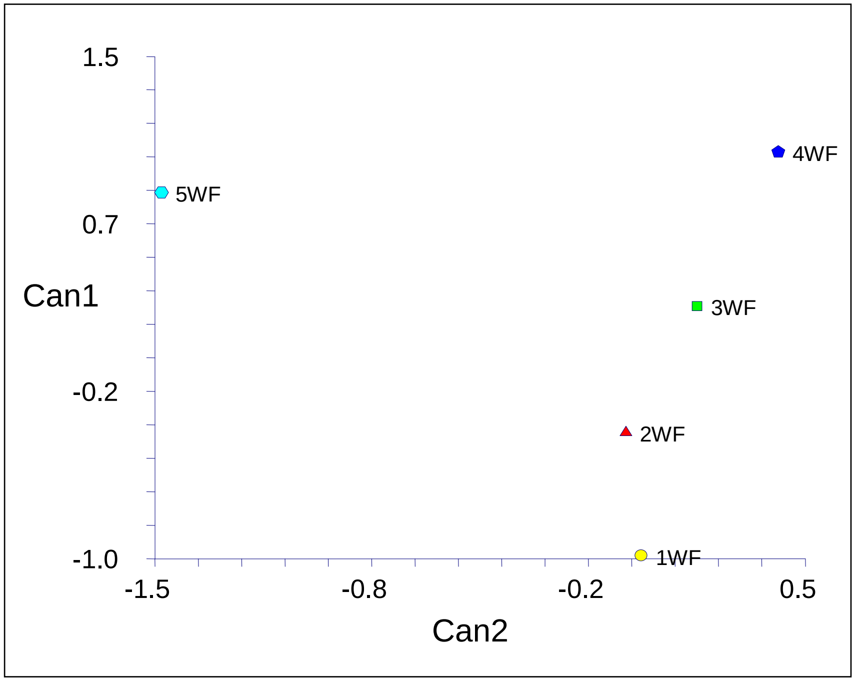

Figure 13b: Canonical plot of cohort means of white females

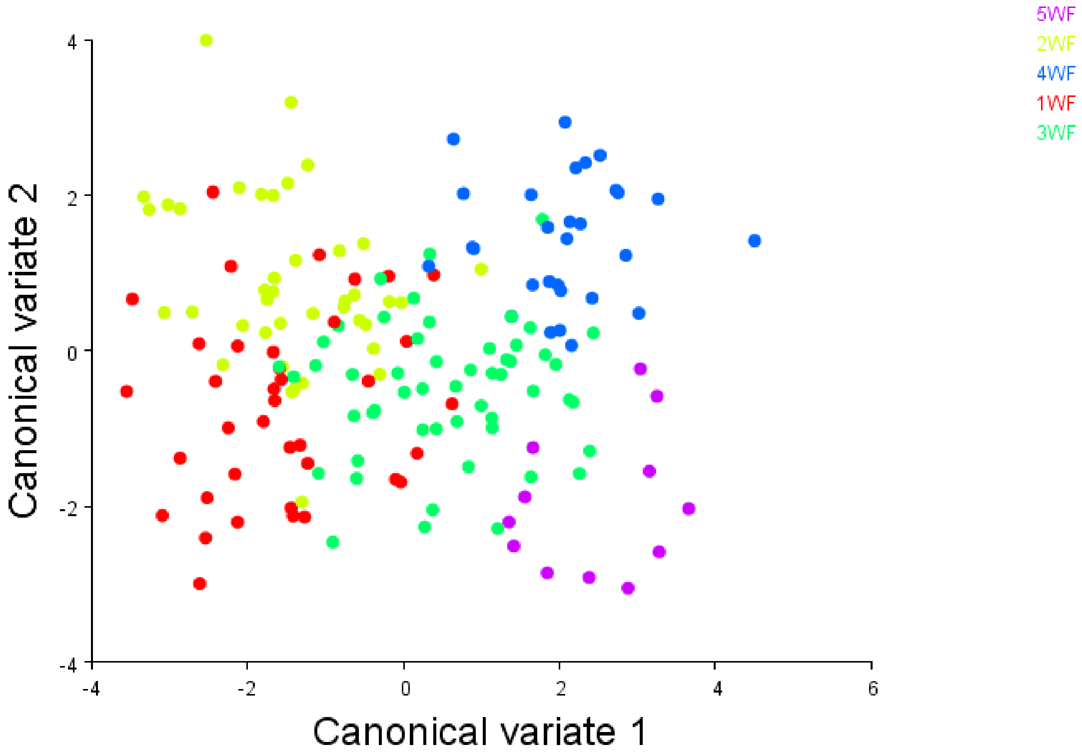

Figure 14: Canonical plot of individual white females produced in MorphoJ

Table 10: Distance matrix between white female cohorts, significance denoted by italics

Cohort	**1WF**	**2WF**	**3WF**	**4WF**
2WF	*2.4457**			
3WF	*2.8548**	*2.8538**		
4WF	*4.1890**	*3.8898**	*2.9515**	
5WF	*4.7961**	*5.0733**	*3.6978**	*4.0115**

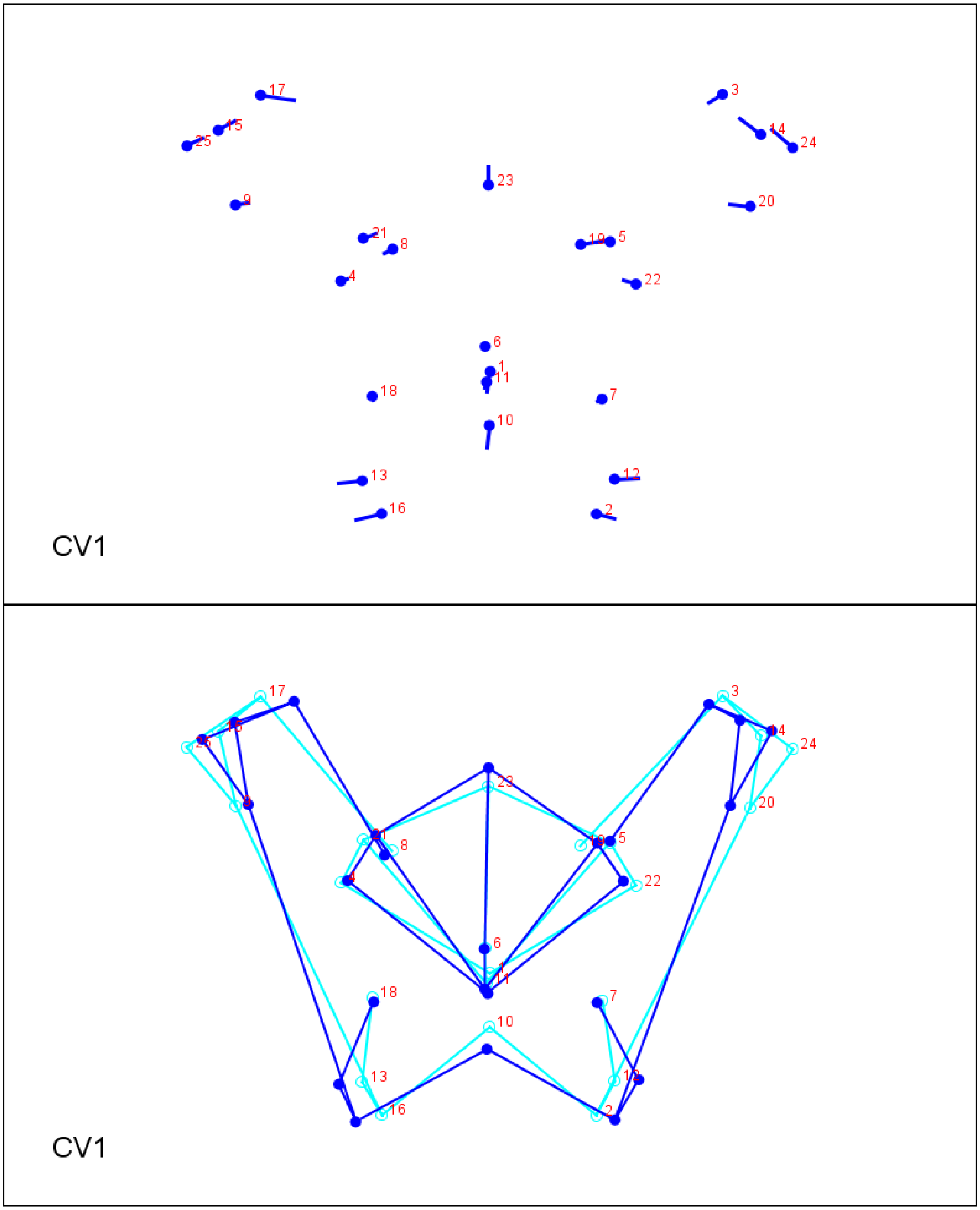

Figure 15: Landmark shifts along first canonical variate in white females. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate one (later cohorts). Landmark identifications of the numbered points can be found in Table A13 in the appendix.

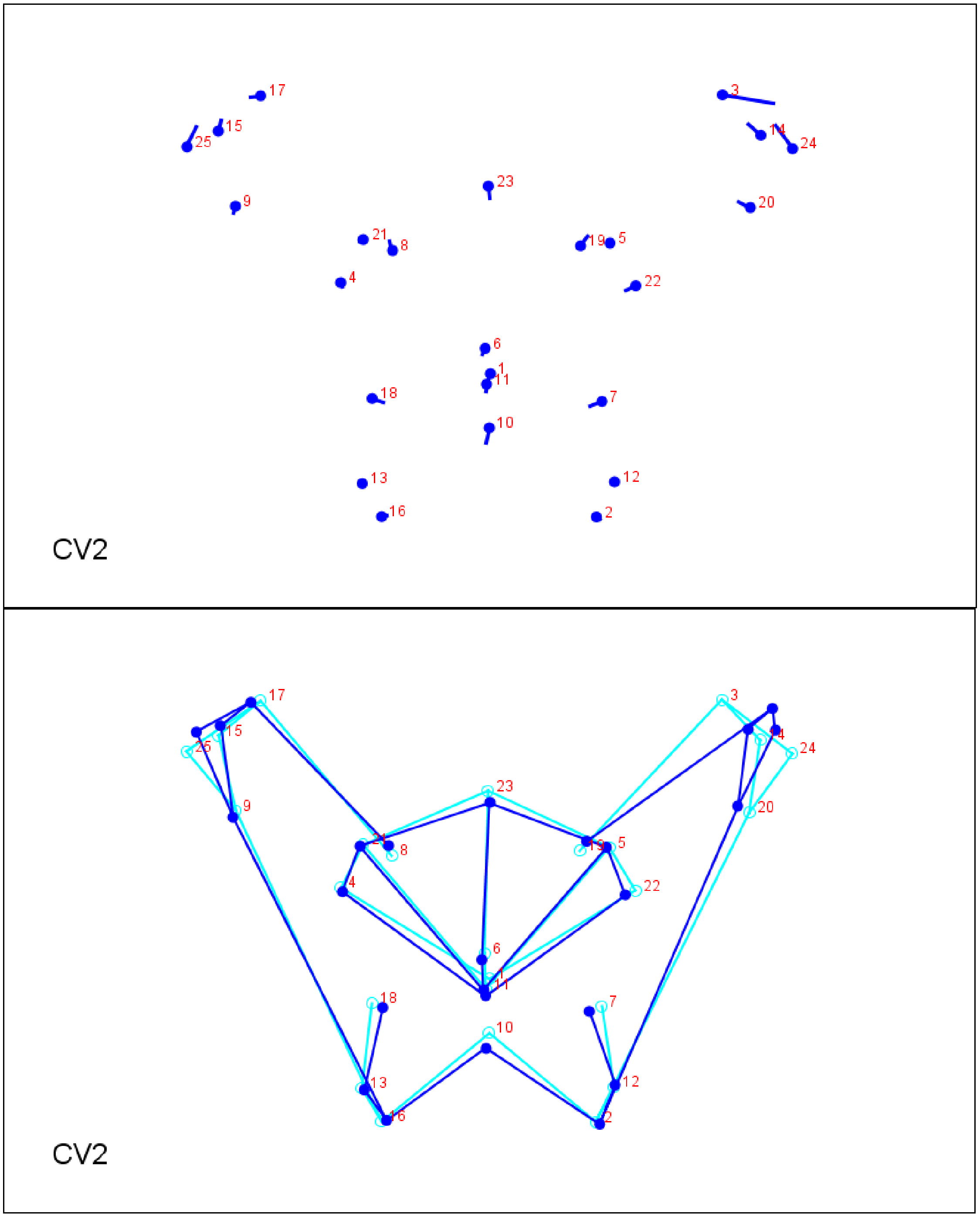

Figure 16: Landmark shifts along second canonical variate in white females. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate two. Landmark identifications of the numbered points can be found in Table A13 in the appendix.

