Four modalities in the evaluation of the pelvic canal in South Africans

by

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DECLARATION

I declare that the dissertation that I am hereby submitting to the University of Pretoria for the MSc degree in Anatomy is my own work and that I have never before submitted it to any other tertiary institution for any degree.

____

Anja Yzabella Wiid

__2__day of _Desember_2016

For those who walked beside me.

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SUMMARY

Variations in the size and shape of the pelvic canal need to be taken into consideration when planning childbirth, as well as for procedures involving the pelvic canal, pelvic floor and perineum. Although variations between sex and ancestral groups, as well as correlations with stature and aging have been described, studies considering the extent of these differences when childbirth or surgical procedures are planned are limited. The aim of this study was to document the shape and size of pivotal dimensions by means of four modalities of the pelvic canal in South African individuals of African (SAA) and European (SAE) ancestry. A total of 121 intact cadaver pelves, distributed between the sexes and ancestral groups, were sampled from both the University of Pretoria and Sefako Makgatho Health Sciences University. Twenty-eight pelvic landmarks were marked, digitised and direct measurements were measured including the subpubic angle. Shape analyses were performed on the digitised points. Pivotal measurements were repeated on 77 magnetic resonance images (MRI) and 92 computed tomography (CT) scans. Basic descriptive statistics, tests for statistical significance and correlations with age and stature were made. All horizontal measurements of the pelvic canal and the subpubic angles were significantly greater in SAE females than in the other groups and correlated with the greatest dimensions found in the literature. Measurements of SAA females corresponded with other African groups and were larger than in SAA males. Females of both ancestral groups presented, as expected, with a significantly more spacious pelvic canal shape. Longitudinal dimensions were the greatest in SAE males, apart from the true height of the pelvis which was greater in SAA males. Females and SAE presented with statistically wider pelvic canal shapes anteriorly, creating greater anterior pelvic spaces and subpubic regions. The shorter pubic symphysis in SAA females encroached on this space longitudinally. Pelvic outlet shape variations were not statistically significant. Pelvic dimensions (more evident in SAE and females) had a stronger positive correlation with stature than with aging. When comparing modalities, especially when considering MRI, measurements crossing the midline were less repeatable. Taller SAE women may present with larger dimensions, facilitating childbirth. Stature should, therefore, be considered when selecting childbirth options. The smaller inlet and anterior pelvic space in SAA women might cause obstructed labour, however the foetal size should be considered. A narrower pelvis was

found in SAA and in males, which may impede vision, access and space for surgical excisions and lead to technical difficulties. The perineal space was also smaller as a result of smaller subpubic angles and intertuberous diameters in males and more specifically, SAA males, which might influence the ease of performing of procedures. Antenatal or pre-operative pelvimetry on MRI or CT scans for comparison with population specific reference values could be useful when considering childbirth options or pelvic and perineal procedures. Care should be taken when interpreting the diameters crossing the midline on MRI scans. Future studies involving more individuals and verified in the clinical setting could be useful for improving the relevance of this study.

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Ephesians 3:20, NKJV

Now to Him who is able to do exceedingly abundantly above all that we ask or think, according to the power that work in us, to Him be glory in the church by Christ Jesus to all generations, forever and ever. Amen.

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1. INTRODUCTION

The pelvic canal, also known as the lesser pelvis, true pelvis, pelvis minor or birth canal in females, is the space delineated by the pelvic brim or inlet and the pelvic outlet.[1] The true pelvis is a narrow continuation of the false pelvis, which is the wide upper part of the pelvic girdle, and is composed of irregular but complete walls around the pelvic cavity.

Apart from the well-known differences between the sexes, measurable differences have been documented the size and proportions of skeletal components of the pelvis between South Africans of European ancestry (SAE) and South Africans of African ancestry (SAA).[2-5] In addition, correlations between pelvic dimensions, stature and aging have been described.[6]

Variations in the dimensions of the pelvic canal, including the size and shape, need to be taken into consideration when planning childbirth, as well as for procedures involving the pelvic canal and perineum.[7-9] The specific size and shape of the pelvic canal may not only be a constraint for childbirth, but also for access during surgical procedures, caused by structures that might encroach on surgical pathways. Although variations between groups have been described and may be expected,[4] studies considering the extent of these differences when childbirth and perineal procedures are planned, are limited.

As some of the pelvic dimensions can be correlated with the stature of an individual, stature is often used in obstetric practice as an early warning for possible cephalopelvic disproportion (CPD).[1,10] It is further well known that a more spacious pelvic canal is found in larger adult body size which has an effect on the gestational period and foetal weight.[7-9] According to Kurki,[11] there is a complex relationship between obstetric sufficiency and general body size. Females of shorter stature tend to have smaller infants or are at greater risk of obstructed labour. Therefore, taller individuals present with an increased chance of reproductive success.[12] Alongside stature, age also contribute to the variation of pelvic dimensions,[13] which may be useful when assessing patients for surgery or planning childbirth options.

CPD, or the disproportion of the foetal head size as compared to the size of the maternal pelvis, is common among Africans and is a major cause of maternal and perinatal mortality and morbidity.[14] Several studies have been conducted on African-American and European-

American women regarding the pelvic dimensions, but the data may not correlate to South African ancestral groups.[15,16]

Smaller pelvic dimensions in individuals of African descent not only have far reaching implications in obstetric practice,[17] but may also play a role in pelvic surgical procedures involving male and female pelvic structures, for they may obscure vision, access and space for the surgical excision. Thus, the consideration of the variations in pelvic anatomy between ancestral group, sex and individual when planning pelvic surgery is important, as it is expected to influence the outcome of certain procedures such as radical retropubic prostatectomy, rectal surgery and laparoscopic procedures.[18]

Variations in the pelvic dimensions may also proof important when planning perineal procedures. Many perineal procedures, especially those related to stress urinary incontinence, directly involve the pubic bone, ischiopubic ramus and obturator foramina. The area between the ischiopubic rami, as reflected by the subpubic angle and the length of the rami, determines the size of the dissection plane and therefore the ease of performance of these procedures.

Specific dimensions of the bony pelvis relating to pelvic and perineal surgery, as well as childbirth, have not been fully investigated in South Africans. These dimensions may be important in both males and females during pelvic surgical procedures and during childbirth in assessing the possibility of a favourable outcome in vaginal deliveries.[19-21] Thus, possible findings of the pelvic shape and size variations could be implemented to predict the impact that ancestral group, stature and sex could have on planned procedures or child birth. Appropriate decisions regarding surgical techniques or methods of delivery could then be made.

Apart from the clinical implication: obstetric and surgical, the shape and size of the pelvic canal also have forensic and anthropological significance.[22,23]

There is, therefore, a need to determine the implicated pelvic dimensions in both sexes and ancestral groups while taking age and stature into account. Direct measurements on intact cadaver pelves, magnetic resonance images (MRI) and computed tomography (CT) scans were taken. Shape analyses of the pelvic inlet, midpelvis, pelvic outlet and pelvic canal were performed to accompany the linear measurement results. Direct measurements on intact cadaver pelves were favoured to mathematical derivation from 3D landmarks as to enable direct comparison with measurements taken on 2D MRI or CT scans in the clinic, as well as in the literature reviewed.

2. LITERATURE REVIEW

In the following literature review, includes a revision of the relevant anatomy of the pelvic canal. The factors that are associated with the variations in the size and shape of the pelvic canal in the literature are considered, along with the clinical implications of these variations. The four modalities used to measure the pelvic canal and shape are discussed. Finally, all these aspects considered are integrated to motivate the relevance of this study and the modalities that will be used.

2.1 Relevant Anatomy

In this section the anatomy of the bony pelvis is considered, followed by an account of the components of the pelvic canal and the dimensions used to assess its shape and size variations. Known factors associated with shape and size variations of the pelvic canal are reviewed.

2.1.1 Anatomy of the bony pelvis

The bony pelvis is located between the abdomen and lower limbs, more specifically between the fifth lumbar vertebra and the femoral heads. The pelvic bones are relatively large in order to withstand weight bearing forces and provide attachment for muscles. It consists of two parts: the major/false pelvis and minor/true pelvis or pelvic canal, which is of concern in this study (Figure 2.1). The true and false pelvis is separated from one another by mean of the pelvic brim (pelvic inlet/ *linea terminalis*). The false pelvis is the flared part of the bony pelvis, which form part of the abdomen, while the true pelvis (pelvic canal) is situated below the pelvic brim.

The bones of the pelvic canal support and protect the internal viscera. The pelvic canal is enclosed by the os coxae on either side, articulating at the pubic symphysis anteriorly, and posteriorly with the sacrum. Articulations are by means of semi immobile joints, except during pregnancy and parturition.[22,23]

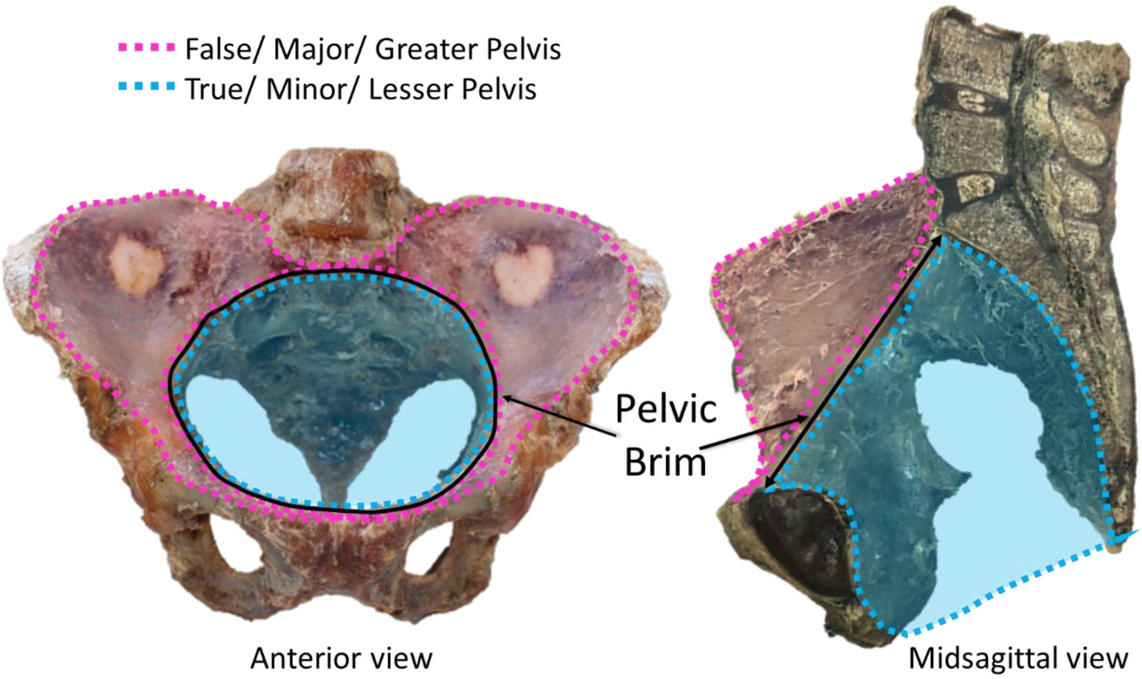


Figure 2.1: The true and false pelvis

The os coxa is formed by the fusion of three separate bones, the pubis, ischium and ilium. The common meeting point of the three separate bones is found in the acetabulum. The primary ossification centres are found in the separate units which fuse *in utero*. The ilium ossifies around 8 weeks *in utero*, while the ischium and pubic bone ossify 4-6 months *in utero*. The secondary ossification centres are located in the acetabulum and fuse at puberty. Before puberty commences the bones are kept in place by cartilage.[24]

The ilium contributes two-fifths to the acetabulum and consists of three surfaces and a superior margin, the iliac crest. The lateral surface faces the gluteal region and is roughened by gluteal muscle attachments, while the medial concave surface, the iliac fossa, is smooth and forms the greater pelvis. The sacropelvic surface facing the lesser pelvis can be found medially and postero-inferiorly and is separated from the iliac fossa by the arcuate line. The rough posterior part of the sacropelvic surface (auricular area) fits in the corresponding area on the sacrum, to form the sacro-iliac joint.[23,25]

The ischium is a U-shaped bone, with a body and a ramus. The body of the ischium contributes two-fifths to the acetabulum, while the ramus joins the inferior pubic ramus and forms one pillar of the pubic arch. The inferior surface of the ischium has an ischial tuberosity, providing attachment areas for the hamstring muscles and sacrotuberous ligament. The posterior border of the ischium continues as the ischial spine, which provides attachment for the sacrospinous ligament and coccygeus muscle and fuses above with the ilium to complete the greater sciatic notch.[22,25]

The pubis, as a complete unit, consists of three parts: a superior and inferior ramus and a body. It is located in the anteromedial portion of the pelvis and contributes one-fifth to the acetabulum. The body of the pubis is a flat quadrangular bone and forms part of the border of the obturator foramen for the attachment of the obturator membrane. The superior border consists of the pubic crest and pubic tubercle where muscles and ligaments attach. The long oval medial or symphysial surfaces of the left and the right pubic bones face each other, which are both covered with hyaline cartilage. The posterior surface is related to the bladder, with the retropubic space intervening. The inferior pubic ramus connects the pubic body with the ischium, while the superior ramus has a ridge known as the *pecten pubis* (pectineal line). The pectineal line is continuous posteriorl with the arcuate line of the ilium to form the *linea terminalis* or iliopectineal line. The superior surface of the superior ramus is almost triangular and extends from the pubic tubercle to the iliopubic eminence (the junction between the ilium and the pubis).[22,23,25,26] The subpubic angle is the angle formed below the pubic symphysis, between the inferior rami in an articulated pelvis. This area is also known as the subpubic arch.[22,27,28] The angle is of forensic[22,28] and clinical importance.[27,29]

The obturator foramen is located laterally to the pubic body and inferior pubic ramus, and medial to the ischium and the acetabulum. The obturator foramen is found in the anterior portion of the pelvis, at the midpelvic level (i.e. along the pelvic canal between the pelvic inlet and pelvic outlet). The obturator foramen is closed by the obturator membrane. Anteriorly, the membrane attaches to the anterior obturator tubercle at the anterior end of the inferior border of the superior pubic ramus, and posteriorly to the posterior obturator tubercle on the anterior border of the acetabular notch. These tubercles are often not very distinctive.[22,23,25]

2.1.1.1 Joints and ligaments pertaining to the pelvis

The primary joints of the pelvic girdle are the two sacroiliac joints and the pubic symphysis. The sacroiliac joints link the axial skeleton to the inferior appendicular skeleton. The lumbosacral and sacrococcygeal joints directly relate to the pelvic girdle. Strong ligaments support and strengthen these joints.[22,23,25]

The sacroiliac joint is a large weight-bearing joint. This joint consists of an anterior synovial joint between the auricular surfaces and a posterior syndesmosis between the tuberosities of the sacrum and ilium. The joint has limited mobility and increased stability, as it needs to transmit the weight of most of the body to the hip bones and then to the femur. Various ligaments are involved in keeping the sacroiliac joint stable. These include the anterior sacroiliac, interosseous sacroiliac, posterior sacroiliac, iliolumbar, sacrotuberous and sacrospinous ligaments.[22,23,25]

Of importance to this literature review are the sacrospinous- and sacrotuberous ligaments. The sacrospinous ligament extends from the iliac spine to the base of the coccyx, while the sacrotuberous ligament extends from the ischial tuberosity to the lateral sides of the sacrum and coccyx. The two ligaments convert the greater and lesser sciatic notches into the greater and lesser sciatic foramina but, more importantly, complete the pelvic outlet.[22,23,30]

The symphysial surfaces of the pubic bones are covered with hyaline cartilage and are connected by a fibrocartilaginous interpubic disc, forming a secondary cartilaginous joint, namely the pubic symphysis. The interpubic disc is generally wider in females. The hyaline cartilage is evidently connected to the fibrocartilaginous disc which is held into place by the surrounding ligaments. The superior pubic ligament connects the superior aspects of the pubic bones. The inferior (arcuate) ligament supports the inferior aspects of the joint. The inferior ligament rounds off the acute subpubic angle and forms part of it.[22,23,25]

2.1.2 Components of the pelvic canal

The pelvic canal is separated from the pelvis major by the oblique plane of the pelvic inlet, also known as the pelvic brim (Figure 2.1). The pelvic brim consists of the continuous segments of the *linea terminalis,* which include the iliac arcuate line, pectineal line (*pectin pubis)* and the pubic crest.[25]

The pelvic canal is the space bound antero-inferiorly by the pubic symphysis, body of the pubic bone, rami of the pubis, and posteriorly by the concave anterior surfaces of the sacrum and coccyx. The pelvic canal is a short, curved space with a noticeably longer posterior wall than the anterior wall.[22] Thus, the depth of the pelvic cavity anteriorly is ± 5 cm and posteriorly ± 15 cm.[26] The pelvic canal encloses parts of the reproductive organs, bladder and rectum. The true pelvis is on average larger in females than in males, contrary to other parts of the skeleton which are greater in males than females.[31] The bigger pelvic canal in females acts as a passage way for the foetal head during child birth and is therefore also referred to as the birth canal.[25]

The pelvic canal can be quantified by the size, shape and relative orientation of three delineated horizontal rings, namely the pelvic inlet, midpelvis and pelvic outlet, as represented in Figure 2.2. Measurements of the horizontal pelvic rings include the sacral length, height and depth of the pelvis and the oblique and obstetric conjugates. These will be described with in Chapter 3 (Materials and Methods).

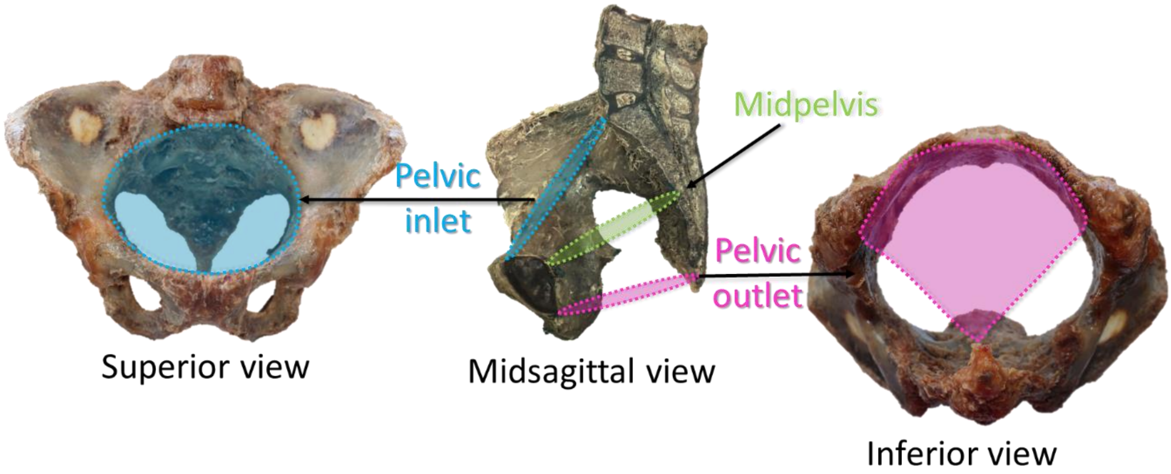


Figure 2.2: Pelvic rings

2.1.2.1 Pelvic inlet

The pelvic inlet is bound by continuous segments, starting at the sacral promontory posteriorly, sacral alae postero-laterally, arcuate- and iliopectineal lines medially and anteriorly the pubic symphysis (Figure 2.2).[22,32]

The pelvic inlet is often described by means of three dimensions. These dimensions include the anteroposterior diameter of the inlet (true conjugate), the transverse inlet diameter and the oblique inlet diameter. The term 'conjugate' is more frequently used in the clinical context and relates to the delineated horizontal pelvic rings: pelvic inlet, midpelvis and pelvic outlet (Figure 2.3). In general, the term 'conjugate' refers to the perpendicular diameters of a conical shape[33] which, in this study, it would be the pelvic canal. The pelvic conjugates (true, diagonal and obstetric) are defined clinically as the diameters reflecting the size and shape of the pelvis.

The true conjugate is the distance from the most supero-anterior point on the sacral promontory to the superior midline point on the dorsal aspect of the pubic symphysis (Figure 2.3). On average, the anteroposterior diameter is 10.0 cm for an adult male, while the female diameter is slightly larger with an average of 11.2 cm.[19,22,34] The diameter unfortunately cannot be measured directly during a pelvic examination, because of the presence of the bladder, and is therefore often done on X-rays.[22,25]

The true conjugate, however, does not represent the shortest anteroposterior distance for the foetus to pass through during the birth process. The obstetrical conjugate is the shortest distance and is defined as the distance from the sacral promontory to the most prominent point on the posterior aspect of the pubic symphysis and measures 10 cm or more. Although the obstetric conjugate is the most important of the three for assessing adequacy of the pelvic cavity for childbirth, it cannot be directly measured by palpation. The conjugates of the pelvic inlet and outlet were originally described as dimensions to be palpated during physical examination of pregnant women during vaginal examination. The measurement of these distances would also depend on the expertise of the examiner[35]. The estimation is based on the length and width of the examiner's fingers, thus the conjugates are a rough estimate rather than the actual diameter. Several authors[22,36,37] stated that the obstetrical conjugate is calculated by subtracting 1.5 to 2.0 cm from the diagonal conjugate, since the obstetric conjugate cannot be measured during a pelvic exam. The the limitation may be overcome by a simple MRI and Ultrasound. According to Katanozaka,[38] the diagonal conjugate is therefore dependent on the height and slope of the pubic bone.

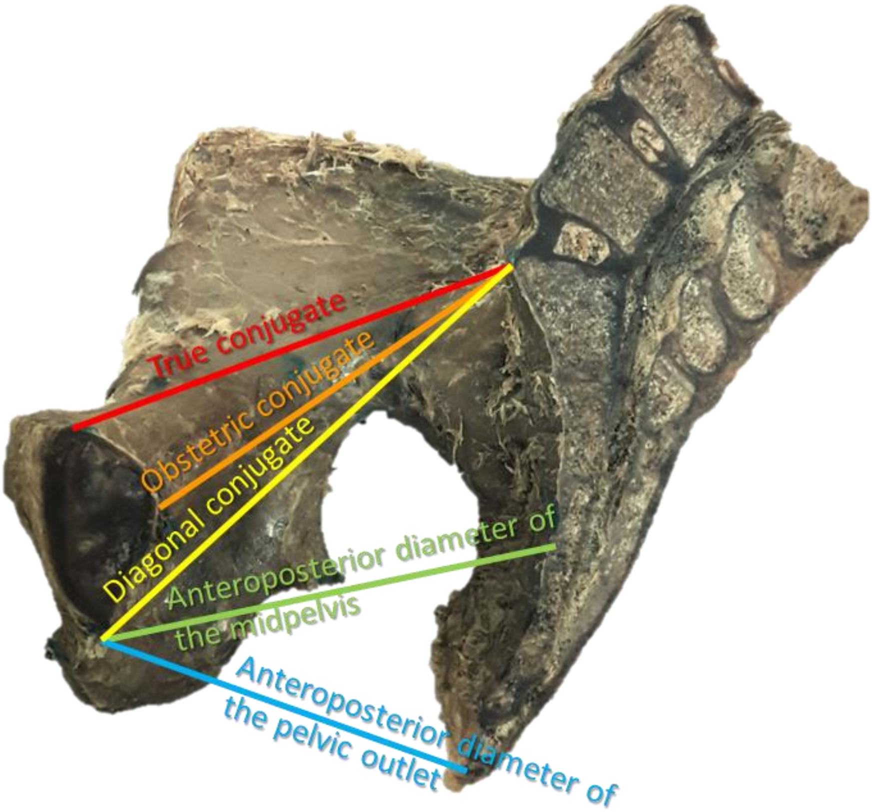


Figure 2.3: Conjugates

Katanozaka[38] and Sonal[39] measured the obstetric conjugate ultrasonically in Japanese and Indian populations respectively. The obstetric conjugate varied between the groups. The Japanese population had a distance of 12.90 ± 0.88 cm, while the Indian population had a distance of 11.4 ± 1.07 cm.

The transverse conjugate (Figure 2.4) is the greatest transverse width on the superior aperture or brim. The transverse inlet diameter, on average, for males is 12.5 cm and for females 13.1 cm[21]. The oblique diameter is measured from the iliopectineal eminence of the one side to the opposite sacroiliac joint and is, on average, for males and females 12.0 cm and 12.5 cm, respectively[22]. The averages may vary between ancestral groups[40].

Figure 2.4 Transverse conjugate/ Transverse inlet

According to Greulich and Thomas,[41] the pelvic inlet shapes can be classified into four main types, as indicated in Figure 2.5. Classification of pelvic shape is either done by general visual impression of the pelvic shape, or derived from the relative size and position of the transverse and true conjugates[32,41-43] The gynaecoid pelvis is said to have an ideal shape for normal vaginal delivery, with a round to slightly oval inlet (true conjugate slightly shorter than the transverse inlet). The true and transverse diameters intersect approximately in the midline. The android pelvis has a more triangular or heart-shaped inlet, which seems to be associated with prominent ischial spines and a more angulated pubic arch. The true and transverse diameters intersect more posteriorly. The anthropoid pelvis has an elongated true conjugate. The platypelloid pelvis has a flat inlet with a shortened true diameter or elongated in the transverse conjugate.[2,43,44]

A recent study conducted in 2015 by Kuliukas *et al*. investigated the Caldwell-Moloy classification system by means of geometric morphometric analysis.[45] The authors argue that the traditional midwifery teachings of the Caldwell-Moloy system should be reconsidered, since their results show that geometric morphometric findings do not correlate with the four distinct pelvic inlet types. Instead, it was a collection of several variations. They state that it is more helpful to view the pelvic shape as a whole, as it has many components that might affect childbirth.[45]

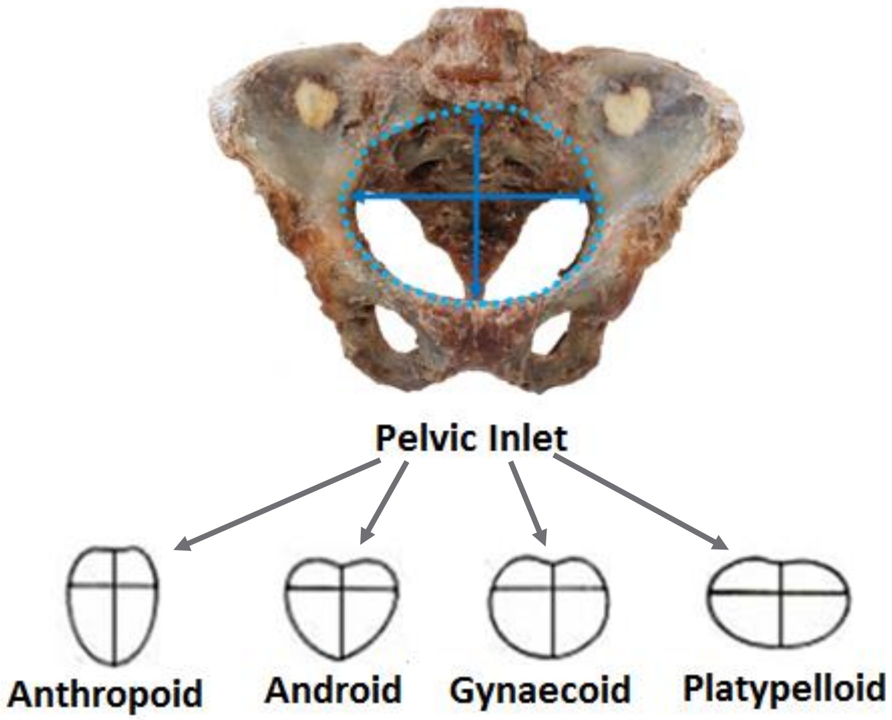


Figure 2.5: Pelvic shape classification (Adapted from the Caldwell-Moloy pelvic shape classification method[42]

2.1.2.2 Midpelvis

The midpelvic plane corresponds to the level of the projection of the ischial spines and is important for clinicians, as midpelvic arrest of the foetal head occurs, as the name implies, during parturition at this position. The ischial spines are often the limiting factor at the midpelvic level and is therefore assessed by the interspinous distance.[36]

The interspinous diameter is described as the greatest distance between the ischial spines. The interspinous distance is found to be the narrowest part of the pelvic canal through which the infant's head must pass during the birth process. According to Moore *et al*.[22], the interspinous diameter should be more than 10 cm.[22,25,36] Stranding *et al.* state that the average diameter needed for an adult female is 9.5 cm.[25] This smaller diameter would allow a foetus with an average foetal head size of 9 cm through the canal.[25] However, this distance is thought not fixed. Increased levels of sex hormones and *relaxin* cause the pelvic ligaments to relax during the latter half of pregnancy, allowing for increased movement in the pelvic joints. Relaxation of the sacroiliac joints and the pubic symphysis permits increases of up to 10-15% in the transverse and interspinous diameters, easing the passage of the foetus[22]. On the other hand, the true conjugate diameter remains unaffected by the process[22]. This correlates with the findings of Huerta-Enochian *et al.* who investigated the change in the maternal pelvic dimensions by MRI during the third trimester up to the postpartum period. They established that the maternal pelvic dimensions remain relatively stable throughout pregnancy and delivery.[17]

The diameters at the midpelvic level are collectively called the diameters of the pelvic cavity and include, in addition to the interspinous distance, also the widest transverse diameter, anteroposterior diameter and oblique left and right inlet diameters. The anteroposterior diameter is measured from the posterior surface of the pubic symphysis to the midpoint of the third sacral segment (the S3/S4 junction). The male average is 10.5 cm and the female average is 13 cm. The transverse diameter is the widest transverse distance between the side walls of the cavity, and often the greatest transverse dimension in the whole cavity. It measures about 12 cm in the adult male and 12.5 cm in the adult female. The oblique diameter is the distance from the lowest point of one sacroiliac joint to the midpoint of the contralateral obturator membrane and measures about 11 cm in the male and 13.1 cm in the adult female. All measurements vary with the individual and racial groups.[25]

2.1.2.3 Pelvic outlet

The pelvic outlet is delineated antero-inferior by the inferior border of the pubic symphysis and the inferior pubic rami (subpubic arch), laterally by the medial surfaces of the ischial tuberosities, and posteriorly by the tip of the coccyx. Where the bony framework is deficient, the sacrotuberous ligaments are found connecting the ischial tuberosities and the infero-lateral border of the sacrum bilaterally.[22,32] Together with the ligaments and bony landmarks, the pelvic outlet represents a rhomboidal shape.[25] The pelvic outlet is just not a defined rigid structure, especially in its posterior half which is completed by ligaments, making the pelvic outlet more a theoretical boundary.[25]

The diameters of the pelvic outlet are not only important in obstetrics, but also in pelvic floor surgery involving incontinence procedures. A narrow pelvic outlet, particularly in the subpubic region, may be a confounding factor for several subpubic procedures and vaginal delivery.[27]

The dimensions of the pelvic outlet include the transverse diameter and the anteroposterior diameter of the outlet. The transverse diameter is commonly known as the intertuberous/ bituberous diameter between the medial surfaces of the ischial tuberosities, it is on average 8.5 cm in males and 11.8 cm in females.[25] The anteroposterior diameter, on average, for males is 8 cm and for females 12.5 cm.

The closer the ischial tuberosities are situated, the smaller the subpubic angle is and therefore, the narrower the pelvic outlet.[27] As a quick way of assessing the feasibility for vaginal childbirth or perineal procedures, the subpubic angle may be measured radiographically, sonographically, by MRI or by palpation in the clinic.[46] According to Frudinger,[27] the subpubic angle should be more than 90˚ to avoid complications during delivery. Moore and Dalley[22] suggested that, if the ischial tuberosities are far enough apart to permit three fingers side by side, the subpubic angle is considered wide enough to allow passage of the average head size of a full term infant.

Despite the important clinical applications of the subpubic angle and the expected inter-population variations thereof, only a few studies exist to elucidate these variations among groups.[47-50] Igbigbi and Nanono-Igibi[47] found that the subpubic angle in an Ugandan population ranges from 75 ˚ to 155˚ (mean of 116.11˚) in females.[47] These subpubic angles were determined by anteroposterior radiographs. However, the values are significantly smaller than the subpubic angles of a Malawian population, with a mean value of 129.07˚.[51] Igbigbi and Nanono-Igibi[47] suggests that these differences are an indication of regional variation of the subpubic angle among 'black' subjects.[47]

Small and co-workers quantified the subpubic angle in South African males and females of both South Africans of European ancestry (SAE) and South Africans of African ancestry (SAA).[50] They reconstructed the pelves by using elastic bands and placed them in a custom-built stand to facilitate photography of the subpubic angles. The photographs were imported into Microsoft Paint (version 6.1) and a tangent line was drawn on both sides of the articulated pelves from the inferior point where the two pubic bones meet to the ischial tuberosities. The results showed the mean value of the subpubic angles in SAA males and females were 63.98˚ and 84.18˚ respectively, while those in SAE males and females were larger, with mean angles of 70.78˚ and 93.98˚, respectively.

2.1.3 Factors associated with variations in the dimensions of the pelvic canal

Osteometric and morphological pelvic variations have been reported between different ancestral, sex, stature and socio-economic groups, which could possibly be attributed to genetic, dietary and environmental factors.[11,12,19,21,37,42,44,52,53,54]

2.1.3.1 Sexual differences

The pelvis is one of the most sexually dimorphic bones in the human body.[55] Differences in sex can be determined as early as foetal life. The pelvic dimensions during infancy are greater in males than in females, although in females, the size of the pelvic cavity remains larger until about 22 months.[6] In adults the sexual differences correlate to functionality, namely the requirements of childbirth and differences in robusticity.[56] Robusticity, as well as child bearing modifications therefore play a role in producing metric and non-metric manifestations of sexual dimorphism.[31,54]

The reproductive adaptation particularly affects the pelvic canal and to a variable degree the proportions and dimensions of the greater pelvis in females. Numerous differences between the male and female pelvis have been reported (Table 2.1). The female pelvis appears broader, yet more gracile and lighter with more slender bones, in comparison to the male pelvis which has a more robust appearance, with more prominent muscle attachments.[3,22,54] Metric measurements for males exceed most corresponding measurements for females.[54]

Since males are more muscular and therefore more heavily built, the overall dimensions of the pelvis are greater in males. Markings for muscles are more pronounced and the general architecture is relatively stouter. The iliac crests are more rugged and curved more medially at the anterior ends, than in females. The iliac blades are more vertically orientated in the female, but do not extend as far upwards, in comparison to males. The iliac fossae are therefore shallower and the *pectin pubis* is more vertical.[25]

The differences between sexes and population groups are greater in the inferior aperature than the pelvic brim.[28] A traditional view on the Caldwell-Moloy classification system, classified 25% of all women to have the android (male-like) shape pelvic inlet, which would make childbirth more difficult, but Kuliukas *et al.* proved by means of geometric morphometric analysis that both male and female pelves demonstrate two distinct groups, with no overlap whatsoever.[45]

The obturator foramen is large and oval in males, but smaller and almost triangular in females[22]. Findings by Ridgeway *et al.* on the female bony pelvis indicated that there is considerable variability in the bony architecture of the obturator foramen, especially on its internal border.[52] The pubic bone shape in males is more triangular whereas for females, it is more rectangular.[25]

In males the ischial spines are closer together, being classically inverted,[25] thus automatically making the interspinous diameter smaller that the interspinous diameter in females. The sciatic notch in females is much wider than in males.

The subpubic angle has been shown to be one of the most sexually dimorphic dimensions of the pelvis.[47] Both quantitative and qualitative approaches have been used to assess the variability of the subpubic angle.[29,50] An increased distance between the ischial tuberosities found in females will account for a greater subpubic angle, as well as variations in the ischiopubic rami.[25,55] The subpubic angle is more angular or closed in males (50˚ - 60˚) than in females where this angle is more rounded or rather obtuse (greater than 80˚ - 85˚).[25] In females a significant variation in the degree of openness of the pubic arch has been established.[57]

The sexual differences in the anatomy of the urogenital tract account for the variations noted in the ischiopubic rami and the subpubic angle.[25,55,58] The ischiopubic rami in males have a noticeably rough and robust appearance due to the attachment of the penile crura, in contrast to the clitoral attachment area which is poorly developed in females.[25]

Phenice *et al.* developed a qualitative method for determining sex in articulated pelves.[59] The method relies on the variability in shape of the subpubic concavity and medial aspect of the ischiopubic ramus to ascribe sex.[47,50] Morphometric assessments demonstrated a U-shaped, obtuse angle with strongly everted ishiopubic rami in females. In male articulated pelves the subpubic angle was found to be V-shaped, sharp angled and with only slightly everted ischiopubic rami.[60] These visual techniques are quick and easy to perform, but have a high degree of intra- and inter-observer subjectivity.[50,55]

In table 2.1, a brief summary of the main differences between male and females pelves is presented.

Table 2.1: Summarized sex differences in the pelvis[22,23,26,32]

Bony Pelvis	Male	Female
General structure	Thick and heavy	Thin and light
Greater pelvis	Deep	Shallow
Lesser pelvis	Narrow and deep, tapering	Wide and shallow, cylindrical
Pelvic inlet	Heart-shaped, narrow	Oval and rounded, wide
Subpubic angle	Narrower (<70˚), inverted V	Wider (>80˚), inverted U
Greater sciatic notch	Narrow (~70˚)	Almost 90˚

2.1.3.2 Population group variations

The variations in the pelvis, variations in dimensions of the pelvic canal between population groups are not uncommon. Numerous studies have assessed these differences osteometrically and morphologically.[11,42,44,61] Metric and morphological variations in pelvic shape and size have been demonstrated between North American whites and blacks,[62-64] between North American whites and South African whites,[3,4,54] and among American blacks and African blacks.[3,60,65] In the case of South Africans of European ancestry, it is thought that, due to temporal change, founder effect, and admixture, they have become osteologically distinguishable from both their European and North American counterparts.[3,66,67] For these reasons, dimensions of pelves belonging to South Africans of African and European ancestry are expected to differ from standards derived from the literature (Tables 5.1 – 5.5).

Measures of the posterior space, angulation of the sacrum, bi-ischial breadth and subpubic angle have been found to be most dimorphic and variable in White and African Americans and Amerindians.[28,68]

A great deal of variation exists[42] with regard to robusticity alongside the degree of sexual dimorphism between ancestral groups and body size.[11,42,44,61] Malnutrition may be a factor affecting these diameters directly or indirectly by influencing stature. Nutritional status and the availability of food may also account for differences between ancestral groups due to socio-economic factors individual upbringing. More specifically in the South Africa context, Patriquin *et al.* demonstrated a significant difference ($p<0.001$) in the measurements taken between SAE and SAA males and females.[3] They reported that all the dimensions were larger in SAE than in SAA, with the exception of anterior width of the greater sciatic notch, which was larger in SAA males than in SAE males. These findings on the interpopulation variations of the pelvic diameters corresponded with previous studies that demonstrated a difference in other parts of the skeleton for both SAA and SAE.[4,66,69] Kurki[11] examined skeletal remains from various global locations by analysing the size and shape of the pelvic canal in relation to the body size. Kurki[11] found that South Africans of African ancestry had a unique pelvic shape due to a rather small and petite body shape. Pelvic shape differences also reflect climatic variation in body build and proportions.[11]

The differences between sexes and ancestral groups are greater in the inferior aperture than the pelvic brim.[28,47] Patriquin *et al*. suggest that to some extent, the shape of the pelvis may correlate with that of the skull, since the skull must pass through the pelvis during the birth process.[54] In SAA, the pelvic shape consisted of a small pelvic inlet relative to an elongated lower pelvic canal, anteroposteriorly.[11] This finding supports the opinion that every population should have its own standards that are tailored to the unique metric and morphological characteristics of that population.[3,37,54]

2.1.3.3 Stature

Stature has been shown to have an influence on certain pelvic dimensions. The influence on the anteroposterior dimension or true conjugate of the pelvic inlet is often used as a measure for favourable obstetric outcomes.

Bernard[70] conducted a study on a group of Scottish women. The group of women were further subdivided into two groups. The first group had a mean maternal height of 152 cm, along with a mean true conjugate of 10.8 cm. The second group of women had a mean maternal height of 167 cm and an average true conjugate of 12.7 cm. The results showed that the degree of mechanical difficulty during labour was inversely proportional to the height of the patients (Table 2.2).