Shape: Black Males

After performing canonical variates analysis on the black males, only the first canonical variate exhibited a significant eigenvalue. CV1 accounted for 55.8% of the total variation between the cohorts with a canonical correlation of 0.64. While the second CV did not have a significant eigenvalue, it accounted for 22.6% of the variation and has a canonical correlation of 0.47. The plots of the canonical variates are shown in Figures 17a, b, and 18. Figures 17a and 17b were produced using NCSS and depict the individual values and the mean value, respectively. Figure 18 was produced in Morphologika2. The two programs show the same separation of groups. The distance matrix shown in Table 11 indicates that there are significant differences between each cohort.

Figure 19 illustrates the morphological changes along CV1. While the traditional metrics indicated that the males were more variable than the females, the landmark shifts in the black males appear to be comparable to those of the females. There was a decrease in the bi-iliac flare, the sacral breadth, and the inlet transverse diameter. Also along canonical variate one was an increase in the outlet transverse diameter. Additionally, even though canonical variate two was not significant, it is shown in Figure 20 since there is clearly a separation between the Bass black males and the other collections. Along CV2, there is a decrease in the transverse diameter of the outlet, but the most obvious difference is the anterior shift of the bi-iliac flare with an increase in iliac breadth.

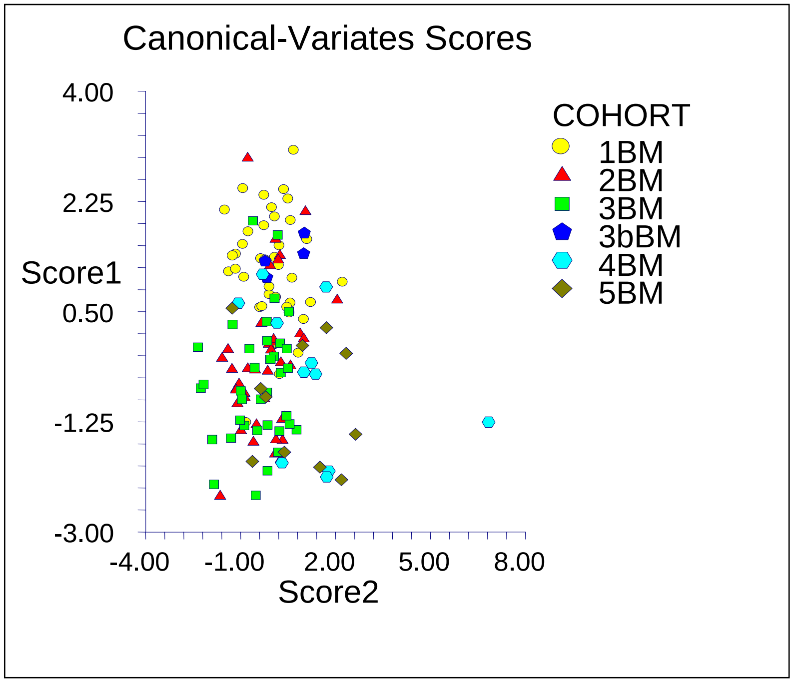

Figure 17a: Canonical plot of individual black males

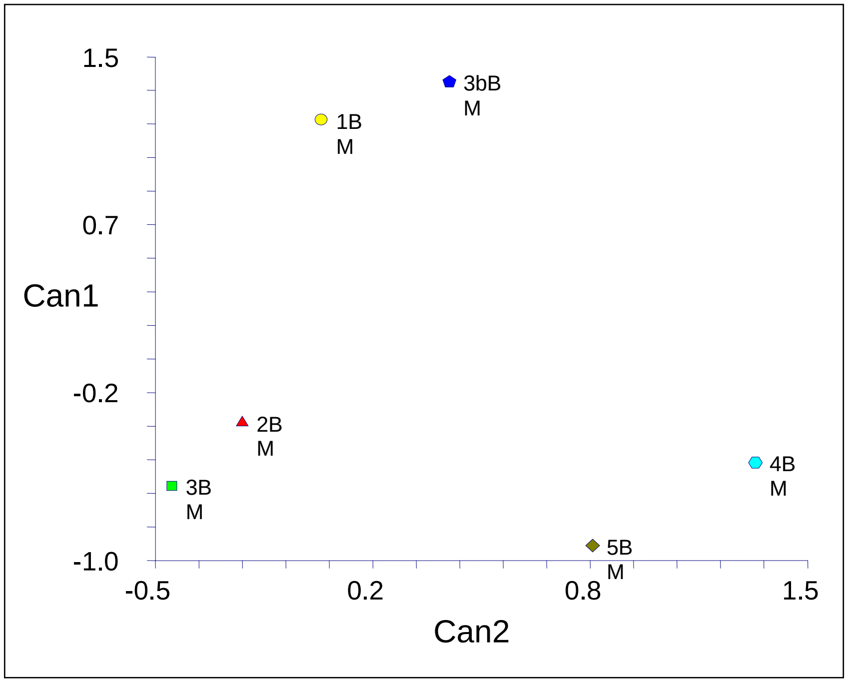

Figure 17b: Canonical plot of cohort means of black males

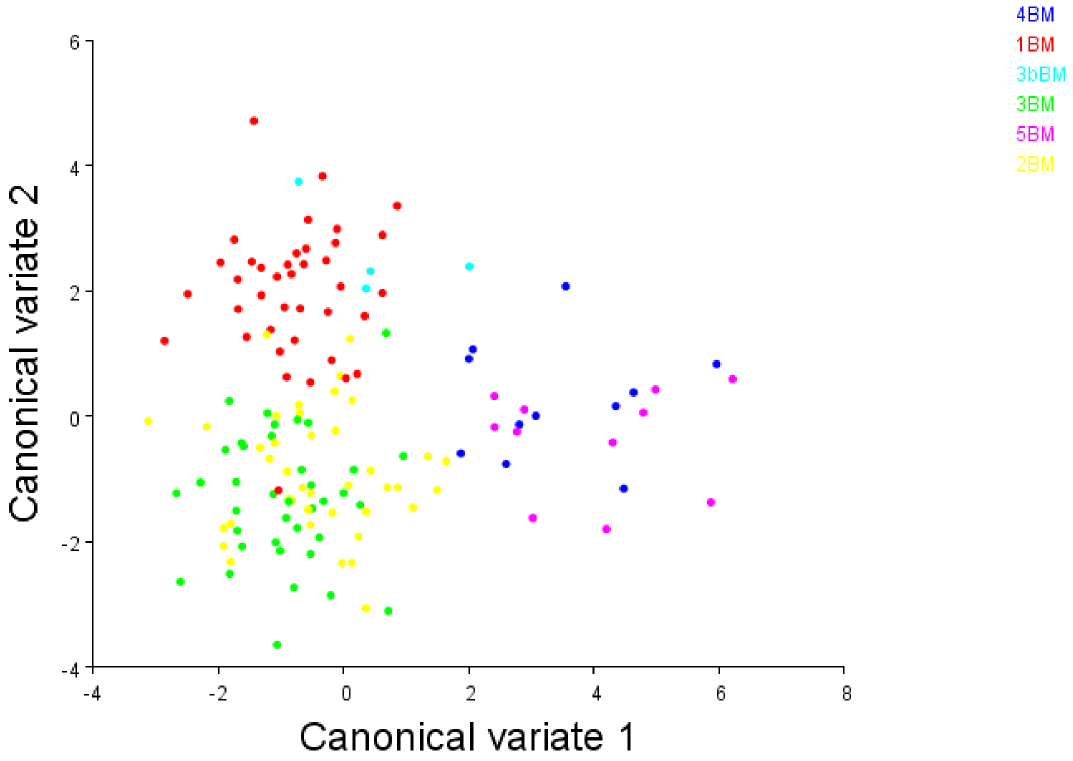

Figure 18: Canonical plot of individual black males produced in MorphoJ

Table 11: Distance matrix between black male cohorts, significance denoted by italics

Cohort	1BM	2BM	3BM	3bBM	4BM
2BM	*3.3624**				
3BM	*3.5272**	*2.6184**			
3bBM	*5.3527**	*5.8736**	*6.3212**		
4BM	*5.3160**	*5.0223**	*5.2931**	*6.3394**	
5BM	*5.7085**	*5.2728**	*5.6311**	*7.2977**	*4.8595**

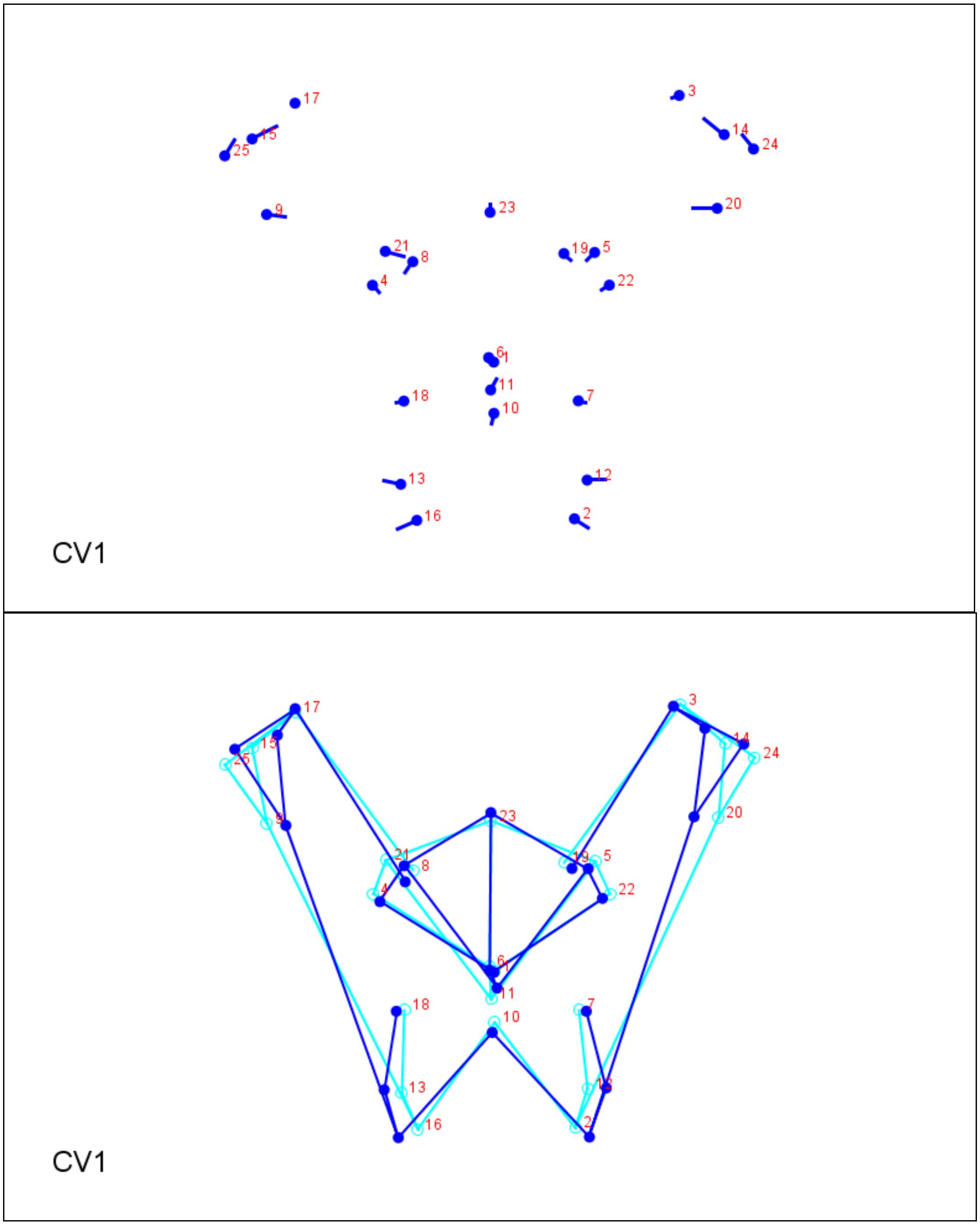

Figure 19: Landmark shifts along first canonical variate in black males. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate one (later cohorts). Landmark identifications of the numbered points can be found in Table A13 in the appendix.