Adadevoh *et al.* further correlated the size of the true conjugate with the height of an individual.[37] Adadevoh *et al.* found that Ghanaian subjects without CPD had a true conjugate of 10.61 ± 0.81 cm and height of 157.2 ± 5.69 cm on average.[37] However, individuals with CPD were found to have a significantly shorter true conjugate of 9.54 ± 0.63 cm and a height of 152.68 ± 5.46 cm.

Steward and co-workers determined the true obstetric conjugate in Shona and Zulu women.[71] Among the Shona women, who experienced major CDP during labour, requiring a Caesarean-section, they found a mean maternal height of 151.32 cm and a mean true conjugate of 9.9 cm. The Zulu women with CPD had a mean true conjugate of 9.6 cm (maternal heights were not stated) (Table 2.2).[71] Merchant *et al.* reported that Guatemalan women with a maternal height of 146 cm, compared to 160 cm, have a two and half times higher risk of intra-partum caesarean delivery.[16] It can therefore be said from the literature reviewed, that women who had CPD, had mean conjugate values of less than 10 cm and mean maternal heights less than 155 cm.[16] (Table 2.2).

Nutritional status influences pelvic size and stature. Bernard,[70] for instance, suggested that women with poor nutritional status are shorter in stature and have smaller pelvic brims in comparison to women with better nutritional status. In order to distinguish a malnourished women from genetically short women, Baird[72] suggested a threshold height. He suggested that malnourished women, who experienced stunted growth during development, are below 155 cm in height and have flat pelvic brims. Thus women with a height of 157 – 163 cm have smaller pelves in proportion to their height, but their pelves are not pathologically flattened and the pelvic brim shape remains favourable for childbirth.

Another aspect that needs to be considered is that smaller women tend to have smaller babies, some of whom will show signs of intra-uterine growth restriction. This raises the possibility that the biological relationship between mother and foetus size may protect shorter women suffering from excess delivery complications.[12,16]

Table 2.2 Height and true conjugate amongst various population groups

		Characteristic associated with CPD (predisposing)		Characteristics not associated with CPD	
Author	**Population**	**Maternal height (cm)**	**True conjugate diameter (cm)**	**Maternal height (cm)**	**True conjugate diameter (cm)**
Adadevoh[37]	Ghanaian	152.68	9.54	157.20	10.61
Steward[71]	Shona	151.32	9.90	156.80	11.50
Steward[71]	Zulu	-	9.60	-	10.4
Bernard[70]	Scottish	152.00	10.80	167.64	12.70
Merchant[16]	Guatemala city	152.30	-	-	-

2.1.3.4 Aging

Growth of the skeletal framework starts as early as intra-urtine life up to the fusion of the epiphyseal plates in the long bones during adolescence.[73,74] The effect of aging on bones usually relates to osteoporosis and reabsorption, which make the bones brittle and fragile,[75] thus bone growth is not expected during aging. A recent study conducted by Berger *et al.* explored the pelvic changes as the patient aged.[13] They made use of retrospective CT scans, measuring different transverse diameters along the whole pelvis, between the femur heads and L4 vertebra. What Berger *et al*. found was that the pelvis increases in the transverse dimensions, thus widening a small amount with each year of aging.[13]

2.2 Clinical relevance

Adequate access for clinical procedures of the pelvis and perineum might be affected by the size of the pelvic canal. Clinical procedures in women includes: stress urinary incontinence procedures, hysterectomy and sarcospinous colpopexy, and in men: radical retropubic prostatectomy; and in both sexes: surgical procedures for inferior pubectomy in posterior urethralplasty, rectal cancer and rectal prolapse procedures.[76] When planning pelvic and perineal procedures or childbirth options, variations in the pelvic dimensions between sex-ancestral groups or with stature should be taken into consideration[52,77] in order to determine appropriate adaptations to surgical techniques or decisions regarding methods of delivery.

2.2.1 Parturition

Knowledge of the pelvic shape and size is of the utmost importance when considering childbirth options. Childbirth in humans is far more complicated[78,79] than in other mammals, including other primates.[80] The concomitant changes in pelvic architecture resulting from bipedalism and foetal encephalisation led to some obstetric dilemma that resulted in an increase in the risk of mother-foetal mortality.

Before the birth of a baby, the foetus must undergo a series of rotations in order to navigate itself successfully through the birth canal.[78] Due to the constricted canal, the foetus must orientate itself in such a way that the largest diameters of the head and the shoulders are in line with the more spacious parts of the pelvic canal. The resulting position is then that of the foetus facing sideways, as the larger head fits in the wider transverse diameter of the pelvic inlet.[78]

Sexual dimorphism in the pelvis facilitates parturition.[31] The pelvic canal in a female is rendered more spacious than in males, due to means of a slightly elongated pubis, more laterally placed ischial tuberosities and ischial spines, more posteriorly placed auricular surfaces and wider sciatic notches. The greater female values are associated with an increased backward sacral tilt and greater anteroposterior pelvic diameter, especially at lower vertebral levels.[81] The narrowing of the lateral walls of the pelvic canal at the level of the midplane compresses the foetal head and consequently allows rotation so that its lies anteroposteriorly along its long axis.[31,45] Differential pubic growth is also expressed in the subpubic arch being smaller and more angular in males, while it is greater and more rounded in females.

Clinically, dissimilarities in pelvic anatomy may be associated with variations in obstetric outcomes. The size and shape of the pelvis, as often described at the three horizontal planes along the birth canal, are important when contemplating vaginal delivery and will predict how the foetus will move from the pelvic inlet through the midpelvis and the pelvic outlet.[82] The pelvic shape can therefore determine the type of foetal presentation and mechanism of labour.[29]

According to obstetric teaching, a narrow pelvic outlet prompts a difficult vaginal delivery. The subpubic angle is often used to make a quick assessment as to whether the pelvic outlet, and possibly canal, are sufficient for the passage of the foetus.[27,83,84] Another simple clinical pelvimetry technique, namely estimation of the intertuberous diameter, could be used as a reflection of the subpubic angle.[27,85] A smaller angle typically indicates a narrower pelvic outlet. To avoid problems during vaginal delivery the angle should be at least 90˚. A small, narrow subpubic angle is likely to displace the foetal head posteriorly towards the perineal soft tissue and anal sphincter, thereby causing potential injury to these structures.[22,27] In the study by Frudinger *et al*. women with a subpubic angle of less than 90˚ had considerably prolonged first and second stages of labour when compared with women who had a wider angle.[27] Moreover, anal continence deteriorated more in women with a narrow subpubic angle after delivery.[27]

Cephalopelvic disproportion is a major cause of maternal and perinatal mortality and morbidity among Africans.[37] It will therefore be of value to determine whether certain ancestral groups or individual body variations are likely to be associated with pelvic diameters favouring vaginal delivery.

2.2.2 Stress urinary incontinence

Stress urinary incontinence (SUI) is defined by the International Urogynecological Association/ Internation Continence Society, as the involuntary loss of urine due to physical exertion or by sneezing or coughing.[86] Where as Lee *et al.* related SUI to the presence of intrinsic sphincter deficiency rendering it unable to resist increased abdominal pressures during certain activities[52,87]. Variations in pelvic anatomy could potentially be associated with the occurrence of pelvic floor disorders involving the urinary sphincter mechanism and concomitant stress urinary incontinence. Handa and co-workers, showed that a wider transverse inlet and a shorter obstetrical conjugate were significantly associated with pelvic floor disorders in females. [88] They also found that the pelvic shape with the lowest risk may be a heart shaped (anthropoid) pelvis. By definition these pelves have a narrower transverse inlet and a wider obstetrical conjugate. They also noted that the prevalence of the anthropoid pelvis was greater in 'black' women. Handa[64] reported that the incidence of SUI and pelvic organ prolapse were found to be less frequent in African-American than white American women.

Stav and co-workers[89] also found that pelvic inlet and outlet dimensions were significantly larger in incontinent women.[90,91] Berger and associates evaluated the subpubic angle in nulliparous continent, primiparous continent and primiparous incontinent females. Postpartum stress urinary incontinence is associated with a wider subpubic angle.[92]

However, Abdool *et al*. in their study on nulliparous women in South Africa, found by ultra-sound and clinical examination that, regardless of pelvic dimensions, black South African women had greater pelvic organ descent and greater distensibility compared to South African women from East Asian or European descent. It therefore seems that other factors, apart from pelvic dimensions, could be involved in organ prolapse and stress urinary incontinence.[93]

Not only do certain pelvic shapes predispose to SUI, but also the performance of several surgical treatments for SUI are influenced by the possible variations in pelvic anatomy. Surgical treatments include the application of different slings (e.g. bulbo-urethral sling, tension-free vaginal tape, trans-obturator tape, four-armed male sling system and the female mini-arc single-incision sling system). The subpubic angle is an important landmark for the applications of the various slings.[87,89,92] However, the subpubic angle is not a true reflection of the subpubic space, as the subpubic concavity forming the pubic arch is not taken into account.[59] More studies regarding the subpubic space are needed to fully understand the possible variations in this area.

The shape, size and position of the obturator foramen are other important aspects that need to be considered when performing transobturator slings. Ridgeway and associates stated that it is not exactly know how the size of the obturator foramenina affects the location of the vessels and nerves, but they do believe that women with smaller foramina are at higher risk during these procedures.[52]

Possible variations in the shape and size of the pelvis between population groups may possibly have an influence on the relative positions of the neurovascular bundles to the bony pelvis. Neurovascular bundles may become exposed and endangered during surgical procedures.[94] Van der Walt *et al*. found that the dorsal nerve of the clitoris or penis was closer to the bony frame in South Africans of European ancestry, while it was more exposed in South Africans of African ancestry.[94]

The study conducted by Ridgeway *et al.* was performed on African American and European American woman.[52] This data may not correlate with the South African population as suggested by Patriquin[5] and Adadevoh[37]. The authors emphasized the need for every population to have its own standards that are tailored to the unique metric and morphological characteristics of that population.

Guidelines, taking into account the relative distances and angles between landmarks and the most desirable course of the surgical instruments related to various bony structures, could prove to be invaluable in doing these procedures with more confidence, ease and safety.

2.2.3 Inferior pubectomy in posterior urethroplasty

Pelvic fracture urethral distraction occurs in 10% of individuals who suffered pelvic fractures.[95,96] The severe shearing forces, necessary to fracture the pelvis, are transmitted to the urethra and result in disruption distal to the urogenital diaphragm. Repair needs to be performed on both the fractured pelvis and the injured urethra. Urethroplasty entails surgery to repair the injuries incurred to the walls of the urethra.[97]

Visual pre-operative pelvimetry is used to ensure that there is adequate space for surgery. As the significant anatomical structures are located near the subpubic angle, measurements of the subpubic angle are excellent predictors of the accessibility of the urogenital area, and the possible impact on surgery.[97] The subpubic angle can be measured by means of an X-ray, perineal ultrasound, CT and MRI. If the subpubic space is not adequate, the perineal approach in urethroplasty, for the repair of structures resulting from a posterior urethral distraction injury,[96] may necessitate an inferior pubectomy.[97] The inferior pubectomy involves a wedge excision of the inferior pubic arch. Inferior pubectomy is conducted to improve exposure of the posterior urethra and facilitate scar excision.

2.2.4 Radical retropubic prostatectomy

Radical retropubic prostatectomy (RRP) is a surgical procedure where the prostate gland is removed by means of an incision in the abdomen or the perineum. This curative treatment is recommended in early onset prostatic cancer.[98]

The procedure is performed with greater ease when the pelvic shape is wide and shallow.[20] Hong *et al.* claim that the size of the pelvis, the interspinous dimension (narrowest distance between ischial spines) and the intertuberous dimension (widest distance between the ischial tuberosities) are essential when performing RRP.[20] Wider pelves with greater transverse diameters, interspinous and intertuberous distances are preferable, as opposed to narrower and steep pelves. Narrower pelves create a surgical challenge, since they cause difficulty in accessing the prostate gland, especially its apex.[99]

Pelvic dimensions such as pelvic depth and height are also important in the current era of laparoscopic and robot–assisted retropubic prostatectomy, as instruments are manipulated in a confined space where there is limited freedom of movement.[20]

Von Bodman and co-workers found that population variations in pelvimetric measurements exit, which affects the surgical margins during RRP surgery.[100] The authors claim that African American men have significantly smaller pelvic inlets and subpubic angles than white American men.

2.2.5 Rectal cancer

Rectal cancer is a disease in which malignant cancer cells forms in the wall of the rectum. These cancerous tumour can be surgically removed.

Narrow and deep pelves complicates surgery for rectal cancer, by the abdominal or the laparoscopy approach, as the vision and access to the pelvis is restricted by the pelvic anatomy.[19,21] Killeen and co-workers explained that a prominent sacral promontory or a narrow transverse plane could cause anatomical bottle-necks (restrictions), impeding vision, access and space in which instruments can be manipulated.[19]

Consequently, smaller pelvic dimensions could impede operations involving rectal cancers, which require adequate vision, maximum retraction and access to the depth of the pelvis through the pelvic inlet. Reduced pelvic dimensions are a foremost factor influencing the difficulty of safe surgical excision. Salerno *et al.* explain that the pelvic depth and width, as well as the tumour size relative to the pelvic dimensions, influence the difficulty in surgical excision.[21]

2.2.6 Hysterectomy

Hysterectomy is the surgical removal of the uterus. This may be performed vaginally, abdominally or laparoscopically.[101,102] The main factor which determines the route of surgical entry is the body mass index (BMI). About 20.9% of all hysterectomies are performed vaginally in South Africa.[103]

Vaginal hysterectomy is complicated by the presence of a narrow pubic arch and a subpubic angle less than 90˚, which increase the risk of failure.[57,104]

2.2.7 Sacrospinous colpopexy

Sacrospinous colpopexy is a procedure by which the vagina is suspended up towards the sacrospinous ligament in the surgical treatment of uterovaginal and/or vaginal vault prolapse.[105]

Vaginal vault prolapse may occur after a hysterectomy. In the absence of the uterus, the surrounding ligaments, which support the upper part of the vagina, gradually fall towards the vaginal opening. This contrast with a vaginal prolapse, which is a condition of the vagina and/or uterus falling out their natural occurring positions. Transvaginal sacrospinous colpopexy is used as reconstructive surgery for vaginal vault prolapse[34,106] and for uterovaginal prolapse. Transvaginal sacrospinous colpexy involves placing a stitch from the vaginal cuff to the sacrospinous ligament, approximately 2cm medial to the ischial spine.[106] This technique has the advantage that it could preserve the individual's fertility.[105]

Guttman and associates emphasise that bony landmarks should be used for a safer, more effective surgery.[34] The interspinous pelvic dimension, the obstetric conjugate as well as the distance from the ischial spine to the midpoint of the lateral wall of the sacrum could be useful.[106] A good correlation between the length of the sacrospinous ligament and the obstetric conjugate was noted.[106] The longer the sacrospinous ligament, the longer the obstetric conjugate.

2.3 Modalities to assess pelvic shape and size

To quantify variations in the pelvic dimensions, or to determine the suitability of the pelvic size and shape for clinical procedures and childbirth, various clinical and imaging tools are used. Pelvic measurements and various parameters have been determined clinically by palpation, ultrasonographically, radiographically including computerised tomography (CT) scanning, intra-operatively, by magnetic resonance imaging (MRI), photographically, or directly on skeletonised cadaveric specimens.[36,50,53,107,108]

To determine the capacity of the female pelvis for childbearing, the diameters of the pelvis may be noted manually during a pelvic examination.[3,37,53,109] However, these manual measurements have proven to be of little clinical value and are considered by some as obsolete.[25] Pelvimetry may also be determined radiographically,[28,38,53,83,84] with ultra-sound[38,46,93] and MRI.[107,109] Precise measurements are not possible without radiographic techniques, which not take soft tissue into account.

Metric ratios and indices have been used to create an impression of the shape differences between pelves. When using metric assessments, however, detailed underlying variations in the three-dimensional (3D) structure cannot be captured.[58] Geometric morphometric analysis, on the other hand, has proven to be a valuable and reliable alternative to verify morphological characteristics observed with more traditional methods.[54,58,110] For this reason, landmarks will be digitised with a Microscribe® for more detailed 3D shape analyses by geometric morphometrics in this analysis.

2.3.1 Linear measurements

Although measurements may be derived from direct measurements and palpation, linear measurements (or measurements in one direction) it may also be performed directly on dried bone, MRI and CT scans.[110]

2.3.1.1 Direct measurements on cadaver skeletal material

In traditional, as well as in geometric morphometric studies, the shape of the pelvis is often quantified after the reassembly of the two hip bones and the sacrum.[50,111,112] However, on dry bones, the morphology of the cartilaginous tissues that form the two sacroiliac joints and the pubic symphysis before death remains unknown, leading to potential inaccuracies and errors during the reassembly process.[111]

2.3.1.2 Radiographic pelvimetry

Radiographic pelvimetry is a metric method that can be used to assess variation in the subpubic angle.[83,84] The subpubic angle of various populations such as Ijaws and Igbos,[83] Malawians,[28] Egyptians,[113] Ugandans,[47] Londoners,[29] Ikwerres and Kalabaris[84] and Nigerians[48,49,114] have been quantified using radiographs. Authors found significant differences in the size of the subpubic angle between the sexes and population groups.[28,29,47]

Unfortunately, the use of Roentgen rays (X-rays) is limited during pregnancy as it causes ionizing radiation, which may increase the risk of childhood cancer to the foetus.[50,109]

2.3.1.3 Computed tomography scans

Standard pelvimetry on radiographs has largely been replaced by CT scans because of the advantage of rapid and reduced ionizing radiation imaging with the possibility of exact anatomical measurement of the bony pelvis.[115,116] CT scans further allow for direct and accurate measurements of various distances in a three dimensional space.[116,117] CT scan pelvimetry also assists in diagnostic accuracy in cases such as dystocia and cephalopelvic disproportion.[116,118]

Average and critical limit values in certain dimensions of the pelvis on CT scans have been determined. The critical values may be associated with the probability of CPD. The average anteroposterior dimension of the female pelvic inlet is 12.5 cm, that of the midpelvis is 11.5 cm, while the critical values are slightly less with 10 cm for both the inlet and midpelvis. The transverse value for the pelvic inlet is 13 cm and the midpelvis is 10.5 cm, with the critical value of 12 cm for the transverse inlet and 9.5 cm for the transverse midpelvis.[36]

To avoid error in the measurements, it is important that the acquired image plane a set correctly. This is occasionally problematic in the case of MRI scans. CT scans overcome imaging errors due to the continuous Z-axis coverage and the post-processing possibilities. Therefore, CT scans offer reliable, high-quality pelvimetry which is clinically usable.[118]

2.3.1.4 Magnetic Resonance Imaging

MRI is a newer modality utilised to assess whether vaginal delivery is possible.[64,115,118,119] MRI provides images of the bony pelvis and surrounding soft tissue in 3D planes. MRI is the imaging modality of choice for maternal pelvic assessments and is preferred to X-rays and computed tomography.

Pelvimetry (measurement of the bony pelvis) may so be performed by MRI and comparison of dimensions made when pelvic disorders are suspected. MRI pelvimetry in females is used to assess pelvic inlet and outlet as an indirect measure of predicting successful vaginal childbirth. Reference values for pivotal dimensions for childbirth have been determined for certain population groups.[50,109]

MRI pelvimetry in males has not been widely researched.[21] However, as MRI provides a non-invasive method to assess pelvic dimensions, it is considered useful in the work-up for pelvic surgery, for example in rectal surgery for rectal cancer.[21]

In clinical applications, MRI pelvimetry has shown a disadvantage in regard to higher inter-observer errors compared to CT scan pelvimetry.[109]

2.3.2 Geometric Morphometrics

Geometric morphometrics is a method by which the shape of rigid 3D morphological structures with curves and bulges can be quantified.[58,110] In this way, morphological characteristics observed, by traditional methods, can be verified.[58,61] The shape is statistically interpretable by using and defining landmarks to describe the 3D space. This type of analysis allows visual identification of the exact areas of the morphological structure that exhibits variations between specimens or groups.[61] In addition to a visual image, values are created that may be statistically compared. Multivariate statistics can then be applied to investigate morphological variations with direct reference to the anatomical context of the structure involved,[110] thus quantifying the morphological characteristics. This allows for more detailed assessment of the specific area in which different morphology is observed between separate skeletons.[120,121]

Geometric morphometrics is based on the analysis of specific standard landmarks on the specimens and by selecting the landmarks representing the shape. The landmarks being identified should be homologous in each specimen being compared. The resulting shape is derived by eliminating the location, size and rotational effects from the landmark configuration of the chosen specimens or set of landmarks. Thus, the morphological shape variations can be visualised.[122]

Each landmark is supplied with a set of three coordinates, *x, y* and *z*. These coordinates are used in the Procrustes analysis to correct for size and position differences before Principal Component Analysis (PCA) is conducted. PCA examines the Principal Component (PC) that reflect variation between specimens. The first two principal components identified are generally the ones with the highest degree of variation in shape. Shape variation may be visualised on a Cartesian transformation grid and on a PCA plot, usually PC1 against PC2.[123]

Geometric morphometric shape analysis of specified areas on the loose os coxae has been used to study sexual differences in pelvic shape.[81,58,110,124] Gonzalez and co-workers,[110] amongst others, found that significant pelvic sexual dimorphism existed and varied among various the population groups.[110,124]

Bonneau and co-workers used geometric morphometrics to compared the shape of fresh articulated pelves to the dry reassembled pelves of the same individuals.[111] Selected landmarks were digitised with the use of a Microscribe® on both wet intact and dry reassembled pelves.[111] The results indicated a significant variation between the dimensions and shape of the dry and articulated pelves. The researchers attributed this variation to the absence of the symphyseal disc in the reassembled dry pelves and secondly to the morphology of the sacroiliac joint.[111]

Problem statement:

By studying the pelvic dimensions using means of four modalities, more clarity regarding uncertainties in some measurements can be reached. The four modalities employed include: direct measurements on intact pelves, CT scans, MRI and geometric shape analysis on the 3D landmarks defined on the intact cadaver pelves for the linear measurements.

It is envisaged that reference values for South Africans may be established and used when decisions are made regarding method of delivery or pelvic and perineal procedures. This study does not only to overcome the paucity in standards for pelvic dimensions in South Africans, but also to examine the influence that the methodology used could have on these measurements.

2.4 Aim

The purpose of this study was to document the shape and size of pivotal dimensions of the pelvic canal in South African individuals of African and European ancestry by means of four modalities. Variations among ancestral groups, sexes, stature and aging were investigated. The possible effects that these variations could have on planned procedures and childbirth were reflected upon.

Research objectives:

1. To analyse defleshed, non-disarticulated pelves of approximately 120 cadavers representative of both sexes and ancestral groups (South Africans of African and European ancestry) for metric and geometric morphometric shape.

2. To repeat pivotal dimensions on approximately 80 MRI scans representative of both sexes and ancestral groups.

3. To repeat pivotal dimensions on approximately 80 pelves CT scanned pelves, representative of both sexes and ancestral groups.

4. To reflect on the variations between measurements derived from cadavers and those derived from MRI and CT measurements.

5. To establish reference values that could be used in obstetric settings, as well as for pelvic and perineal procedures.

3. MATERIALS AND METHODS

Direct linear measurements on intact cadaver pelves, CT scans and MRI were used to assess the variations between sex-ancestral groups. The possible impact that the various modalities could have on the measurements were also considered. Three-dimensional shape variations were further established on intact cadaver pelves by geometric morphometrics. Correlations with stature were made, as the height of an individual has often been considered to be a predictor for method of delivery or outcome of pelvic surgery. Aging has further been reported to have an effect on linear measurements and therefore regression models were created to address this possible interaction as well.

3.1 Materials

The materials used are described in greater detail in the following sections under the headings: intact non-disarticulated pelves and those derived from special investigations: MRI and CT scanning.

3.1.1 Intact non-disarticulated pelves

A total of 121 intact cadaver pelves from the Anatomy Departments of both the University of Pretoria and Sefako Makgatho Health Sciences University (formerly University of Limpopo, Medunsa Campus) were sampled. The sample was representative of both sexes and ancestral groups. For the purpose of this study the sample was subdivided into two ancestral groups: South Africans of African ancestry (SAA) and South Africans of European ancestry (SAE). The SAA group is the main population group to consider when dealing with South African patients as they have long been the inhabitants of South Africa.[125] Although members of SAA are not considered by all to be a homogenous group, the osteological differences were considered too small to justify separation. SAE are primarily descendants of people from the Netherlands, Germany, France, Great Britain and Portugal. Temporal change, Founder's effect and admixture had an effect on the genetic composition of SAE,[3,125,126] differentiating them from both their European and North American counterparts so that they became osteologically distinguishable.[3,66] SAA can also be considered to be osteologically distinguishable from their African and Afro-American counter parts.[127]

The distributions between the groups are detailed in Table 3.1. The sample consisted of 31 SAA males, 25 SAE males, 32 SAA females and 33 SAE females. The ancestral group, age and sex of the cadaveric remains were obtained from the records at both anatomy departments, but kept confidential.

Table 3.1: Distribution of individuals and univariate analysis of ages (in years) and stature (in cm) among sex-ancestral groups

	N	Stature	Age
SAA Females	32	**160.51 cm** (144.93 – 189.07) [9.31]	**35.53 years** (20 – 75) [13.10]
SAA Males	31	**170.33 cm** (160.76 – 189.96) [7.24]	**48.58 years** (19 – 66) [12.66]
SAE Females	33	**165.71 cm** (155.13 – 175.91) [5.31]	**72.53 years** (23 – 99) [17.84]
SAE Males	25	**176.88 cm** (159.90 – 195.87) [8.33]	**68.44 years** (29 – 90) [16.49]
Total	121		

In each set of data:
Mean in **bold**
Minimum and maximum in round brackets ()
Standard deviation in square brackets []

The pelves were previously dissected and partially defleshed without disarticulation. Removing adherent soft tissue without disarticulation of the pelvis facilitated the identification of the bony landmarks and measurements. Pelves demonstrating visible pathology, surgical alteration, skeletal abnormality or deformity were excluded as it could have had an effect on the measurements.[128]

3.1.2 Magnetic Resonance Images and Computed Tomography scans

A total of 77 Magnetic Resonance Images (MRI) and 92 Computed Tomography (CT) scans were sampled retrospectively from the Radiology Department of the Steve Biko Academic Hospital. The sample was representative of both sexes and ancestral groups as previously defined. The sample distribution between the groups is represented in Table 3.2. The MRI sample consisted of 21 SAA males, 20 SAE males, 22 SAA females and 14 SAE females, while the CT sample comprised of 21 SAA males, 27 SAE males, 26 SAA females and 18 SAE females.

Table 3.2: Distribution of both MRI and CT scans among sex-ancestral groups

	MRI		CT scan	
	SAA	**SAE**	**SAA**	**SAE**
Males	21	20	21	27
Females	22	14	26	18
Subtotal	43	34	47	45
Total	77		92	

3.2 Methodology

Apart from the sex, ancestral group and age of the subjects, height was also an important factor that needed to be considered in the variation of pelvic morphology. Height estimations were derived from left femur lengths measured on an osteometric board which was standardised to the nearest millimetre as illustrated in Figure 3.1.

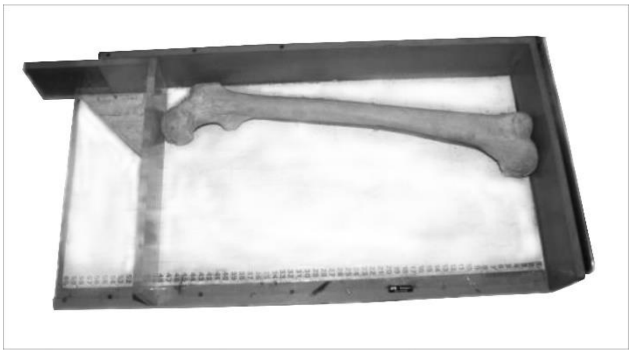


Figure 3.1: Osteometric board with a left femur

The physiological length of the femur (PLF) is the total length of the femur taken on an osteometric board.[129-131] It is measured by using the technique described by Moore-Jenson[132]. This measurement is defined as the maximum distance from the most superior point on the head of the femur to the most inferior point on the distal condyles, when the posterior surface of the femur is placed parallel to the long axis of the osteometric board.[132] The medial and lateral condyles were pressed against the vertical end board, while applying the movable upright board to the femoral head until the maximum length is obtained (Figure 3.1.).

Regression formulae developed by Dayal *et al.*[128] and Lundy and Feldesman[129] are specific for each of the South African ancestral groups, and are not suitable for stature estimation of other ancestral of population groups.[128,129,133]

The height of each specimen was derived by using the methods described by Lundy and Feldesman[129] in the case of SAA, and Dayal *et al.* in the case of SAE (Table 3.3).[128] Fully[133] found that the living stature deviated less than ± 2 cm from the estimated stature.[128,129,133]

The values used for determining stature are derived from the below-mentioned formula (Table 3.3).

TSH: intercept + [PFL x slope] ± SEE

The total skeletal height (TSH) is equal to the intercept plus the PFL in centimetres times the slope, plus or minus the standard error of estimation.

The formula is a symbolic representation straight line of the equation: [$y = mx + c$]

The intercept represents the minimum possible height obtained, while the slope quantifies the steepness of the line. The slope therefore is equal to the change in "*y*" for each unit change in "*x*". The main purpose of the standard error values is to calculate the 95% confidence intervals. Considering the assumptions of linear regression, there is a 95% probability that the 95% confidence interval of the slope contains the true value of the slope, and that the 95% confidence interval for the intercept contains the true value of the intercept.

Table 3.3: Values for the estimation of stature in South Africans

	SAA males[1]	SAA females[1]	SAE males[2]	SAE females[2]
Bone measurement	PLF	PLF	PLF	PLF
Intercept	45.721	27.424	51.17	34.69
Slope	2.403	2.769	2.30	2.64
R	0.896	0.896	0.92	0.93
SEE	2.77	2.789	2.64	2.40

[1]Revised from Lundy and Feldesman[129]
[2]Revised from Dayal *et al.*[128]

Living stature is then calculated by adding Raxter *et al.* value for soft tissue[134] by means of two equations.

First stature equation - If an individual's age is known, the living stature can be calculated by using the following formula:

Stature: 1.009 x TSH (cm) – 0.0426 x age + 12.1

Second stature equation – Age is unknown, calculate the stature by using the following formula:

Stature: 0.996 x TSH (cm) +11.7

3.2.1 Direct linear measurements on intact cadaver pelves

All measurements were taken on intact articulated pelves. Points were marked and measurements between points were taken using a sliding digital calliper and spreading calliper calibrated in millimetres. Points and corresponding measurements were grouped into those pertaining to the pelvic inlet (Table 3.4 and Figures 3.2 and 3.3), midpelvis (Table 3.5 and Figures 3.4 and 3.5), pelvic outlet (Table 3.6 and Figure 3.6), pubic region (Table 3.7 and Figures 3.7 - 3.9), as well as conjugates and dimensions that connect the inlet, outlet and midpelvis (Table 3.8 and Figures 3.10 and 3.11).

Table 3. 4: Pelvic inlet dimensions

Measurement		Description	Figure
API	Anteroposterior dimension of the pelvic inlet (true conjugate)	Most anterosuperior point on sacral promontory to dorsomedial aspect of superior most point on pubic symphysis.	3.2 3.3
TI	Transverse dimension of the pelvic inlet	Maximum distance between iliopectineal lines. This diameter is visually aligned to be perpendicular to the anteroposterior diameter of the inlet	3.3
LIPL	Left Iliopectineal line, straight length	Apex of auricular surface (superoanterior most point on left sacro-iliac joint) to superior most point on dorsomedial aspect of pubic symphysis	3.3
RIPL	Right Iliopectineal line, straight length	Apex of auricular surface (most anterosuperior point on right sacro-iliac joint) to superior most point on dorsomedial aspect of pubic symphysis	3.3

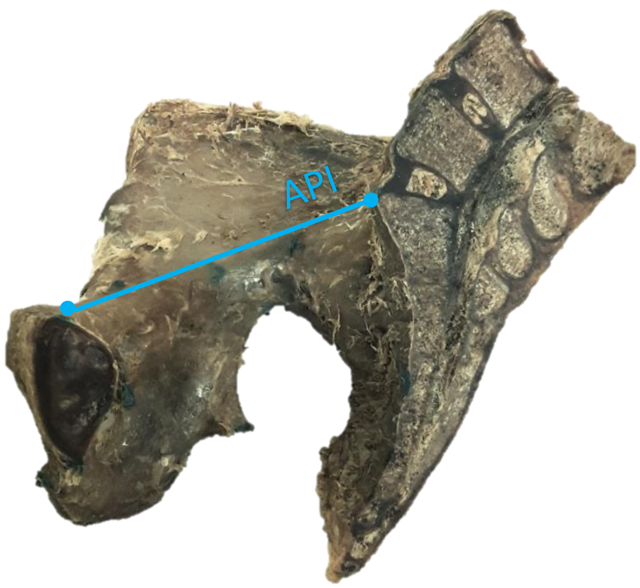


Figure 3.2: Anteroposterior dimension of the pelvic inlet/ true conjugate indicated on a midsagittal section of the pelvis

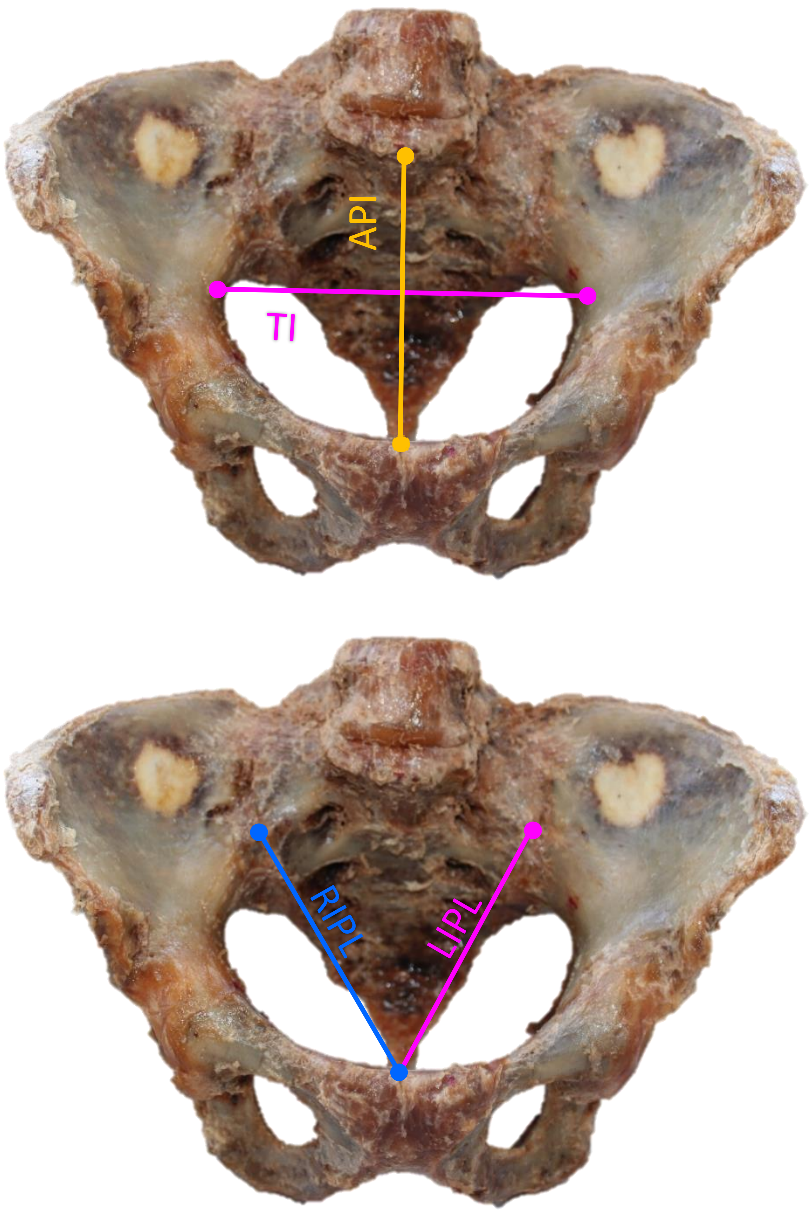


Figure 3.3: Pelvic inlet measurements indicated on the antero-superior view of the intact pelvis

Table 3.5: Midpelvic dimensions

Measurement		Description	Figure
SACHOL	Anteroposterior dimension of the midpelvis	From transverse line between 3rd and 4th sacral vertebrae to most inferior point on dorsomedial aspect of pubic symphysis	3.4
IS	Transverse dimension of the midpelvis, known as interspinous diameter	Distance between tips of the left and right ischial spines	3.5
LOI	Left inlet oblique	Inferior most landmark on right sacroiliac joint to the tip of left ischial spine	3.5
ROI	Right inlet oblique	Inferior most landmark on left sacroiliac joint to the tip of right ischial spine	3.5

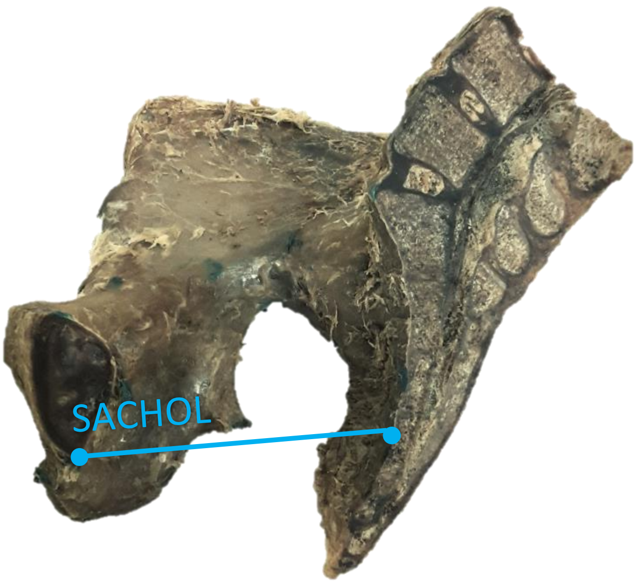


Figure 3.4: Anteroposterior dimension of the midpelvis (SACHOL)

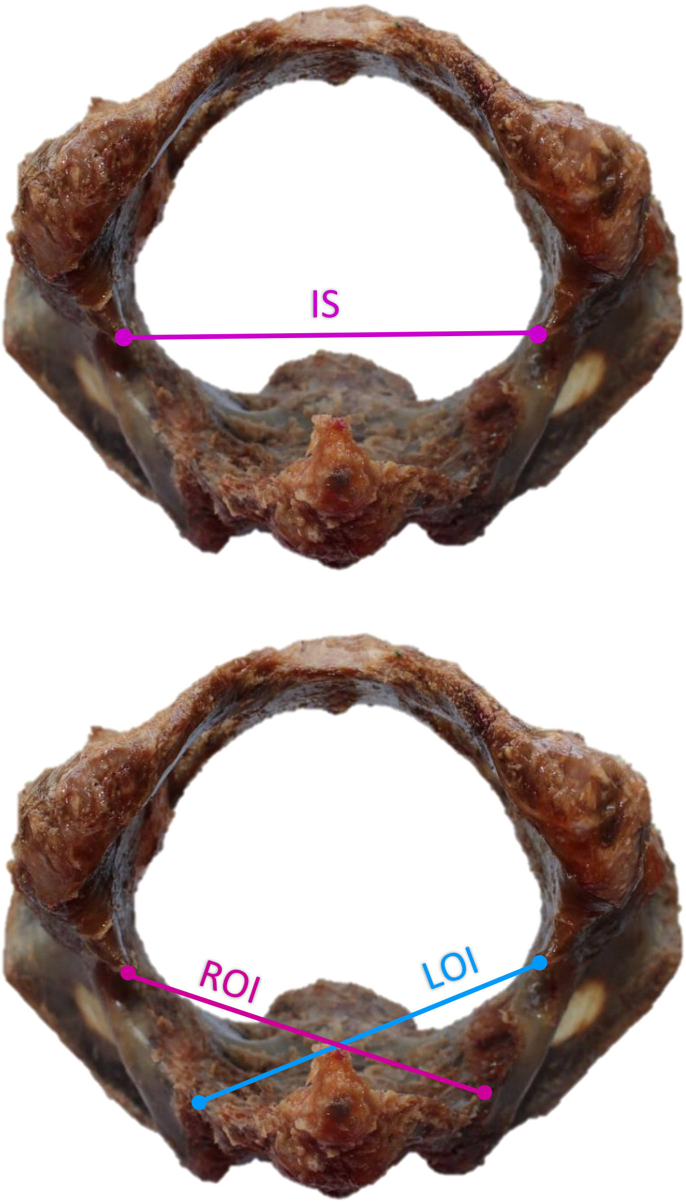


Figure 3.5: Interspinous diameter as well as left and right oblique inlet

Table 3.6: Pelvic outlet

Measurement		Description	Figure
APO	Anteroposterior dimension of the Outlet	Tip of coccyx to most inferior point on the dorsomedial aspect of most inferior point on pubic symphysis	3.6
IT	Transverse dimension of the pelvic outlet, known as the intertuberous diameter	Distance between the most inferior points of the left and right ischial tuberosities	3.6

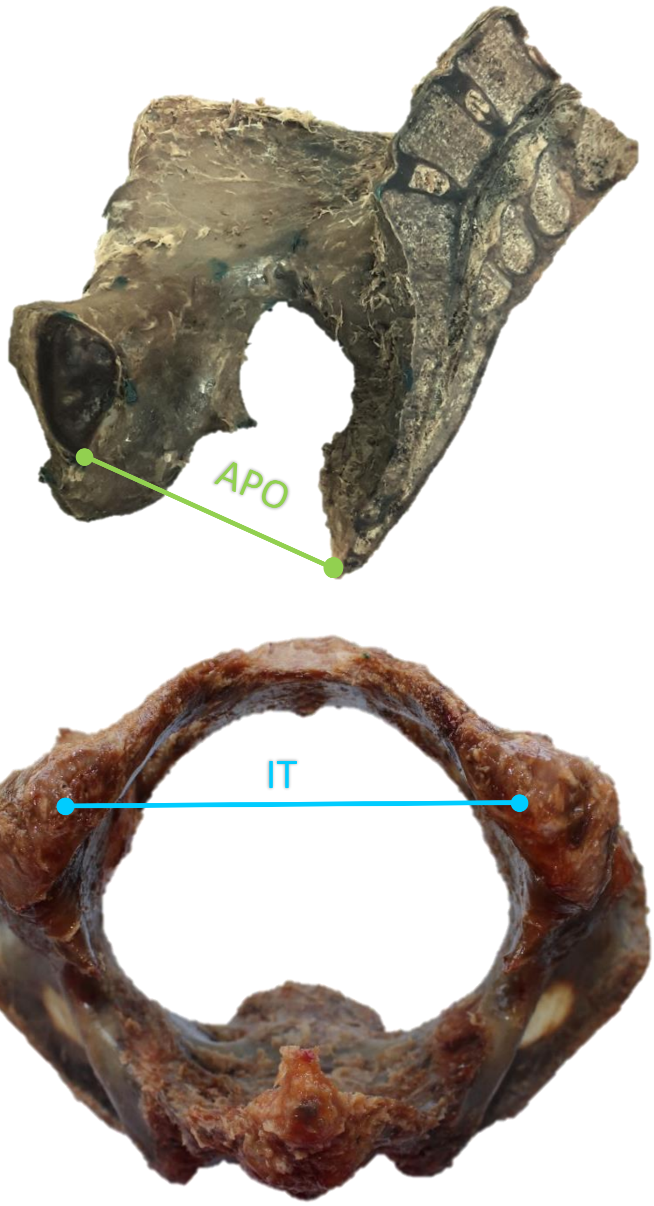


Figure 3.6: Pelvic outlet dimensions on the intact cadaver pelvis

Table 3.7: Measurements involving the pubic region

Measurement		Description	Figure
LIPR_IPS	Triangle bordered by most inferior points on ischiopubic rami and inferior point of the subpubic symphysis.	Inferior most point on left ischiopubic ramus (distinct elevation can be felt) to inferior most point on pubic symphysis	3.7
RIPR_IPS		Most inferior landmark on right ischiopubic rami (distinct elevation can be felt) to most inferior point on pubic symphysis	3.7
LRIPR		Distance between the inferior most landmarks on the left and right ischiopubic rami	3.7
ANG	Subpubic angle	Protractor is placed on anterior surface on top of the pubic symphysis with midpoint (0^0) against inferior most landmark on pubic symphysis. Ruler in direction of ischiopubic ramus	3.7
TDSPS	Transverse diameter of superior pubic symphysis	Maximum transverse diameter between most superomedial points of left and right pubic symphysis	3.7
TDIPS	Transverse diameter Inferior pubic symphysis	Maximum transverse diameter between most inferomedial points of left and right pubic symphysis	3.7
LPS	Maximum length of pubic symphysis	Measured from most superior point on pubic symphysis to the most inferior point on pubic symphysis	3.7

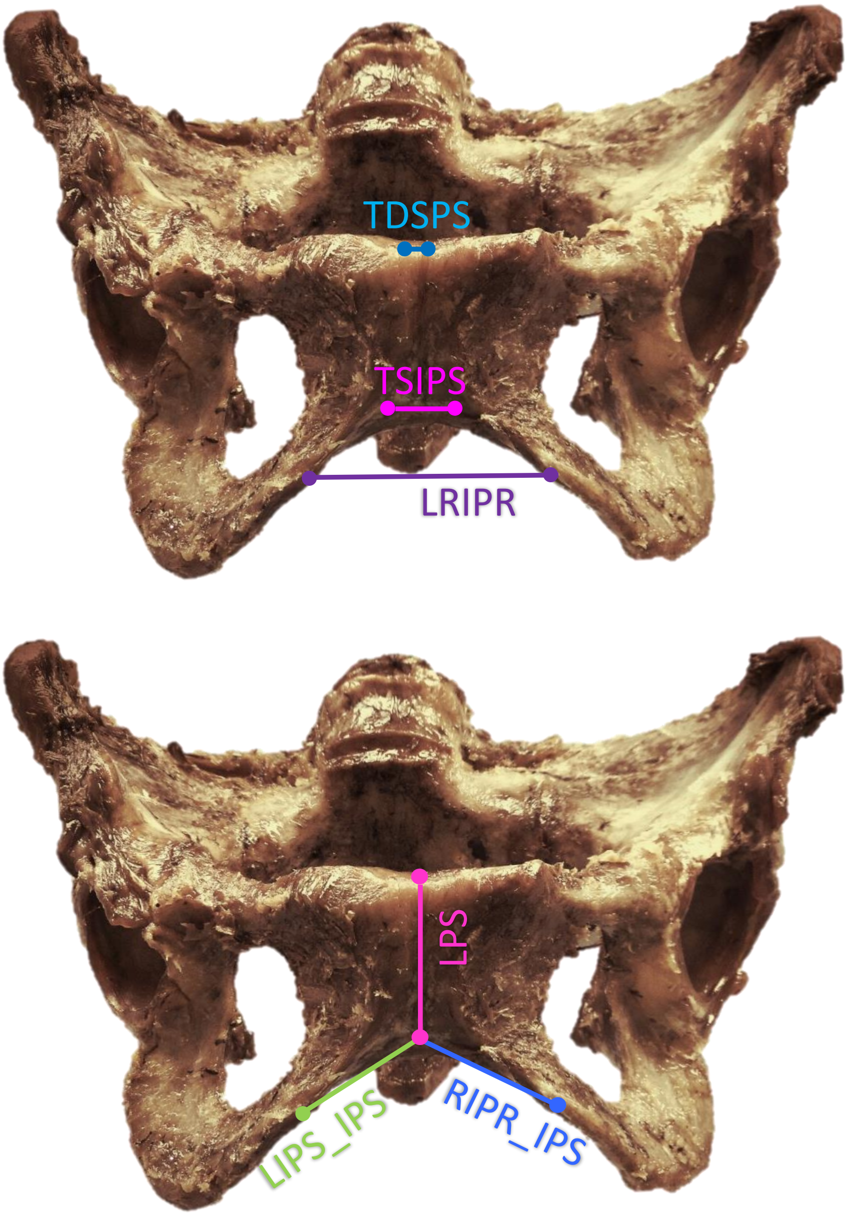


Figure 3.7 Measurements involving the pubic region on an antero-inferior view of the pelvis

Apart from the direct measurement of the subpubic angle by a protractor on the intact cadaver pelves, it was also verified by two mathematical methodologies. These mathematical methods were chosen to evaluate on possible errors of using a protractor to measure the angle manually on an irregular surface and to enable further comparisons to the literature.[27]

The direct measurement, ANG was taken between the medial aspects of the ischiopubic rami, while the wider subpubic angle was mathematically derived from a triangle described between vertices (LIPR, IPS and RIPR) which was used to determine the subpubic angle.

This mathematic calculation of the subpubic angle entailed using basic trigonometry principles of a right angled triangle, which involved relationships of lengths, ratios and angles[135] referred to as ANG. Measurements LIPR_IPS and RIPR_IPS and LRIPR were taken by using a digital sliding calliper (up to two decimal places). Frudinger *et al.* used a similar method in their research studies pertaining to the subpubic angle on perineal and anal sphincter trauma and anal incontinence after parturition.[27]

The first step in the calculation was to determine the half of the pelvic outlet LRIPR and the length of the inferior pubic rami (LIPS_IPS and RIPR_IPS), which stretches from the inferior pubic symphysis to the distinct elevation on the ischiopubic rami. The ratio gives the sine of half the subpubic angle. In the calculation of the subpubic angle (θ) it was assumed that the two inferior pubic rami were not equal to each other and therefore is composed of two possibly dissimilar angles: α_1 and α_2. The mathematical definition of each angle can be found in the following equations:

$$\alpha_1 = 2sin\left(\frac{a/2}{b}\right)$$

$$\alpha_2 = 2sin\left(\frac{a/2}{c}\right)$$

That the angle, therefore, is:

$$\theta = \alpha_1 + \alpha_2$$

$$b \neq c$$

<u>Legend:</u> a = LRIPR; b = LIPR_IPS; c = RIPR_IPS (Figure 3.8)

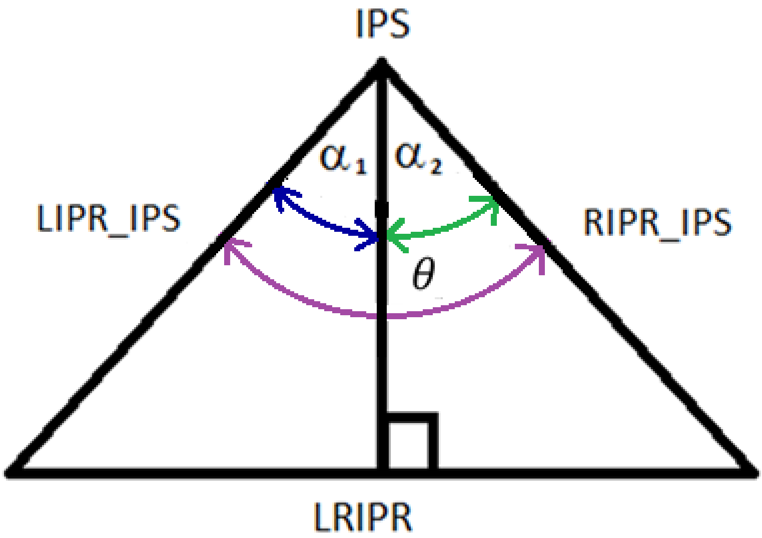


Figure 3.8: Measurements involving the mathematical calculation of the subpubic angle ($\boldsymbol{\theta}$)

The second methodology to verify the subpubic angle entailed the use of the xyz coordinates of the 3D points digitised on the vertices of two created triangles (Figure 3.9). The first subpubic triangle was created with the vertices LIPR, IPS and RIPR, while the second, urogenital triangle was created with the vertices LIIT, IPS and RIIT. These xyz coordinates were used to calculate angles at the most inferior point on the pubic symphysis. The first triangle or subpubic triangle was created between the two most inferior landmarks on the left and right ischiopubic rami (LIPR_and RIPR) respectively, to the inferior most point of the pubic symphysis. The second triangle or urogenital triangle was created between the two most inferior landmarks on the left and right ischial tuberosity (LIIT and RIIT) respectively, to the inferior most point of the pubic symphysis.

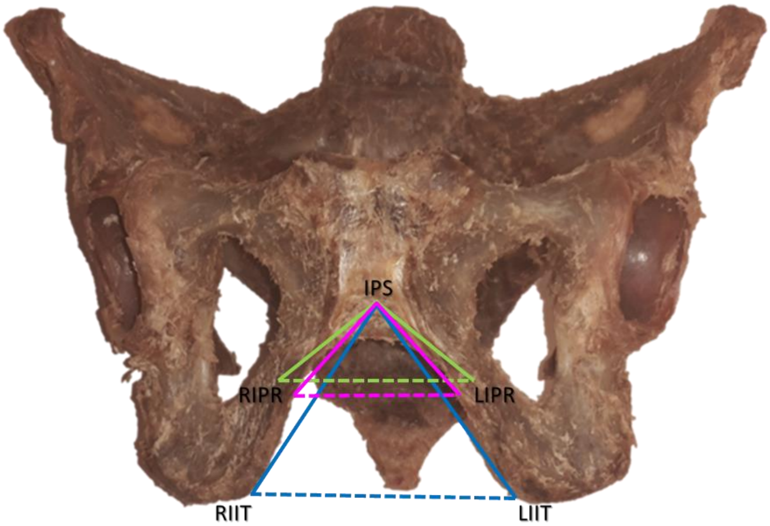


Figure 3.9: Three dimensional digitised vertices on the pubic region on an antero-inferior view of the pelvis

Table 3.8: Dimensions connecting the pelvic inlet, pelvic outlet, midpelvis and conjugates

Measurement		**Description**	**Figure**
SL	Sacral length	The most anterosuperior point on the sacral promontory to tip of the coccyx	3.10
LDTP	Left depth of true pelvis	The apex of the left auricular surface (most anterosuperior landmark on left sacro-iliac joint) to the most inferior point on left ischial tuberosity	-
RDTP	Right depth of true pelvis	The right apex of the auricular surface (most anterosuperior landmark on right sacro-iliac joint) to most inferior point on left ischial tuberosity	3.10
LHTP	Left height of the pelvis	Left iliopubic eminence (most medial point) approximately perpendicular to the lowest point of the left ischial tuberosity	-
RHTP	Right height of the pelvis	Right iliopubic eminence (most medial point) approximately perpendicular to the lowest point of the right ischial tuberosity	3.10
OBS_CONJ	Obstetric conjugate	Midpoint of the pubic symphysis to the most anterosuperior r point on sacral promontory	3.11
DIA_CONJ	Diagonal conjugate	Most inferior point on pubic symphysis to the most anterosuperior point on sacral promontory	3.11

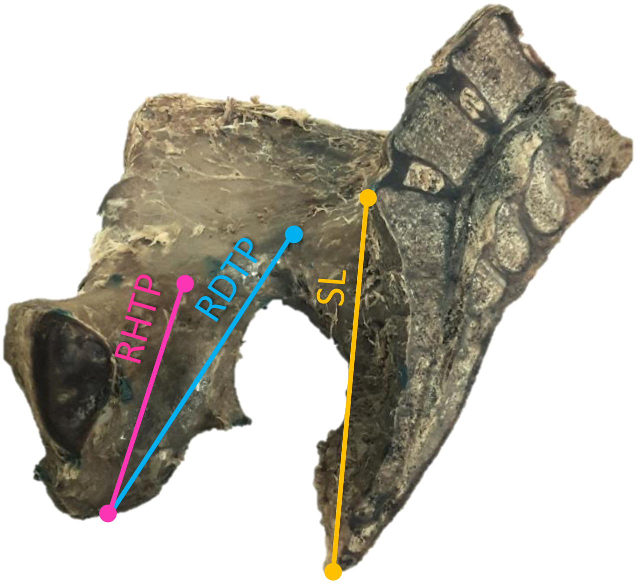


Figure 3.10: Measurements that connect the three pelvic planes demonstrated on the right side of a midsagittal section of an intact cadaver pelvis

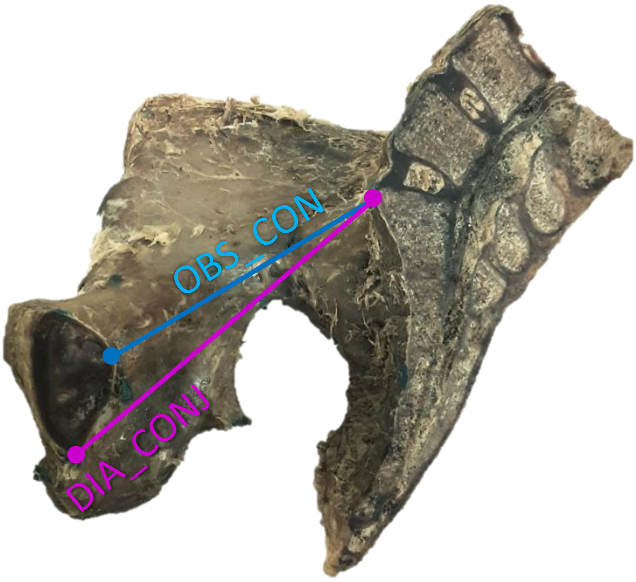


Figure 3.11: Diagonal and Obstetric conjugate demonstrated on the right side of a midsagittal section of an intact cadaver pelvis

3.2.2 Dimensions on MRI and CT scans

All selected dimensions were based on the measurements used in Handa *et al.*[64] are given in Table 3.9 and Figures 3.12 and 3.13.

Table 3.9: Measurements taken on MRI and CT scans

	Measurement	Description	Figure
API	Anteroposterior pelvic inlet/ True conjugate	The distance from the superior point of the pubic symphysis to superior point of the sacral promontory. Measurements is taken on a sagittal plane.	3.12
TI	Transverse inlet diameter (coronal view)	The greatest distance between the medial aspects of the arcuate lines. Measurement will be taken in a trans axial plane.	3.12
APO	Anteroposterior pelvic outlet/ pubococcygeal line	The distance from the superior most point of the pubic symphysis to the midpoint of the last vertebral joint the coccyx. Measurement is be taken in a sagittal plane.	3.12
IS	Interspinous distance	The distance between the left and right ischial spines. Measurement is taken in an axial plane.	3.13
IT	Intertuberous distance	The distance between the left and right ischial tuberosities. Measurement is taken in an axial plane.	3.13
SACHOL	Depth of sacral hollow	The distance from the most inferior point of the pubic symphysis to the sacral hollow at the level of the ischial spines, between the 3rd and 4th sacral vertebra.	3.12
SL	Length of sacrum	The distance of the sacral promontory to the tip of the coccyx. Measurement is taken in the midsagittal plane.	3.12
ANG	Subpubic angle	The angle will be measured with the pubic symphysis as the apex. Measurement is taken on a coronal view in degrees.	3.13

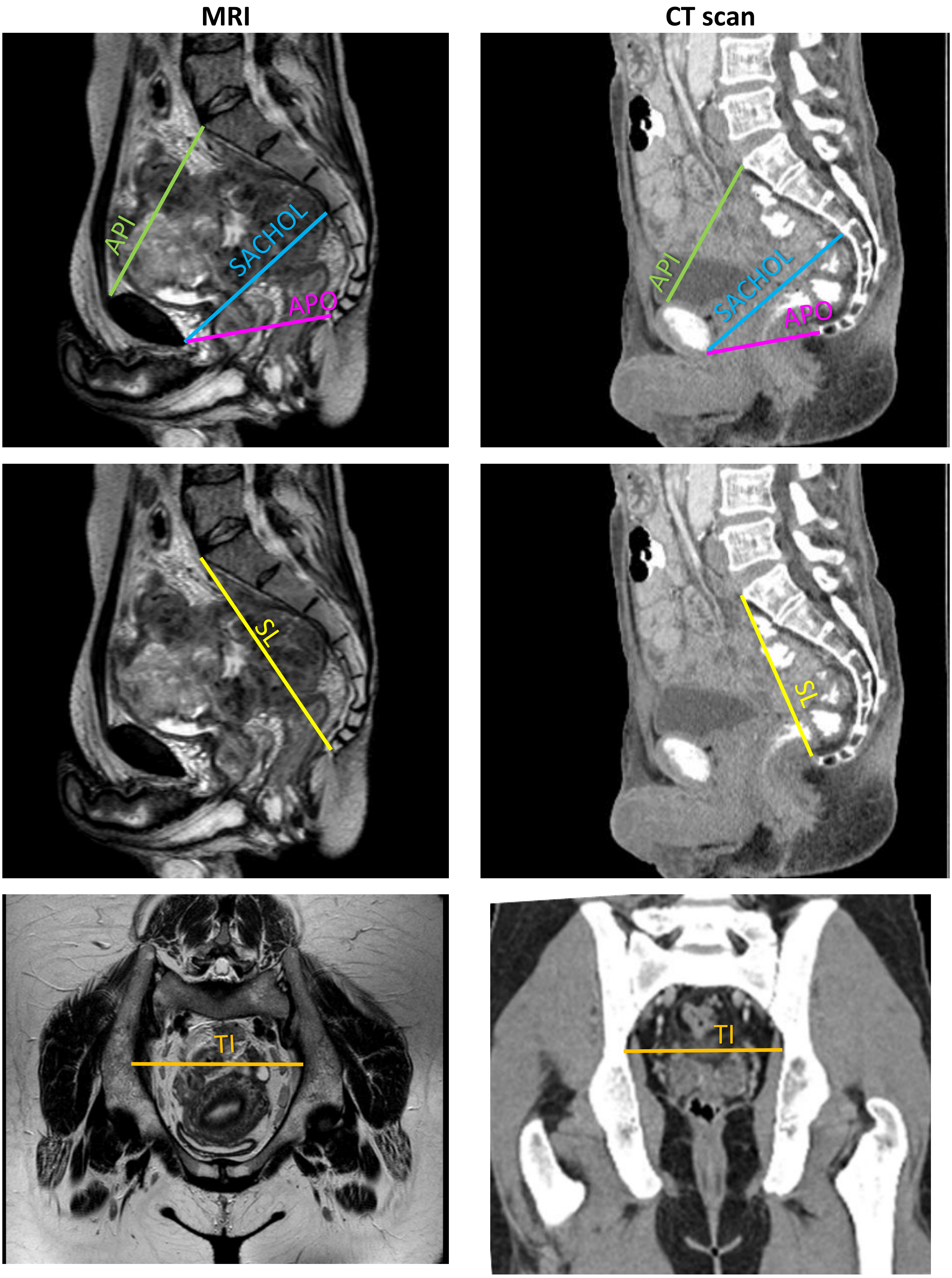


Figure 3.12: Comparison of measurements taken on MRI (left) and CT scan (right) (different subjects)

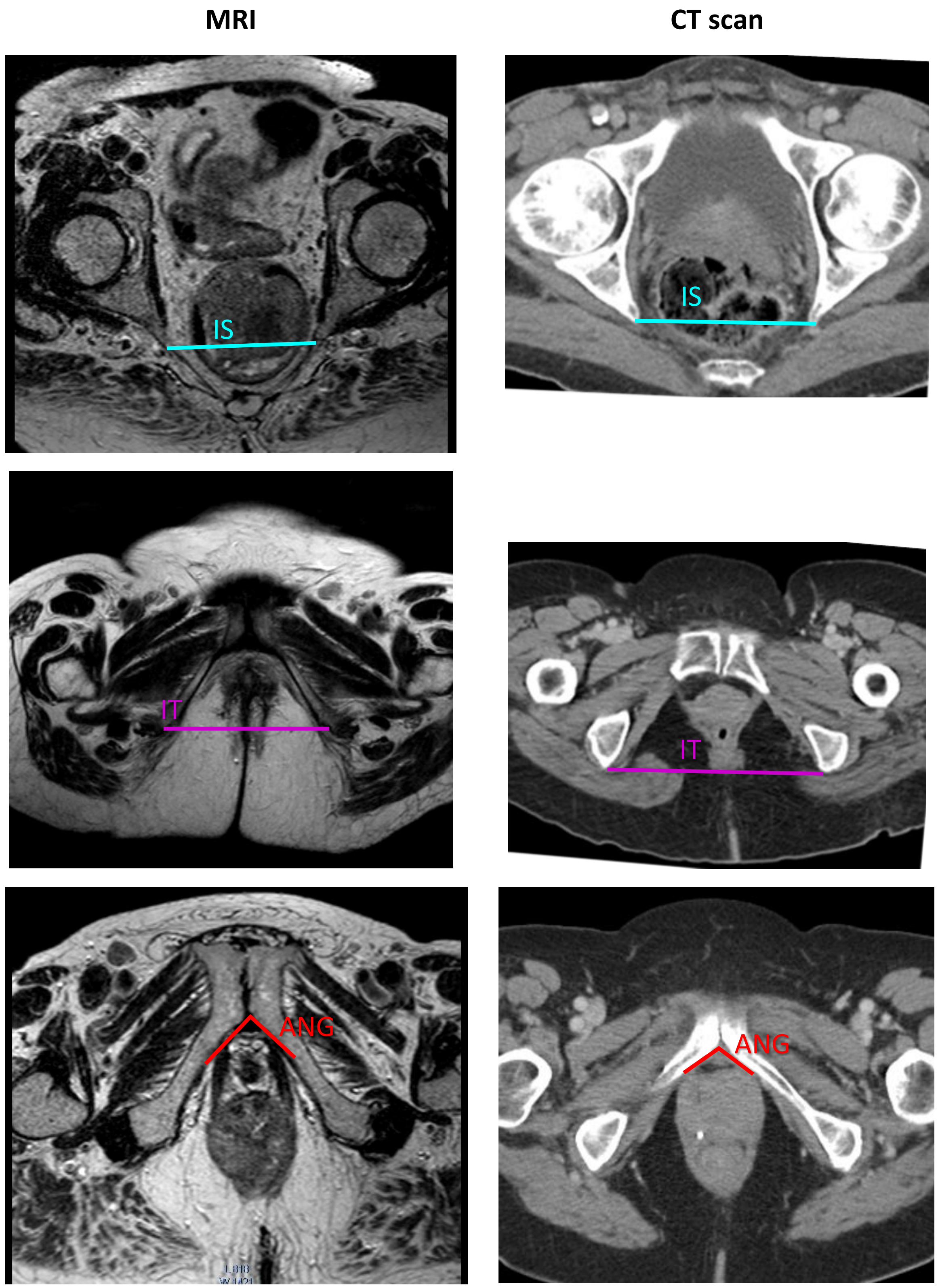


Figure 3.13: Comparison of MRI (left) and CT scan (right) measurements (different subjects)

3.2.3 Shape analysis on intact cadaver pelves

Geometric morphometrics is a method by which the shape of rigid 3D morphological structures with curves and bulges can be quantified. The shape is statistically interpretable by using and defining landmarks to describe the 3D space.[110] The analysis allows visual identification of the exact areas of the morphological structure that causes variations between specimens or groups.[61] In addition to a visual image, values are created that can be statistically compared. Multivariate statistics can be applied to investigate morphological variations with direct reference to the anatomical context of the structure involved.

Selected landmarks for shape analysis were digitised with the use of a 3DXL MicroScribe® digitiser on intact non-disarticulated pelves (Figure 3.14). The 3DXL MicroScribe® digitiser is a registered trademark of the Immersion Corporation. It delivers spatial information regarding a 3D object to a computer system. The x, y and z coordinates of each 3D landmark are imported to the connected computer in an Excel spreadsheet. Thereafter shape analysis was performed on all the non-disarticulated cadaver pelves, by means of a free software package, Morphologika2 v2.5.[7,80]

Figure 3.14: 3DXL MicroScribe® digitiser pointing to a bony landmark

The landmarks were grouped into those pertaining to the pelvic inlet, midpelvis, pelvic outlet, pubic region and the pelvic canal. A generalised full Procrustes analysis was performed. By means of the Procrustes analyses the effects of size, rotation and translation are eradicated so that the landmarks of each specimen can be superimposed for assessment of shape variations between groups.[80,136]

The distributions of variances were plotted for principal component 1 (PC 1) versus principal component 2 (PC 2) to visually evaluate the scattering patterns amongst the groups. Demonstration of the mean shape by wireframe images for the pelvic inlet, midpelvis, pelvic outlet, pubic region and the pelvic canal were further used to confirm impressions from the scattering patterns.

After visual representation of the PC1 and PC2 in Morphologika2 v2.5, PAST (PAleontological STatistics v1.92)[137] was used to test for statistical significant differences between pelvic shape variations among the sex-ancestral groups.[137]

3.2.3.1 Selected bony landmarks

All landmarks were identified and marked in the standard anatomical position. Points for shape analysis and associated wireframe connectors were grouped into those pertaining to the pelvic inlet (Table 3.10 and Figure 3.15), midpelvis (Table 3.11 and Figure 3.16), pelvic outlet (Table 3.12 and Figure 3.17), pubic region (Figure 3.18) and lastly, all landmarks were connected to appreciate the entire pelvic cavity (Figure 3.19).

Table 3.10: Pelvic inlet landmarks

	Landmark	Description
SPR	Sacral promontory	Most anterosuperior point on sacral promontory in midsagittal plane[78,111,130,138]
LSSIJ	Left sacro-iliac joint	Most anterosuperior point at the junction of the sacrum and ilium[111,139,140], where the arcuate line meets the auricular surface[78,138]
LAL	Left arcuate line	Point of maximum curvature of the arcuate line of the ilium on the left. Bilateral landmarks delineate the greatest transverse diameter of the pelvic inlet[78,130,138]
LIE	Left iliopubic eminence	Most medial point on the iliopubic eminence where the arcuate and pectinate lines meet[139,140]
SPS	Pubic symphysis	Most superior point on the medial aspect of pubic symphysis[78,111,130,139,140]
RIE	Right iliopubic eminence	Most medial point of the iliopubic eminence where the arcuate and pectinate lines meet [139,140]
RAL	Right arcualte line	Point of maximum curvature of the arcuate line of the ilium on the right (most lateral point)
RSSIJ	Right sacro-iliac joint	Most anterosuperior point at the junction of the sacrum and ilium[139], where the arcuate line meets the auricular surface[78,138]

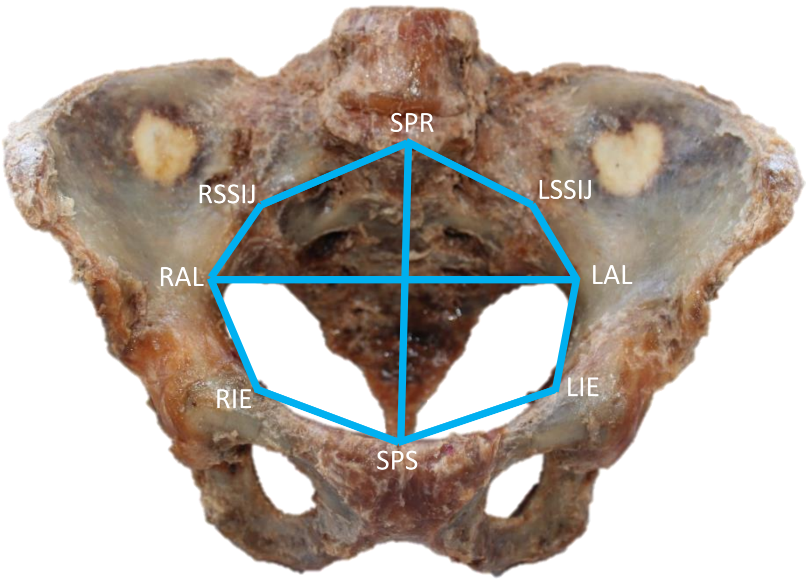


Figure 3.15: Pelvic inlet wireframe connecting pelvic inlet landmarks

Table 3.11: Midpelvic landmarks

	Landmark	Description
S3/4	Sacral 3/4 joint	Midpoint on junction of sacral joints 3/4 in midsagittal plane[111]
LISIJ	Left sacro-iliac joint	Most inferior point at the junction of the sacrum and ilium[111]
LGSN	Left greater sciatic notch	Point of maximum curvature in the greater sciatic notch[58,78]
LIS	Left iliac spine	Tip of the ischial spine [78,111,130,138,139]
LPOF	Left posterior obturator foramen	Most posterior landmark located between the two posterior obturator tubercles along the posterior margin of the obturator foramen on the left[78,139]
LAOF	Left anterior border obturator foramen	Most anterior landmark located on the anterior border of the obturator foramen[139] on the left or the centre of inflection on the anterior margin of the obturator foramen[78]
MPS	Mid pubic symphysis point	Midpoint landmark on the posterior aspect of pubic symphysis. The most prominent point in the dorsomedial surface of the pubic symphysis[130]
RAOF	Right anterior border obturator foramen	Most anterior landmark on the border of the obturator foramen[139] on the right or the centre of inflection on the anterior margin of the obturator foramen[78]
RPOF	Right posterior border obturator foramen	Most posterior landmark located between the two posterior obturator tubercles along the posterior margin of the obturator foramen on the right[78,139]
RIS	Right Ischial spine	Tip of the ischial spine[78,111,130,139]
RSGN	Right Greater sciatic notch	Point of maximum curvature in the greater sciatic notch[58,78]
RISIJ	Right Sacro-iliac joint	Inferior most point at the junction of the sacrum and ilium[111]

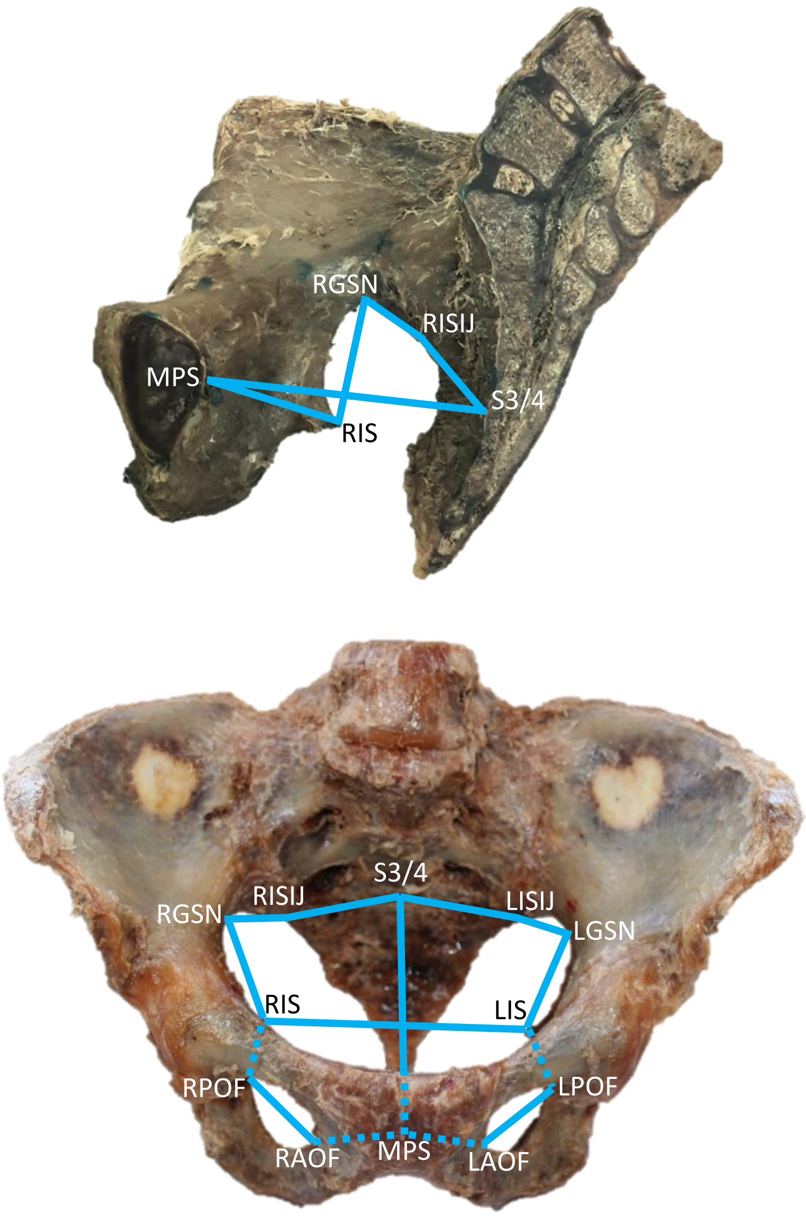


Figure 3.16: Midpelvic wireframe connecting midpelvic landmarks

Table 3.12: Pelvic outlet parameters

	Landmark	Description
COC	Tip of coccyx	Most inferior point on the tip of the coccyx[138]
LIIT	Left inferior end of ischial tuberosity	Most inferior point on the ischial tuberosity[129,138,139]
LIPR	Left ischiopubic ramus	Most inferior point on the ischiopubic ramus[111,138]. When sweeping one's finger across the area, a distinct elevation will be felt.
IPS	Inferior point on Pubic symphysis	Most inferior point in the midline of the medial surface of pubic symphysis.[78,111,130,138,139]
RIRP	Right ischiopubic ramus	Most inferior point on the ischiopubic ramus. When sweeping one's finger across the area, a distinct elevation will be felt.[111,138]
RIIT	Right inferior end of ischial tuberosity	Most inferior point on the ischial tuberosity[130,138,139]

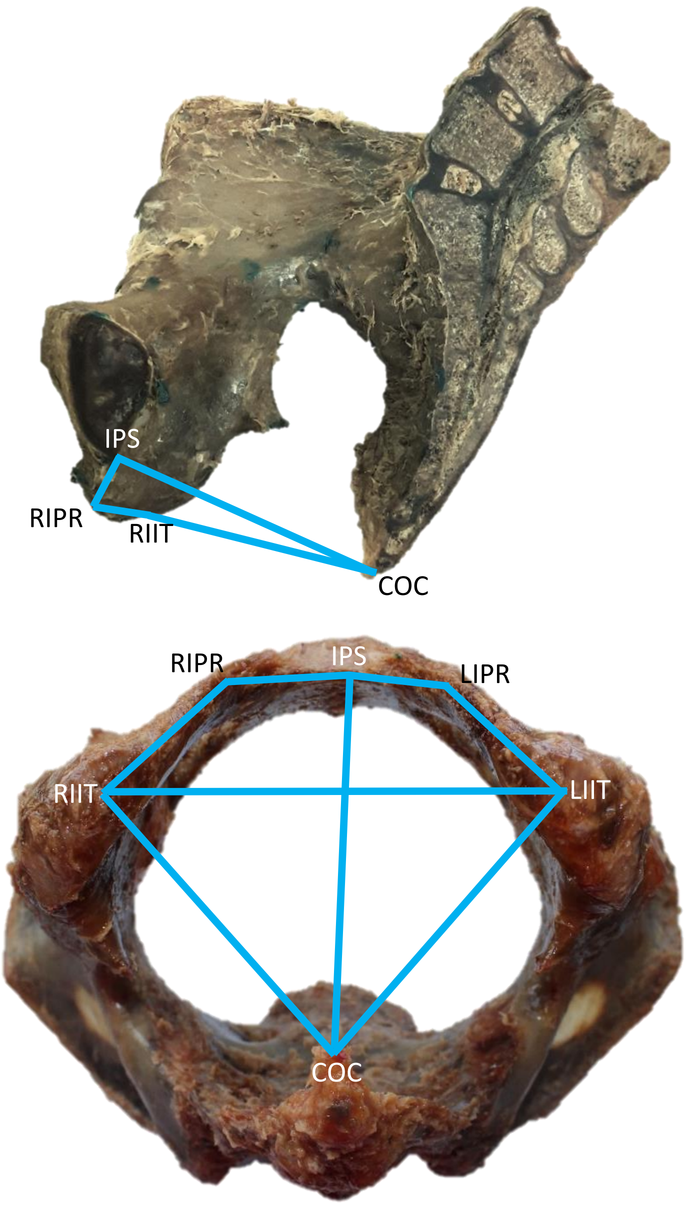


Figure 3.17: Pelvic outlet wireframe connecting pelvic outlet landmarks

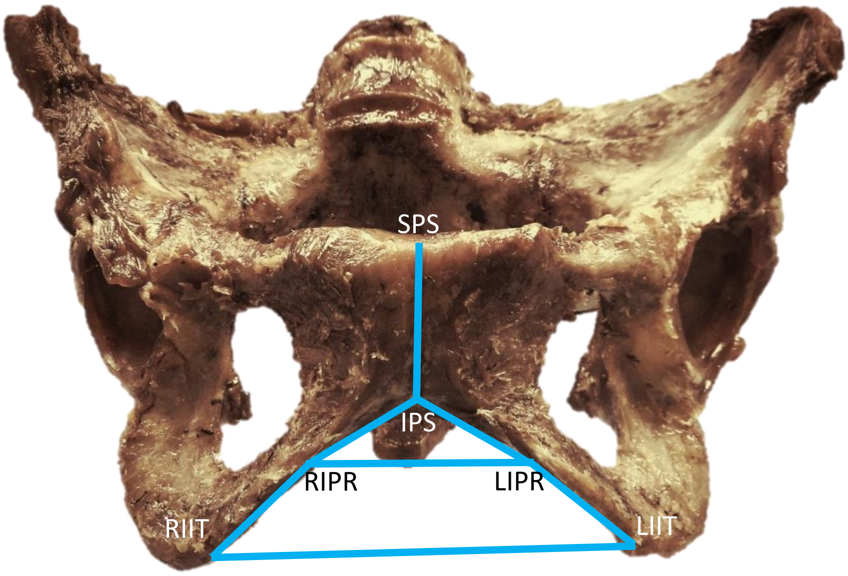


Figure 3.18: Pubic region wireframe connecting pubic region landmarks

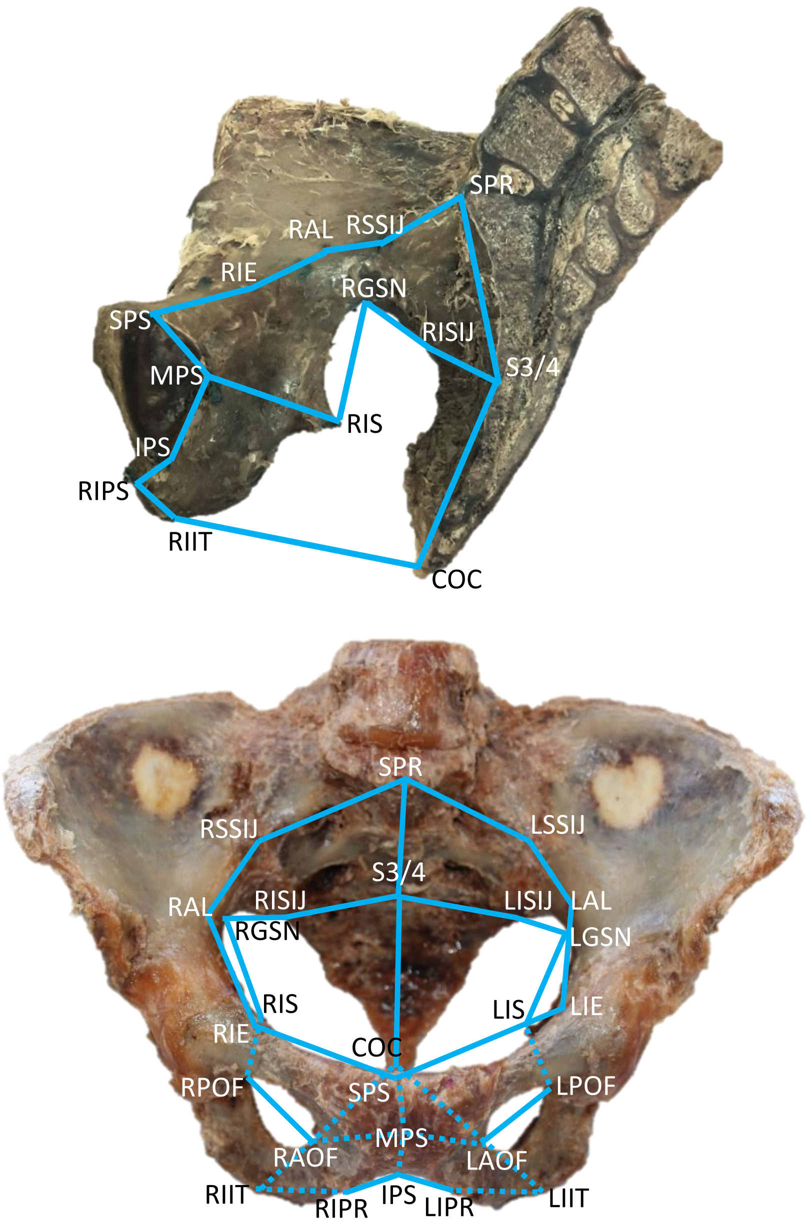


Figure 3.19: Pelvic canal wireframe connecting all landmarks

3.3 Statistical analysis of measurements taken

Various statistical analyses underpinned this study. The first phase of analysis involved the calculation and presentation of the descriptive statistics such as means and standard deviations for linear measurements taken. These statistics may provide important reference values for practitioners. Where relevant confidence intervals are also presented, it was assumed that the underlying distributions of measurements would conform to a normal distribution (i.e. assuming central limit theorem for n > 30). Results were reported by demographic group (SAE males, SAE females, SAA males, SAA females), with the aim of explaining variation in the data.