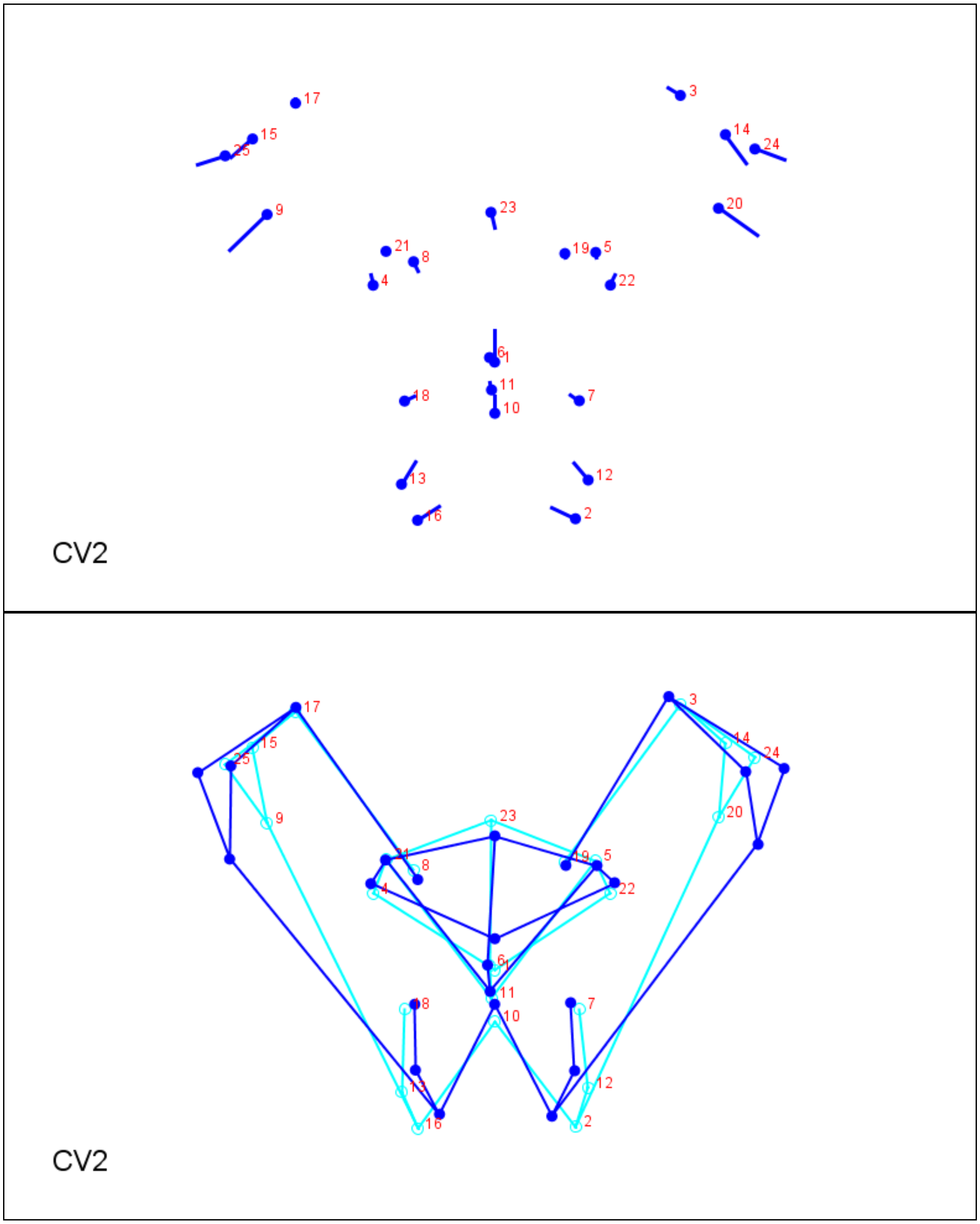

Figure 20: Landmark shifts along second canonical variate in black males. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate two. Landmark identifications of the numbered points can be found in Table A13 in the appendix.

Shape: White Males

Two canonical variates were significant in separating the differences between the cohorts in white males. Canonical variate one and canonical variates two account for nearly 83% of the total variation with CV1 responsible for 60.6%. The canonical correlations for the first two canonical variates were 0.66 and 0.47 respectively. Figures 21a, b, and 22 illustrate the canonical plots. Again, figures 21a and 21b were produced using NCSS and depict the individual values and the mean value, respectively. Figure 22 was produced in Morphologika2. In the white males, CV1, again, separated the cohorts temporally while CV2, like in the black males, separated the Bass males from the Terry/Todd males. The distance between each cohort is significant and is depicted in Table 12.

Similar to the black males, the morphology changes along canonical variate one include an increase in the inlet AP and outlet transverse diameters as well as a decrease in bi-iliac flare. In addition, the white males exhibit a decrease in the inlet transverse diameter. Canonical variate two, which separates the Bass males from the other two collections, involves an increase in bi-iliac flare, a decrease in the midplane transverse diameter, and a medial movement of the posterior superior iliac spines. Illustrations of the morphological shifts are shown in Figures 23 and 24. Traditional metrics indicated that the white males were the most variable of the samples with several significant inter-landmark distances; this is more difficult to state after examining the changes in shape using geometric morphometry.

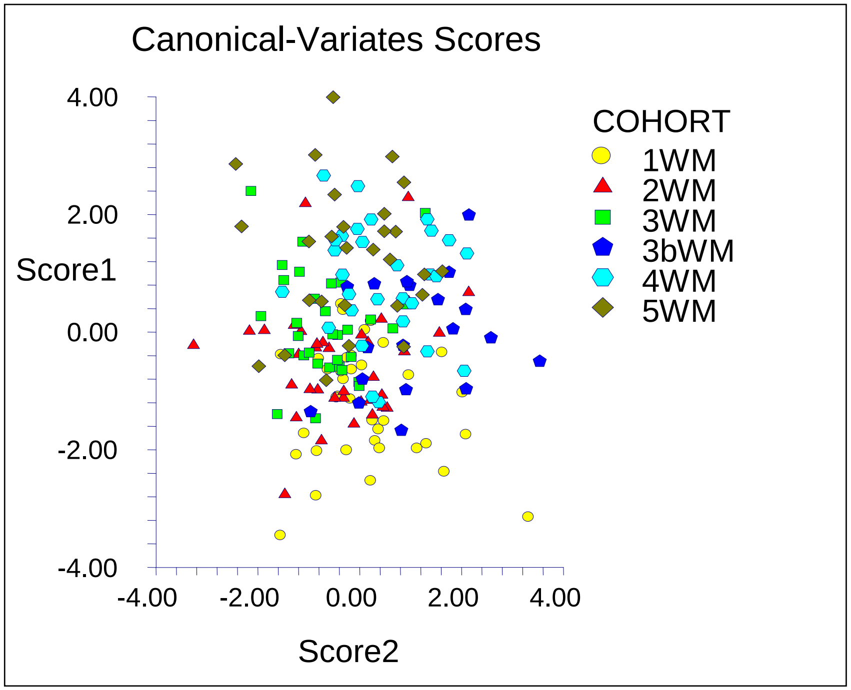

Figure 21a: Canonical plot of individual white males

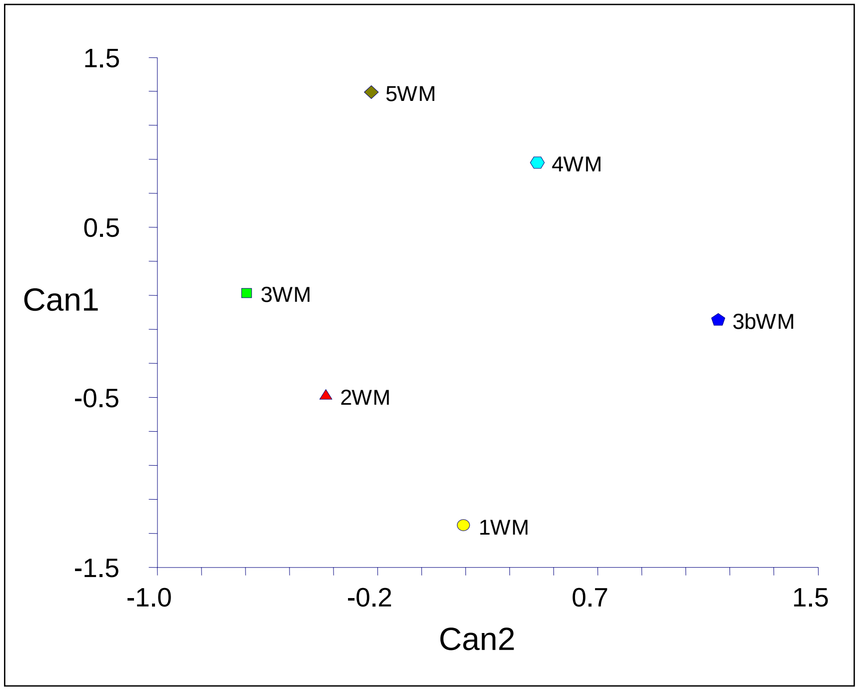

Figure 21b: Canonical plot of cohort means of white males

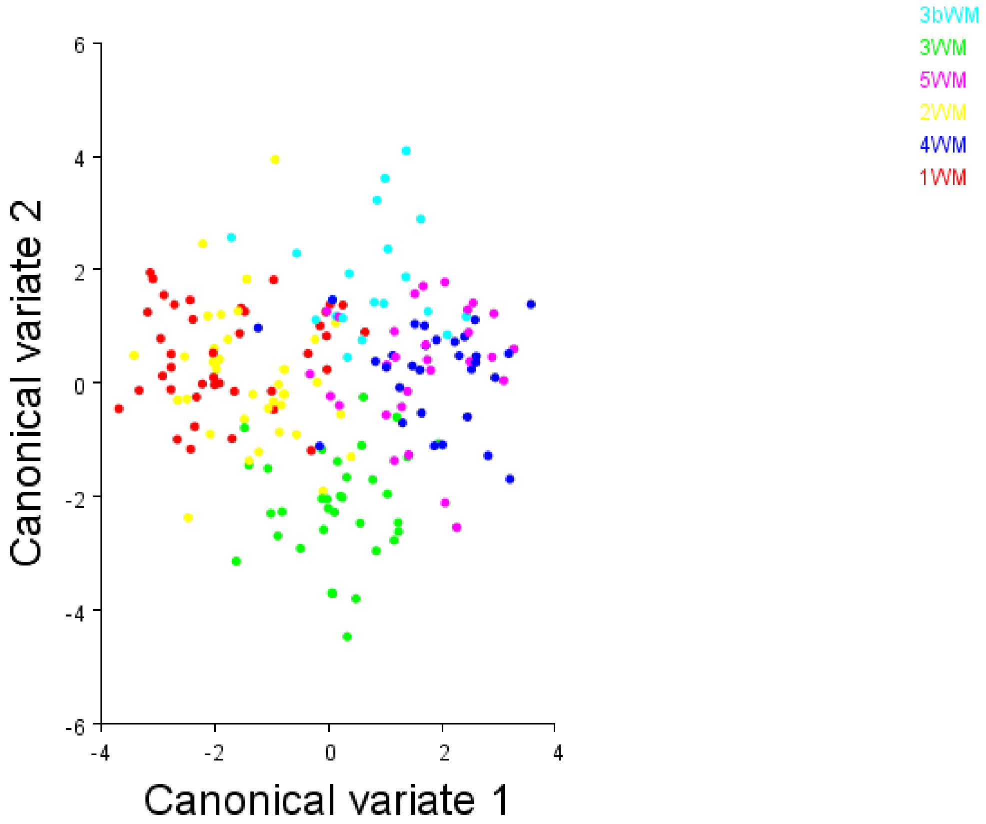

Figure 22: Canonical plot of individual white males produced in MorphoJ

Table 12: Distance matrix between white male cohorts, significance denoted by italics

Cohort	1BM	2BM	3BM	3bBM	4BM
2BM	*3.3624**				
3BM	*3.5272**	*2.6184**			
3bBM	*5.3527**	*5.8736**	*6.3212**		
4BM	*5.3160**	*5.0223**	*5.2931**	*6.3394**	
5BM	*5.7085**	*5.2728**	*5.6311**	*7.2977**	*4.8595**