In the case of shape analyses, multivariate statistical analyses were performed on the principal components of shape variation of each feature. Statistical significance of these variations could so be assessed amongst sex and ancestral group or combinations of these groups in the sample.

A second phase of analyses involved the application of various ANOVA models in order to test the effects of height and age as covariate factors. Interactions between factors, as well as the effects of individual factors, were investigated.

Least square means regressions were performed on each pelvic measurement with aging and stature as independent variables, as well as for the variation in pelvic shape for each sex-ancestral group in isolation (females SAE, males SAE, females SAA, males SAA). The statistical analyses for the shape variation were performed using the R-package: geomorph.[141,142] The correlation coefficient (r) and coefficient of determination (r^2) were calculated to measure the strength and direction of the linear relationship. A correlation coefficient may range from -1 to a perfect negative relationship and +1 for a perfect positive relationship between variables. The percentage of variance (r^2) refers to the proportion of variance explained by the linear relationship between the particular dimension and age. The main purpose of finding a relationship is that the knowledge of the relationship may enable events to be predicted to a specified degree.

Lastly, ANOVA was used to test for significant differences in measurements between modalities and ancestral-sex groups.

3.4 Ethical considerations

The skeletal material originates from two sources, namely donations and unclaimed bodies. In South Africa, under the National Health Act No. 61 of 2003, anyone may donate his/her body for tissue transplants, medical training and/or research. This act also provides for any destitute individual who dies in a public hospital to have the body donated. If an individual dies in a public institution and is not removed for burial by a spouse, a relative or a friend within 24 hours after death, the body may be handed over to an institution such as a university for the purpose of medical research. The body is registered as unclaimed, even though the identity of the individual may be known. Alternatively, an individual can register as a 'whole body' donor at the Tissue Bank of the Faculty of Health Sciences at the University of Pretoria, prior to death. After death, a spouse or family member is also permitted to donate the body, provided that the deceased did not specifically state that his/her body is not to be donated. Donated bodies of individuals over 65 years of age, or individuals who had a disease (such as cancer) cannot be used for tissue transplants. These bodies are automatically handed over to the Department of Anatomy for medical training and research.[143]

Ethical approval from the Research Committee of the Faculty of Health Sciences of the University of Pretoria was obtained for this MSc degree (Protocol no: 502/2014), titled: 'Four modalities in the evaluation of the pelvic canal in South Africans'.

4. RESULTS

The dimensions of the pelves in four sex-ancestral groups were recorded. Basic descriptive statistics (i.e. the mean, standard deviation (SD), range and 95% confidence intervals) of all the data were performed. Statistical comparisons of parameters were made between the various sex-ancestral groups and correlated to stature and age, using one-way ANOVA. The broad application of these data was to possibly link the stature of the individuals within these groups to various pelvic dimensions and to examine the effect of aging. Shape analysis was also considered for each of the groups.

4.1 Measurements on intact cadaver pelves

Measurements on the intact cadaver pelves were grouped into those pertaining to the pelvic inlet, midpelvis and pelvic outlet for analytic purposes.

4.1.1 Pelvic inlet

The measurements that pertain to the pelvic inlet comprise the anteroposterior inlet diameter (API), transverse inlet diameter (TI), left iliopectineal line (LIPL) and the right iliopectineal line (RIPL) as seen in (Figures 3.2 and 3.3). In Table 4.1 the descriptive statistics of the pelvic inlet measurements between sex-ancestral groups are given. All pelvic inlet measurements were the greatest in SAE female, followed by SAE male and SAA female. The smallest measurements were found in SAA male. API demonstrated statistically significant differences between ancestral groups and sexes. TI, LIPL and RIPL demonstrated statistical significant differences between ancestral groups and between the sexes in SAE individuals, but not in SAA individuals. All pelvic inlet measurements were statistically significantly greater in SAE female than all other sex-ancestral groups. The pelvic inlet shape was therefore statistically significantly greater in all directions than in the other sex-ancestral groups. SAA female had statistically significantly greater pelvic inlet anteroposterior diameter than in males, but the transverse diameter was not significantly greater.

Table 4. 1 Descriptive statistics of pelvic inlet measurements in the sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N=32	N=31	N=33	N=25
API	**110.17** [b e]	**102.35** [a c e]	**124.67** [a b d]	**114.02** [c d]
	9.82	11.30	11.90	10.32
	(91.29-133.93)	(74.17-120.96)	(77.72-141.08)	(90.79-133.27)
	[106.63-113.71]	[98.20-106.49]	[120.45-128.89]	[109.76-118.28]
TI	**116.15** [g]	**112.39** [f h]	**133.09** [f g i]	**126.32** [h i]
	9.68	6.78	8.69	7.82
	(91.29-137.32)	(99.75-131.09)	(118.35-151.4)	(107.99-138.74)
	[112.66-119.64]	[109.91-114.88]	[130.02-136.16]	[123.09-129.55]
LIPL	**115.12** [m n o]	**106.81** [k l n]	**126.56** [k m]	**121.39** [l o]
	8.04	7.45	8.63	8.53
	(96.15-133.52)	(91.41-121.18)	(98.22-145.15)	(96.63-134.55)
	[112.23-118.02]	[104.07-109.54]	[123.50-129.62]	[117.88-124.91]
RIPL	**115.11** [r s t]	**109.07** [p q t]	**127.15** [p r]	**122.39** [q s]
	8.25	7.61	8.74	8.89
	(95.42-135.12)	(91.71-124.46)	(98.21-143.73)	(97.25-133.18)
	[112.13-118.08]	[106.28-111.87]	[124.05-130.25]	[118.72-126.06]

N=number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] p < 0.0001	[f] p <0.0001	[k] p < 0.0001	[p] p < 0.0001
[b] p < 0.0001	[g] p <0.0001	[l] p < 0.0001	[q] p < 0.0001
[c] p = 0.0007	[h] p <0.0001	[m] p < 0.0001	[r] p < 0.0001
[d] p = 0.0020	[i] p <0.0001	[n] p = 0.0005	[s] p = 0.0079
[e] p = 0.0263	[j] p :0.0145	[o] p = 0.0242	[t] p = 0.0255

4.1.2 Midpelvic landmarks

The measurements that pertain to the midpelvis include anteroposterior midpelvis diameter (SACHOL), interspinous diameter (IS), left oblique inlet (LOI) and right oblique inlet (ROI), (Figures 3.4 and 3.5). In Table 4.2, the descriptive statistics of the midpelvis measurements between sex-ancestral groups are given.

All midpelvic measurements were the greatest in SAE female, followed by SAE male and SAA female, apart from IS. The smallest measurements were found in SAA male. IS was the greatest in SAE female followed by SAA female, SAE male and then SAA male. SACHOL demonstrated statistically significant differences between ancestral groups, but not between the sexes. IS, LOI and ROI demonstrated statistical significant differences between ancestral groups and between sexes. All midpelvic measurements were statistically significantly greater in SAE individuals than in SAA individuals. The midpelvis was therefore statistically significantly greater in all directions in SAE individuals than in SAA individuals. In addition, the transverse and oblique midpelvic diameters were statistically significantly greater in females and in SAE individuals.

Table 4.2: Descriptive statistics of the midpelvic measurements in the sex-ancestral groups

	African Ancestral group		**European Ancestral group**	
	Females	**Males**	**Females**	**Males**
	N=32	N=31	N=33	N=25
SACHOL	**119.50**[c]	**111.61**[a,b]	**132.51**[a,c]	**128.66**[b]
	10.56	7.76	11.20	9.10
	(101.06-143.66)	(96.46-127.63)	(99.78-155.22)	(111.52-154.49)
	[115.69-123.31]	[108.76-114.46]	[128.53-136.48]	[123.69-133.74]
IS	**95.83** [f,g,h]	**81.91** [d,f,i]	**106.01** [d,e,g]	**88.74** [e,h,i]
	10.40	8.43	10.50	7.51
	(70.79-120.54)	(69.1-109.14)	(80.02-133.97)	(74.91-103.77)
	[92.09-99.58]	[78.81-85.00]	[102.27-109.73]	[85.63-91.84]
LOI	**106.26** [l,m,o]	**98.15** [j,k,m]	**117.93** [j,l,n]	**111.95** [k,n,o]
	8.41	5.61	8.42	8.62
	(89.37-119.67)	(87.09-109.29)	(99.07-136.27)	(91.94-126.82)
	[103.23-109.29]	[96.10-100.21]	[114.94-120.91]	[108.40-115.51]
ROI	**106.34** [r,s]	**98.40** [p,q,s]	**116.38** [p,r,t]	**109.64** [q,t]
	7.78	4.74	7.55	7.31
	(88.24-118.6)	(89.41-108.47)	(100.05-129.63)	(94.16-122.2)
	[103.53-109.14]	[96.66-100.13]	[113.71-119.06]	[106.63-112.67]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p < 0.0001$	[f] $p < 0.0001$	[k] $p < 0.0001$	[p] $p < 0.0001$
[b] $p = 0.0056$	[g] $p = 0.0002$	[l] $p < 0.0001$	[q] $p < 0.0001$
[c] $p = 0.0023$	[h] $p = 0.0280$	[m] $p = 0.0004$	[r] $p < 0.0001$
[d] $p < 0.0001$	[i] $p = 0.0395$	[n] $p = 0.0246$	[s] $p < 0.0001$
[e] $p < 0.0001$	[j] $p < 0.0001$	[o] $p = 0.0371$	[t] $p < 0.0022$

4.1.3 Pelvic outlet

The measurements that pertain to the pelvic outlet include the anteroposterior outlet diameter (APO) and intertuberous diameter (IT), as seen in Figure 3.6. In Table 4.3 the descriptive statistics of the pelvic outlet measurements between sex-ancestral groups are given. The pelvic outlet measurements in SAE individuals and females were statistically significantly greater than in SAA individuals and males, with the greatest measurements in female SAE.

Table 4.3: Descriptive statistics of the pelvic outlet measurements in the sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 32	N = 31	N = 33	N = 25
APO	**88.59** [b e]	**79.76** [a b c]	**95.79** [a d e]	**88.51** [c d]
	9.37	8.37	13.74	7.23
	(74.35-111.09)	(65.94-103.64)	(70.26-129.23)	(77.46-103.38)
	[85.21-91.97]	[76.69-82.83]	[90.91-100.66]	[85.53-91.50]
IT	**88.04** [h i]	**71.52** [f h j]	**99.15** [f g i]	**81.66** [g j]
	12.80	14.05	14.86	8.63
	(73.13-104.08)	(46.82-125.8)	(63.00-128.87)	(69.52-89.62)
	[83.42-9265]	[66.36-76.67]	[93.88-104.42]	[78.10-85.22]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p < 0.0001$	[d] $p = 0.0398$	[g] $p < 0.0001$	[i] $p = 0.0045$
[b] $p = 0.0044$	[e] $p = 0.0263$	[h] $p < 0.0001$	[j] $p = 0.0230$
[c] $p = 0.0094$	[f] $p < 0.0001$		

4.1.4 Dimensions that connect inlet, midpelvis or outlet

The pelvic inlet, midpelvis and pelvic outlet define the pelvic canal and therefore, the relative distances between these entities is also important to consider. The measurements that connect the pelvic inlet, midpelvis or outlet (at varying positions) can be noted in Figure 3.10. In Table 4.4 these measurements consist of sacral length (SL), left depth of true pelvis (LDTP), right depth of true pelvis (RDTP), left height of the pelvis (LHTP) and right height of the pelvis

(RHTP). The descriptive statistics of the measurements that connect the inlet, midpelvis and outlet between sex-ancestral groups are given.

SL, LDTP and RDTP measurements were the greatest in SAE male, followed by SAE female. SL was the smallest in SAA female, while LDTP and RDTP measurements were the smallest in SAA male. LHTP and RHTP was the greatest in SAA male, followed by SAE male, then SAE female. SAA female presented with the smallest measurements. Apart from the comparison between males when considering LHTP and RHTP, statistical significant sex and ancestry differences existed in the LDTP, RDTP, LHTP and RHTP measurements.

Table 4.4 Descriptive statistics of the measurements that connect the pelvic inlet, midpelvis and pelvic outlet between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 32	N = 31	N = 33	N = 25
SL	**116.10** [a]	**118.01** [b]	**122.13**	**130.66** [a b]
	13.47	13.33	12.19	13.05
	(97.54-146.97)	(86.2-144.39)	(96.42-147.00)	(104.87-159.48)
	[111.24-120.96]	[133.11-122.89]	[117.81-126.46]	[125.27-136.05]
LDTP	**123.54** [e f g]	**114.67** [c d g]	**132.45** [d f h]	**140.16** [c e h]
	9.83	15.79	7.19	9.39
	(107.41-142.26)	(90.75-142.32)	(114.28-146.00)	(109.41-156.82)
	[120.00-127.09]	[108.88-120.46]	[129.90-135.00]	[136.29-144.04]
RDTP	**123.60** [k l m]	**113.01** [j i l]	**131.90** [j m n]	**139.47** [i k n]
	9.15	15.10	9.94	7.77
	(102.85-138.17)	(92.08-139.25)	(106.61-147.90)	(114.69-154.18)
	[120.30-126.90]	[107.47-118.55]	[129.09-134.72]	[136.26-142.68]
LHTP	**90.30** [o p s]	**112.5** [o q]	**98.43** [q r s]	**110.60** [p r]
	5.82	14.88	4.77	5.60
	(76.11-103.29)	(83.65-135.78)	(87.05-111.83)	(97.42-121.38)
	[88.20-92.40]	[107.04-117.96]	[96.75-100.13]	[108.28-112.90]
RHTP	**89.4** [t u x]	**112.08** [t v]	**98.51** [v w x]	**110.75** [u w]
	6.31	15.13	5.35	4.80
	(79.68-102.12)	(82.11-137.77)	(86.52-114.35)	(97.42-118.96)
	[87.12-91.68]	[106.53-117.63]	[96.62-100.41]	[108.77-112.73]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] p = 0.0003
[b] p = 0.0025
[c] p < 0.0001
[d] p < 0.0001
[e] p < 0.0001
[f] p = 0.0080
[g] p = 0.0097
[h] p = 0.0460
[i] p < 0.0001
[j] p < 0.0001
[k] p < 0.0001
[l] p = 0.0006
[m] p = 0.0098
[n] p = 0.0375
[o] p < 0.0001
[p] p < 0.0001
[q] p < 0.0001
[r] p < 0.0001
[s] p = 0.0018
[t] p < 0.0001
[u] p < 0.0001
[v] p < 0.0001
[w] p < 0.0001
[x] p = 0.0005

4.1.4.1 Conjugates

Specific clinically relevant diameters of the pelvis, including measurements from the pelvic inlet, midpelvis or pelvic outlet, or those connecting the pelvic inlet, midpelvis or pelvic outlet are referred to as conjugates. Examples include the API, SACHOL and APO, in addition to the obstetric conjugate (OBS_CONJ) and the diagonal conjugate (DIA_CONJ) as seen in Figure 3.11. In Table 4.5 the descriptive statistics of these conjugates are given. OBS_CONJ and DIA_CONJ measurements were greater in SAE females and in SAE males compared to SAA males and SAA females. These differences were not statistically significant, except when considering ancestral group variations in the DIA_CONJ measurement.

Table 4.5 Descriptive statistics of the conjugates between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 32	N = 31	N = 33	N =25
OBS_CONJ	**122.04** 12.24 (94.54-147.57) [117.62-126.45]	**113.71** [a] 12.08 (85.13-132.63) [109.28-118.14]	**129.62** [a] 12.59 (100.35-149.95) [119.44-140.16]	**121.31** 10.57 (96.04-139.01) [116.94-125.67]
DIA_CONJ	**110.81** [c e] 10.78 (89.36-139.23) [106.92-114.69]	**106.07** [b d] 13.65 (74.97-138.92] [101.06-111.07]	**128.06** [b c] 13.37 (83.90-158.22) [123.32-132.80]	**122.26** [d e] 15.02 (96.34-149.00) [116.06-128.46]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p = 0.0092$ [d] $p < 0.0001$
[b] $p < 0.0001$ [e] $p = 0.0080$
[c] $p < 0.0001$

4.1.5 Measurements involving the pubic region

The measurements that pertain to the pubic symphysis and subpubic region include, the length of the pubic symphysis (LPS), transverse diameter of superior pubic symphysis (TDSPS), transverse diameter of inferior pubic symphysis (TDIPS), length of the inferior pubic ramus measured from the midpoint on the inferior pubic symphysis on the left (LIPR_IPS) and on the right (RIPR_IPS) and direct measurement of the subpubic angle, as seen in Figure 3.7.

The subpubic angle (ANG) is mathematically derived forming a triangle from the IPS, with the LIPR_IPS and RIPR_IPS as sides (the respected lengths of the ischiopubic rami on both sides) and LRIPR, distance between the left and right ischiopubic rami, form the base of the triangle (Figure 3.8). The descriptive statistics of the measurements that pertain to the pubic symphysis and subpubic region between sex-ancestral groups are given in Table 4.6 and those of the subpubic angle measurements are in Table 4.7. LPS was the longest in SAE male and was statistically significantly longer than the other three sex-ancestral groups. TDISP, LRIPR, LIPR_IPS and RIPR_IPS and all subpubic angle measurements presented with the greatest measurements in females and more specifically, SAE female, while TDSPS was the greatest in SAA females. Although TDSPS in SAA female was the greatest, it differed only significantly from SAA male but not from the other groups. TDISP differed statistically significantly between ancestral groups but not between sex groups. LRIPR, LIPR_IPS and RIPR_IPS and all subpubic angle measurements differed significantly between sex groups.

Table 4.6 Descriptive statistics of the pubic region between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 32	N = 31	N = 33	N = 25
LPS	**43.84** [a] 5.31 (31.83-53.86) [41.92-45.75]	**45.26** [c] 4.20 (37.89-53.59) [43.72-46.80]	**45.23** [b] 4.08 (34.86-54.33) [43.78-46.67]	**49.01** [a b c] 4.27 (41.69-56.86) [47.25-50.77]
TDSPS	**8.64** [d] 4.35 (3.65-23.69) [7.07-10.21]	**5.74** [d] 3.06 (2.42-15.47) [4.62-6.87]	**7.44** 3.11 () [6.28-8.59]	**6.51** 2.39 () [5.18-7.64]
TDISP	**18.52** [f h] 5.49 (5.99-27.61) [16.54-20.50]	**9.85** [e f] 3.73 (4.1-19.7) [8.48-11.22]	**18.62** [e g] 5.10 (4.10-26.73) [16.81-20.43]	**10.81** [g h] 2.84 (5.82-18.91) [9.64-11.98]
LRIPR	**50.85** [k l] 7.84 (33.18-64.49) [48.02-53.68]	**37.78** [i k] 5.59 (24.21-50.43) [35.73-39.83]	**54.91** [i j] 8.17 (31.74-70.85) [52.01-57.80]	**40.42** [j l] 8.20 (24.39-60.48) [37.03-43.80]
LIPR_IPS	**29.71** [n] 4.71 (18.26-40.83) [28.00-31.41]	**24.94** [m n] 4.98 (16.84-36.73) [23.11-26.76]	**32.08** [m o] 5.05 (24.39-46.00) [30.29-33.87]	**27.56** [o] 5.78 (17.82-38.63) [25.18-29.95]
RIPR_IPS	**28.28** [r s] 4.17 (19.95-36.74) [26.78-29.79]	**24.36** [p r] 4.53 (14.04-33.69) [22.70-26.02]	**31.57** [p q s] 3.96 (23.66-39.00) [30.16-33.00]	**27.52** [q] 5.76 (17.99-41.47) [25.14-29.09]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] p = 0.0002	[f] p < 0.0001	[k] p < 0.0001	[p] p < 0.0001
[b] p = 0.0104	[g] p < 0.0001	[l] p < 0.0001	[q] p < 0.0063
[c] p = 0.0128	[h] p < 0.0001	[m] p < 0.0001	[r] p < 0.0051
[d] p = 0.0046	[i] p < 0.0001	[n] p < 0.0018	[s] p < 0.0235
[e] p < 0.0001	[j] p < 0.0001	[o] p < 0.0061	

Table 4.7: Descriptive statistics of the subpubic angle derived from the various methodologies between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
Subpubic angle derived from:	N = 32	N = 31	N = 33	N = 25
Direct along medial aspect of ischiopubic rami	**106.20**[a] 14.18 (80-143)	**79.19**[a] 11.59 (58-98)	**108.70**[d] 12.09 (75-132)	**83.38**[b] 8.20 (69-100)
Subpubic triangle measurements	**120.39**[c] 16.84 (85.59-161.78)	**103.90**[c] **22.20** (58.87-142.54)	**122.51**[b] **14.47** (62.18-145.52)	**94.34**[b] **16.23** (66.84–133.96)
3D coordinates of the subpubic triangle	**117.79** [e] 14.75 (80.95-140.5)	**100.50** [e] 12.67 (80.16-141.62)	**118.58** [f] 10.01 (98.19-141.62)	**94.54** [f] 11.71 (75.7-118.62)
3D coordinates of the urogenital triangle	**89.31** [g] 8.49 (70.59 - 109.8)	**74.04** [g] 7.44 (57.87-102.01)	**87.56** [h] 8.26 (71.23-103.58)	**74.32** [h] 6.11 (62.48-86.37)

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis

[a] p = 0.0029; [b; c; d; e; f; g; h]: p = 0.0001

As expected, subpubic angles derived from subpubic triangle measurements and those from 3D coordinates corresponded and were greater than the direct subpubic angles along the medial aspects of the ischiopubic rami (Figure 3.9). The subpubic angles derived from the 3D coordinates of the urogenital triangle were the smallest of the four modalities. This finding is in keeping with the appearance of the subpubic region being an arch, presenting with greater angles closer to the IPS, but smaller measurements when this arch was disregarded and a direct distance from the IPS to the inferior ischial tuberosities was considered.

Further, it was found that asymmetrical subpubic arches were the rule rather the exception. As for the asymmetrical appearance was possibly due to the wedge-shape of the pubic symphysis, this phenomenon was seen in many cases, which partly contributed to the width of these subpubic arches.

4.2 Measurements pertaining to special investigations: Magnetic Resonance Imaging (MRI) and Computer Tomography (CT)

Measurements performed in the clinical setting on MRI and CT scans comprise the anteroposterior inlet diameter (API), transverse inlet diameter (TI), anteroposterior outlet (APO), interspinous distance (IS), intertuberous distance (IT), anteroposterior midpelvic diameter (sometimes referred to as the depth of sacral hollow (SACHOL) in clinical situations), subpubic angle (ANG) and the length of the sacrum (SL) (Figures 3.12 and 3.13). In Tables 4.8 and 4.9, the descriptive statistics of the MRI and CT scans measurements between sex-ancestral groups can be noted respectively. As before, SL was the greatest in males and more specifically SAE male, followed by SAA female with SAE female presenting with the shortest SL. Significantly differences were found when comparing the means of SL between SAE male and SAE female. API, TI, APO, IS, IT, SACHOL and ANG measurements were the greatest in SAE female. TI and SACHOL were significantly greater in SAE individuals, while API, APO, IS, IT and ANG were the greatest in females, but these variations were only statistically significant between the sexes when considering API in SAE individuals, and IS and IT in both ancestral groups.

Table 4.8 Descriptive statistics of the CT scans between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 26	N = 21	N = 18	N = 27
API	**111.35** [b] 10.01 (90.8-126.7) [107.3-115.4]	**105.12** [a] 9.13 (84.2-121.1) [100.96-109.28]	**120.90** [a c] 12.35 (94.8-138.3) [114.77-127.05]	**111.50** [b c] 11.07 (95.8-142.2) [107.11-115.88]
TI	**120.67** [e] 10.32 (85.0-136.9) [116.50-124.84]	**113.03** [d g] 6.44 (100.5-124.5) [110.10-115.96]	**128.33** [d e f] 4.98 (114.8-136.6) [126.6-131.93]	**122.69** [f g] 5.19 (113.4-132.2) [120.58-124.68]
APO	**91.35** 11.40 (61.9-118.6) [86.75-95.96]	**83.06** 8.81 (68.6-97.4) [79.05-87.07]	**91.98** 14.92 (66.3-129.8) [84.56-99.40]	**84.3** 9.62 (65.1-108.7) [80.49-88.11]
IS	**100.67** [k l m] 11.69 (64.8-120.0) [95.95-105.39]	**84.67** [i k] 7.52 (72.4-103.8) [81.25-88.10]	**107.84** [i j m] 7.32 (92.3-121.4) [102.43-112.28]	**90.87** [j l] 6.82 (74.9-103.9) [88.17-93.57]
IT	**109.59** [p q r] 11.24 (74.0-126.2) [105.05-114.13]	**94.38** [n p] 9.30 (80.2-122.6) [90.15-98.61]	**121.05** [n o q] 7.06 (109.2-132.5) [117.05-126.92]	**105.72** [o r] 9.19 (87.0-132.6) [102.09-109.36]
SACHOL	**121.7** [u] 9.30 (92.6-137.7) [117.94-125.46]	**119.33** [s t] 5.48 (111.5-129.5) [116.83-121.83]	**128.99** [s u] 8.94 (109.7-147.6) [124.55-133.44]	**126.65** [t] 10.48 (107.1-152.2) [122.51-130.80]
ANG	**103.51** 11.37 (80.89-129.17) [97.48-109.08]	**84.05** 10.98 (65.03-105.38) [77.78-82.83]	**114.83** 12.18 (96.12-138.52) [106.86-111.93]	**88.85** 10.72 (70.69-113.62) [73.52-1047.2]
SL	**114.36** [w] 9.24 (88.1-123.08) [110.63-118.09]	**118.90** 11.69 (92.6-137.8) [113.54-124.18]	**113.73** [v] 10.87 (96.3-131.1) [108.32-119.13]	**124.86** [v w] 10.77 (101.8-145.3) [120.60-129.12]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p < 0.0001$	[g] $p = 0.0060$	[m] $p = 0.0145$	[s] $p = 0.0059$
[b] $p = 0.0219$	[h] $p = 0.0447$	[n] $p < 0.0001$	[t] $p = 0.0294$
[c] $p = 0.0234$	[i] $p < 0.0001$	[o] $p < 0.0001$	[u] $p = 0.439$
[d] $p < 0.0001$	[j] $p < 0.0001$	[p] $p < 0.0001$	[v] $p = 0.0047$
[e] $p < 0.0001$	[k] $p < 0.0001$	[q] $p < 0.0001$	[w] $p = 0.0029$
[f] $p = 0.0001$	[l] $p = 0.0015$	[r] $p = 0.0011$	

Table 4.9 Descriptive statistics of the MRI between sex-ancestral groups

	African Ancestral group		European Ancestral group	
	Females	**Males**	**Females**	**Males**
	N = 22	N = 21	N = 14	N = 20
API	**106.24** [a] 12.45 (78.64-121.2) [100.72-111.76]	**106.32** [b] 8.97 (88.62-116.43) [102.24-110.40]	**120.11** [b] 6.57 (109.71-134.15) [116.32-123.90]	**111.51** [a] 10.33 (89.98-135.79) [106.68-116.35]
TI	**123.02** [e f g] 9.56 (95.99-137.28) [118.79-127.26]	**113.98** [c d f] 5.68 (105.52-125.82) [111.39-116.57]	**134.11** [c e] 8.81 (118.66-148.63) [129.03-139.20]	**131.14** [d g] 12.06 (120.03-141.26) [125.24-137.07]
APO	**92.57** 10.40 (76.8-112.97) [87.96-97.18]	**90.06** 9.08 (72.25-108.63) [85.93-94.20]	**87.38** 11.30 (74.6-110.32) [80.86-93.92]	**88.66** 11.85 (65.12-112.02) [83.11-94.20]
IS	**97.85** [j] 13.46 (56.91-117.48) [91.88-103.82]	**84.27** [h j] 9.66 (60.14-100.58) [79.87-88.67]	**106.69** [h i] 11.82 (74.58-123.32) [99.87-113.52]	**89.03** [i] 8.22 (73.93-106.16) [85.19-92.88]
IT	**106.23** [l] 11.88 (75.67-125.02) [100.96-111.50]	**91.63** [k l] 12.16 (61.17-111.68) [86.09-97.17]	**113.87** [k m] 13.64 (84.79-136.3) [105.99-121.74]	**100.56** [m] 12.66 (82.96-134.12) [94.64-106.49]
SACHOL	**122.46** [o] 9.94 (106.47-145.57) [118.05-126.87]	**119.25** [n] 7.64 (100.85-133.19) [115.78-122.73]	**124.49** 10.21 (111.25-149.89) [118.59-130.39]	**130.93 8** [n o] 8.53 (115.96-153.58) [126.94-134.93]
ANG	**112.82** 15.14 (87.49-155.32) [102.92-119.30]	**91.89** 15.29 (58.44-127.16) [81.00-104.23]	**120.70** 9.79 (106.55-135.60) [112.42-130.93]	**92.12** 17.76 (66.56-142.68) [80.47-101.95]
SL	**109.09** [p q] 13.83 (89.22-136.77) [102.96-115.22]	**119.37** [q] 13.33 (86.52-140.54) [113.30-125.44]	**118.59** 9.52 (105.3-140.96) [113.09-124.09]	**126.26** [p] 10.03 (111.78-142.57) [121.56-130.95]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p = 0.0008$	[e] $p = 0.0057$	[i] $p < 0.0001$	[m] $p < 0.0161$	[q] $p = 0.0335$
[b] $p < 0.0010$	[f] $p = 0.0136$	[j] $p < 0.0007$	[n] $p = 0.0005$	
[c] $p < 0.0001$	[g] $p = 0.0355$	[k] $p < 0.0001$	[o] $p < 0.0175$	
[d] $p < 0.0001$	[h] $p < 0.0001$	[l] $p < 0.0015$	[p] $p = 0.0001$	

As with the CT scans, SL was the greatest in males, specifically male SAE. Significant sex differences were only found in SAA individuals. API, TI, APO, IS, IT and ANG measurements were the greatest in females and the variations were only statistically significant in IS and IT.

4.3 Comparison between the three modalities

The overall mean values of the lineal measurements across all four ancestral-sex groups were used. Eight common diameters derived from the three modalities (direct cadaveric measurements, MRI and CT) respectively, were compared among the three modalities. The measurements comprised the API, APO, TI, SL, ANG, IS, IT, SACHOL/APM (Table 4.10).

Table 4.10 Descriptive statistics between three modalities

	Direct measurements	MRI	CT scans
	N =121	N = 77	N = 92
API	**110.70** 11.67 (74.17-141.08) [107.89-113.52]	**110.15** 11.20 (78.64-135.79) [109.30-114.83]	**111.84** 11.67 (84.2-142.2) [107.38-112.93]
TI	**119.78** [a] 11.55 (99.75-151.4) [117.12-122.43]	**124.68** [a] 12.10 (95.99-139.03) [121.94-127.43]	**122.52** 124.28 (85.00-189.9) [119.98-125.06]
APO	**86.01** 10.50 (65.94-111.09) [83.59-88.43]	**89.93** 10.59 (65.12-112.97) [87.54-92.33]	**87.51** 11.69 (61.9-129.8) [85.09-89.93]
SL	**120.08** 14.32 (86.2-153.8) [116.78-123.37]	**118.08** 13.48 (86.5-142.57) [115.02-121.14]	**118.35** 11.41 (88.1-145.3) [115.98-120.71]
IS	**91.55** 12.83 (69.1-133.97) [88.58-94.52]	**93.46** 13.48 (56.91-123.32) [90.40-96.52]	**95.87** 12.83 (64.8-141.3) [93.21-98.53]
IT	**82.36** [b c] 15.96 (43.00-125.8) [78.69-86.03]	**102.17** [b d] 14.53 (61.18-136.3) [98.87-105.46]	**107.75** [c d] 13.96 (89.9-144.5) [104.89-110.61]
ANG	**93.84** [e] 1.99 (62.00-143) [89.90-97.78]	**103.17** [e] 1.97 (58.44-155.33) [99.28-107.06]	**96.99** 1.80 (65.03-138.52) [93.43-100.54]
SACHOL	**118.97** [g h] 9.50 (100.52-155.22) [114.82-123.12]	**124.16** [g] 9.92 (100.85-153.58) [121.91-126.41]	**124.04** [h] 9.5 (92.6-152.2) [122.07-126.01]

N = number per group
The mean value (mm) indicated in bold
Standard deviation normal text
Range, minimum and maximum value in parenthesis
95% confidence interval values in square brackets

[a] $p = 0.0331$ [d] $p = 0.0392$ [h] $p = 0.0314$
[b] $p < 0.0001$ [e] $p = 0.0030$
[c] $p < 0.0001$ [g] $p = 0.0357$

When comparing the three modalities, the direct measurements were consistently smaller than MRI and CT scans. Significantly different measurements were found when MRI and direct measurements were used in the case of TI, IT, ANG and SACHOL, while significant different measurements were found when CT scans and direct measurements were used in the case of IT and SACHOL. Significantly different measurements were found when comparing MRI and CT scans in the case of IT. IT diameter seemed to be the most variable measurement among the modalities used.

4.4 Shape analysis on intact cadaver pelves

In this section, results of the shape variations of each pelvic component separately (pelvic inlet, midpelvis, pelvic outlet and subpubic region), as well as the total pelvic canal shape as demarcated by the digitisation of a set of landmarks, are represented on XY-graphs in a Principal Component environment. Principal Component Analyses (PCA), which followed on the Procrustes analyses, are depicted as XY-graphs where Principal Component (PC) 1 (contributing to the greatest shape difference) is represented on the X-axis, vs. PC2 (contributing to the second greatest shape difference) is represented on the Y-axis. The distribution of the variation in shape amongst individuals can be visualised on the graph. Scatter points belonging to each sex-ancestral group were allocated a specific colour: SAA males: green, SAA females: purple, SAE males: blue and SAE females: pink. Wire frames (landmark connecting diagrams) were inserted at specific locations on the graph to indicate the variations of the particular feature at that point.

Two group multivariate permutations, as part of the multivariate statistical analyses package in PAST software, were performed on the PC scores for each pelvic feature.[120] Statistical significance of these variations could be assessed amongst sex or ancestral groups. Finally, the Procrustes mean shape was used to visually represent and describe the variations between sex-ancestral groups.

4.4.1 Pelvic inlet

The pelvic inlet shape between various combinations of sex-ancestral groups are presented in the following sections. Shape analyses of the pelvic inlet, as represented by the digitised landmarks (the sacral promontory, left and right antero-superior point of the sacro-iliac joint, left and right arcuate line; left and right iliopubic eminence and the superior midpoint on the pubic symphysis) and depicted in Figure 3.15, were performed among the sex-ancestral groups. Wireframes connecting the pelvic inlet landmarks were used to illustrate the variations between sex-ancestral groups on the PC1 vs. PC2 scatter plots. The antero-superior view, as well as the lateral views of the mean shapes, are depicted and compared. Following on the PC1 and PC2 comparisons, the Procrustes mean pelvic inlet shape in each of the four sex-ancestral groups were determined separately.

4.4.1.1 Comparison of the pelvic inlet shape between sexes and ancestral groups

In Figure 4.1, the analysis of variances along PC1 vs. PC2 can be noted between males and females of African and European ancestry.