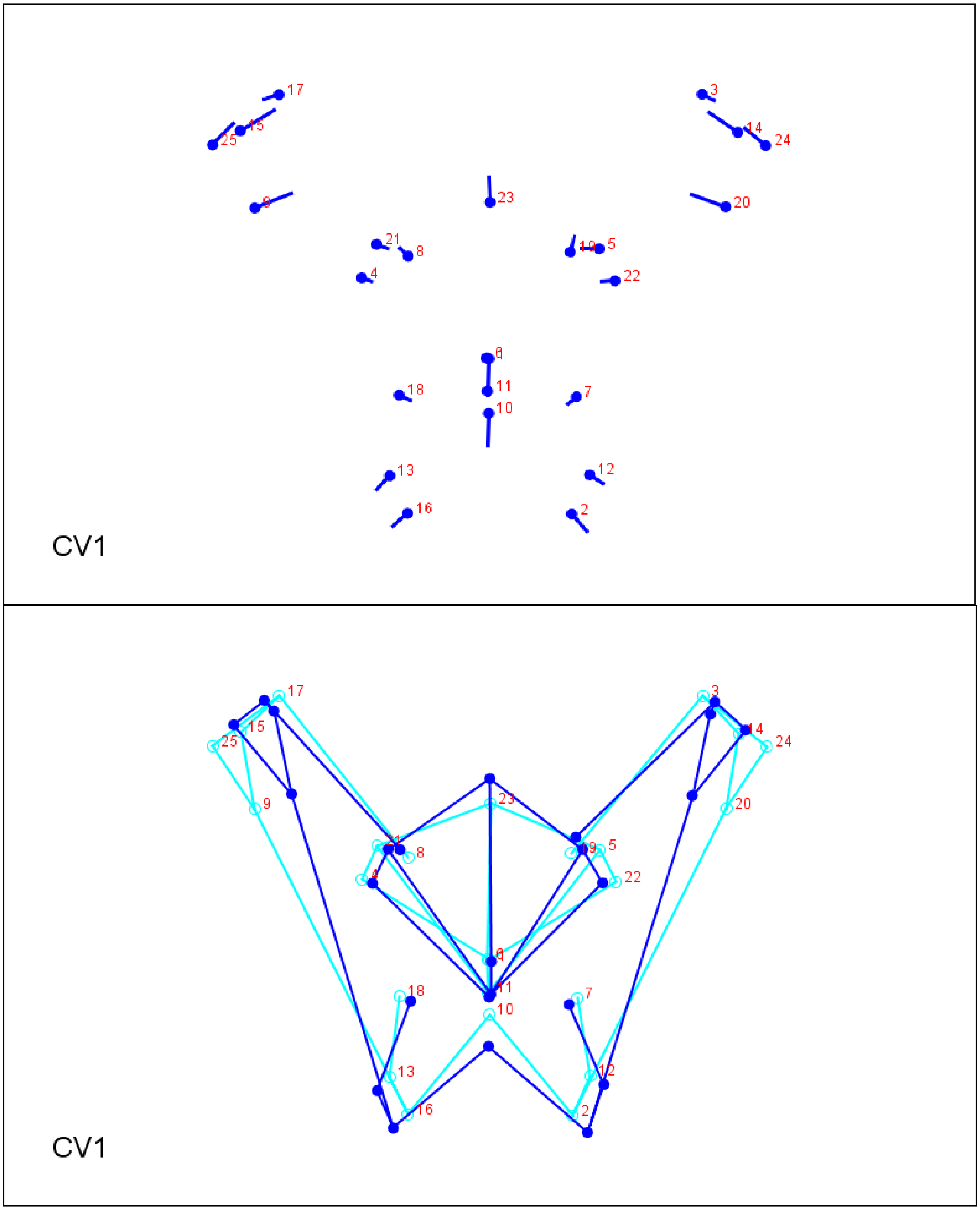

Figure 23: Landmark shifts along first canonical variate in white males. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate one (later cohorts). Landmark identifications of the numbered points can be found in Table A13 in the appendix.

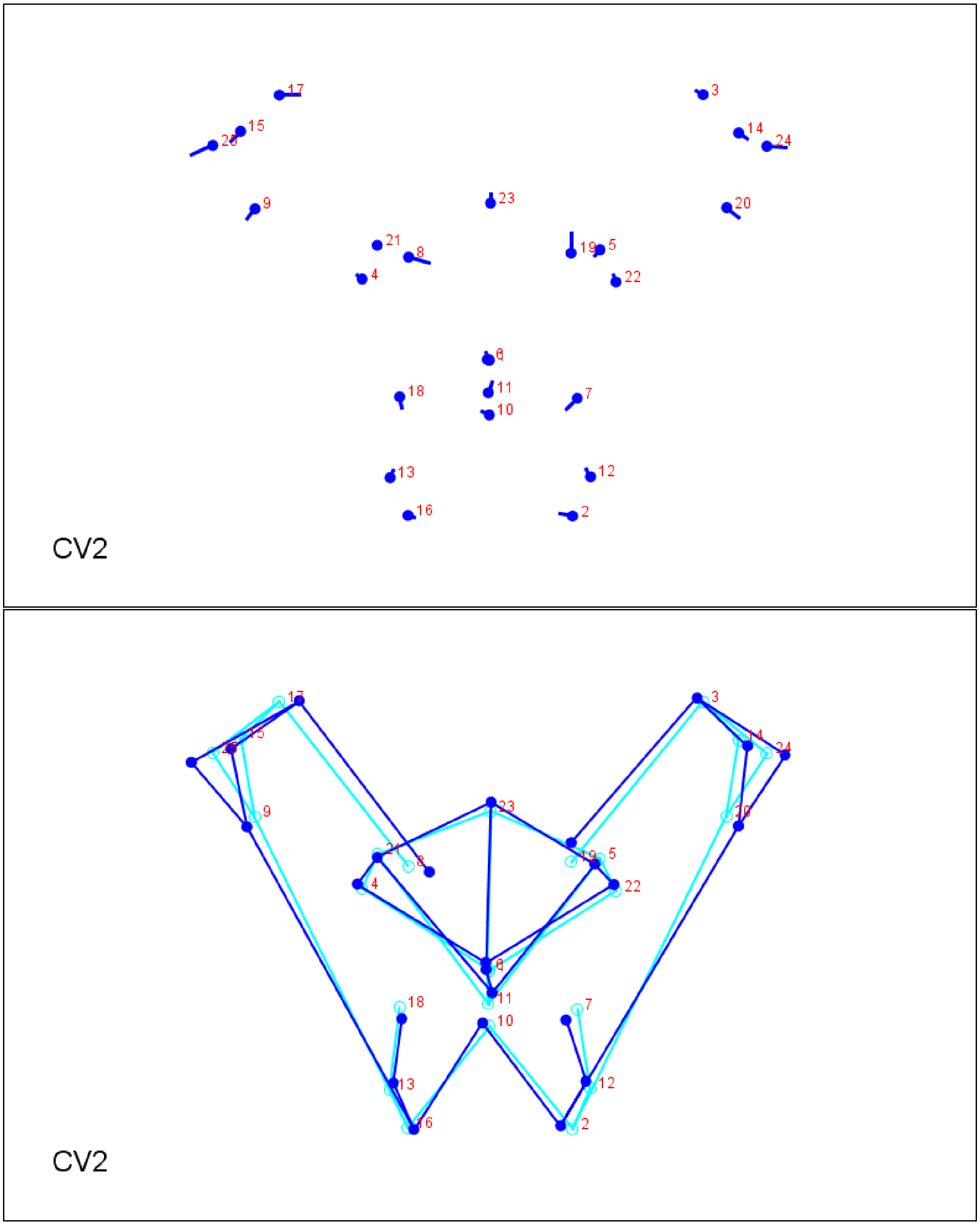

Figure 24: Landmark shifts along second canonical variate in white males. The light blue wireframe represents the starting form while the dark blue wireframe represents change over canonical variate two. Landmark identifications of the numbered points can be found in Table A13 in the appendix.

Shape: Collection Difference

Canonical variate analysis was next performed on each group to determine if significant separation based on collection occurred along the canonical variates. These plots are shown in Figures 25a,b – 28a,b. For each group, CV1 and CV2 were significant in separating the groups by collection except for the black females; the black females were only significantly separated along CV1. The first CV separated the groups temporally; black females in Bass cohort 3 and 5 do not fit neatly into the temporal division, this is again, perhaps, due to their small sample sizes. Canonical variate two demarcates the collections into Terry versus Todd with the Bass samples straddling the line. The white males are more clearly separated into three distinct collections along CV2; this could be due to the more even sample sizes available in each of the cohort break downs.

The results of the CVA on the cohorts separated by collection support the decision to pool collections. While there are collection differences, the temporal separation is much more significant.

Shape: Multivariate Regression Analysis

The 14 principal components were regressed on year of birth to determine which PCs were significant between the cohorts. The results are shown in Table 13. While several of the PCs show significance, they are built to maximize total sample variance. Since the difference between the cohorts is of ultimate interest, the morphological changes based on the PCs are of less concern than those based on the canonical variates already discussed.

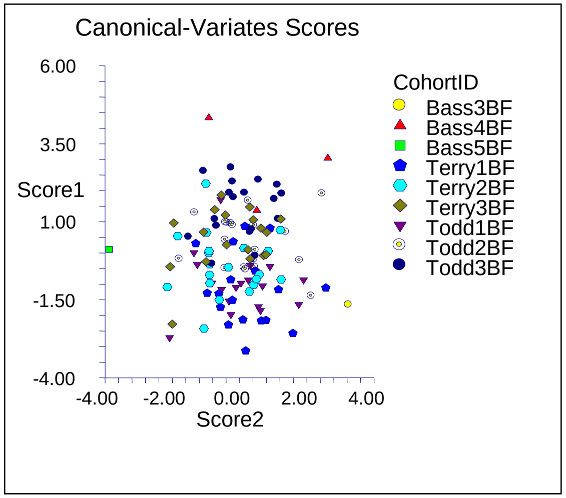

Figure 25a: Canonical plot of individual black females

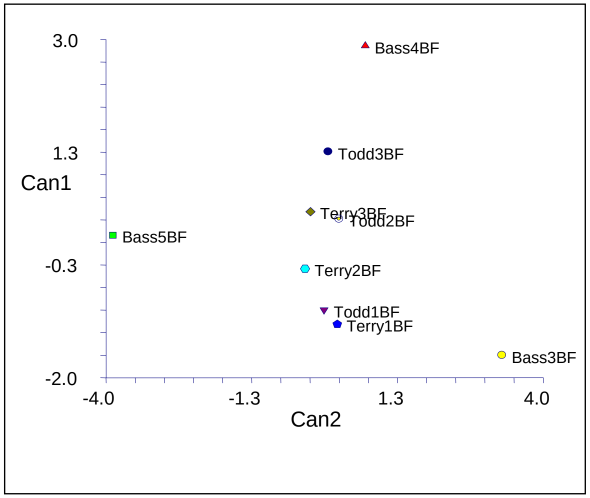

Figure 25b: Canonical plot of cohort means of black females

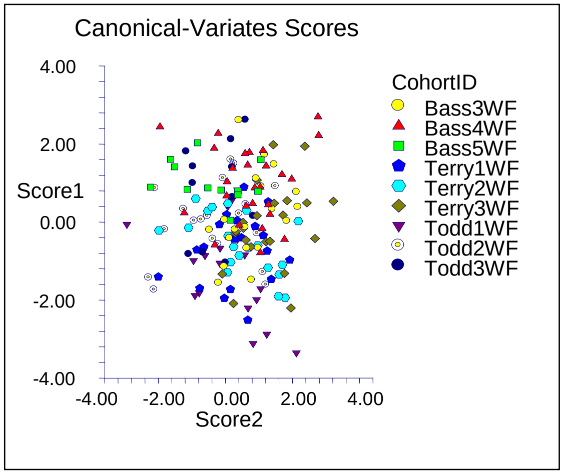

Figure 26a: Canonical plot of individual white females

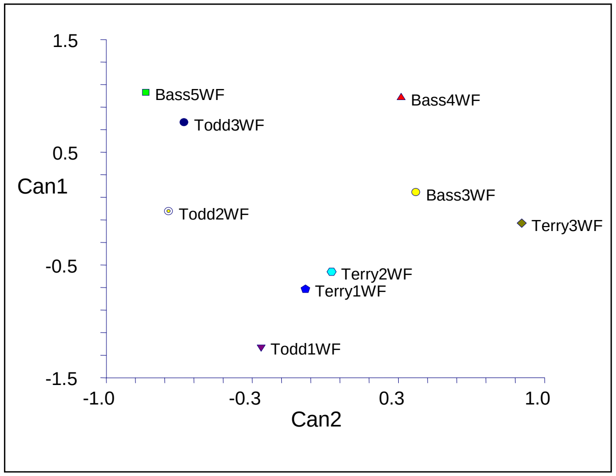

Figure 26b: Canonical plot of cohort means of white females

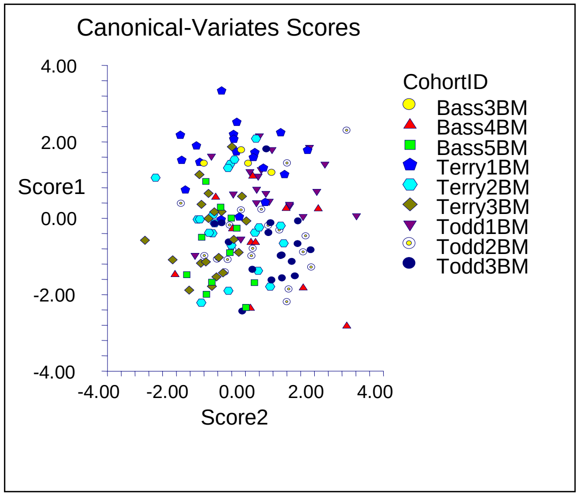

Figure 27a: Canonical plot of individual black males

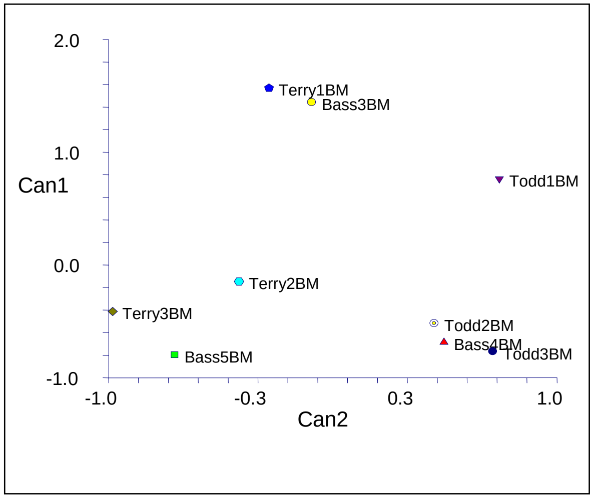

Figure 27b: Canonical plot of cohort means of black males

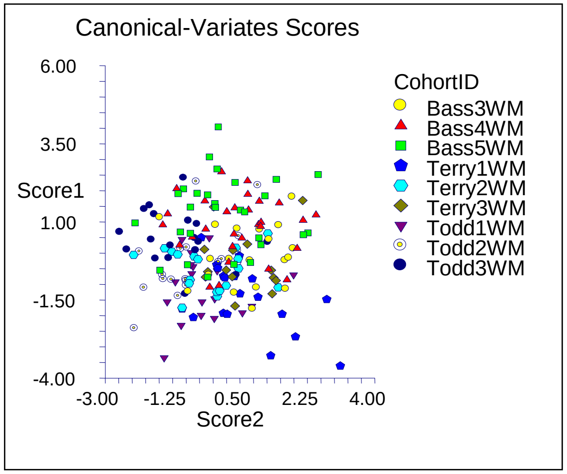

Figure 28a: Canonical plot of individual white males

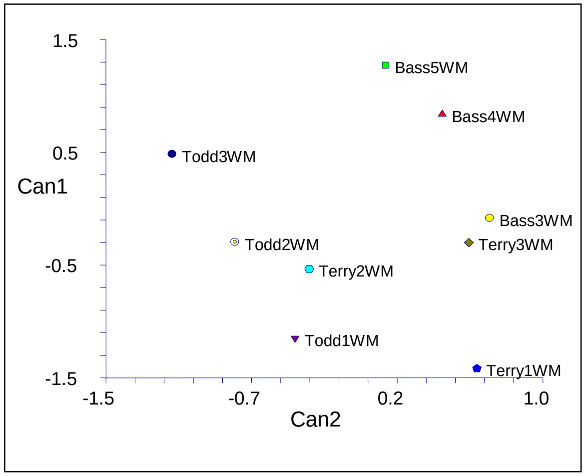

Figure 28b: Canonical plot of cohort means of white males

Table 13: Multivariate regression analysis: PC1-PC14 regressed on year of birth

MANOVA Analysis: PC1- PC 14 and cohort		
Group	**p-value**	**Significant PCs**
Black Females	*0.000051**	2, 6, 7, 8, 12
White Females	*0.000002**	2, 3, 7, 10, 11, 13
Black Males	*0.000007**	1, 5, 14
White Males	*0.000000**	1, 3, 7, 14

Size: Centroid Size and Cohort

Centroid size was calculated for each individual in addition to principal components. In geometric morphometry, the centroid size is used to assess changes in size independent of shape. To determine if there were significant size changes over time, multiple regression analysis and MANOVA were used to determine whether there was a size difference between birth cohort groups.

The plots of centroid size versus year of birth are shown in Figures 29 and 30. Regression analysis indicated that only the white males experience a significant size difference, an increase, as compared to year of birth (Table 14). This result is supported with MANOVA (Table 14). Again, the MANOVA results were only significant for the white males. Interestingly, a plot of the cohort means indicates that white males increase in size until cohort 5 where there is a decrease in the mean centroid size. The plot of the centroid size means for the white males is shown in figure 31.

In contrast to the MANOVA, the ANOVA produced by MorphoJ, shown in Table 16, indicates that there are no significant differences in size between the cohorts based on centroid size. However, ANOVA run on the Procrustes coordinates exhibit significant differences in shape in each group (Table 15).

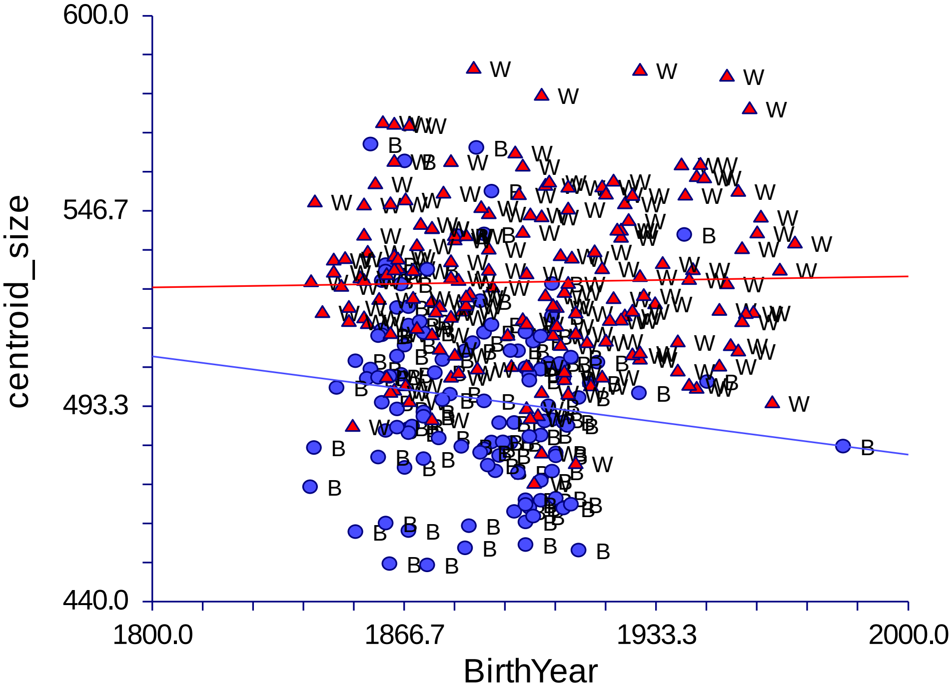

Figure 29: Plot of centroid size by birth-year for females

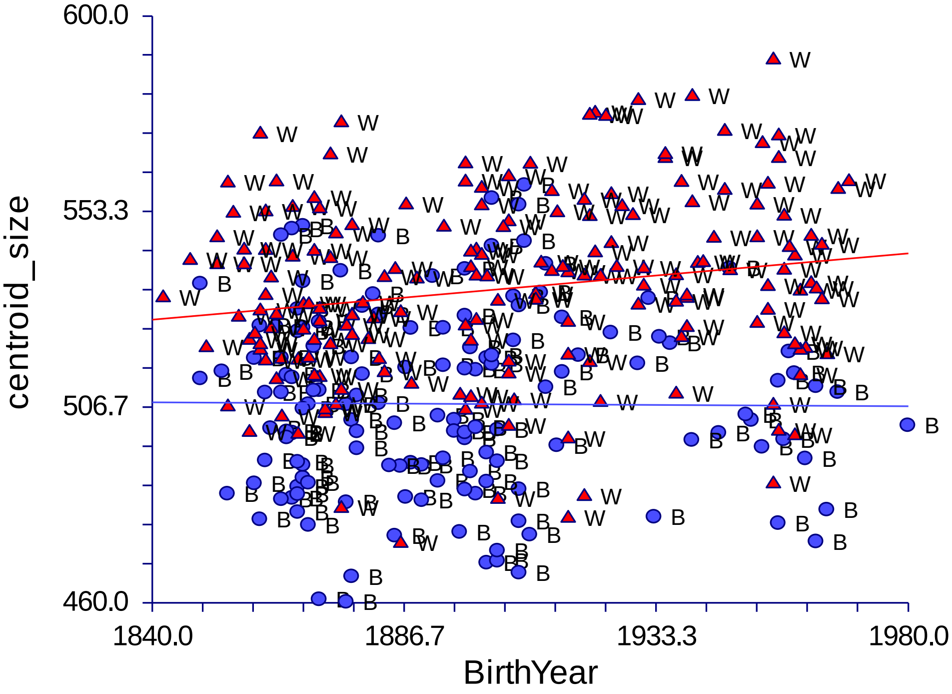

Figure 30: Plot of centroid size by birth-year for males

Table 14: Regression Analysis and MANOVA analyses of centroid size

	Regression Analysis: Centroid size by birth year	**MANOVA: Centroid size by cohort**
Group	**p-value**	**p-value**
Black Females	0.110361	0.110361
White Females	0.490078	0.490078
Black Males	0.868750	0.868750
White Males	*0.000978**	*0.000978**

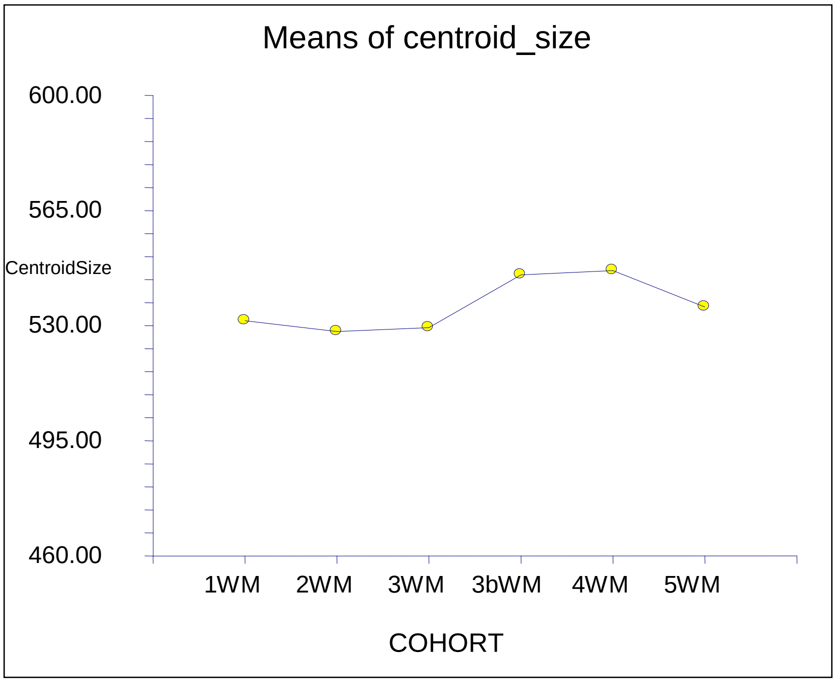

Figure 31: Plot of white male centroid mean by cohort

Table 15: ANOVA of centroid size and shape by cohort (MorphoJ)

ANOVA of Procrustes Coordinates		
Group	**Centroid Size: p-value**	**Shape: p-value**
Black Females	0.8909	<.0001
White Females	0.6980	<.0001
Black Males	0.7409	<.0001
White Males	0.5553	<.0001

Size: Collection, Cause of Death, Age at Death

In order to determine if factors other than birth year/cohort were affecting the centroid size, additional MANOVA were run on the samples using collection, cause of death, and age at death as independent variables. The only significant difference in size occurred among the white males in the MANOVA of collection. There was a significant size difference between the Bass collection compared to the Terry and Todd collections. The significant results are shown in Table 16 and Figure 32. This result is not surprising after finding a significant difference in cohort size of white males and cohorts in the previous section.

Table 16: MANOVA of centroid size by collection

MANOVA Analysis: Centroid size by Collection	
Group	**p-value**
Black Females	0.649859
White Females	0.512975
Black Males	0.654403
White Males	*0.000410**

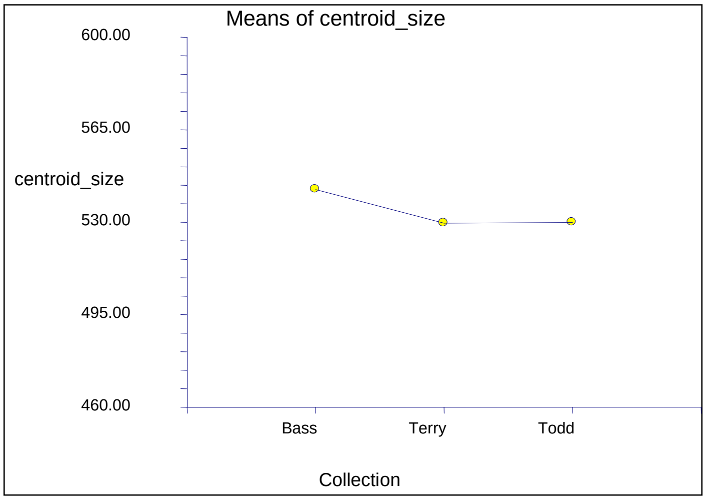

Figure 32: Plot of white male centroid mean by collection

Size: Variable Selection

Finally, a McHenry's variable selection was run on the centroid size to determine which variable combination produce the most appropriate model for determining size. Sex, ancestry, collection, year of birth, and year of birth were used for the first run. Death type was added in a second variable selection; it was not included in the first run since the death type was only defined for 273 of the 608 individuals used in the geometric morphometric analyses. The causes of death were separated into two types: cardiac and infectious. Those individuals who died from any type of heart or cardiovascular disease fell under the first category while those who suffered from inflictions such as syphilis, tuberculosis, influenza, or other contagious disease fell under the second category. Variable selection was not run on the principal component scores because these scores were produced through running the sex/ancestry groups separately which prevents the PCs from being comparable and biased against the variables of sex and ancestry as independent variables.