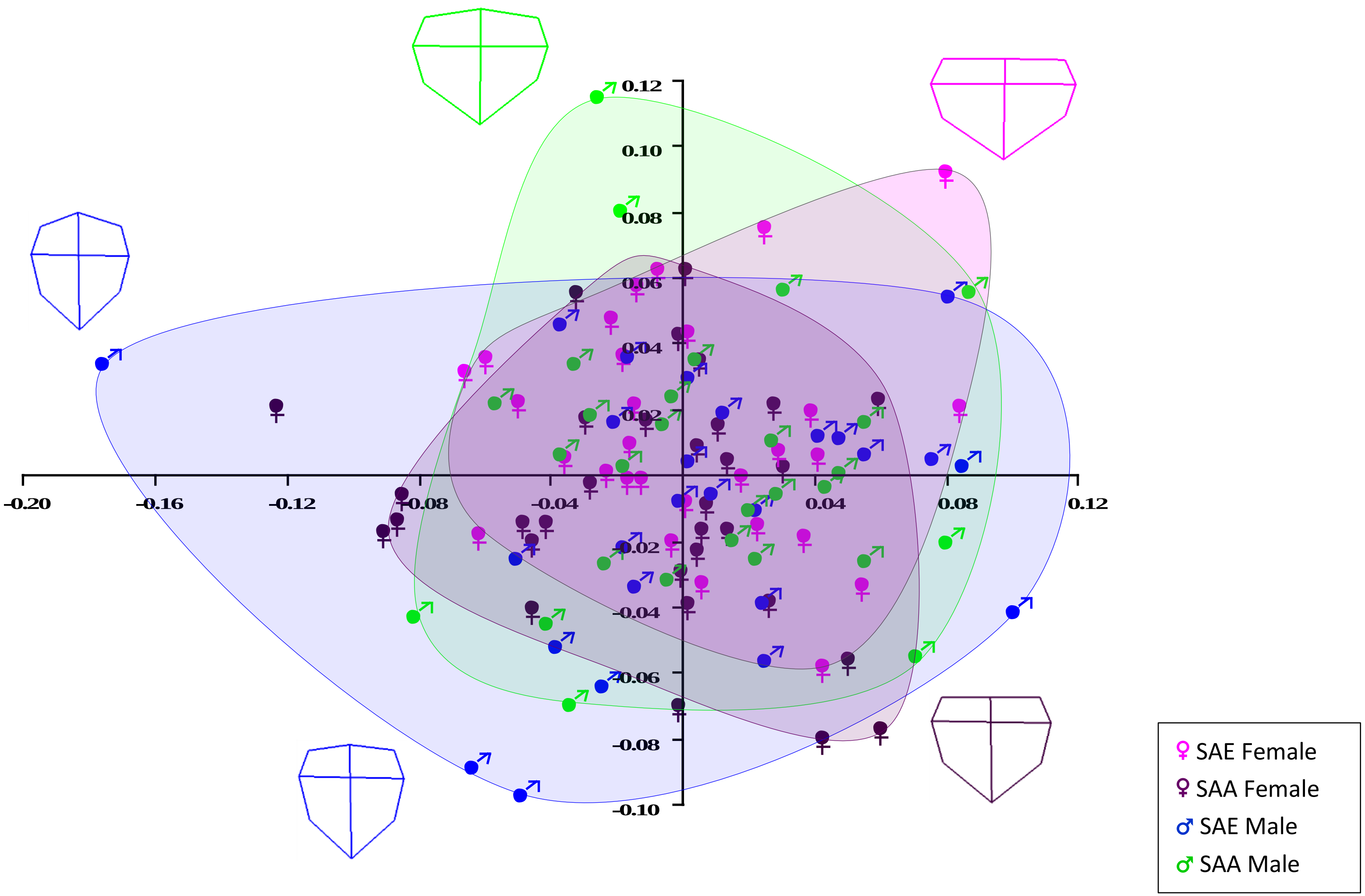


Figure 4.1: PC1 vs. PC2 in the comparison of the shape variation in the pelvic inlet among of sex-ancestral groups

Although the scatter points representing individual pelvic inlet shapes are widely distributed in space, greater clustering takes place in the centre of the graph. The p-value for inter-sex variation is 0.001, while inter-ancestry variation is 0.0025. Pelvic inlets represented on the right hand side of the graph have the widest transverse diameters and a more anteriorly or inward oriented promontory, while those shapes on the left hand side of the graph have a narrower transverse diameter with the sacral promontory situated more posteriorly or outward.

4.4.1.2 Comparison of the pelvic inlet shape between ancestral groups within sexes

In Figures 4.2 and 4.3 the analyses of variances between females and males of African ancestry (SAA), as compared to European ancestry (SAE), can be noted respectively, along PC1 vs. PC2.

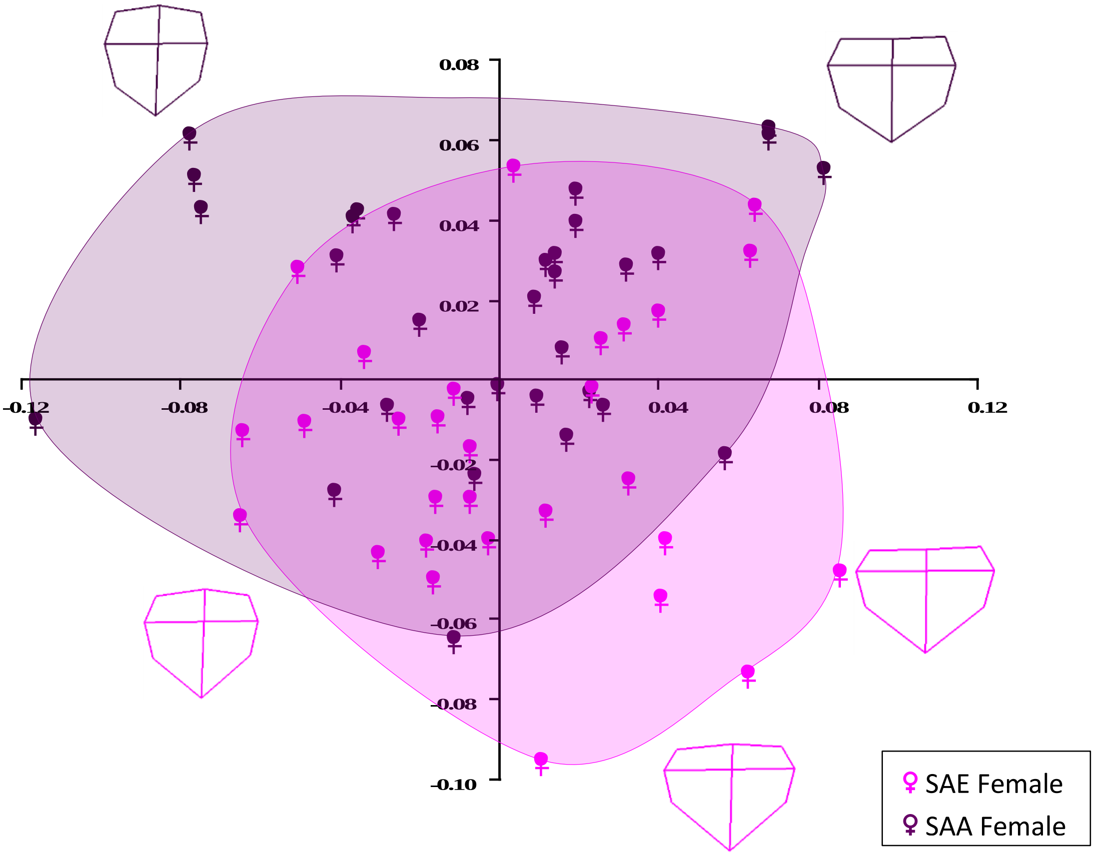


Figure 4.2 PC1 vs. PC2 in the comparison of the shape variation in the pelvic inlet between SAA female and SAE female

The scatter points representing the pelvic inlet shapes in both ancestral groups overlap noticeably in the centre of the graph. Female SAA scatter points tend to represent the extremes on the upper right and upper left quadrant of the graph, while female SAE scatter points tend to represent the extremes on the lower right quadrant of the graph. The extremes in the right upper quadrant present with anteriorly projecting midpoints on the sacral promontory. The extremes in the left upper quadrant present with a transversely narrowed pelvic inlet shape. On the other hand, the extremes in the right lower quadrant have wider inlets and more posteriorly outward projecting midpoints on the sacral promontory. The p-value for the inter-ancestral group variation was 0.003, thus highlighting the significant difference.

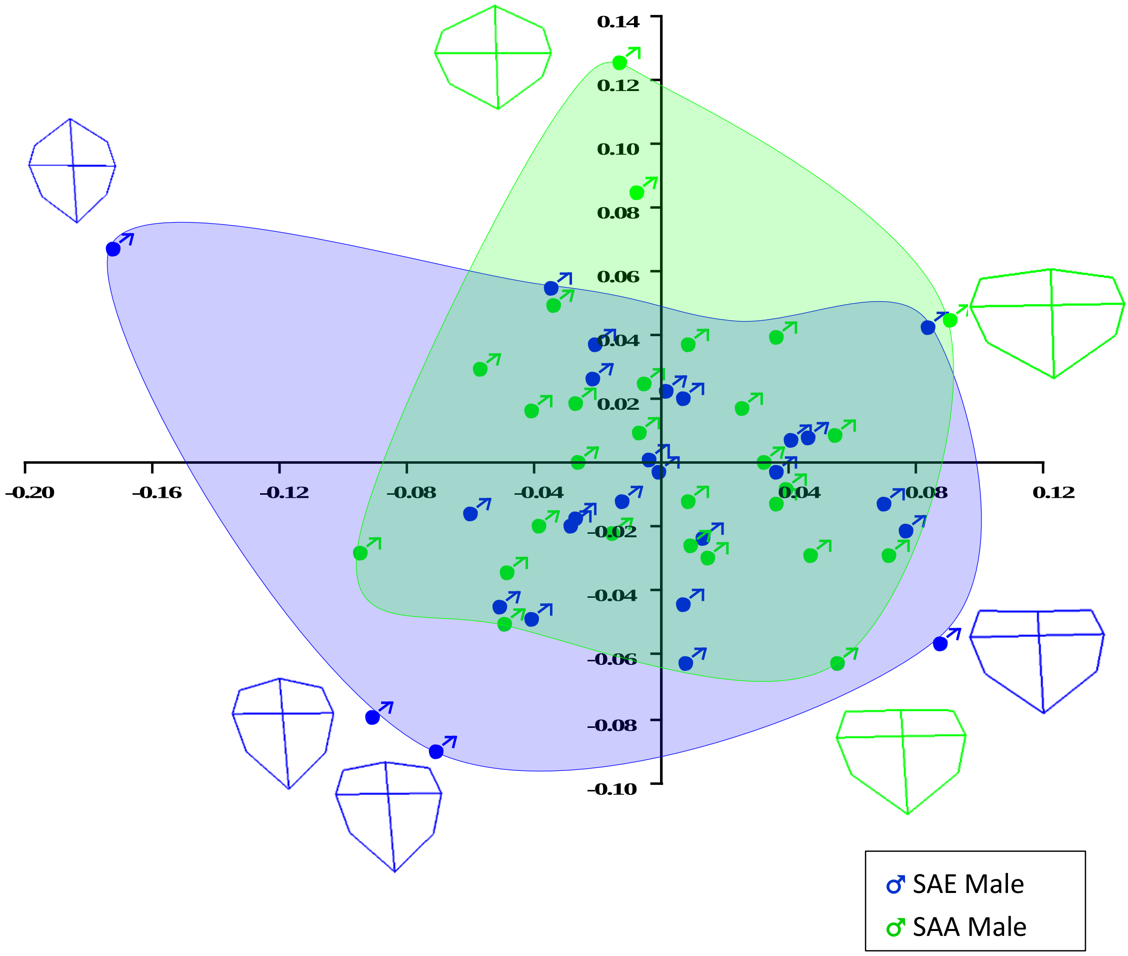


Figure 4.3 PC1 vs. PC2 in the comparison of the shape variation in the pelvic inlet between SAA male and SAE male

The scatter points representing the pelvic inlet shapes of both ancestral groups overlap noticeably in the centre of the graph. The scatter points belonging to SAE male tend to dominate the right upper quadrant, while the SAE male are seen in the lower left and lower right quadrants. Pelvic inlets in the lower quadrants seem to have the widest diameter in a relatively more posterior position than in the upper quadrants. The p-value was determined as 0.051.

4.4.1.3 Comparison of the pelvic inlet shape between sexes within ancestral groups

The analysis of variance along PC1 vs. PC2 in the comparison between SAA female and SAA male is depicted in Figure 4.4 and between SAE male and SAE females in Figure 4.5.

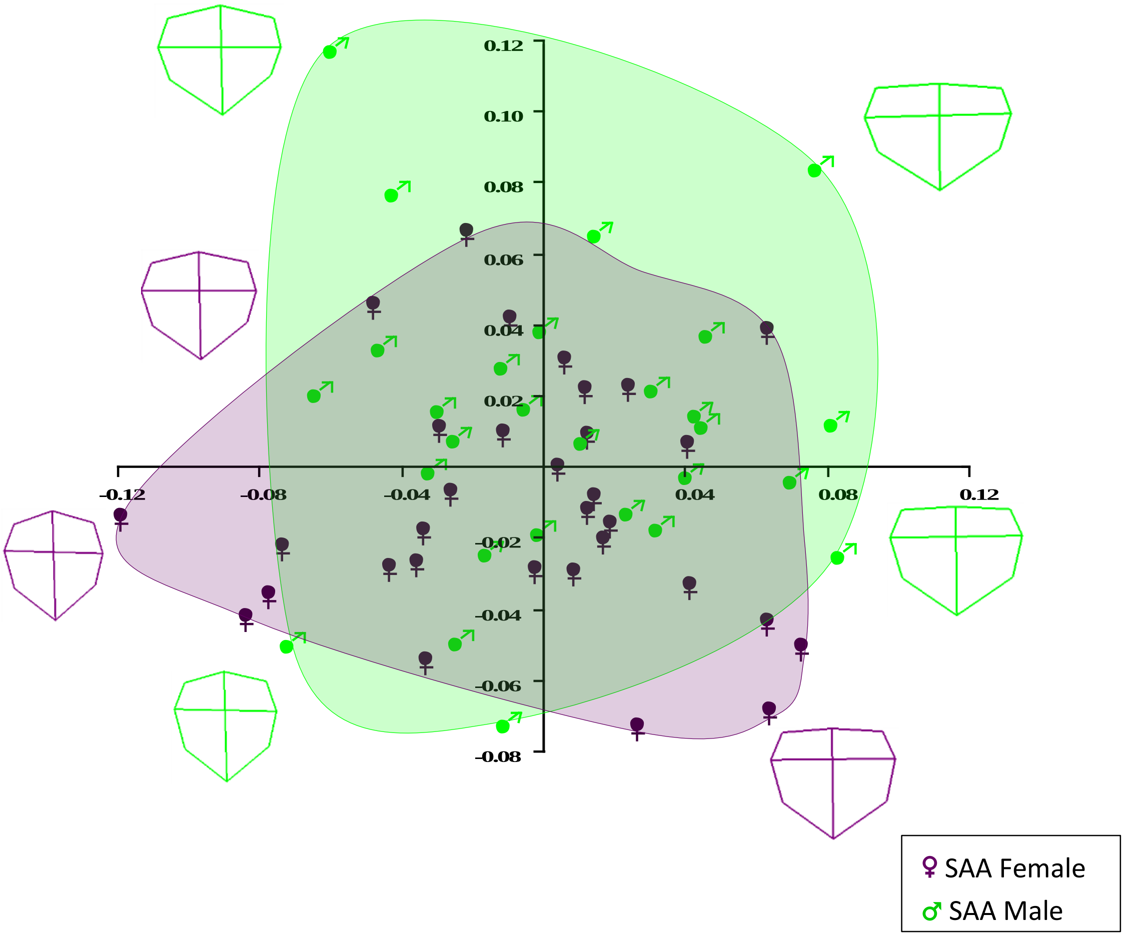


Figure 4.4 PC1 vs. PC2 in the comparison of the shape variation in the pelvic inlet between SAA male and SAA female

When comparing the pelvic inlet shape in the sexes in SAA, the scatter points overlap each other predominantly in the centre of the graph. Male SAA dominate the upper two quadrants, while female SAA dominate the lower quadrants. The p-value for the inter-sex variation is 0.017. The pelvic inlet in the upper quadrants presents with relatively wider shapes in a transverse direction.

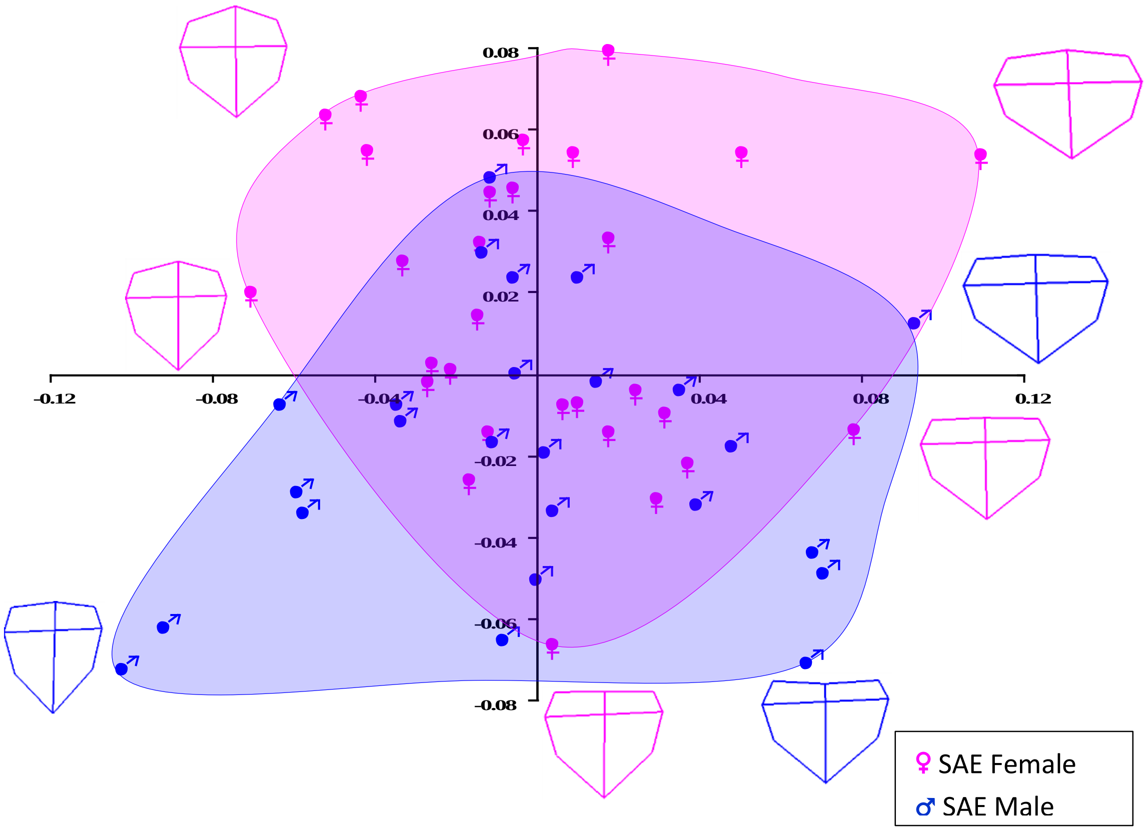


Figure 4.5 PC1 vs. PC2 in the comparison of the shape variation in the pelvic inlet between SAE male and SAE female

Although the scatter points representing the pelvic inlet shape overlap significantly between the sexes, variations were statistically significant (p-value = 0.0075). SAE male seem to dominate the lower quadrants, with only a few male individuals found in the upper quadrants, while female scatter points dominate in the upper quadrants. The pelvic inlet shapes of the upper two quadrants present with wider shapes and more posteriorly located midpoints on the sacral promontory. The widest transverse diameter is also situated more anteriorly than in the lower two quadrants.

4.4.1.4 Procrustes mean pelvic inlet shape for comparisons between sex-ancestral groups

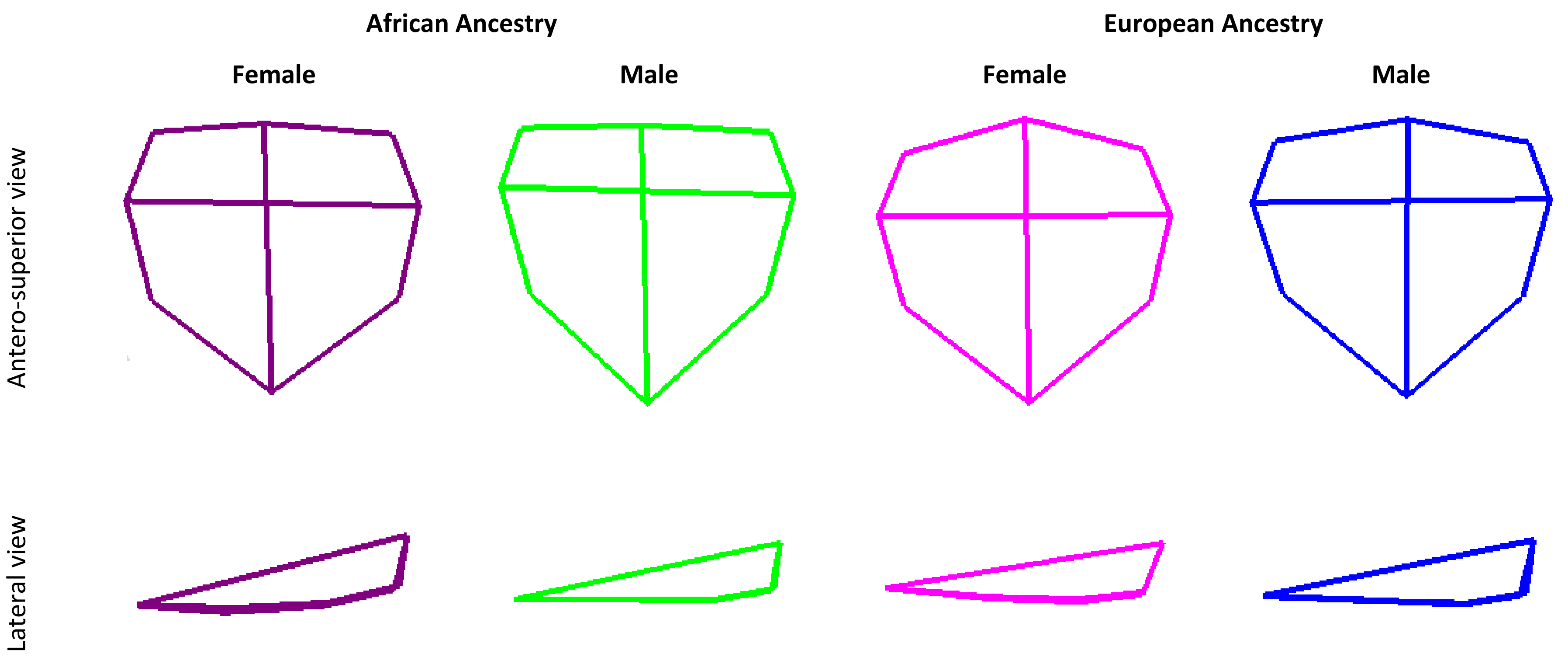


Figure 4.6: The Procrustes mean pelvic inlet shape of each of the four sex-ancestral groups

The differences noted in the Procrustes mean pelvic inlet shapes between the sex-ancestral groups reflect the variations in the wire frames by PCA as well as the multivariate analyses for statistical significance (Figure 4.6). On average, females of African ancestry present with more anteriorly projecting midpoints on the sacral promontory than females of European ancestry. When comparing the Procrustes mean shape in males, a similar variation between ancestral groups are noted as in females. The extremes in the PCA graphs, however, also showed transversely narrower pelvic inlets with the greatest transverse diameter at a more posterior position possibly denoting a relatively smaller anterior pelvis in males of African ancestry as compared to males of European ancestry.

Although in the PCA graphs some extreme outliers presented with wider transverse shapes in males, this was not the case when considering the Procrustes mean. In both ancestral groups the pelvic inlet shape of females presented with more posteriorly located midpoints on the sacral promontory with the widest transverse diameter situated relatively more anteriorly than in males.

4.4.2 Midpelvis

Geometric shape analysis was performed to compare the midpelvic shape between the four sex-ancestral groups as defined by the digitised landmarks comprising the midpoint of the S3/4 sacral joints, left and right inferior point of the sacro-iliac joint, left and right ischial spines, the left and right most posterior point on the posterior border of the obturator foramen, the left and right most anterior point on the anterior border of the obturator foramen, midpoint of pubic symphysis and, lastly, the most superior points in the left and right greater sciatic notch as depicted in Figure 3.16. Wireframes connecting the midpelvic landmarks were used to illustrate the shape variations among sex-ancestral groups on the PC1 vs. PC2 scatter plots. In each case an antero-superior view as well as lateral view of the midpelvic wireframe are presented. Following on the PC1 and PC2 comparisons, the Procrustes mean midpelvic shape in each of the four sex-ancestral groups were determined separately.

4.4.2.1. Comparison of midpelvic shape between sexes and ancestral groups

Comparison of the shape of the midpelvis between the sexes and ancestral groups by means of the analysis of variance along PC1 vs. PC2 can be noted in Figure 4.7

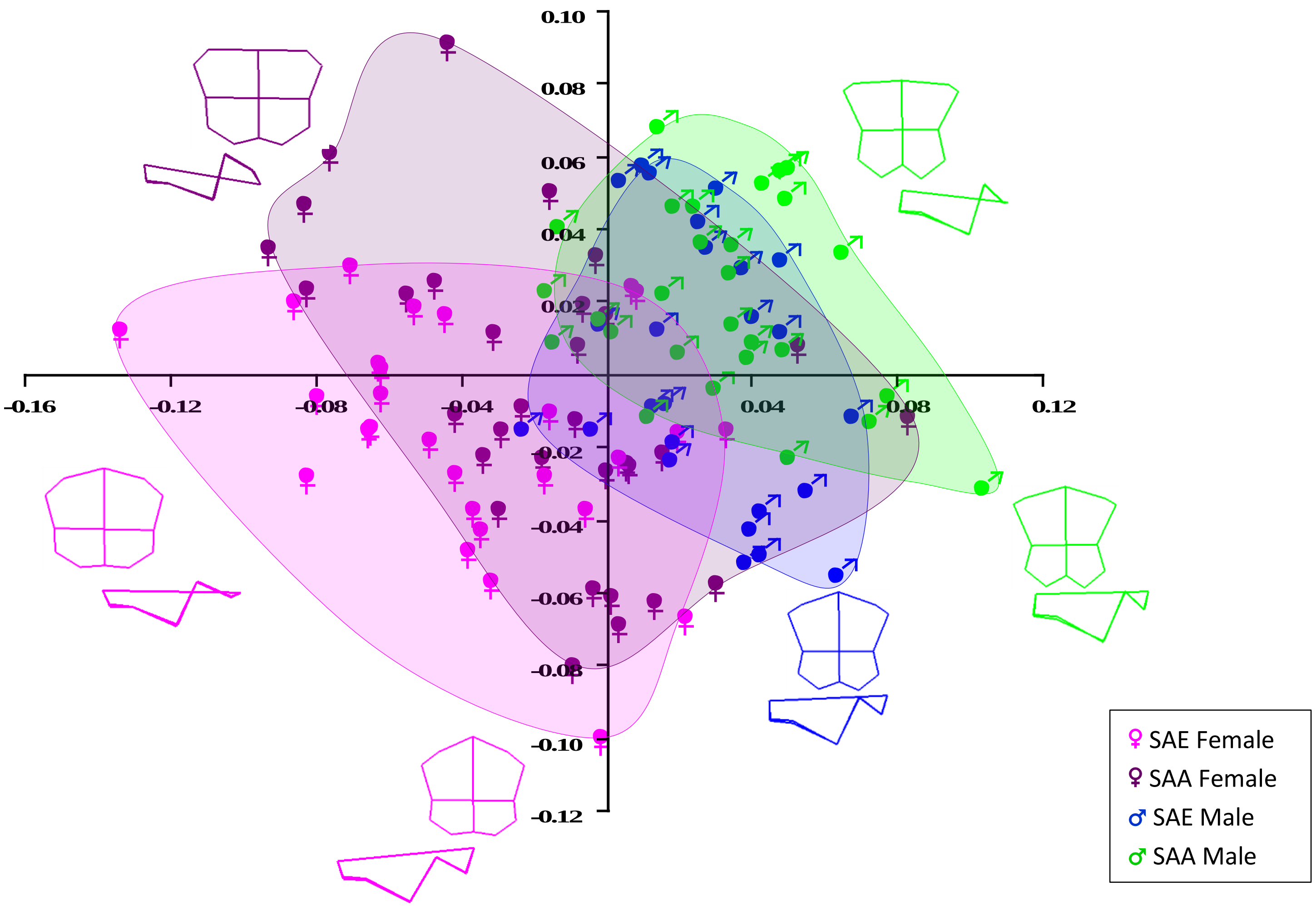


Figure 4.7 PC1 vs. PC2 in the comparison of the shape variation in the midpelvis between sexes and ancestral groups

Although the scatter points representing the sexes and ancestral groups demonstrate a great deal of overlap on the PCA graph (PC1 vs. PC2) when comparing midpelvic shapes, some sex-ancestral group clustering was noted. On the right hand side of the graph male scatter points predominated, with a narrower transverse shape than on the left hand side. On the left hand side of the graph, female scatter points predominated. Male scatter points were confined to a smaller area as compared to female scatter points. The wider distribution of the female midpelvic shapes as compared to the male midpelvic shapes in the PC1 vs. PC2 comparison could be indicative of a greater variation in female shapes as compared to male shapes. In both sexes, scatter points belonging to SAA were found more towards the upper half of the graph, characterised by flatter sacral hollows as compared to SAE clustered more in the lower half of the graph, with relatively deeper sacral hollows. The p-values for the inter-sex and inter-ancestral variations are both equal to 0.0005.

4.4.2.2. Comparison of midpelvic shape between ancestral group within sexes

The midpelvic shape variation between ancestral groups within sexes is compared. Figure 4.8 it shows the shape variation along PC1 vs. PC2 for females, and the variation is shown in for males in Figure 4.9.

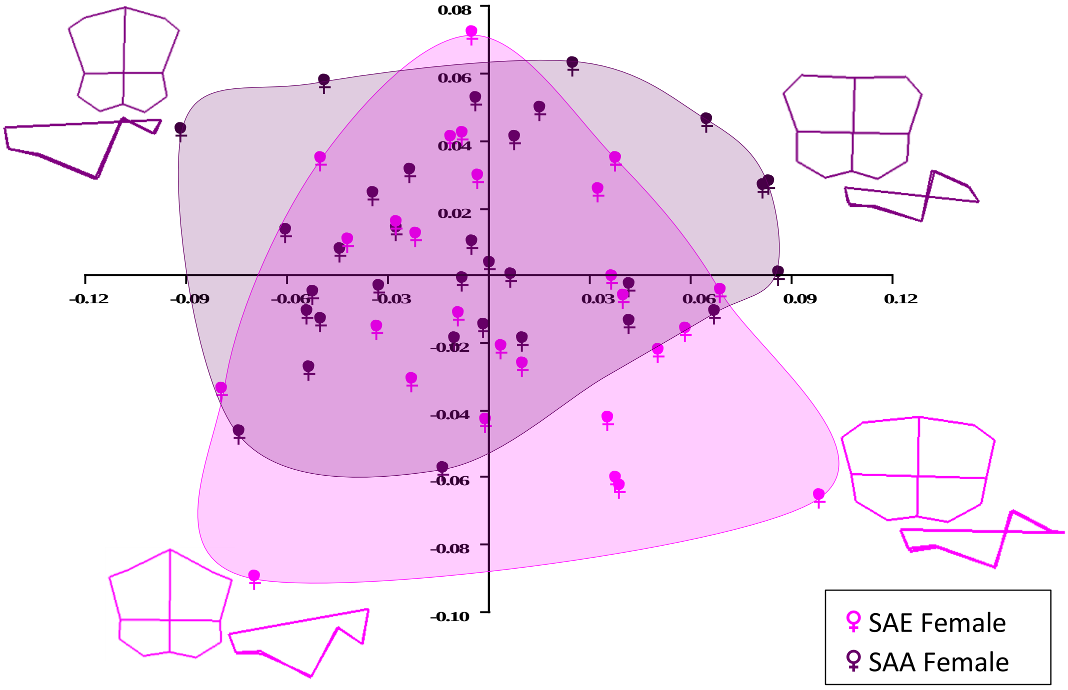


Figure 4.8 PC1 vs. PC2 in the comparison of the shape variation for the midpelvis between SAA female and SAE female

Although the ancestral groups scatter points overlap to a great extent, SAA female tend to occupy the extremes on the left upper and right upper quadrant of the graph, while the SAE female occupy the extremes on the lower quadrants of the graph. The p-value for the inter-ancestral group variation was 0.008. The wireframes of both ancestral groups showed a great variation of the posterior aspect of the midpelvic shape. The posterior aspect reflects the degree of concavity of the sacrum. SAE Female, however, often presented with wider midpelvic shapes than female SAA, which could partly be responsible for the associated wider angle noted in the anterior portion of the midpelvic shape.

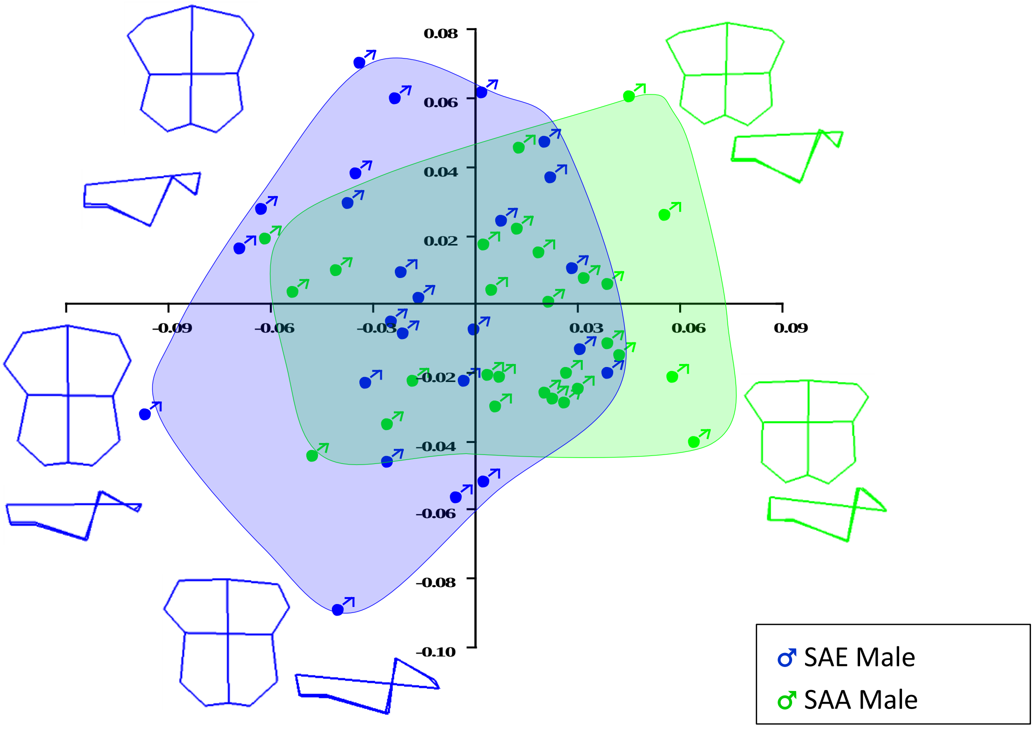


Figure 4.9 PC1 vs. PC2 in the comparison of the shape variation for the midpelvis between SAA male and SAE male

A great deal of overlap amongst the scatter groups belonging to the two ancestral groups can be noted in the PC1 vs. PC2 scatter plot (Figure 4.9). The extreme outliers on the right hand side of the graph belonged to SAA male, while SAE male scatter point outliers were found on the left hand side of the graph. Extreme midpelvic shapes representing SAE male on the left hand side of the graph were strikingly longer in the anteroposterior axis compared to shapes on the extreme right hand side representing SAA male. The difference between the midpelvic shape of SAA male and SAE male was highly significant with a p-value of 0.0005.

4.4.2.3 Comparison of midpelvic shape between sexes within ancestral groups

The midpelvic shape variation between sexes within ancestral groups is compared. In Figure 4.10, analysis of variance along PC1 vs. PC2 can be seen comparing female SAA and male SAA, and male SAE and female SAE are compared in Figure 4.11.

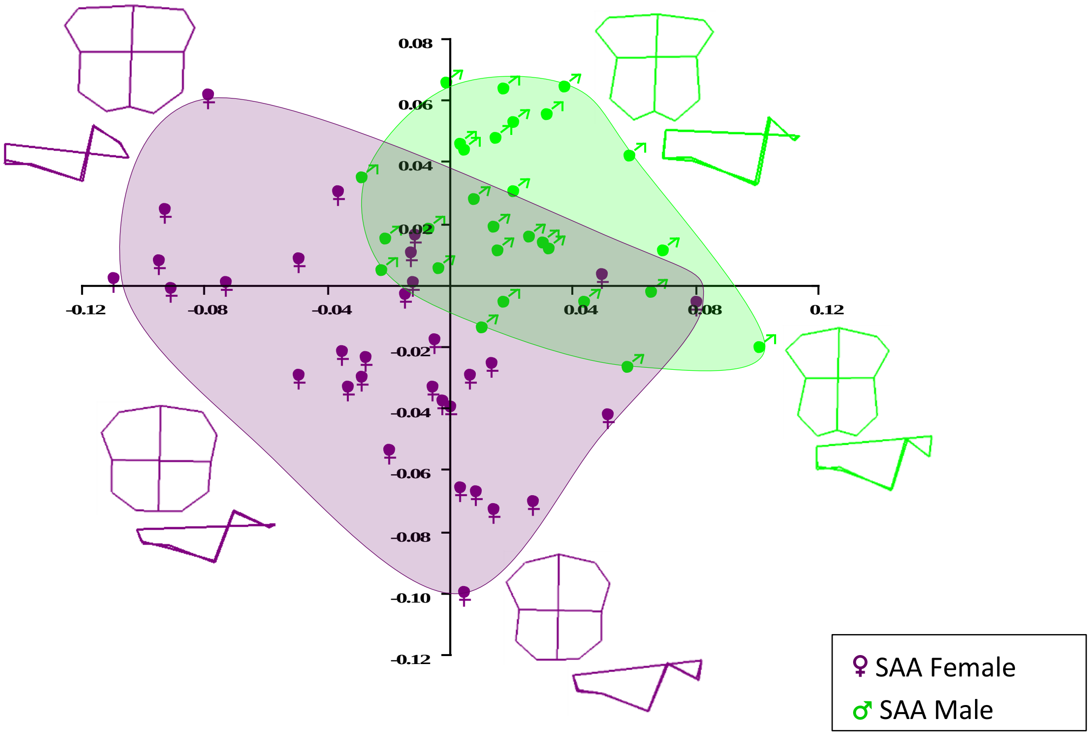


Figure 4.10 PC1 vs. PC2 in the comparison of the shape variation for the midpelvis between SAA male and SAA female

When comparing male SAA to female SAA, the midpelvic shape demonstrated a significant difference (p-value of 0.0005) with only a limited degree of overlap. Males were more often represented in the right half of the graph as opposed to females, who were more often represented in the left half of the graph. The anterior part of the pelvis in males clustering in the right half of the graph demonstrated a more acute angulation at the posterior part of the symphysis pubis as if it was intruding into the pelvic cavity from the anterior border of the obturator foramen. Female scatter plots found in the left half of the graph presented with a less angulated appearance anteriorly. The posterior portion of the pelvis appeared relatively smaller in male SAA as compared to female SAA, with the distance between the superior point on the sacral notch approximating the inferior point on the sacro-iliac joint. Greater variation in the midpelvic shape in females (as reflected in the wider distribution of scatter points on the graph) was also noted than in males.