The model produced from the entire sample, excluding the variable of death type, ancestry and sex were the first two variables included in the model followed by death age. Year of birth and collection were added in the later models, but they do not appreciably increase the R^2 value of the model. This indicates that separating the sample by ancestry and sex prior to testing for secular change was indeed essential. The early entry of death age is likely an artifact of the ages of the samples included in the collections; plots of the age at death in each collection can be found in the appendix. The models are shown in Tables 17 and 18.

With the addition of death type, death age becomes more prominent in the model. This is due to the highly skewed distribution of age and type of death. Those dying of cardiac disease are far older than those individuals dying from infectious illness; plots with age distributions can be found in the appendix. However, after death age is explained, the next two variables are ancestry and sex which is similar to the first model selection. While these results support the separation of the sample into sex/ancestry groups, they also indicate that collection membership, and the environmental differences associated with being in differing collections, have less effect on size than demographic parameters.

Table 17: McHenry's Variable Selection Using Centroid Size

Model Size	**R-Squared**	**R-Squared Change**	**Variable Names**
1	0.288651	0.288651	Ancestry
2	0.319700	0.031049	Sex, Ancestry
3	0.335424	0.015724	Sex, Ancestry, DeathAge
4	0.343976	0.008552	BirthYear, Sex, Ancestry, DeathAge
5	0.344025	0.000049	Collection, BirthYear, Sex, Ancestry, DeathAge

Table 18: McHenry's Variable Selection Using Centroid Size including death type

Model Size	**R-Squared**	**R-Squared Change**	**Variable Names**
1	0.202544	0.202544	Ancestry
2	0.223327	0.020783	Ancestry, DeathAge
3	0.244683	0.021356	Sex, Ancestry, DeathAge
4	0.245775	0.001092	Sex, Ancestry, DeathAge, DeathType
5	0.245966	0.000191	Collection, Sex, Ancestry, DeathAge, DeathType
6	0.245970	0.000004	Collection, BirthYear, Sex, Ancestry, DeathAge, DeathType

Chapter 6

Discussion & Conclusion

The goal of this research was to determine if secular change occurred in the modern human pelvis of individuals living in the United States who were born between 1840 and 1980. One hundred and forty years is a relatively short time to expect significant changes to occur in the bony pelvis which is arguably one of the most important skeletal elements in modern humans. However, there have been unprecedented changes in technology, culture, health, and healthcare over the last century and a half in addition to the novel environment that makes up the melting pot culture of the United States. The evolution of the pelvis occurred because of changes in locomotion and birthing; this has been studied extensively. Changes in the pelvis due to improved nutrition, exogamy, decreased disease load, environment, and technology are all of interest in understanding the current form and projected form of the modern human pelvis.

Several hypotheses underlie this research. Overarching all of these questions was the assumption that the pelvis would mirror changes found in other elements of the skeleton. Stature, long bone length, and cranial base height have increased overtime with improvements in the way of life in the United States. The change in allometry in the long bones was also observed to change more than the length of bone taken singly. Also, males, specifically white males, have been shown to be more variable than other groups while black females are more stable (Jantz 1996; Meadows Jantz and Jantz 1999). In addition to the assumption that the pelvis would experience change due to improved conditions, it was also expected that technology would also play a role in altering the pelvis - specifically, cesarean sections. Women who, historically, were unable to give birth would die or their offspring would die. Infant mortality has experienced a dramatic decrease as has maternal death during birth. With the adoption of cesarean sections and their increased use, it was expected that some effect would result in the human bony pelvis. Evolution of the human birth canal differs in males and females; parturition required the females to adopt a less efficient bipedal form. If the selection pressure of parturition was relaxed, perhaps bipedalism would shift the female morphology to one more similar to that expressed in males. The results of this study were both expected and contradictory based on these assumptions.

Initial Testing

Sex and ancestry differences were expected. Measurements were collected with the intention of splitting the groups into samples based on ancestry and sex. The significant differences between these demographic groups supported their separation. Males were more variable than the females, and this also fit with previous studies. This was true when comparing across collections. The Hamann-Todd and Terry individuals were more similar to each other than they were to the Bass individuals; however, the differences between the females of the same cohort were not significant while the Bass males were significantly bigger than the other collections in the same cohort. This was not surprising. The Hamann-Todd and Terry collections have similar history. Each was created from an anatomical collection made of dissected cadaveric remains of largely lower income or unclaimed individuals while the Bass collection is predominantly made up of individuals who were family or self donated. Again, the stability of the female form enabled the collections to be pooled while the Bass males were separated from the Terry and Hamann-Todd males.

Body & Pelvis Size

Initially, the non-significant change found in femoral head diameter was a surprise; however, this result is largely consistent with those found in Cridlin's research (2007). Because the secular change of the femoral head was determined to be statistically insignificant, accounting for body size using the femoral head was not useful in this research. Clearly, body size has increased; however, the femur head diameter may better reflect body mass (or perhaps lean body mass) rather than stature. However, since the differences in raw inter-landmark distances were of interest in this study of secular changes, accounting for changes in body size is likely counterproductive to the aim of this research.

Centroid sizes indicated that only the white males are getting significantly bigger in later cohorts, but all of the groups are changing in dimension in very similar ways. Expected increases in os coxal height and width were not significant indicating that increased stature may not necessarily lead to bigger pelves.

Pelvic Canal Shape

Using traditional metric analyses and 3D geometric morphometrics provided a way to compare two different types of data and two different methods in their ability to identify secular change. In this study of size and shape change, the two methods supported each other. Secular change is occurring in the human bony pelvis. The calculated measurements derived from the inter-landmark metrics (Turner's Index and Pelvic Shape) indicated that shape changes occurred between the cohorts and inter-landmark distances significantly changed over time. However, not all of the distances changed equally or in the same direction. Here, geometric morphometrics was better able to illustrate the shape changes that had occurred over the 140 years.

In the literature review, the development of rotational birth was discussed. This type of birthing mechanism is hypothesized to have developed because of the differences in dimension between the inlet, midplane, and outlet of the female birth canal. The inlet has the widest dimension in a transverse direction while the outlet is widest in an anteroposterior direction. Additionally, malnutrition has been shown to further complicate the birthing process by shortening the inlet AP dimension which makes delivery of neonate even more difficult. Results of this research show that the dimensions of the birth canal are shifting in a way to ease the constraint of the minimum diameter. All females and the white males had significantly longer inlet AP diameters in later cohorts, and all of the groups experienced increases in the outlet transverse diameter. With the increasing outlet transverse diameter, an increase in the subpubic angle was also significant in the females and the white males. The females showed no corresponding increase in inlet transverse or outlet AP diameters. Thus, the shape changes that were indicated in the metric analyses were supported by the 3D results. This increase in AP diameter of the inlet supports the hypothesis that nutrition has improved over the last 140 years, but it also questions the effect cesareans are having on the birth canal. Perhaps technology does have a negative impact on the pelvic canal, but this study sample only includes individuals with birth years earlier than 1983 which precedes the regular use of cesarean sections during difficult delivery. The increase in cesarean sections includes many that are not due to pelvic canal size, and perhaps the results will continue to disprove those found in Germany. Expanding the samples to include later birth years is a future direction for this research as it trying to include women with documented cesarean births.

An interesting finding in this research was the decrease in bi-iliac breadth of the cohorts in each of the groups. While pelvic breath has been shown to correspond to the climatic differences (Mayr 1956) , this decrease cannot be completely explained by differences in climate. In the males, there is a decreasing trend in the Terry/Hamann-Todd males that is mirrored in the Bass males. So, while the decrease is altered by collection, the overall trend is a decrease in bi-iliac breadth. The females also experience this decrease, but the decrease is not altered by collection membership. Bipedal locomotion is more efficient as the iliac blades flare because the flare makes the attachment site for the abductor muscles more lateral; this increases their mechanical advantage during locomotion, also puts less pressure on femoral head (Delprete 2006; Lovejoy 1988).

This decrease in flare is perplexing. Perhaps the decrease in locomotion and increased dependence on technology offsets the need to maintain bipedal efficiency. Another possibility is that the decrease in flare is a result of cultural preference. Narrow hips are considered by some in the United States to be a preferred body type; given the heritability of bi-iliac breadth, culture may be the cause of this alteration of the bony pelvis. The decrease in flare may also be a result of increased stature. In order to maintain body proportion (the body has been modeled as a cylinder), secular changes in height could be causing this decrease in the bi-iliac breadth (Ruff 1991).

Conclusion

There is secular change occurring in the human bony pelvis. Significant changes in shape were shown through both metric and geometric methods using both inter-landmark distances and coordinate data. The parallel changes across cohorts in all of the groups indicate that the changes in the bony pelvis can be explained as a result of improved nutrition and environment. This environment likely includes a variety of factors (exogamy, lifestyle, health, economics, etc.) that are difficult to tease apart. However, this improved environment was experienced when these individuals were neonates and growing children. Increases in the AP diameter are altered by early childhood nutrition and activity. The increases in both the Turner's Index and the calculated Pelvic Shape indicate a decreased occurrence of android shaped pelvic canals. The expansion of the canal also indicates an improvement in environment. Strenuous activity experienced by young people results in the small, triangular shaped inlet.

Further study is needed to determine if the secular change of the pelvis will level off like the increases in stature. Increasing sample sizes of later birth cohorts in addition to expanding the research to include scans of living women are two directions that may begin to answer these questions.

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Appendix

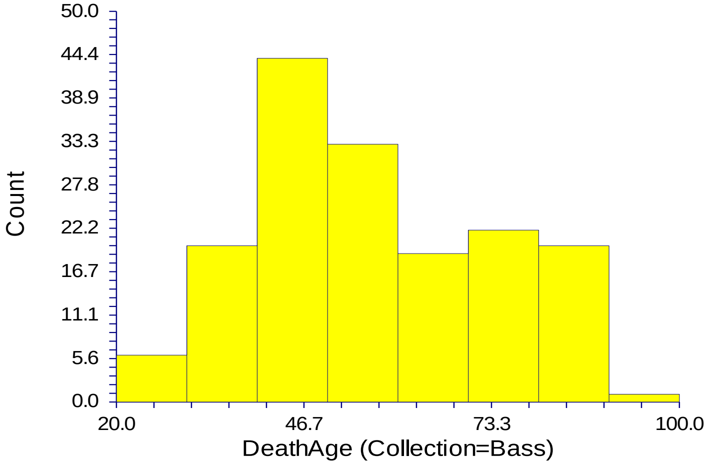

Figure A1: Bass Collection Age at Death Distribution

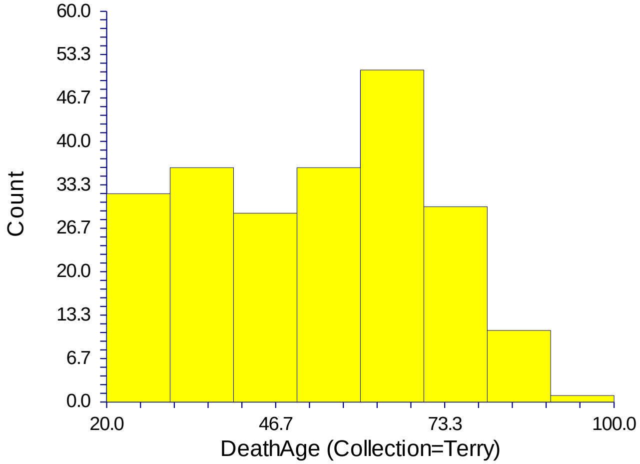

Figure A2: Terry Collection Age at Death Distribution

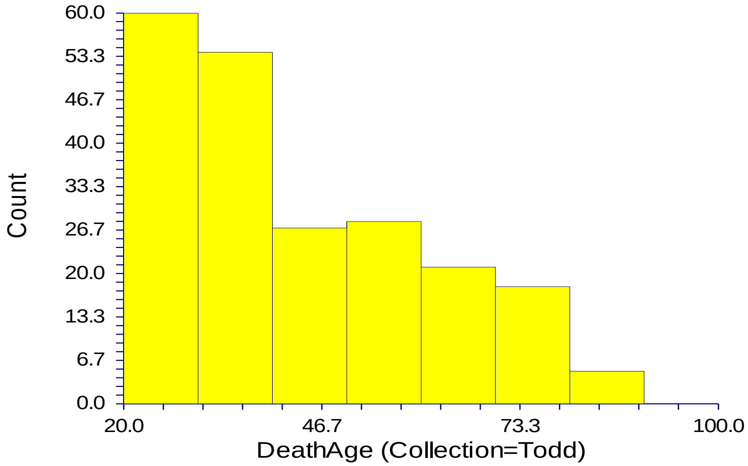

Figure A3: Hamann-Todd Collection Age at Death Distribution

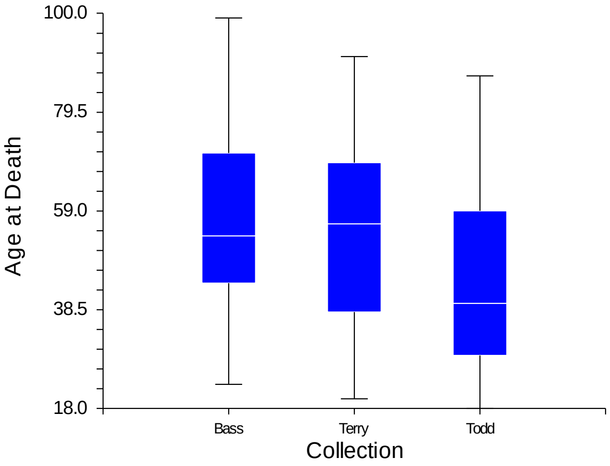

Figure A4: Mean and Standard Deviations of Age at Death

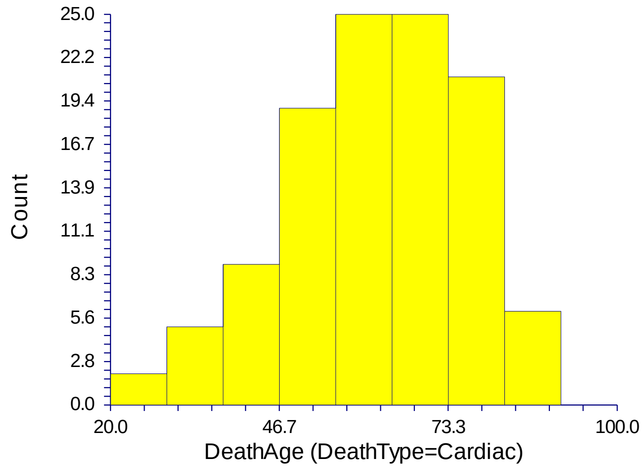

Figure A5: Cardiac Death Age Distribution

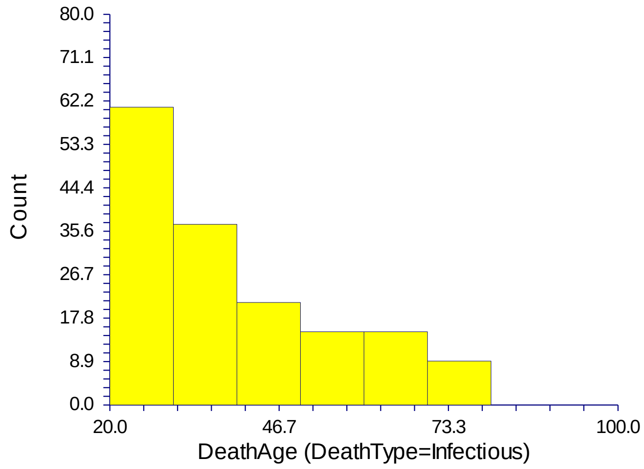

Figure A6: Infectious Death Age Distribution

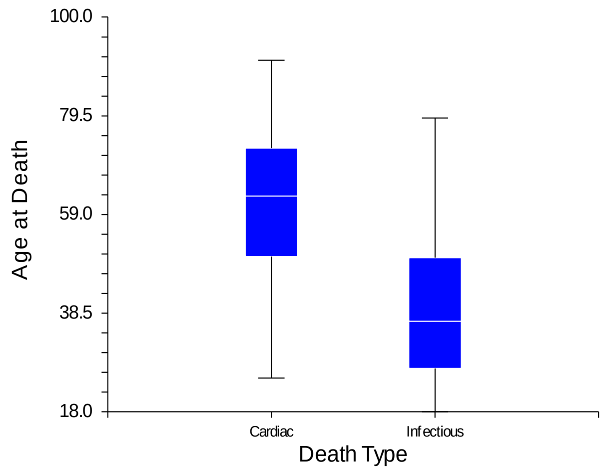

Figure A7: Mean Age and Standard Deviation of Death Type

Table A1: Collection Comparisons for Black Females, Cohort 1&2

Black Females	**Cohort 1**					**Cohort 2**				
	Normal		**Mean**		**p-value α =0.05**	**Normal**		**Mean**		**p-value α =0.05**
	Terry	Todd	Terry	Todd		Terry	Todd	Terry	Todd	
BBE	Yes	Yes	255.84	251.7	0.4519	Yes	Yes	251.15	247.25	0.47864
BBI	Yes	Yes	228.68	228.05	0.90316	Yes	Yes	223.15	222.25	0.74149
IAP	Yes	Yes	104.74	108.95	0.20742	Yes	Yes	109.7	110.1	0.90219
ITD	Yes	Yes	123.63	122	0.54001	Yes	Yes	123.5	122	0.58871
MAP	Yes	Yes	124.63	128.7	0.1742	Yes	Yes	127.85	123.85	0.23827
MTD	Yes	Yes	102.95	100.79	0.42201	Yes	Yes	103.8	103.55	0.93074
OAP	Yes	Yes	119.37	122.85	0.30371	Yes	Yes	122.85	118.8	0.25397
OTD	Yes	Yes	105.74	101.6	0.26559	Yes	Yes	107.75	108.4	0.84964
PBL	No	No	146.42	142.35	0.85491	Yes	Yes	144.8	143.35	0.57501
PBR	Yes	Yes	145.89	146.11	0.94915	Yes	Yes	143.35	142.65	0.76538
PHL	Yes	Yes	197.21	196.85	0.91139	Yes	Yes	193.75	192.35	0.68819
PHR	Yes	Yes	196.58	196.75	0.42201	Yes	No	193.25	192.75	0.73477
SAB	Yes	Yes	106.32	103.75	0.30395	Yes	Yes	105.1	103.6	0.51343
FH	No	Yes	42.53	42.77	0.844076	Yes	Yes	41.67	41.94	0.741487

Table A2: Collection Comparisons for White Females, Cohort 1&2

White Females	**Cohort 1**					**Cohort 2**				
	Normal		**Mean**		**p-value α =0.05**	**Normal**		**Mean**		**p-value α =0.05**
	Terry	Todd	Terry	Todd		Terry	Todd	Terry	Todd	
BBE	Yes	Yes	277.15	280.55	0.49795	Yes	Yes	274.55	267.7	0.15175
BBI	Yes	Yes	248.15	251	0.53403	Yes	Yes	246.2	242.9	0.47534
IAP	Yes	Yes	114.8	109.75	0.14679	Yes	Yes	117.3	113.1	0.13275
ITD	Yes	Yes	136.2	134.15	0.46698	Yes	Yes	135.05	131.4	0.11862
MAP	Yes	Yes	126.25	122.1	0.10008	No	Yes	121.6	123.35	0.39328
MTD	Yes	Yes	105	102.7	0.43652	Yes	Yes	104.45	10.75	0.78293
OAP	Yes	Yes	119.2	116	0.26585	Yes	Yes	114.5	117.05	0.37713
OTD	Yes	Yes	111.1	105.55	*0.046464**	Yes	Yes	111.55	113.05	0.58616
PBL	Yes	Yes	155.89	152.7	0.16992	No	Yes	152.95	152.25	0.83853
PBR	Yes	Yes	153.85	150.53	0.18874	No	Yes	150.8	150	0.74475
PHL	Yes	Yes	204.9	203.05	0.44577	No	Yes	204.9	204.95	0.72432
PHR	Yes	Yes	204.75	202.05	0.27359	No	Yes	204.25	203.6	0.84947
SAB	Yes	Yes	114.1	112.35	0.48556	Yes	Yes	113.1	111.65	0.50459
FH	Yes	Yes	42.86	43.44	0.455706	Yes	Yes	42.67	42.91	0.717941

Table A3: Collection Comparisons for Black Males, Cohort 1&2

Black Males	**Cohort 1**					**Cohort 2**				
	Normal		**Mean**		**p-value α =0.05**	**Normal**		**Mean**		**p-value α =0.05**
	Terry	Todd	Terry	Todd		Terry	Todd	Terry	Todd	
BBE	Yes	Yes	260	258.4	0.70545	Yes	Yes	252.05	249.2	0.49403
BBI	Yes	Yes	233	230.4	0.59706	Yes	Yes	225.95	225.15	0.84447
IAP	Yes	Yes	99.89	97.8	0.50308	Yes	Yes	103.8	101.6	0.49566
ITD	Yes	Yes	113.84	114.9	0.59646	Yes	Yes	114.2	113.1	0.62496
MAP	Yes	Yes	118.16	115.7	0.3071	Yes	Yes	116.2	115.95	0.91757
MTD	No	Yes	79.42	83.3	0.05033	No	Yes	82.35	86.95	*0.026194**
OAP	Yes	Yes	113.53	110.2	0.2018	Yes	Yes	110.1	110.9	0.74901
OTD	Yes	Yes	82.84	87.2	0.09416	Yes	Yes	87.25	92	0.06228
PBL	Yes	Yes	152.84	149.35	0.18207	Yes	Yes	149.2	148.85	0.86982
PBR	Yes	Yes	151.05	148.8	0.34415	Yes	Yes	148.05	148.65	0.77728
PHL	Yes	Yes	218.05	213.5	0.16631	Yes	Yes	212.1	213.1	0.75417
PHR	Yes	Yes	216.11	213.15	0.3247	Yes	Yes	211.45	212.8	0.67678
SAB	Yes	No	100.58	101.85	0.87685	Yes	Yes	101.3	101.2	0.92727
F_H	Yes	Yes	48.78	48.02	0.38299	Yes	Yes	47.97	47.37	0.46605

Table A4: Collection Comparisons for White Males, Cohort 1&2

White Males	**Cohort 1**					**Cohort 2**				
	Normal		**Mean**		**p-value α =0.05**	**Normal**		**Mean**		**p-value α =0.05**
	Terry	Todd	Terry	Todd		Terry	Todd	Terry	Todd	
BBE	Yes	Yes	274	272.1	0.69661	Yes	Yes	270.33	270.6	0.96067
BBI	Yes	Yes	246.95	247.15	0.96709	Yes	Yes	244.06	246.5	0.64555
IAP	Yes	Yes	99.85	101.7	0.37542	Yes	Yes	104.222	103.6	0.83223
ITD	Yes	Yes	126.2	125.45	0.73372	Yes	No	123.78	123.2	0.67116
MAP	Yes	No	115.45	112.35	0.19302	Yes	Yes	115.11	112.4	0.32129
MTD	Yes	Yes	86.15	86.3	0.94654	Yes	Yes	90.78	88.9	0.47092
OAP	Yes	Yes	107.85	103.45	0.09006	Yes	Yes	106.67	104.3	0.41027
OTD	Yes	Yes	93.5	94.05	0.83955	Yes	Yes	97.83	98	0.95945
PBL	Yes	Yes	159.05	156.4	0.20514	Yes	Yes	155.79	153.15	0.36175
PBR	Yes	Yes	157.7	155.65	0.35465	Yes	Yes	154.83	153.85	0.73513
PHL	Yes	Yes	222.6	219.25	0.21789	Yes	Yes	218	219.75	0.54899
PHR	Yes	Yes	221.75	218.9	0.31231	Yes	Yes	217.83	218.35	0.85764
SAB	Yes	Yes	111.75	110.35	0.45959	Yes	Yes	108.39	109.85	0.52544
F_H	Yes	Yes	48.93	47.8085	0.12888	Yes	Yes	48.53	48.59	0.93708

Table A5: Collection Comparisons for Black Females, Cohort 3

Black Females	**Cohort 3**									
	Normal			**Mean**			**ANOVA p-value**	**Individual t-tests α =0.015**		
	Bass	Terry	Todd	Bass	Terry	Todd		Bass/Ter	Bass/Tod	Tod/Ter
BBE	Yes	Yes	Yes	261	244.35	241.15	0.37504	–	–	–
BBI	Yes	Yes	Yes	228	220.8	217.4	0.64604	–	–	–
IAP	Yes	Yes	Yes	108	112.55	111.45	0.82066	–	–	–
ITD	Yes	Yes	Yes	119	118.35	118.1	0.98939	–	–	–
MAP	Yes	Yes	No	121	124.9	118.25	0.08096	–	–	–
MTD	Yes	Yes	Yes	99	100.6	98.32	0.6468	–	–	–
OAP	Yes	Yes	Yes	112	120.55	111.45	*0.020492**	0.42963	0.95514	*0.0060**
OTD	Yes	Yes	Yes	111	110.75	106.6	0.33365	–	–	–
PBL	Yes	Yes	Yes	144	143.6	138.55	0.12961	–	–	–
PBR	Yes	Yes	No	138	142.9	138.1	0.3951	–	–	–
PHL	Yes	Yes	Yes	195	192.5	187.45	0.1817	–	–	–
PHR	Yes	Yes	Yes	192	192.85	188	0.19079	–	–	–
SAB	Yes	Yes	Yes	97	101.3	101.45	0.80824	–	–	–
F_H	Yes	Yes	Yes	42.91	41.77	41	0.4262	–	–	–