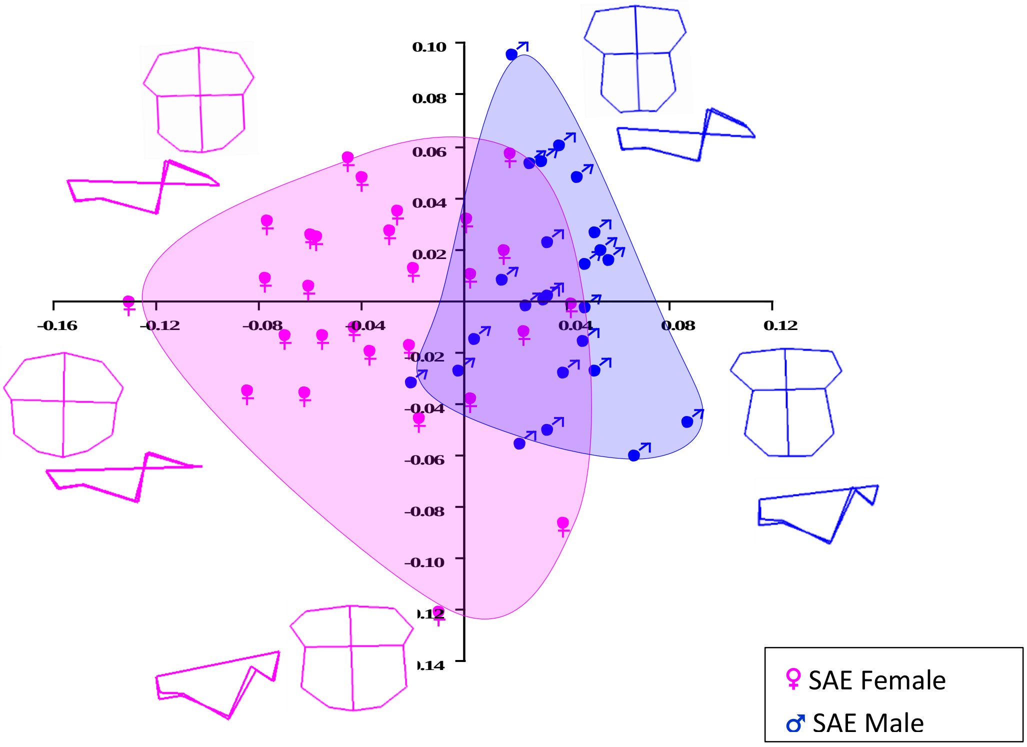


Figure 4.11 PC1 vs. PC2 for the comparison of SAE male and females in the shape variation of the midpelvis

The PC1 vs. PC2 scatter graph of the midpelvic shape demonstrates a degree of overlap when comparing SAE male to female SAE (Figure 4.11). The females however, are predominantly represented in the left half of the graph, especially the left inferior quadrant. As for SAA, a relatively wider midpelvis, more prominent sacral hollow and a flatter inner aspect of the pubic symphysis are noted in females compared to males. Greater variation in the midpelvic shape, as reflected in the wider distribution of scatter points on the graph, was also noted in females as compared to males. The shape variations were statistically significant with a p-value of 0.0005.

4.4.2.4 Procrustes mean midpelvic shape for comparison sex-ancestral groups

The mean midpelvic shape of each sex-ancestral group was determined separately. In Figure 4.12 the antero-superior view, as well as the lateral views of the determined mean shape for each sex-ancestral group, are depicted for comparative purposes.

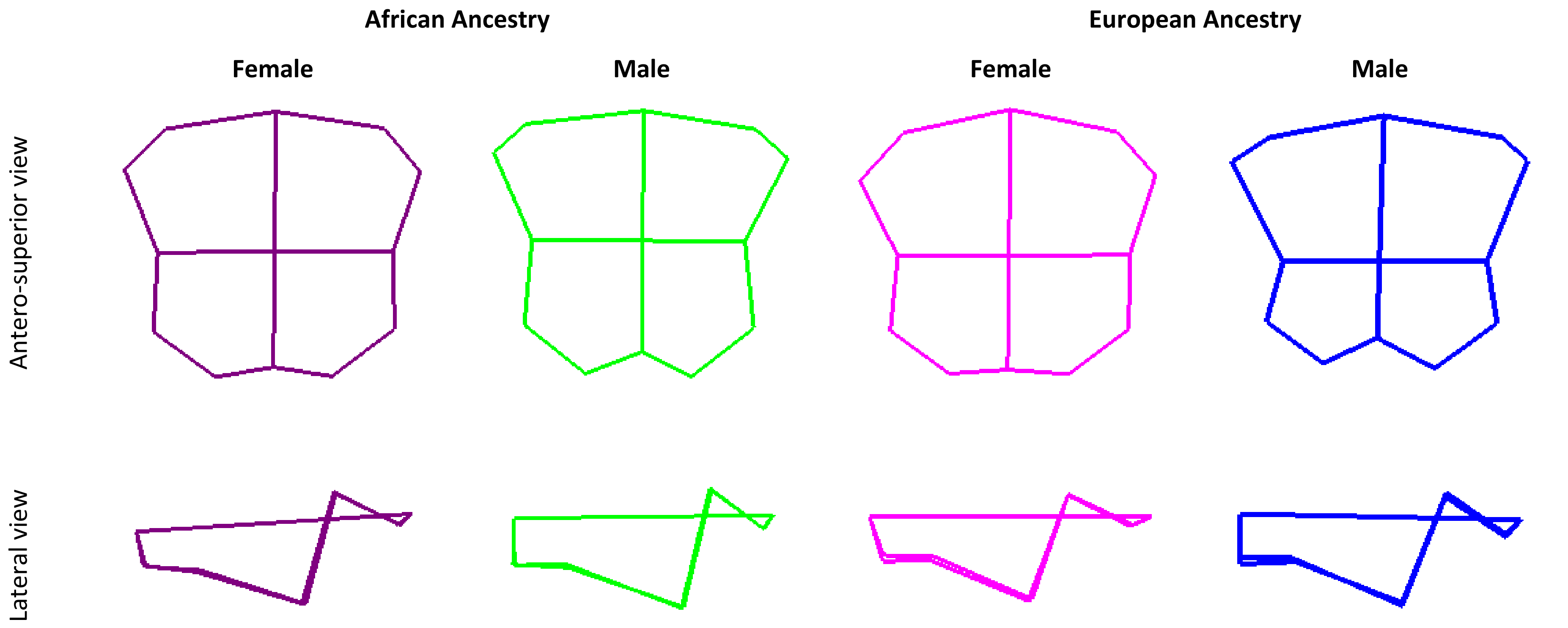


Figure 4.12: The Procrustes mean midpelvic shape of each of the four sex-ancestral groups

The comparison of the Procrustes mean midpelvic shapes reflects the shape variations noted in the PC1 vs. PC2 graphs (Figure 4.12). In summary, a relatively wider midpelvis, a more prominent sacral hollow, a flatter inner aspect of the pubic symphysis and a relatively more spacious posterior aspect between the sacral notch and the sacro-iliac joint are noted in females as compared to males. These shape variations between the sexes seem to be more pronounced in SAE female and accumulatively contribute to a relatively more even or smooth appearance of the midpelvic shape as compared to the more angular midpelvic shape of males.

4.4.3 Pelvic Outlet

Geometric shape analysis was performed to compare the pelvic outlet shape amongst the four sex-ancestral groups by using digitised landmarks. These landmarks comprised of the tip of the coccyx, left and right inferior point on the ischial tuberosities, the points (left and right) on the medial border of the left and right ischiopubic ramus denoting the junction of the inferior pubic ramus to the ischial ramus and the inferior point of the pubic symphysis (Figure 3.17). Wireframes oriented in an antero-superior and lateral view were created by connecting the pelvic outlet landmarks to represent the pelvic outlet shape variations on each PC1 vs. PC2 scatter plot.

4.4.3.1 Comparison of pelvic outlet shape between sex-ancestral groups

In Figure 4.13, the analysis of variance in the pelvic outlet shape along PC1 vs. PC2 is depicted in the comparison between sexes and ancestral groups.

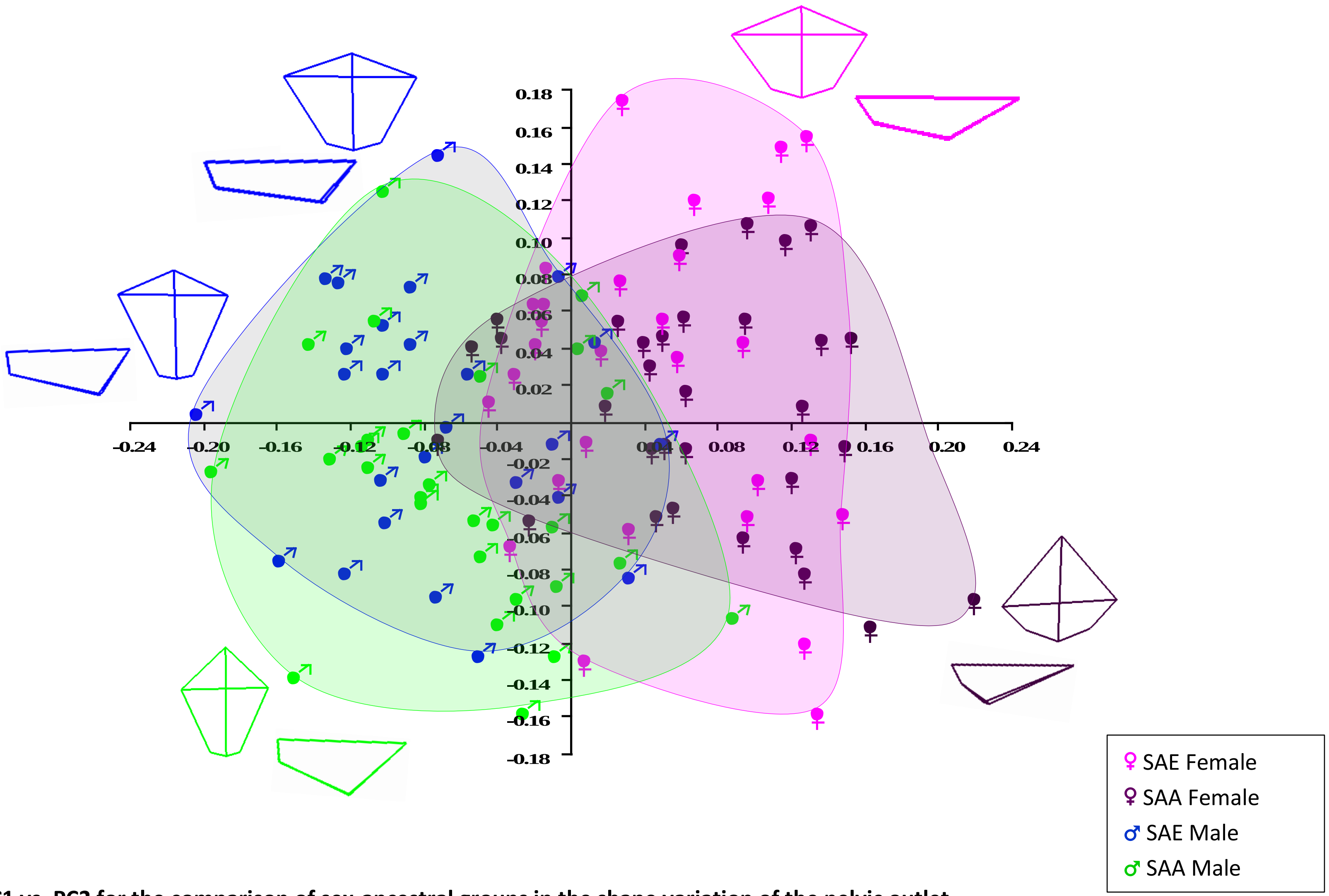


Figure 4.13 PC1 vs. PC2 for the comparison of sex-ancestral groups in the shape variation of the pelvic outlet

Although there is a distinctive overlap of scatter points representing to the four sex-ancestral groups in the centre of the graph, females in general are located on the right side, compared to males, who are located on the left side. Pelvic outlet shapes on the right side (females) appeared wider with the widest transverse diameter more anteriorly placed than in representatives on the left of the graph (males). These variations noted in the PC1 vs. PC2 plot in the pelvic outlet shape are reflected in the statistical analyses: the inter-sex p-value was 0.0005 and inter-ancestral group p-value was 0.073.

4.4.3.2 Comparison of pelvic outlet shape between ancestral groups within sexes

The pelvic outlet shape variations between ancestral groups within sexes are compared. In Figure 4.14 the variances in pelvic outlet shape along PC1 vs. PC2 can be seen for the comparison between females, and in Figure 4.15 for the comparison between males.

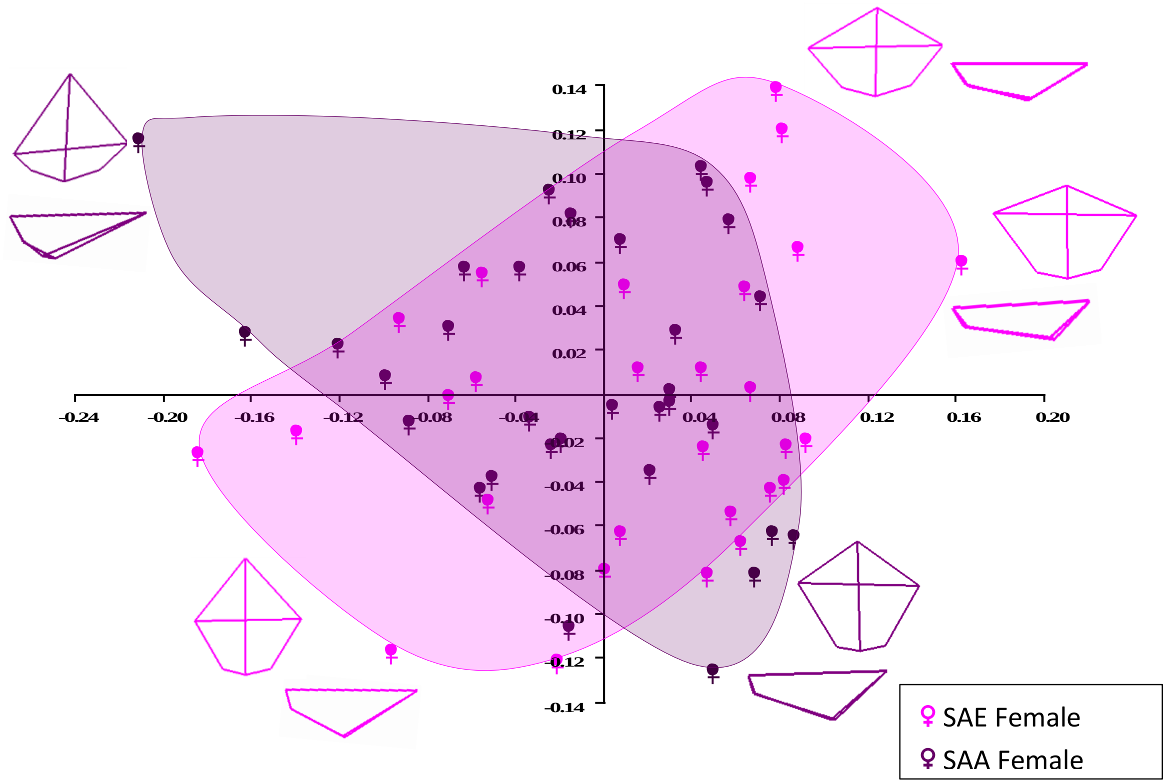


Figure 4.14 PC1 vs. PC2 in the comparison of the shape variation for the pelvic outlet between SAA female and SAE female

The ancestral groups overlap significantly (Figure 4.14), with no group exclusively dominating a quadrant. The p-value is 0.1105. The extremes shapes on the right side of the graph representing SAE female might be a reflection of the generally wider pelvic outlet shape as compared to SAA female.

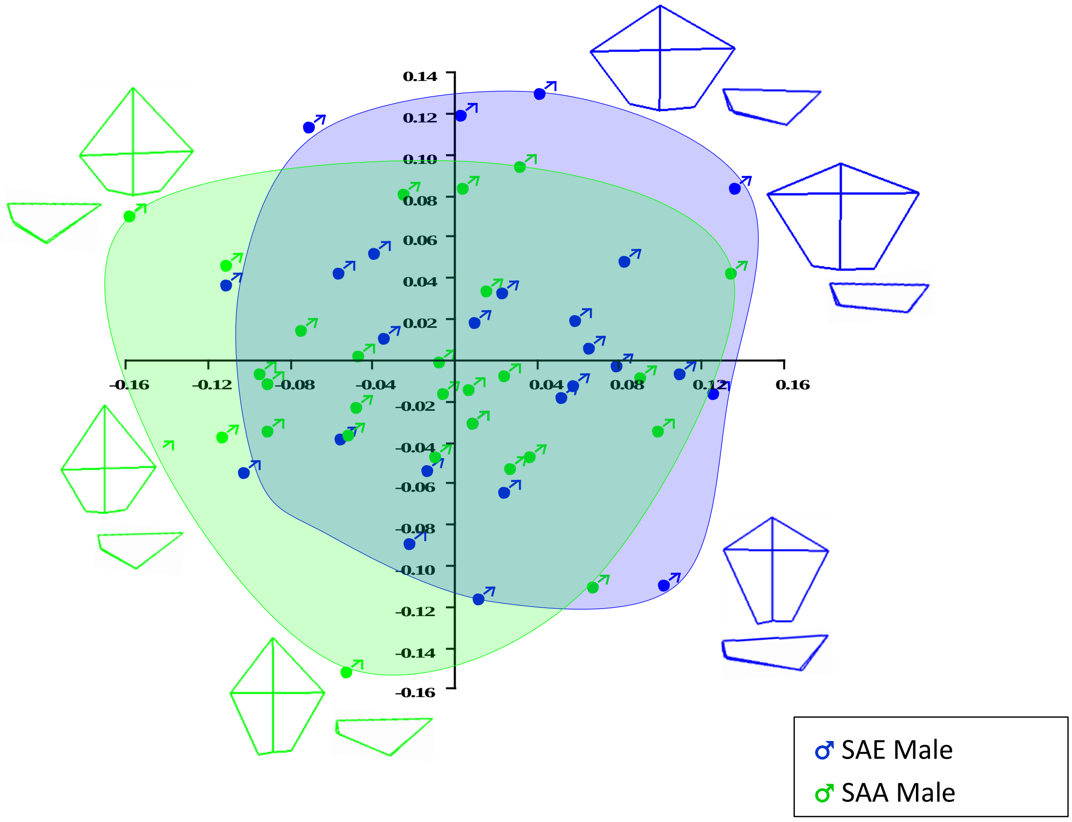


Figure 4.15 PC1 vs. PC2 in the comparison of the shape variation between SAA male and SAE male

The scatter points on the PC1 vs. PC2 graphs (Figure 4.15) overlaps greatly when comparing male pelvic outlet shape. Extreme outliers in the right upper quadrant (SAE male) compared to extreme outliers on the left side of the graph (SAA male) present, in general, with a relatively wider, more posteriorly placed widest transverse diameter. The comparison between SAA male and SAE male was, however, not significant (p-value = 0.064).

4.4.3.3. Comparison of pelvic outlet shape between sexes within ancestral groups

The pelvic outlet shape variations between sexes within ancestral groups are compared. In Figure 4.16 the variation in the pelvic outlet shape along PC1 vs. PC2 comparing the sexes in SAA can be seen, while in Figure 4.17, the comparison between the sexes in SAE is presented.

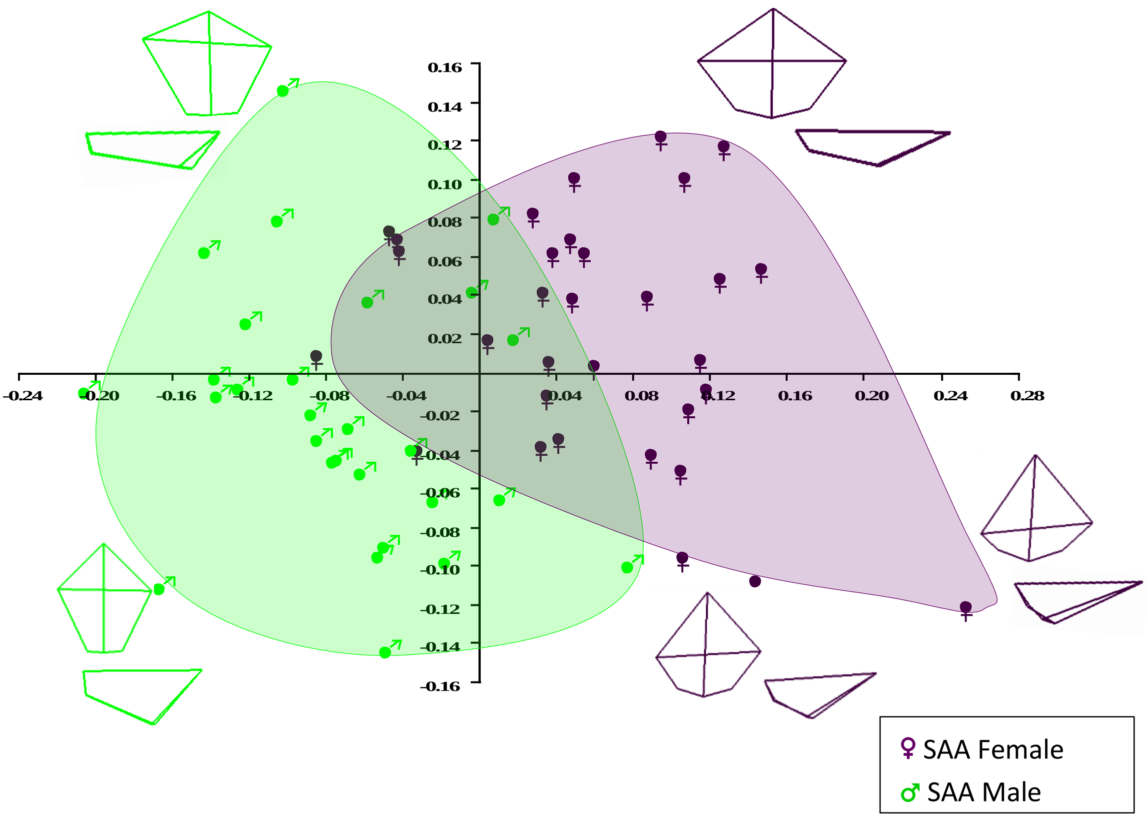


Figure 4.16 PC1 vs. PC2 pelvic outlet shape variation in the comparison of SAA male and SAA female

When comparing sexes in SAA in Figure 4.16, scatter points for to males and females respectively, overlap in the centre of the graph, with SAA female representatives dominating the right side and the male SAA representative dominating the left side. The comparison between the sexes in SAA is statistically significant (p-value = 0.0005). The extreme shapes on the right side of the graph (SAA female), as compared to the left side of the graph (SAA male), might be a reflection of the generally wider shape and more anteriorly placed widest diameter. The relatively more anteriorly placed transverse diameter in females compared to males is also reflected on the lateral pelvic outlet wireframes as the relatively shorter distance from the pubic symphysis to the ischial tuberosities. Lateral views of the pelvic wireframes further demonstrate a relatively longer and more posteriorly located points of junction between the inferior pubic ramus and the ischial ramus in SAA female, as compared to SAA male.

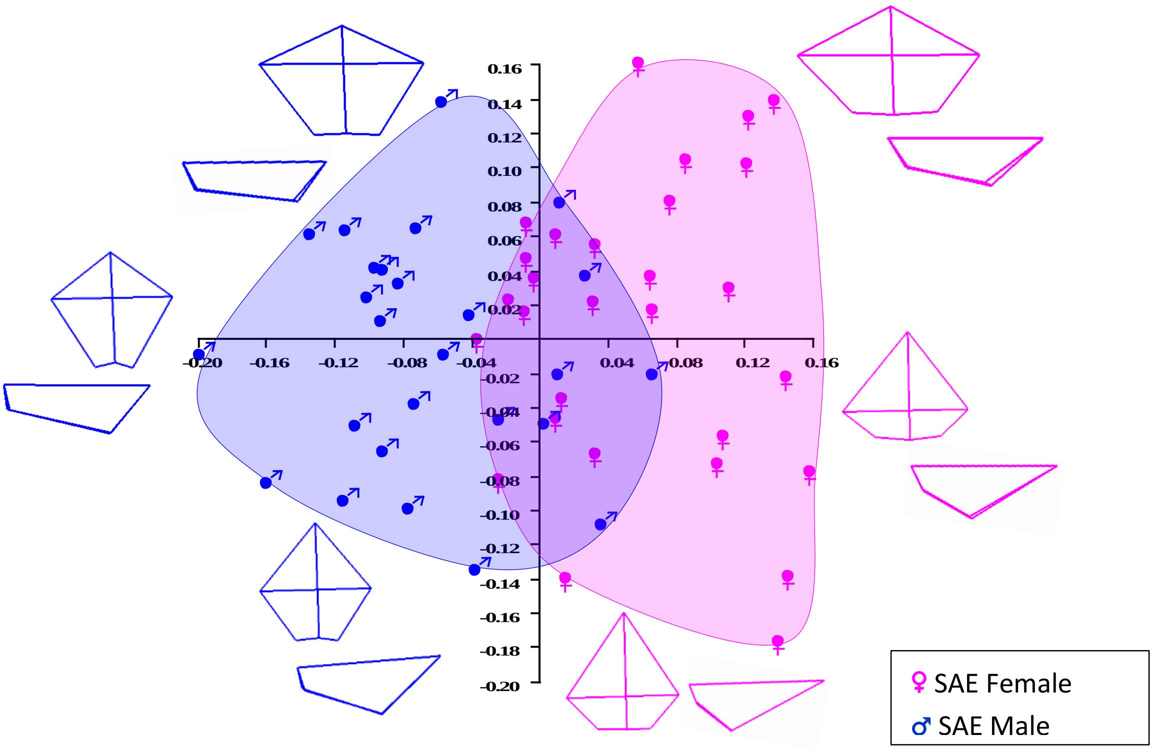


Figure 4.17 PC1 vs. PC2 in the comparison of the shape variation for the pelvic outlet between SAE male and SAE female

There is some overlap of the scatter points representing to the male and female SAE respectively (Figure 4.17). SAE male dominate the left half of the graph, while SAE female dominate the right half of the graph. The p-value of the inter-sex variation is 0.0005. The most obvious difference in the pelvic outlet shape between SAE female and SAE male is the relative position of the greatest transverse diameter. The greatest transverse outlet diameter seems to be located more anteriorly in female SAE, as opposed to SAA male, which is more posterior. SAE female pelvic outlet shapes also appear relatively wider than those of SAE male. As noted in SAA, lateral views of the pelvic wireframes further demonstrate a relatively longer and more posteriorly located points of junction between the inferior pubic ramus and the ischial ramus in SAE female, as compared to SAE male.

4.4.3.4 Procrustes mean pelvic outlet shape for comparison between sex-ancestral groups

The mean pelvic outlet shape of each sex-ancestral group in isolation was determined and is illustrated in Figure 4.18 for descriptive purposes. The antero-superior view and the lateral view are depicted.

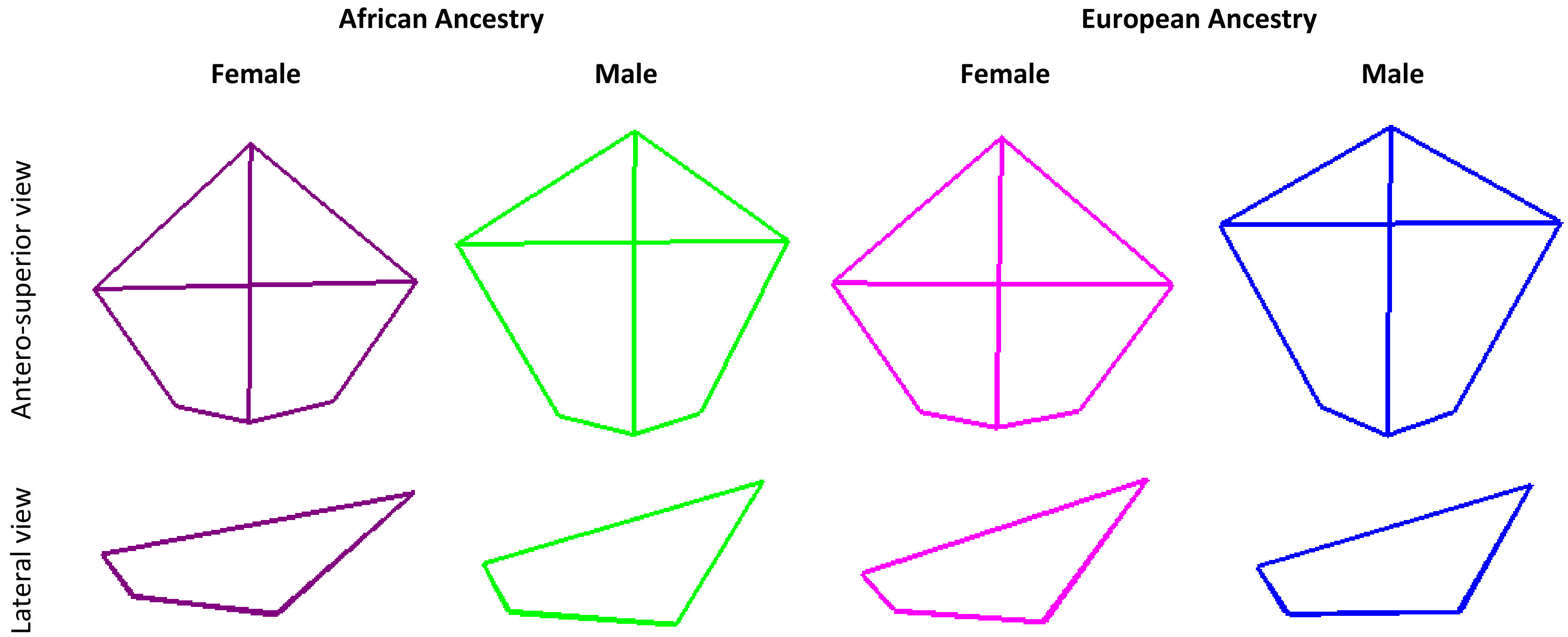


Figure 4.18: The Procrustes mean pelvic outlet shape of each of the four sex-ancestral groups

The Procrustes mean shapes confirm the statistical significant results when comparing sexes, as well as the visual impressions on the PC1 vs. PC2 graphs (Figure 4.18). The greatest transverse outlet diameter is wider and located more anteriorly in females than in to males. A relatively longer posteriorly directed inferior pubic ramus is noted in females as opposed to males. SAE of both sexes presented with relatively wider pelvic outlet shapes than SAA. The greatest transverse outlet diameter appears to be situated more posteriorly in SAE male, compared to SAA male.

4.4.4 Pubic region

Shape analyses of the pubic region were performed among the sex-ancestral groups. The pubic region is defined by the digitised landmarks and comprises the most superior and inferior point of the pubic symphysis, the points of junction of the inferior pubic ramus with the ischial ramus and the inferior points of the ischial tuberosity on either side as depicted in Figure 3.17.

4.4.4.1 Comparison of the pubic region shape between sex-ancestral groups

In Figure 4.19, the analysis of variances along PC1 vs. PC2 for the pubic region are seen in the comparison between sexes and ancestral groups.

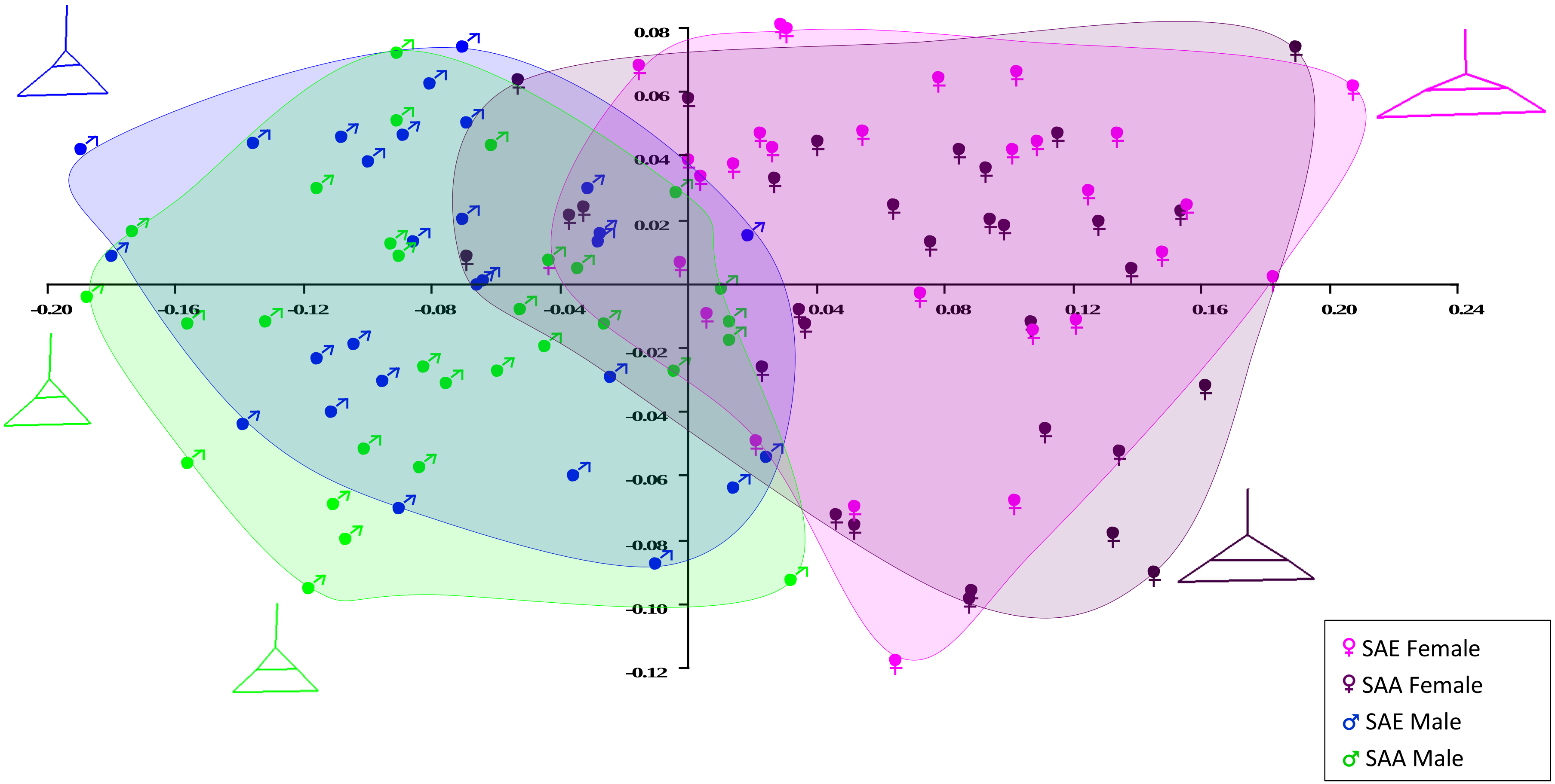


Figure 4.19 PC1 vs. PC2 for the pubic region shape variation in the comparison of SAA male and SAA female

In the PC1 vs. PC2 plot for the variation of shape in the pubic region, the sexes demonstrate limited overlap, while the ancestral groups demonstrate a great extent of overlap. As expected, the females present with wider shapes reflecting the subpubic region and possibly relatively longer inferior pubic rami, as compared to the ischiopubic rami.

4.4.4.2. Comparison of the pubic region between ancestral groups within sexes

The variation in the shape of the pubic region between ancestral groups within sexes is compared. In Figure 4.20, variances along PC1 vs. PC2 can be noted in the comparison between ancestral groups in females, and in Figure 4.21, the comparison between males.

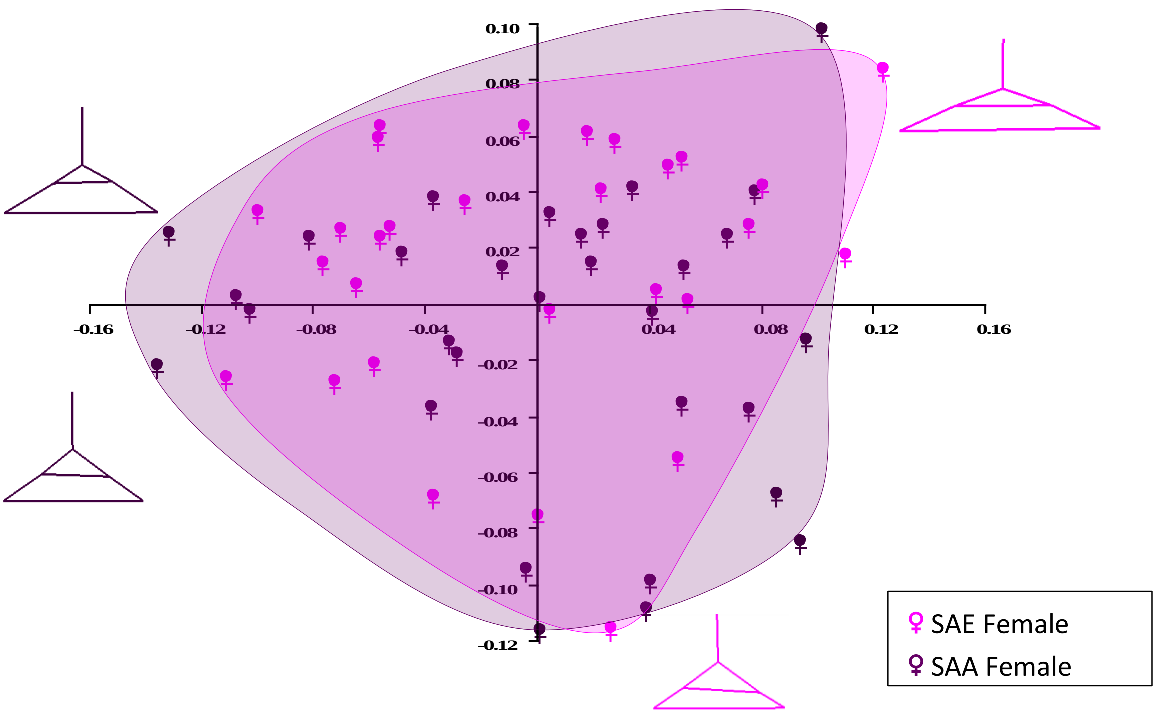


Figure 4.20 PC1 vs. PC2 for the pubic region shape variation in the comparison of SAE female and SAA female

Although in the shape variation of the pubic region, the scatter points of the SAE female and SAA female overlap almost entirely, as determined by two group multivariate permutation, was significant (p-value = 0.019).

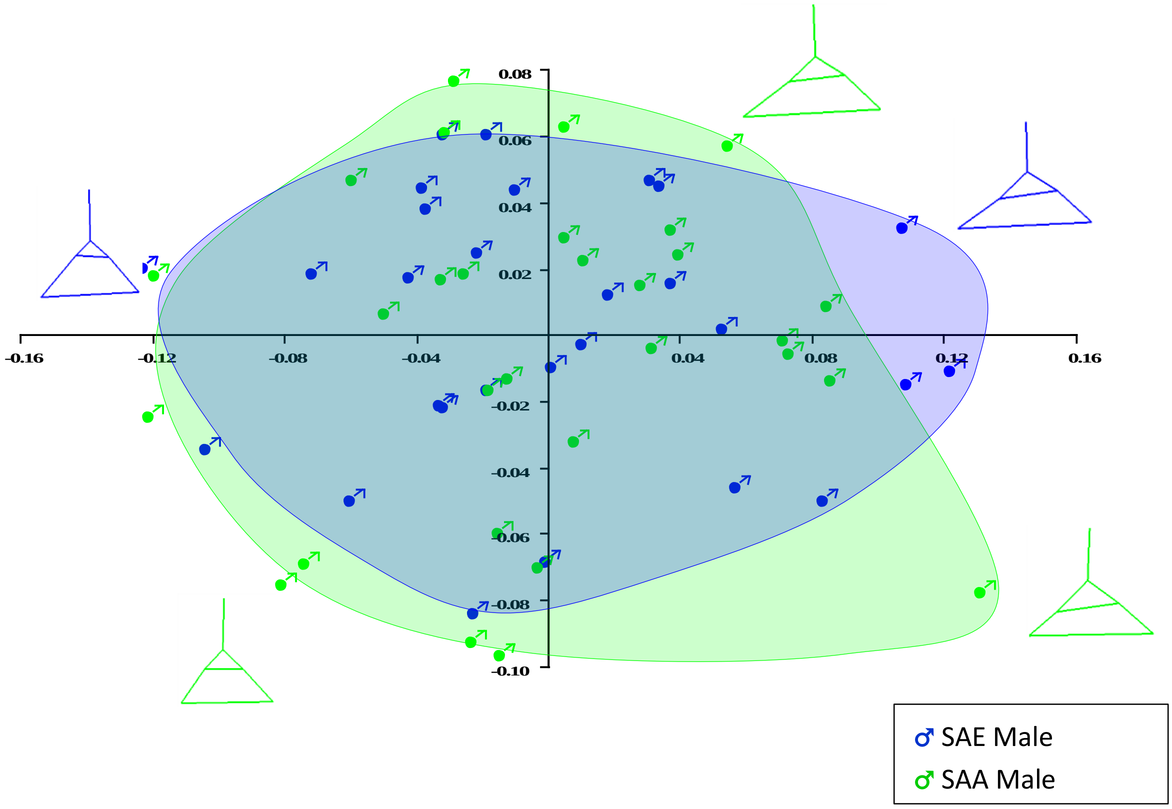


Figure 4.21 PC1 vs. PC2 for the pubic region shape variation in the comparison of SAE male and SAA male

In the PC1 vs. PC2 plot for the shape variation of the pubic region (Figure 4.21), the scatter points of the SAE male and SAA male overlap almost entirely and no statistically significant variation could be noted (p-value = 0.2595). In both male and female ancestral comparisons, SAA demonstrated a wider scattering as compared to SAE, which could denote a greater variability in shape.