Table A6: Collection Comparisons for WhiteFemales, Cohort 3

White Females	**Cohort 3**									
	Normal			**Mean**			**ANOVA p-value**	**Individual t-tests α =0.015**		
	Bass	Terry	Todd	Bass	Terry	Todd		Bass/Ter	Bass/Tod	Tod/Ter
BBE	Yes	Yes	Yes	271.37	269.57	258.73	0.13761	−	−	−
BBI	Yes	Yes	Yes	202.58	201.65	196.64	0.21216	−	−	−
IAP	Yes	Yes	Yes	117.47	118.91	121.09	0.65311	−	−	−
ITD	Yes	Yes	Yes	131.53	131.74	128	0.44041	−	−	−
MAP	Yes	Yes	Yes	126.84	127.48	119.64	0.07443	−	−	−
MTD	Yes	Yes	Yes	102.84	100.48	101.73	0.61191	−	−	−
OAP	Yes	Yes	Yes	119.11	121.61	115	0.32582	−	−	−
OTD	Yes	Yes	Yes	116.84	109.57	110.09	*0.028323**	*0.009989**	0.06028	0.87761
PBL	Yes	Yes	Yes	152.05	152	150.64	0.86822	−	−	−
PBR	Yes	Yes	Yes	150.84	152.57	148.55	0.30195	−	−	−
PHL	Yes	Yes	Yes	203.37	202.57	196.55	0.12982	−	−	−
PHR	Yes	Yes	Yes	109.11	110	107.91	0.72124	−	−	−
SAB	Yes	No	Yes	271.37	269.57	258.73	0.17918	−	−	−
F_H	Yes	Yes	Yes	240.47	241.13	236.83	0.76751	−	−	−

Table A7: Collection Comparisons for Black Males, Cohort 3

Black Males	**Cohort 3**									
	Normal			**Mean**			**ANOVA p-value**	**Individual t-tests α =0.015**		
	Bass	Terry	Todd	Bass	Terry	Todd		Bass/Ter	Bass/Tod	Tod/Ter
BBE	Yes	Yes	Yes	281.25	253.1	249.05	_0.002393*_	_0.004624*_	_0.00052*_	0.43115
BBI	Yes	Yes	Yes	249.25	225.5	225.8	_0.039156*_	0.02488	_0.01152*_	0.95627
IAP	Yes	Yes	Yes	109.25	105.85	102	0.22532	–	–	–
ITD	Yes	Yes	Yes	123.75	113.7	114.35	0.08189	–	–	–
MAP	Yes	Yes	Yes	129.25	118.55	115.95	_0.017372*_	_0.011867*_	0.01535	0.30899
MTD	Yes	Yes	Yes	84	82.3	84.47	0.59428	–	–	–
OAP	Yes	Yes	Yes	122	111.95	112.3	0.07953	–	–	–
OTD	Yes	Yes	Yes	95.25	89.7	88.85	0.38126	–	–	–
PBL	Yes	Yes	Yes	159.75	151.8	147.05	_0.010205*_	0.07776	_0.00584*_	0.0594
PBR	Yes	Yes	No	159	150.95	145.15	0.01683	–	–	–
PHL	Yes	Yes	Yes	227.5	217.65	212.45	_0.044229*_	0.11251	0.0219	0.15247
PHR	Yes	Yes	Yes	226.5	217.25	211.9	_0.042901*_	0.12268	0.02171	0.13573
SAB	Yes	Yes	Yes	108.75	100	102.1	0.0512	–	–	–
F_H	Yes	Yes	Yes	50.669	48.82	47.83	0.09389	–	–	–

Table A8: Collection Comparisons for White Males, Cohort 3

White Males	**Cohort 3**									
	Normal			**Mean**			**ANOVA p-value**	**Individual t-tests α =0.015**		
	Bass	Terry	Todd	Bass	Terry	Todd		Bass/Ter	Bass/Tod	Tod/Ter
BBE	Yes	Yes	Yes	283.95	265.43	266.3	_0.001186*_	_0.003325*_	_0.00045*_	0.88869
BBI	Yes	Yes	Yes	252.7	240.24	240.85	_0.034117*_	0.03681	0.01557	0.9148
IAP	Yes	Yes	Yes	113.15	107.21	110.15	0.1007	–	–	–
ITD	Yes	Yes	Yes	127.15	123.43	123.1	0.18754	–	–	–
MAP	Yes	Yes	Yes	117.9	118.86	116.9	0.70431	–	–	–
MTD	Yes	Yes	Yes	85.1	88.14	85.55	0.4253	–	–	–
OAP	No	Yes	Yes	110.65	112.29	111.1	0.49672	–	–	–
OTD	Yes	Yes	Yes	96.1	96.07	97.3	0.899	–	–	–
PBL	Yes	Yes	Yes	160.85	153.43	155	_0.011900*_	0.01667	_0.01103*_	0.54301
PBR	Yes	Yes	Yes	158.5	154.29	153.72	0.13751	–	–	–
PHL	Yes	Yes	Yes	227.3	219	222.35	0.06903	–	–	–
PHR	Yes	Yes	Yes	226.25	218.93	221.6	0.11269	–	–	–
SAB	Yes	Yes	Yes	110.85	107.14	110.5	0.15942	–	–	–
F_H	Yes	Yes	Yes	49.04	47.89	4835	0.43697	–	–	–

Table A9: Descriptive Statistics Black Females, Cohort 4&5

Black Females	**Cohort 4**			**Cohort 5**			
	Normal	**Mean**	**s.d.**		**Normal**	**Mean**	**s.d.**
BBE	Yes	246	13.11	**BBE**	Yes	229	−
BBI	Yes	218.33	14.05	**BBI**	Yes	204	−
IAP	Yes	126.33	10.69	**IAP**	Yes	123	−
ITD	Yes	126.67	11.15	**ITD**	Yes	116	−
MAP	Yes	124.33	7.23	**MAP**	Yes	132	−
MTD	Yes	105.33	6.5	**MTD**	Yes	106	−
OAP	Yes	115.33	9.07	**OAP**	Yes	127	−
OTD	Yes	113	2.65	**OTD**	Yes	124	−
PBL	Yes	145.33	4.04	**PBL**	Yes	144	−
PBR	Yes	145.67	4.04	**PBR**	Yes	144	−
PHL	Yes	198.67	191	**PHL**	Yes		−
PHR	Yes	199.33	9.45	**PHR**	Yes	189	−
SAB	Yes	105.3	4.51	**SAB**	Yes	92	−
F_H	Yes	41.9	1.27	**F_H**	Yes	40.4	−

Table A10: Descriptive Statistics White Females, Cohort 4&5

White Females	Cohort 4			Cohort 5			
	Normal	**Mean**	**s.d.**		**Normal**	**Mean**	**s.d.**
BBE	Yes	269.93	16.73	**BBE**	Yes	267.33	13.19
BBI	Yes	241.73	15.94	**BBI**	Yes	239.42	13.65
IAP	Yes	122.1	7.85	**IAP**	Yes	120.58	6.87
ITD	Yes	130.47	8.54	**ITD**	Yes	132	10.57
MAP	Yes	126.73	8.49	**MAP**	Yes	131.5	7.95
MTD	Yes	100.93	11.32	**MTD**	Yes	108.08	10.26
OAP	Yes	117.23	8.82	**OAP**	Yes	123.92	7.79
OTD	Yes	117.13	12.35	**OTD**	Yes	123.25	10.64
PBL	Yes	153.5	7.07	**PBL**	Yes	153.75	6.57
PBR	Yes	152.52	7.88	**PBR**	Yes	12.42	7.06
PHL	No	203.07	9.25	**PHL**	Yes	204	11.03
PHR	Yes	203.2	9.36	**PHR**	Yes	202.67	8.9
SAB	Yes	108.77	8.23	**SAB**	Yes	107.92	6.81
F_H	Yes	41.94	1.75	**F_H**	No	42.07	2.36

Table A11: Descriptive Statistics Black Males, Cohort 4&5

Black Males	Cohort 4			Cohort 5			
	Normal	Mean	s.d.		Normal	Mean	s.d.
BBE	Yes	253.91	17.44	**BBE**	Yes	242.91	13.21
BBI	Yes	222.82	15.94	**BBI**	Yes	211.09	13.94
IAP	No	105.82	14.21	**IAP**	Yes	107	8.65
ITD	Yes	115	5.04	**ITD**	Yes	106.18	5.83
MAP	Yes	117.91	7.84	**MAP**	Yes	121.64	6.71
MTD	Yes	88.45	8.96	**MTD**	Yes	83.55	5.8
OAP	No	114.36	15.26	**OAP**	Yes	114.55	6.61
OTD	Yes	99.09	12.77	**OTD**	Yes	92.18	7.85
PBL	Yes	153.64	5.71	**PBL**	Yes	151.46	5.82
PBR	Yes	152.27	5.37	**PBR**	Yes	151	6.91
PHL	Yes	214.28	7.37	**PHL**	Yes	213.73	9.73
PHR	Yes	213.91	7.03	**PHR**	Yes	213.72	8.06
SAB	No	97	14.43	**SAB**	Yes	93.45	4.59
F_H	Yes	47384	2.76	**F_H**	Yes	47.03	1.69

Table A12: Descriptive Statistics White Males, Cohort 4&5

White Males	**Cohort 4**			**Cohort 5**			
	Normal	**Mean**	**s.d.**		**Normal**	**Mean**	**s.d.**
BBE	No	274.07	12.24	**BBE**	Yes	264.4	18.49
BBI	Yes	244.97	12.36	**BBI**	Yes	235.43	19.2
IAP	Yes	118.6	6.55	**IAP**	Yes	117.53	10.08
ITD	Yes	125.43	3.71	**ITD**	Yes	121.23	7.52
MAP	Yes	119.73	7.74	**MAP**	Yes	121	9.7
MTD	Yes	86.87	5.91	**MTD**	Yes	86.85	8.75
OAP	Yes	110.07	7.97	**OAP**	Yes	112.17	10.36
OTD	Yes	103.6	7.63	**OTD**	No	102.13	9.28
PBL	Yes	159.73	6.27	**PBL**	Yes	156.83	7.77
PBR	Yes	159.37	6	**PBR**	Yes	155.03	7.25
PHL	Yes	228.17	8.96	**PHL**	Yes	224.23	10.14
PHR	Yes	227.13	8.63	**PHR**	Yes	223.97	9.51
SAB	Yes	109.27	5.61	**SAB**	Yes	105.97	2.99
F_H	Yes	48.54	2.04	**F_H**	Yes	47.85	2.49

Table A13: Landmark identification numbers used in geometric morphometric figures.

Landmark Number	**Landmark Point**
1	superior pubic symphysis, center
2	ischial tuberosity, left
3	maximum pelvic height on iliac crest, left
4	transverse diameter point, right
5	auricular surface apex point, left
6	point on transverse line of S4 and S5
7	ischial spine, left
8	posterior superior iliac spine, right
9	anterior superior iliac spine, right
10	inferior pubic symphysis, center
11	apex of sacrum at S5, center
12	medial ischial tuberosity, left
13	medial ischial tuberosity, right
14	inner bi-iliac tubercle, left
15	inner bi-iliac tubercle, right
16	inferior ischial tuberosity, right
17	maximum pelvic height on iliac crest, right
18	ischial spine, right
19	posterior superior iliac spine, left
20	posterior inferior iliac spine, left
21	auricular surface apex point, right
22	transverse diameter point, left
23	anterior sacral promontory
24	bi-iliac tuberosity, left
25	bi-iliac tuberosity, right

Vita

Kathryn Roberts Dick was born October 6, 1976 in Bloomington, Illinois. After living in both Wyoming and Florida, she graduated from Bloomington (Illinois) High School in 1995. In May 1999, Kathryn received a Bachelor of Arts degree with honors in History with minors in Biology and Chemistry from Bethel College, North Newton, Kansas, and in July 1999, she married Darin Driscoll. Kathryn graduated with a Master of Arts in the Social Sciences from the University of Chicago in June 2000. After having two children, Kathryn returned to school in August 2004 and began her doctoral work at the University of Tennessee. She received her PhD in Biological Anthropology in May 2010.