4.4.4.3 Comparison of the pubic region between sexes within ancestral groups

The variation in the shape of the pubic region between sexes within ancestral group is compared. Figure 4.22 represents analysis of variance along PC 1 and PC 2 in the comparison between female and SAA male, while male and female SAE can be seen in Figure 4.23.

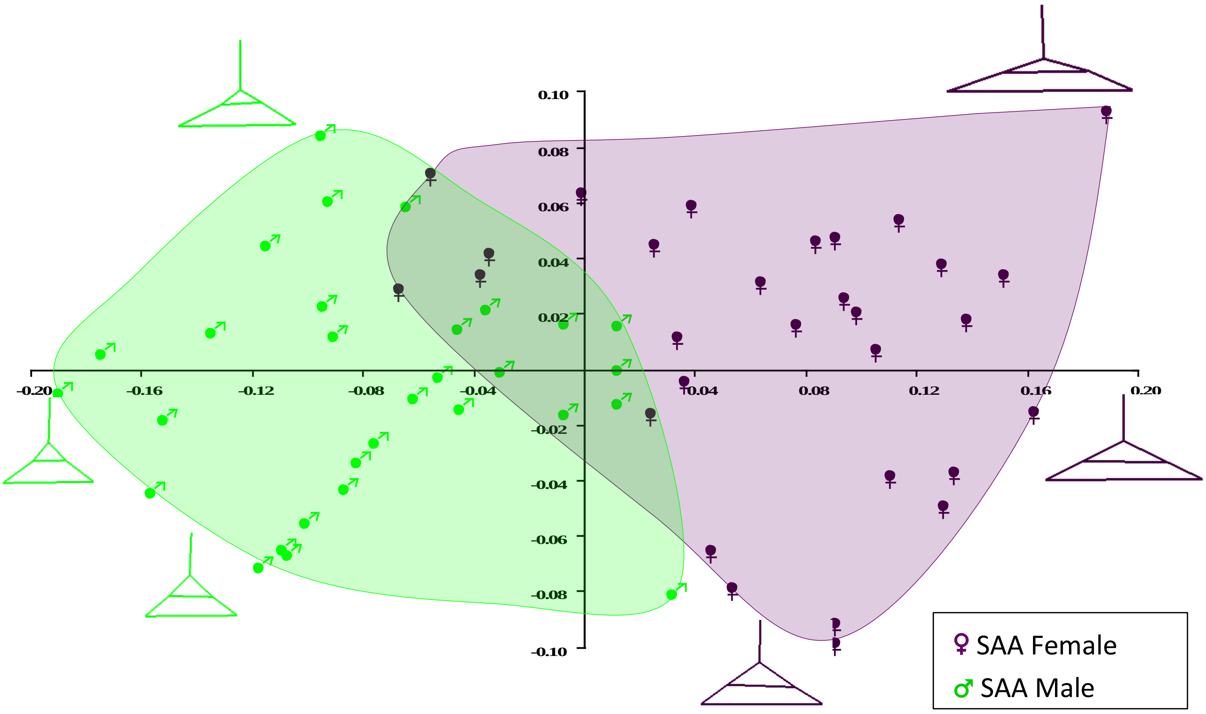


Figure 4.22 PC1 vs. PC2 for the variation in shape of the pubic region in the comparison of SAA male and SAA female

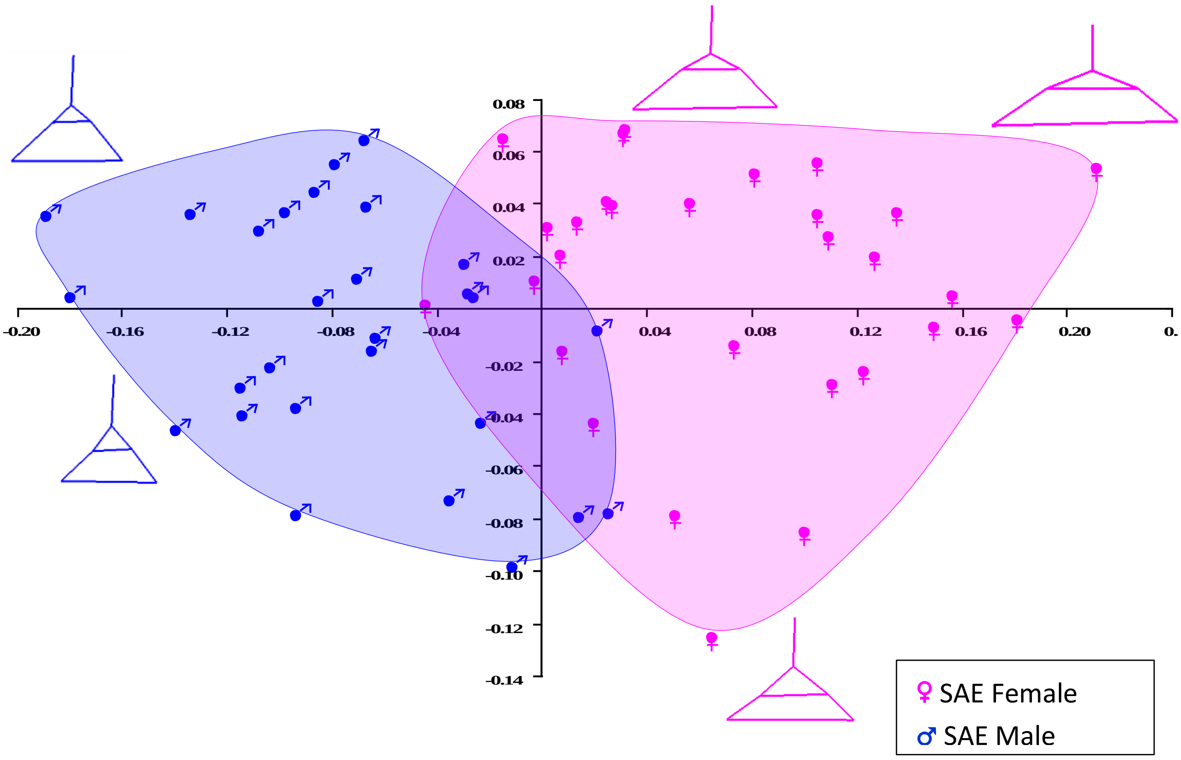


Figure 4.23 PC1 vs. PC2 for the variation in shape of the pubic region in the comparison of SAE male and SAE female

The variation of shape of the pubic region between the sexes within both SAA and SAE (Figures. 4.22 and 4.23) demonstrated a clear separation with minimal overlap. Females of both sexes presented with relatively wider subpubic shapes.

4.4.4.4 Procrustes mean pubic region shape for comparisons between sex-ancestral groups

The mean shape of the pubic region in the four sex ancestral groups were determined separately. In Figure 4.24, the determined mean shape for each sex-ancestral group is compared. The antero-superior views, as well as the lateral views, are depicted.

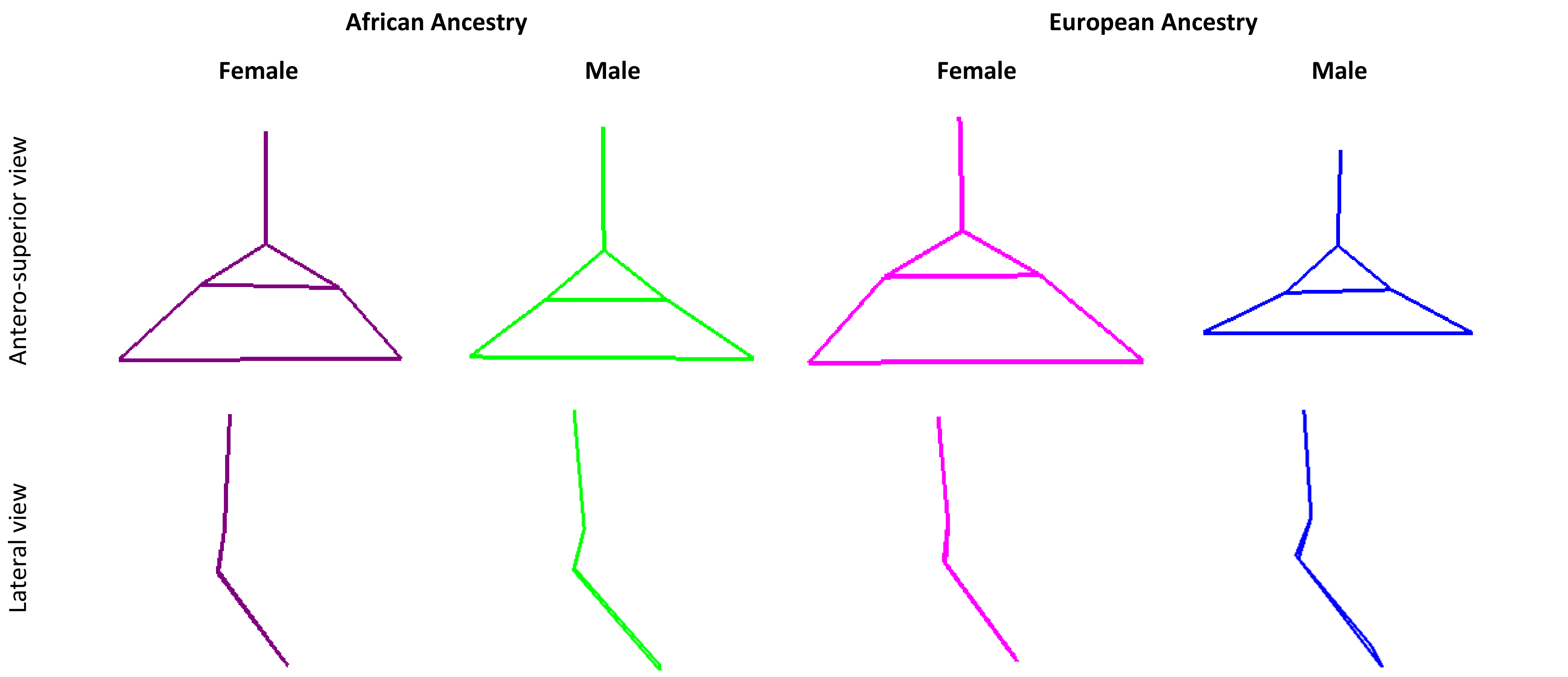


Figure 4.24: The Procrustes mean shape of the pubic region in each of the four sex-ancestral groups

When comparing the mean shapes of the pubic region, the impressions of the variations between the sexes involve wider subpubic regions as previously described (Figure 4.24). Comparison between ancestral groups illustrates a relatively greater subpubic region in SAE compared to SAA, in females.

4.4.5 Pelvic Canal

The pelvic canal comprised the landmarks describing the pelvic inlet, the midpelvis and the pelvic outlet. By using a wireframe to connect the points, a continuous canal could be visualised connecting pelvic inlet, midpelvis and pelvic outlet. Figures 3.19 presents the canal from a lateral and antero-superior view respectively, while visualising the PC1 vs. PC2 for each sex-ancestral group in Figure 4.25.

4.4.5.1 Comparison of the pelvic canal shape between sex- ancestral groups

In Figure 4.25, the analysis of variances along PC1 vs. PC2 for the pelvic canal shape in the comparison between sexes and ancestral groups is illustrated.

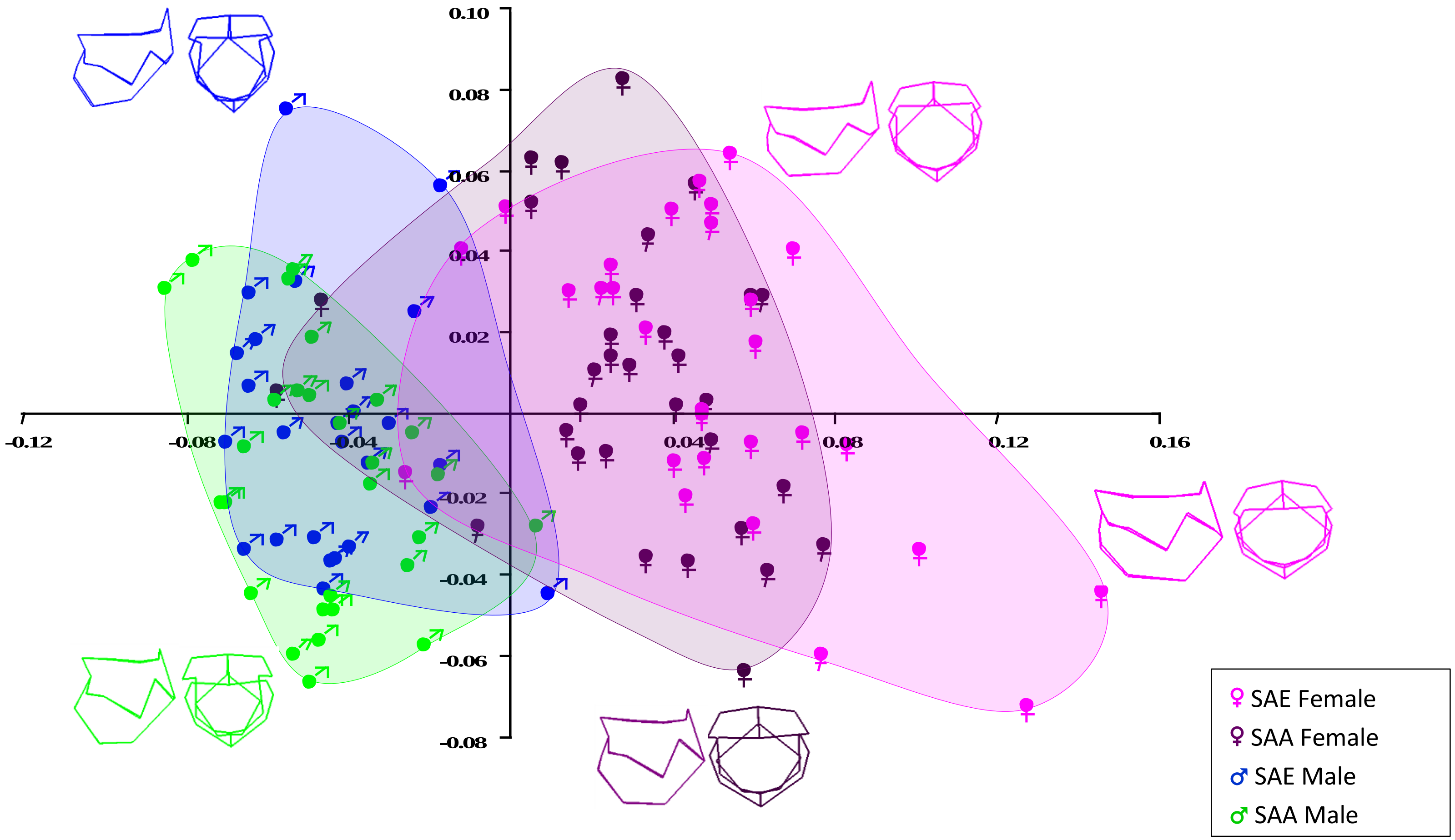


Figure 4.25 PC1 vs. PC2 for the pelvic canal shape variation in the comparison of sex-ancestral groups

The scatter points belonging to the four sex-ancestral groups are distributed from left to right on the graph in the following sequence: SAA male, SAE male, SAA female and SAE female. The distribution of scatter points belonging to each sex-ancestry group becomes progressively wider from left to right, indicating greater variance in the shape of the pelvic canal in females and in SAE. Although some overlap is noted between all four groups, the overlap between the sexes is greater than that between ancestral groups. The distinction between males and females is obvious: scatter points of males are found on the left side of the graph with SAA male on the extreme left, while females on the right side of the graph with SAE female on the extreme right. The pelvic canal wire frames noted on the left side of the graph are generally narrower with a relatively shorter distance between the ischial spines, smaller subpubic areas, as well as higher and more prominent sacral promontories and a more anteriorly placed coccyx, as compared to the right side of the graph. A relatively greater space between the midpelvis and pelvic outlet rings can be noted on the right of the graph (females) as compared to the left of the graph (males). The p-value for both inter-sex and inter-ancestral variations is 0.0005, which is indicative of significant variations.

4.4.5.2 Comparison of pelvic canal shape between ancestral groups within sexes

The variation in pelvic canal shape between ancestral groups within sexes is compared. In Figure 4.26 the analysis of variances along PC1 vs. PC2 can be noted in the comparison between ancestral groups in females and in Figure 4.27, the comparison between males.

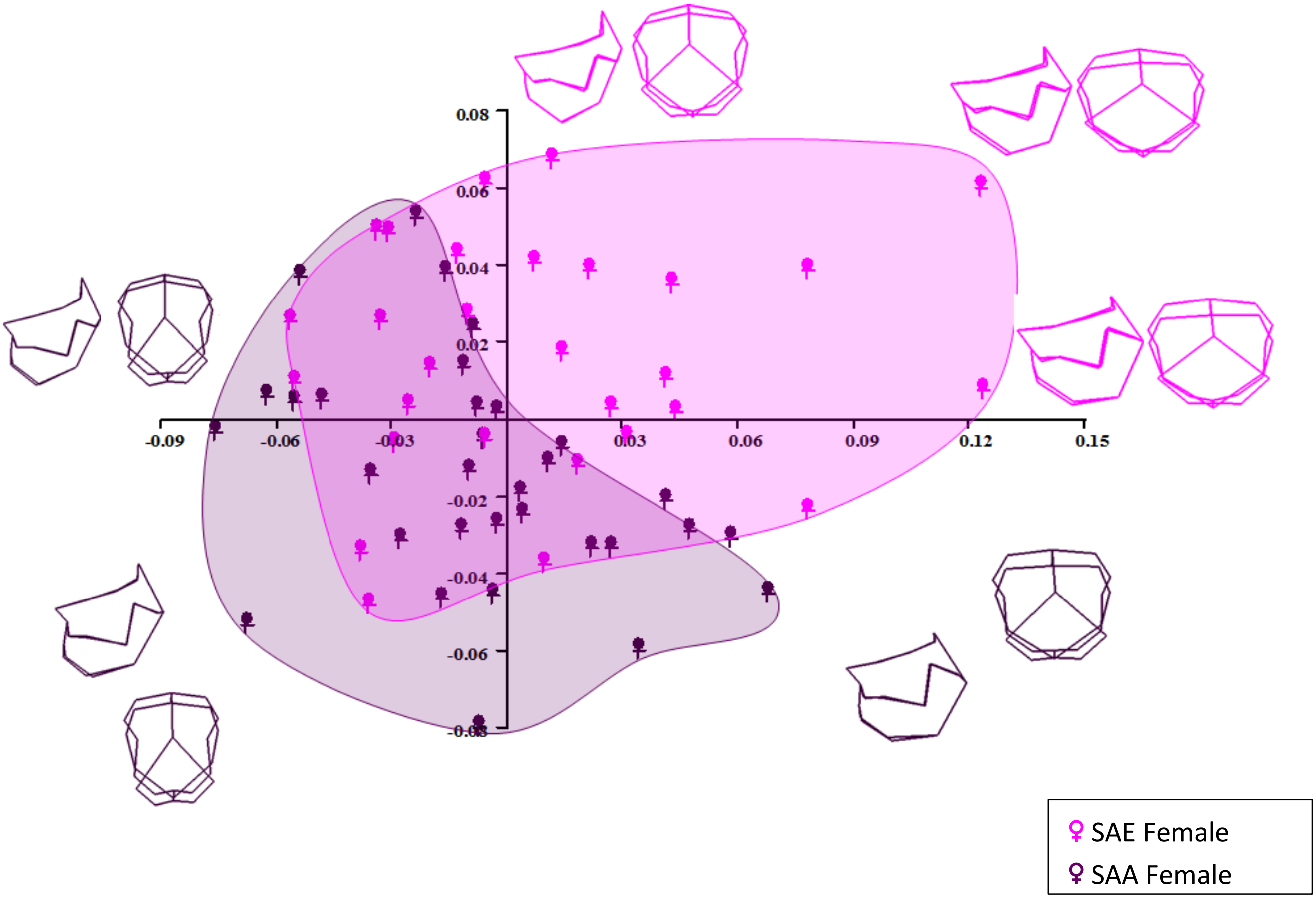


Figure 4.26 PC1 vs. PC2 for the pelvic canal shape variation in the comparison of SAA female and SAE female

In the comparison between females (Figure 4.26), the pelvic canal shape demonstrates some extent of overlap between ancestral groups. Female SAE predominate on the right side of the graph and present with visibly wider pelves and a more spacious canal posteriorly, between the midpelvis and pelvic outlet. Greater variation in pelvic shape can be noted in female SAE. The p-value for the inter-ancestral group variation was 0.0005.

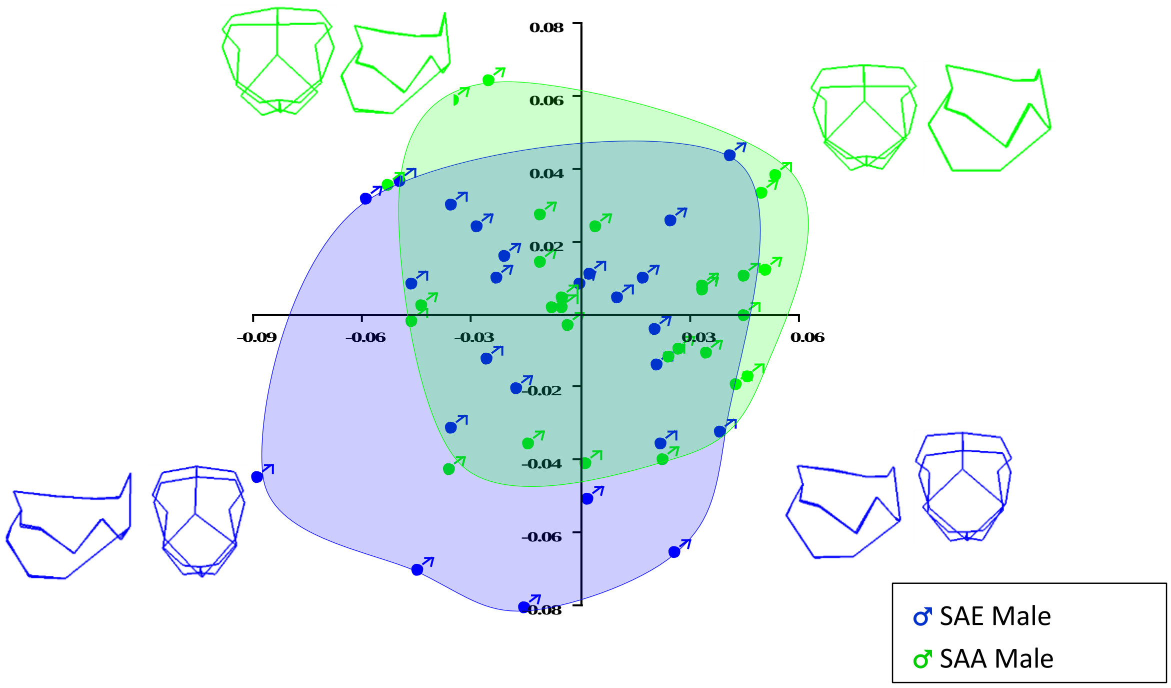


Figure 4.27 PC1 vs. PC2 in the comparison of the shape variation for the pelvic canal between SAA male and SAE male

In the comparison between males, the pelvic canal shape demonstrates an extent of overlap between ancestral groups, with a significant p-value of 0.0005. SAE male predominate in the left lower quadrant of the graph, with a relatively longer antero-posterior diameter and wider subpubic region.

4.4.5.3 Comparison of the pelvic canal shape between sexes within ancestral groups

The variation in pelvic canal shape between sexes within ancestral groups is compared. In Figure 4.28 the analysis of variances along PC1 vs. PC2 can be noted in the comparison between sexes within SAA individuals, and in SAE individuals in Figure 4.29.

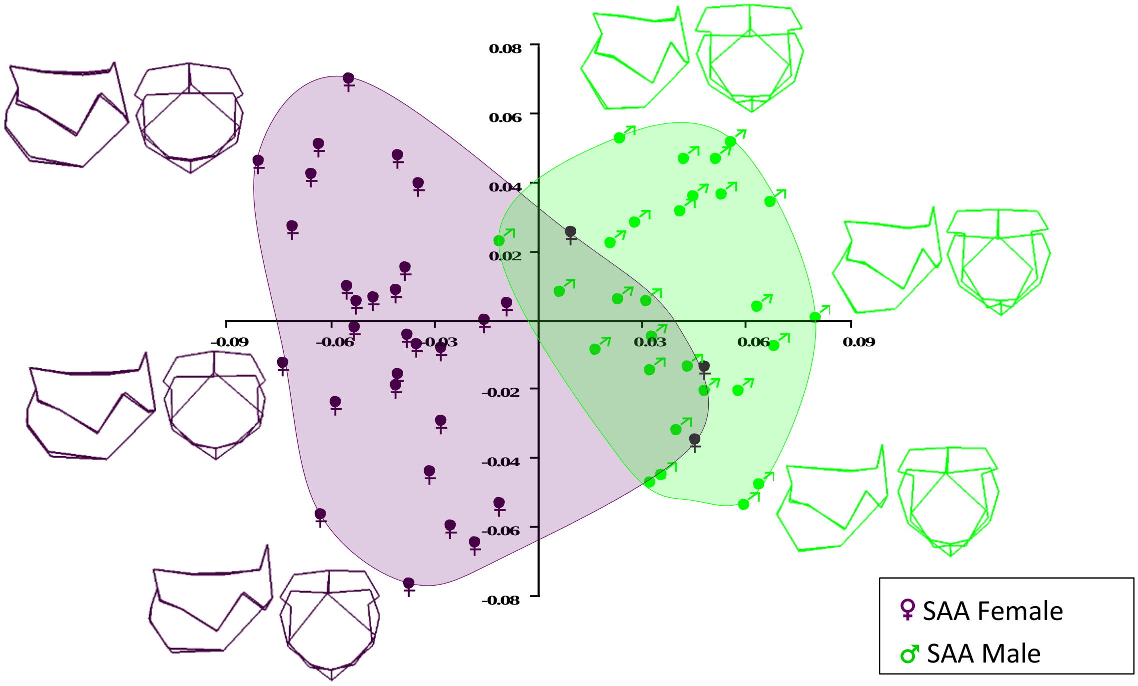


Figure 4.28 PC1 vs. PC2 in the comparison of the shape variation for the pelvic canal between SAA female and SAA male

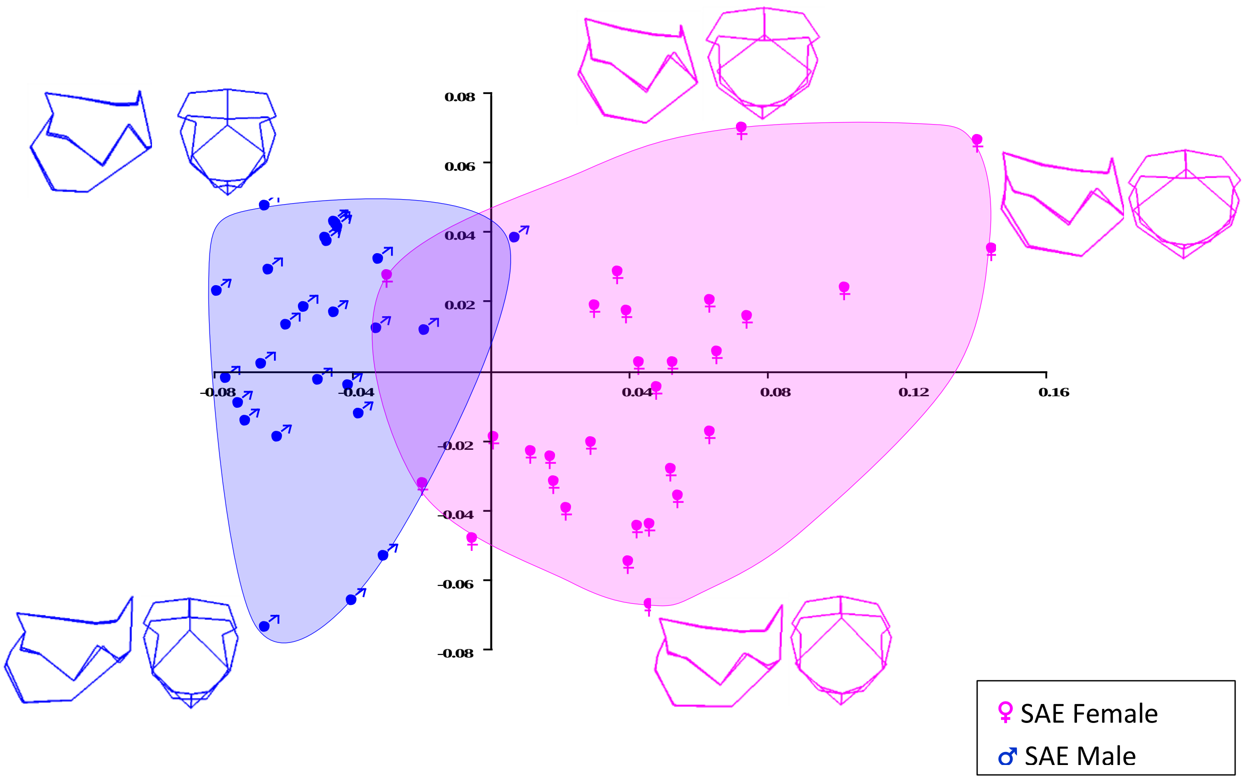


Figure 4.29 PC1 vs. PC2 in the comparison of the shape variation for the pelvic canal between SAE female and SAE male.

Although some extent of overlap exists in the PC1 vs. PC2 plots for the comparison of the pelvic shape between the sexes within ancestral groups, the pelvic canal shape is wider and the area between the midpelvis and pelvic outlet is more spacious with the pubic symphyseal area more elongated in females, as compared to males. The p-value for the inter-sex group variation was 0.0005.

4.4.5.4 Procrustes mean pelvic shape for comparisons between sex-ancestral groups

The mean pelvic shape in the four sex ancestral groups were determined separately. In Figure 4.30 the determined mean shape for each sex-ancestral group is compared to each other. The antero-superior views, as well as the lateral views, are depicted.

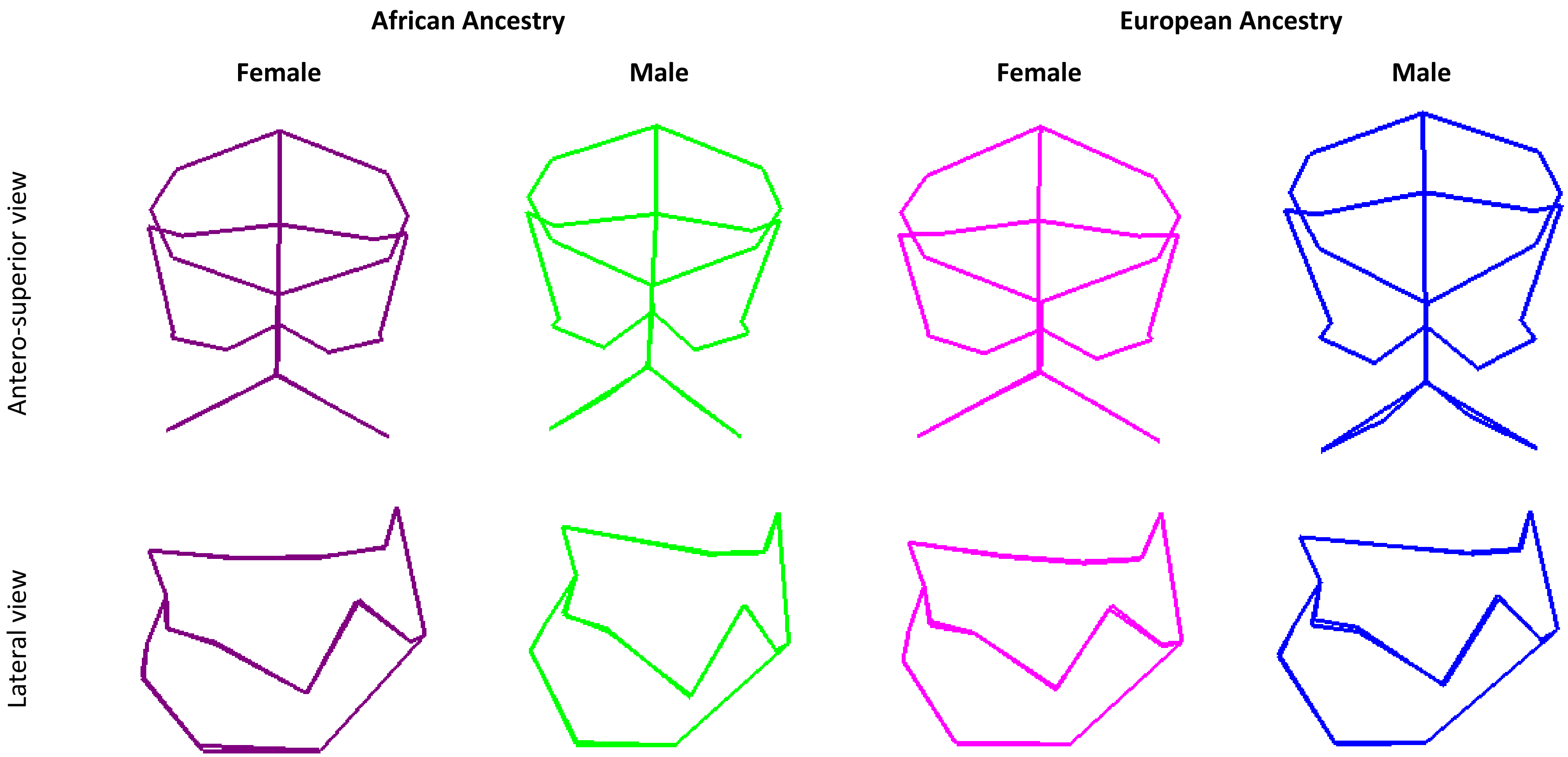


Figure 4.30: The Procrustes mean shape of the pelvic canal in each of the four sex-ancestral groups

The Procrustes mean shape of the pelvic canal did not vary noticeably between SAA female and SAE female. The Procrustes mean shape in SAE males seemed to be greater anteriorly, than in SAA males. Females of both groups presented with a relatively wider shape, especially at the pelvic outlet.

4.4.6 Pelvic shape and stature

The height of the pelvis, as reflected in the dimensions connecting the pelvic inlet, midpelvis and pelvic outlet, demonstrated moderately positive correlations in regard to the stature, which were often statistical significant (Appendix A). Sacral length (SL) (complete sample and in SAA females), depth of true pelvis on the left (LDTP) (complete sample and in females) and on the right (RDTP) (complete sample and in SAA females) respectively, the height of the pelvis on the left (LHTP) (complete sample and in SAA females) and on the right (RHTP) (complete sample and in females) respectively as well as SACHOL (the anteroposterior dimension of the midpelvis) (only SAE males).

The ANG (complete sample) and the distance between the inferior most landmarks on the left and right ischiopubic rami (LRIPR) (complete sample) correlated statistically significantly, but negatively, with stature. The finding that a shorter stature in the complete sample was associated with greater dimensions. The reflection of the shorter stature of females as compared to males was often accompanied by wider pelvic dimensions. The significant negative correlation between wider pelvic dimensions and stature within sex-ancestral groups were studied in isolation. LRIPR showed a non-significant negative correlation in SAA female and a moderate positive and statistically significant correlation with stature in SAA male.

In addition, when sex-ancestral groups were analysed individually, many other dimensions were also found to correlate moderately/ significantly and positively with stature. Noteworthy is that in female SAA many correlations were very weak and negative apart from LIPR_IPS and RIPR_IPS (inferior most landmark on left or right ischiopubic rami, distinct elevation can be felt, to inferior most point on pubic symphysis) which correlated moderately and negatively with stature.

The shape variations noted among pelves belonging to SAE group had a stronger correlation with stature than the shape variations in SAA group. Males of SAE showed the highest correlation to stature than the other ancestral groups. The pelvic canal, as a whole unit has a greater correlation with stature than the pelvic inlet, midpelvis and pelvic outlet components in isolation (Table 4.11).

Table 4.11 Correlations of shape variations with stature

		African Ancestry		European Ancestry	
		Female	**Male**	**Female**	**Male**
Pelvic inlet	r	0.70	0.64	0.89	0.87
	r^2	0.49	0.41	0.80	0.76
Midpelvis	r	0.81	0.69	0.75	0.98
	r^2	0.65	0.48	0.56	0.96
Pelvic outlet	r	0.77	0.69	0.78	0.99
	r^2	0.60	0.47	0.61	0.99
Pelvic canal	r	0.85	0.84	0.91	0.98
	r^2	0.73	0.71	0.82	0.97

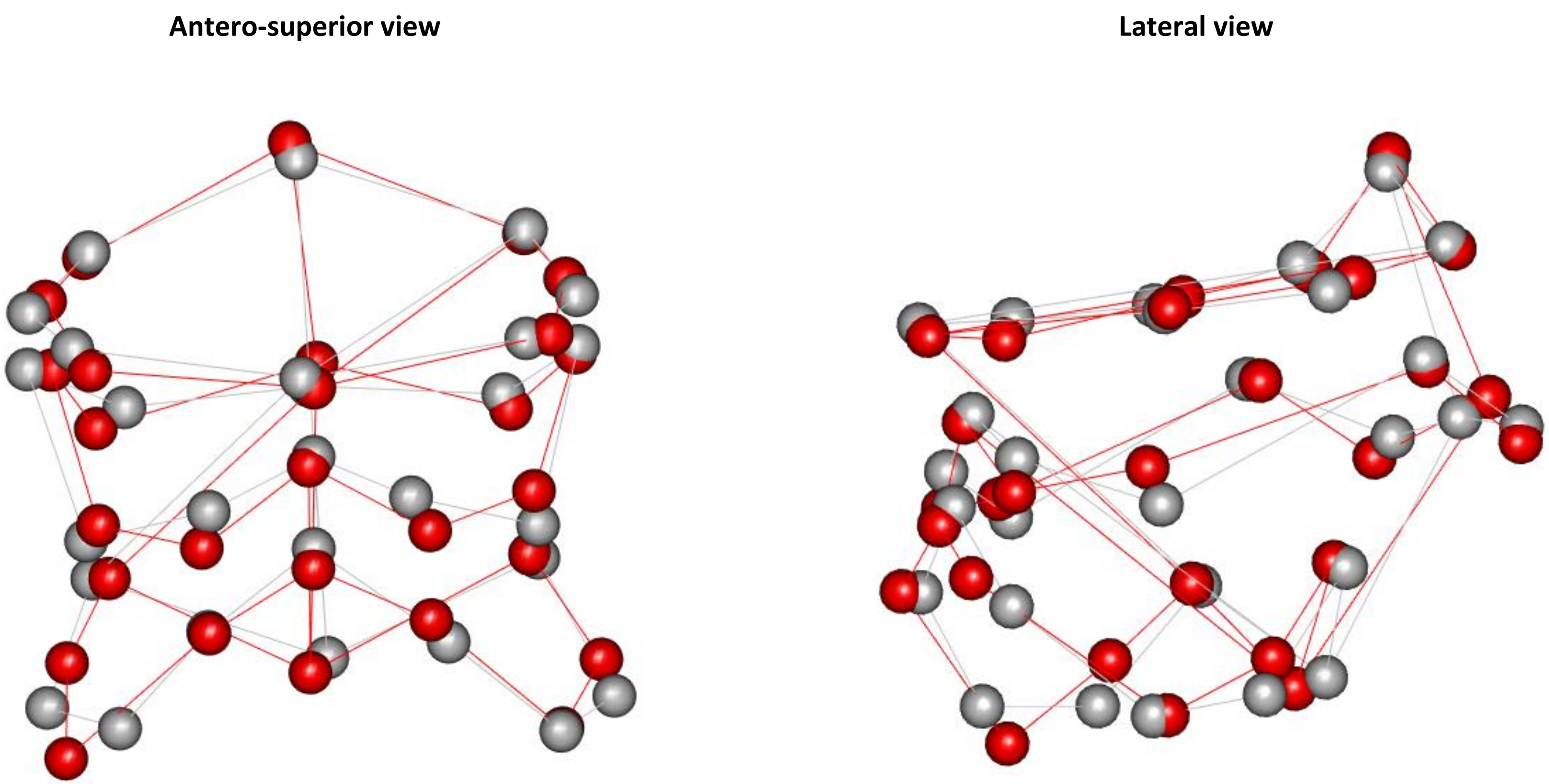
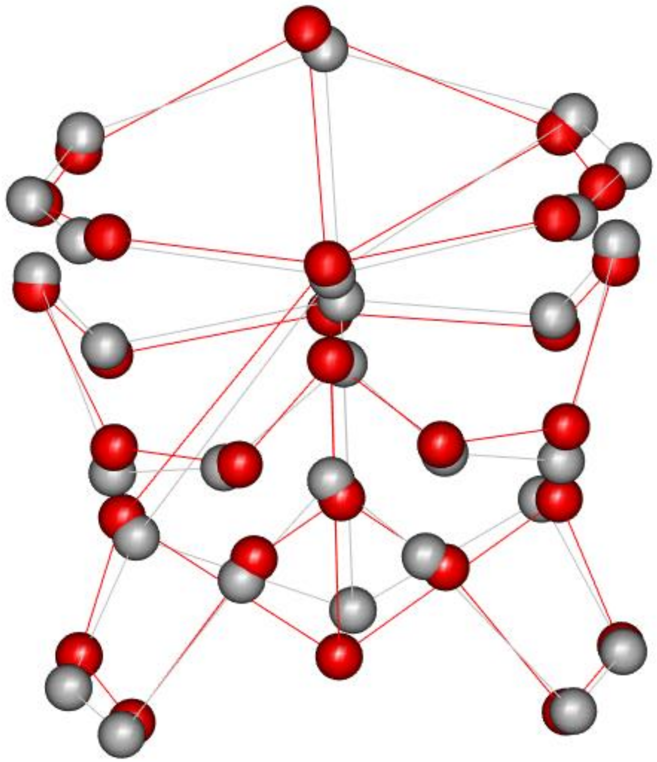


Figure 4.31 Schematic representation of the correlation of the variation in the pelvic shape with variation in stature in SAA Females
Grey spheres: the smaller stature
Red spheres: the greater stature

Antero-superior view



Lateral view

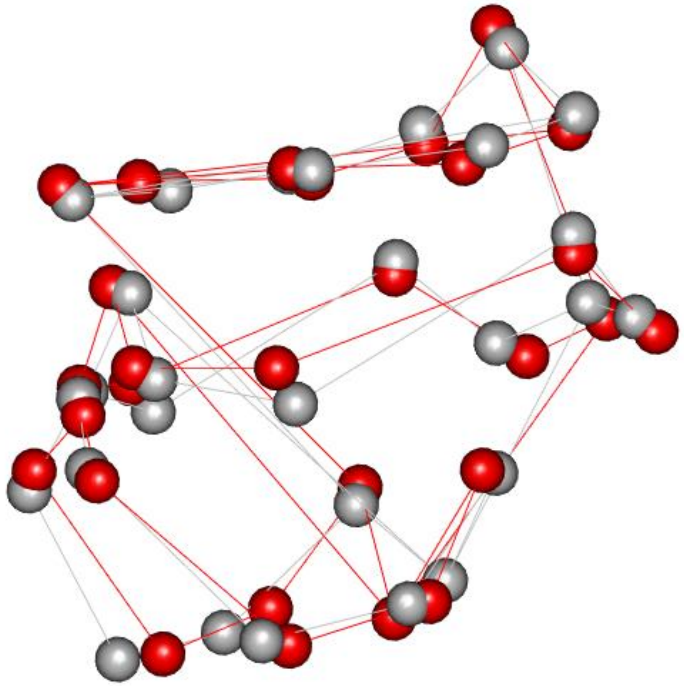


Figure 4.32 Schematic representation of the correlation of the variation in the pelvic shape with variation in stature in SAA Males
Grey spheres: the smaller stature
Red spheres: the greater stature

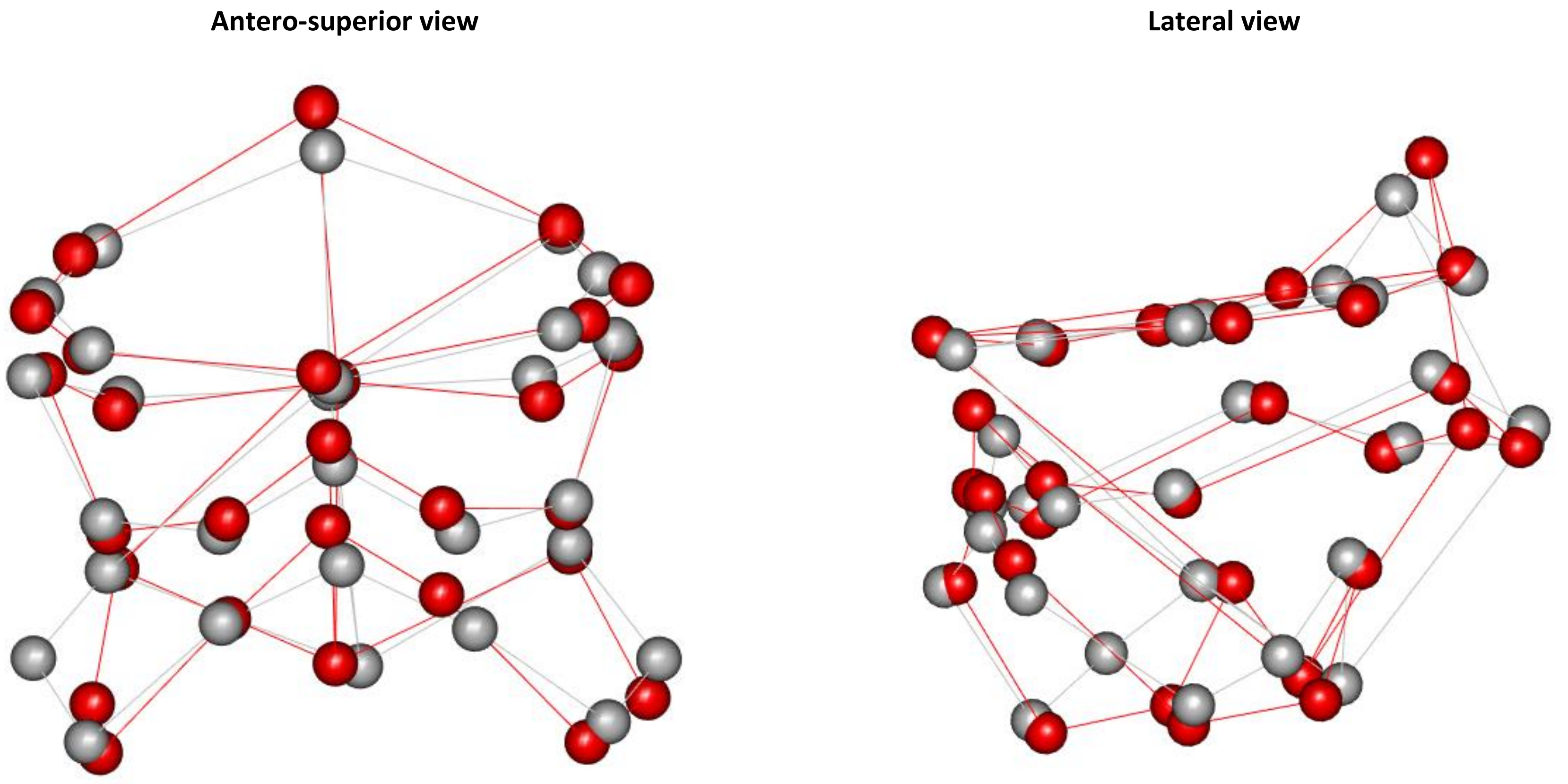


Figure 4.33 Schematic representation of the correlation of the variation in the pelvic shape with variation in stature in SAE Females
Grey spheres: the smaller stature
Red spheres: the greater stature

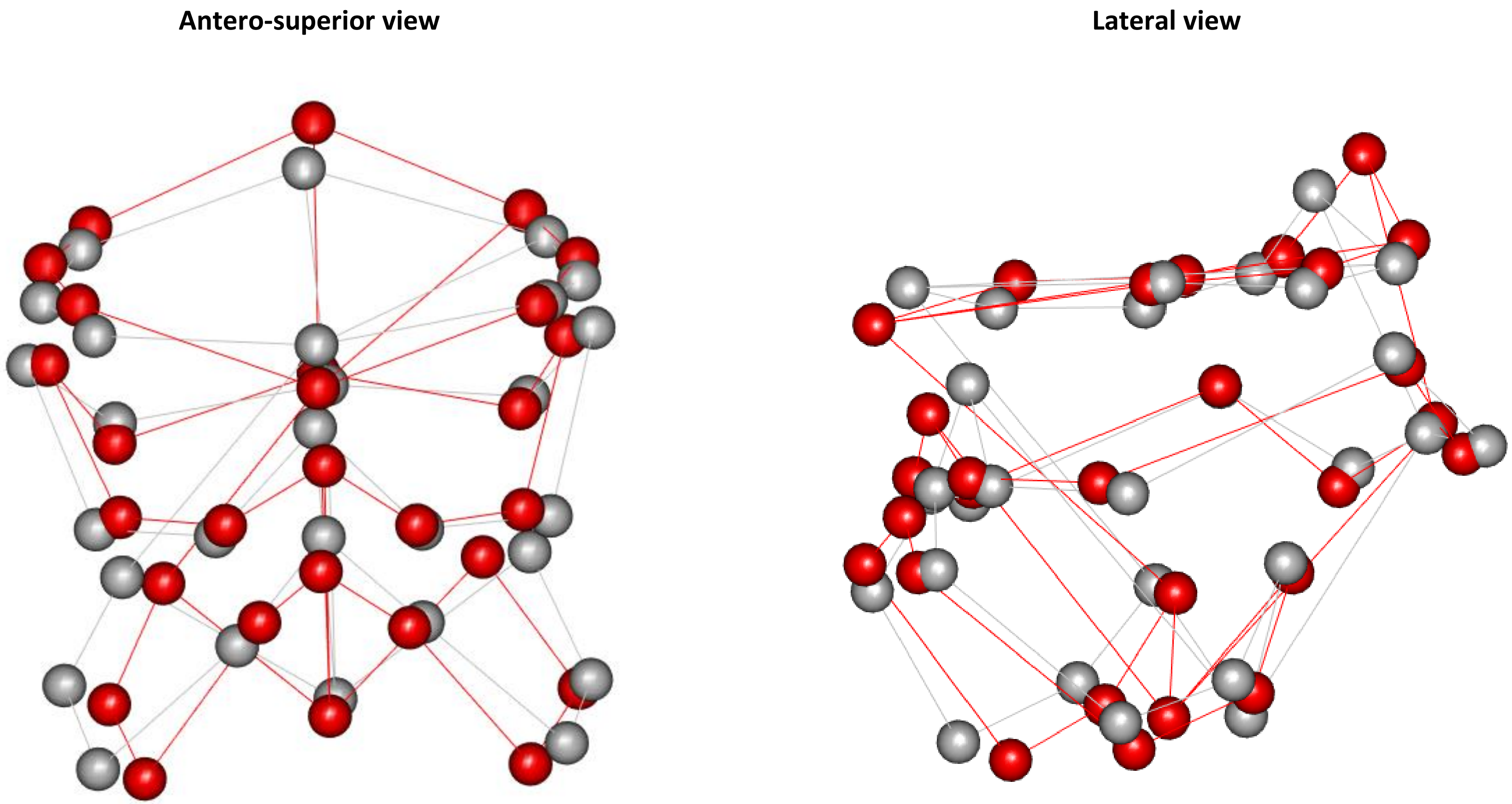


Figure 4.34 Schematic representation of the correlation of the variation in the pelvic shape with variation in stature in SAE Males
Grey spheres: the smaller stature
Red spheres: the greater stature

Figures 4.31 – 4.34 is schematic representation of the correlation of the variation in the pelvic shape with variation in stature. The grey spheres represent the minimum stature, while the red spheres represent the maximum stature. A minimal relative elongation supero-inferiorly, as opposed to the transverse, pelvic canal dimensions can be noted in especially SAE male as the red spheres were more superiorly and inferiorly placed beyond the grey spheres. On the lateral view of the schematic representation, the red spheres extended beyond the grey spheres anteriorly and posteriorly. This relative anteroposterior deepening of the pelvic canal is the least pronounced in SAA male. In SAA female the posterior aspect of the pelvic canal seems to increase with stature. In both male and SAE female, a taller stature was associated with a higher and more posteriorly positioned sacral promontory. In SAA male the pelvic canal seemed to become greater anteriorly with an increase in height.

4.4.7 Pelvic shape and age

Unlike stature correlations, age correlations were mostly weak (Appendix B). Statistically significant and moderate correlations noted in the complete sample were only observed in some instances when sex-ancestral groups were studied in isolation. The diameters correlating with stature in male SAE included: TI, LRHTP, RHTP and LPS in SAE female. SAA female displayed no statistical significant correlations with aging while SAA male only displayed a statistical significant but negative correlation with aging concerning the DIA_CONJ. OBS_CONJ, LPS and SL were statistically significantly correlated to aging in SAE female.

Of note is that the anteroposterior inlet diameter was weakly to moderately negatively but not significantly correlated to aging in all four sex-ancestral groups in isolation. Weak negative correlations to aging were more common in SAA individuals. Because these negative correlations with aging were weak it could at least be interpreted as an absence of enlargement of the diameters in question in these cases.

The following measurements crossing the midline increased with aging: ANG in SAE individuals, TDSPS in SAA female and SAE male, TI in the complete sample and SAE male, IS SAA male and, LOI and ROI only in the complete sample.

Moderate to high correlations between age and shape of the pelvis can be noted in Table 4.12. SAE males had the highest correlation than the other groups and SAA especially females had the lowest correlations. The pelvic canal showed a stronger correlation than the separate components.

Table 4.12: Correlations of least squares regressions between shape and age within each sex-ancestral groups

		African Ancestry		European Ancestry	
		Female	**Male**	**Female**	**Male**
Pelvic inlet	r	0.71	0.66	0.74	0.79
	r^2	0.50	0.43	0.55	0.63
Midpelvis	r	0.69	0.73	0.70	0.84
	r^2	0.47	0.54	0.49	0.70
Pelvic outlet	r	0.75	0.75	0.72	0.73
	r^2	0.57	0.57	0.52	0.54
Pelvic canal	r	0.84	0.79	0.79	0.89
	r^2	0.71	0.63	0.62	0.79

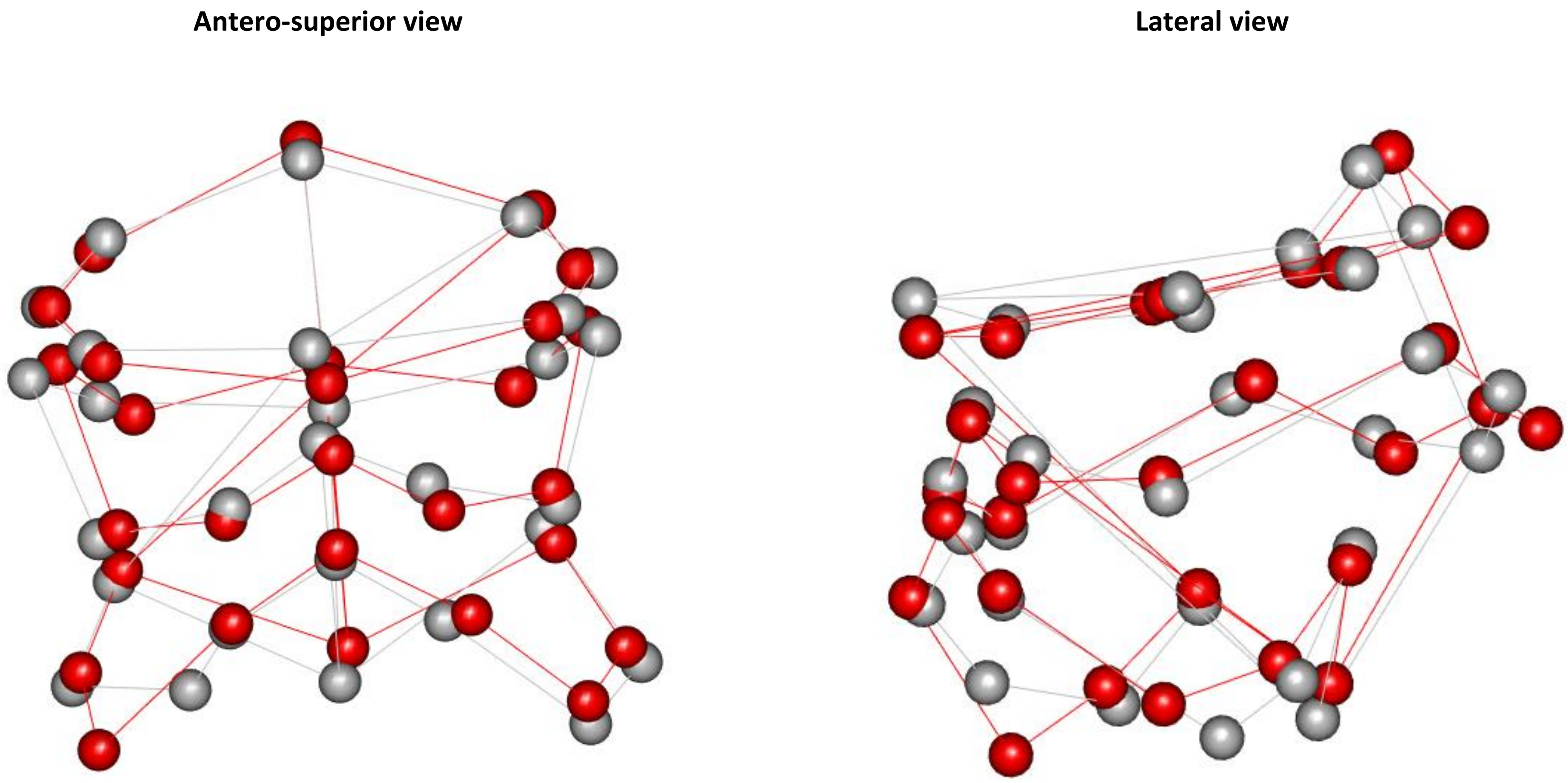


Figure 4.35 Schematic representation of the correlation of the variation in the pelvic shape with age in SAA Females
Grey spheres: the smaller age
Red spheres: the greater age

Antero-superior view **Lateral view**

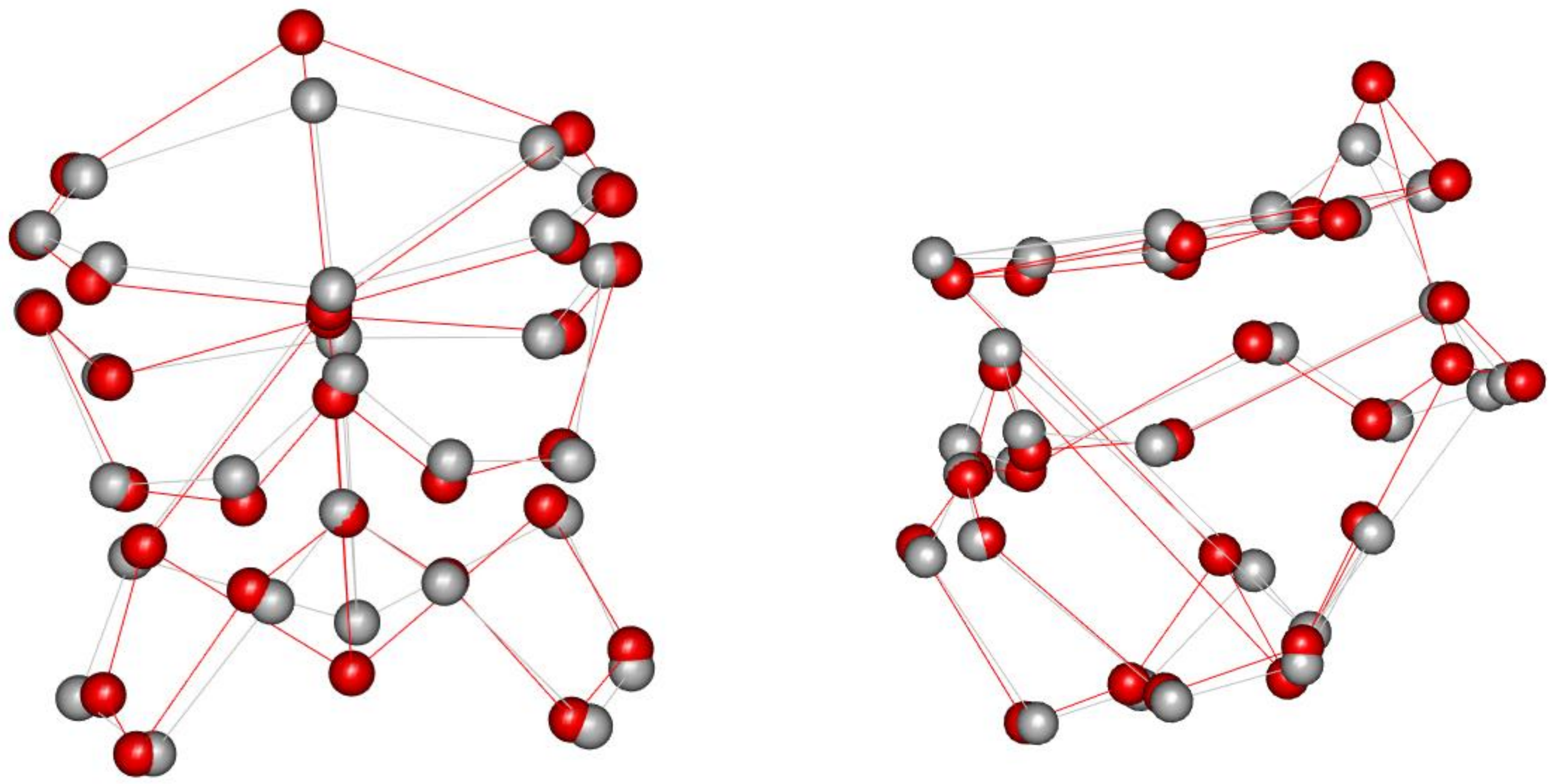


Figure 4.36 Schematic representation of the correlation of the variation in the pelvic shape with age in SAA Males
Grey spheres: the smaller age
Red spheres: the greater age

Antero-superior view **Lateral view**

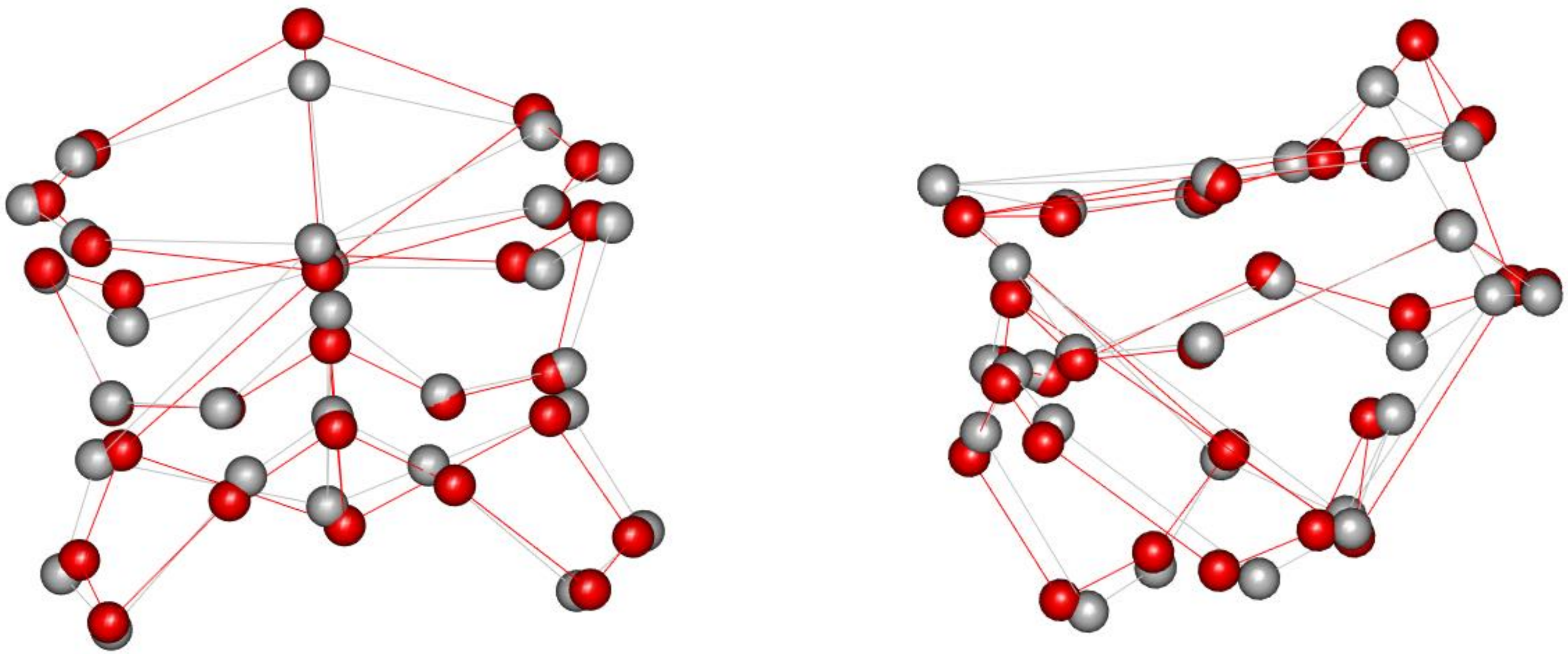


Figure 4.37 Schematic representation of the correlation of the variation in the pelvic shape with age in SAE Females
Grey spheres: the smaller age
Red spheres: the greater age

Antero-superior view **Lateral view**

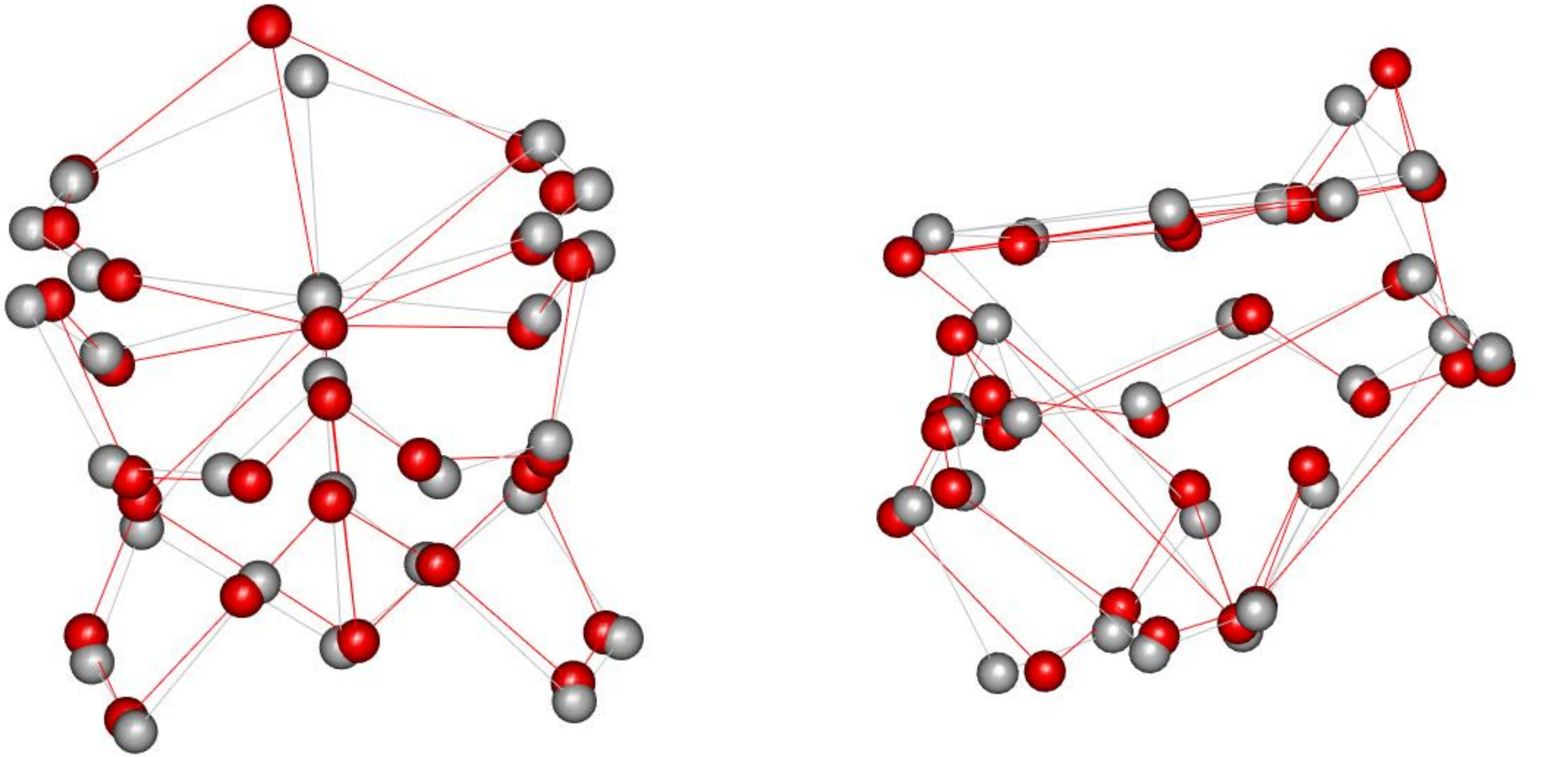


Figure 4.38 Schematic representation of the correlation of the variation in the pelvic shape with age in SAE Males
Grey spheres: the smaller age
Red spheres: the greater age

In Figures 4.35 – 4.38, the variation in the shape of the pelvis with aging can be noted among the various sex-ancestral groups. In all sex-ancestral groups, apart from SAA female, it can be noted that the anteroposterior dimension of the pelvic inlet decreased relatively with age, while in SAE individuals, especially males, the shape becomes wider as well.

4.5 Integrated findings

Greater variation in female shapes were noted as compared to male shapes. The pelvic inlet shape in SAA individuals compared to SAE individuals presented with more anteriorly projecting midpoints on the sacral promontory and narrower inlets, while females compared to males presented a relatively wider midpelvis, a more prominent sacral hollow, a flatter inner aspect of the pubic symphysis and a relatively more spacious posterior aspect between the sacral notch and the sacro-iliac joint with flatter sacral hollows, especially in SAE female. For these reasons the greatest pelvic inlet and midpelvic measurements including the diagonal conjugate were found in SAE female followed by SAE male and then SAA female. The exclusion was the interspinous diameter, which was greater in SAA female than in SAE male.

Pelvic outlet shapes in females appeared wider with the widest transverse diameter more anteriorly placed than in males. The relatively more anteriorly placed transverse diameter in females compared to males is also reflected as the relatively shorter distance from the pubic symphysis to the ischial tuberosities. Relatively longer and more posteriorly located points of junction between the inferior pubic ramus and the ischial ramus in SAA female as compared to SAA male was noted. The greatest transverse outlet diameter appears to be situated more posteriorly in SAE male compare to SAA male. SAA individuals and males also presented with a more anteriorly placed coccyx as compared to SAE individuals and females. These sex-ancestral group shape variations were reflected in the variations of the pelvic outlet dimensions, measurements pertaining to the pubic region and the obstetric conjugate, which were the greatest in SAE female followed by SAA female. They were only marginally greater than in SAE male. In all regards the smallest measurements were found in male SAA. The increased dimensions in this region contributed to a wider and greater subpubic region and pelvic outlet area.

The measurements that connect the pelvic inlet, midpelvis or outlet at varying positions give a reflection of the longitudinal capacity of the pelvic cavity. The distance between the posterior parts of the pelvic inlet to the pelvic outlet was the greatest in SAE male followed by SAE female, SAA female and then SAA male, although in SAA male the sacral length was longer than in SAA female. On the contrary, the distances between the mid-part and anterior part of the pelvic inlet to the pelvic outlet were greater in all males than in females. A relatively greater space between the midpelvis and pelvic outlet rings can be noted in females as compared to males.

Measurements on CT scans were more similar to the direct measurements than measurements taken on MRI scans. CT scan measurements did however differ from MRI with regards to the transverse inlet and the distance from the inferior most point of the pubic symphysis to the sacral hollow at the level of the ischial spines.

Many linear dimensions and variations in shape were found to correlate moderately/ statistically significantly and positively with stature especially in SAE individuals. Noteworthy is that in female SAA many correlations with stature were very weak and even negative.

On the lateral view of the schematic representation, the red spheres extended beyond the grey spheres anteriorly and posteriorly. This relative anteroposterior deepening of the pelvic canal is the least pronounced in SAA male. In SAA female the posterior aspect of the pelvic canal seems to increase with stature. In both male and SAE female, a taller stature was associated with a higher and more posteriorly positioned sacral promontory. In SAA male the pelvic canal seemed to become greater anteriorly with an increase in height.

Unlike stature correlations, age correlations of linear dimensions and shape were mostly weak. Statistically significant and moderate correlations often involved measurements crossing the midline and were more pronounced in SAE individuals and least in SAA female. With aging the pelvic inlet became flatter and the pelvic cavity wider.

5. DISCUSSION

In this study the shape and size variations of pivotal dimensions of the pelvic canal were recorded by four modalities. This includes, direct measurements and geometric morphometric shape analyses on 121 intact cadaver, as well as measurements on 77 MRI and 92 CT scans.

Variations among modalities, among ancestral groups, sexes and correlations along with stature and aging, are discussed in the sections to follow and compared to the authors reported in the literature. The possible effect that these variations could have on planned procedures and childbirth are considered.

5.1. Variations in the pelvic dimensions

Possible factors that could have an effect on the variation of the pelvic canal dimensions are considered in this section.

5.1.1 Influence of various methodologies

Although measurements by means of the three modalities (direct cadaveric measurements, MRI and CT scans) were not performed on the same individuals, although individuals of the same geographic and ancestral group were used. As anticipated, measurements on CT scans corresponded more to the direct measurements on intact cadaver pelves than measurements taken on MRI scans. In previous studies measurements on MRI scans were found to be less repeatable compared to CT pelvimetry.[109, 118]

Measurements crossing the midline (TI, IT, ANG in the case of MRI, and IT, when comparing CT scans) were especially affected with direct measurements on intact cadaver pelves. An important aspect that could be accountable for the difference, is the more restricted image plane manipulation in the case of MRI scans when compared to CT scans. IT diameter seemed to be the most variable measurement between the modalities used. Variability in the location of the most inferior point on the ischial tuberosity could be the confounding factor in this regard. Lack of repeatable identification of landmarks could also have accounted for the significant difference in SACHOL, when MRI and CT were compared to direct measurements. When comparing the three modalities for the common measurements taken, direct measurements were significantly with smaller than those taken from either MRI or CT scans. There is, therefore, a possibility that SACHOL and IT measurements could have been affected by some remaining soft tissue on the bony landmarks located.

During obstetric care, MRI is the modality of choice. Care should be taken, however, to interpret pelvic dimensions derived from MRI, especially those crossing the midline. When measurements are taken in the clinic or intra-operatively, it should be noted that, because of the presence of soft tissue, shorter distances and subpubic angles can be anticipated, than measured on MRI or CT scanning.

5.1.2 Variation between ancestral groups

Differences between ancestral groups were found to be greater in the pelvic outlet than the pelvic inlet.[28,47] Although all metric differences of the pelvic inlet and outlet between ancestral groups in this study were statistically significant ($p < 0.05$), the pelvic inlet variations were significant at a lower level of less significance. This is a contradiction with what has been reported before. The length of the pubic symphysis was shorter, rendering the pelvic cavity shallower and smaller anteriorly in SAA female. This trend was also noted in the shape analyses, with the pelvic outlet shapes not being significantly different, while the pelvic inlet shapes varied significantly between ancestral groups in females ($p = 0.003$).

It is of note, however, that the least significant variation between ancestral groups ($p = 0.0263$) was found when comparing the antero-posterior outlet diameter between females. Although all dimensions were smaller in SAA, the antero-posterior outlet diameter in female SAA was least affected. The pelvic outlet diameters, including the subpubic angle, did not differ significantly between ancestral groups in females.

The LDTP, RDTP and SL were the longest in SAE males, while the LHTP and RHTP was longer in SAA males. This finding implies that the medial/ pelvic cavity aspect of the ischial body is relatively more elongated to create an even deeper pelvic cavity posteriorly, compared to the SAE males.

Many studies have reported a variation in pelvic shape and size among individuals of different ancestries including between population groups of African ancestry and European ancestry.[3,4,54,62,63,65,142] Variation between African and European ancestral groups in this study, were therefore not surprising. As described by Patriquin *et al.* it was found that all but one of the dimensions involving the ischial spine, were larger in SAE than in SAA.[3] These findings on the inter-ancestral variations of the pelvic diameters corresponded with differences described in other parts of the skeleton in South African groups.[4,66,69] Kurki[11,145] analysed the size and shape of the pelvic canal in reference to the body size in several populations. Kurki found that South Africans of African ancestry had a unique pelvic shape due to a rather small and petite body shape. Pelvic shape differences also reflect climate variation in body build and proportions. Socio-economic factors and poor nutrition should be considered as well. Bernard[70] suggested that women with poor nutrition are shorter in stature and have smaller pelvic brims than women with better nutrition.

Kurki[11, 145] also suggested that at least some pelvic canal shape variations were independent of body size variation. The reasons for these differences were thought to be related to genetic differences, as selective pressures may differ amongst populations.[11,145] The findings of this study were in line with those reported by Kurki[11,144] on an archaeological collection. It was found that SAA females displayed small pelvic inlets relative to an elongated lower canal in anterioposterior and posterior lengths. The pelvic inlet shape in SAA, compared to SAE, presented with more anteriorly projecting midpoints on the sacral promontory and narrower inlets. SAA also presented with a more anteriorly placed coccyx, as compared to SAE. Measurements of the posterior pelvic space and subpubic angle have been found to be most dimorphic and greater in SAE.[28,47,68] The increased dimensions in this region in SAE contributed to a wider and greater subpubic region and pelvic outlet area than in SAA.

Patriquin *et al.* suggested that, to some extent, the shape of the pelvis may correlate with that of the skull, since the skull must pass through the pelvis during the birth process.[5,54] This notion could reveal interesting relationships and should be considered in future research studies.

5.1.3 Variation between sex groups

In this study, the greatest variations in measurements was found between sex groups within populations. Well known variations in the shape and size of the pelvis between sexes exist as early as foetal life. During intra-uterine development the pelvic dimensions in males are greater than in females, although, in females the size of the pelvic cavity remains larger compared to males until about 22 months. There after the pelvis increases in size again during puberty.[6,31,54-56] Measurements of the pelvic canal, especially associated with the width of the pelvic canal, were greater in females than in males, while those reflecting the length were greater in males, as evident from the measurements that connect the inlet, midpelvis and outlet.

A greater variation in female pelvic canal shapes was noted. The wider range of shape variations noted in females could be a reflection of a greater growth trajectory in the pelvic canal size during puberty in females to achieve greater dimensions in adulthood.[146] Sexual dimorphism in pubic length, *linea terminalis* length and pelvic inlet circumference may be due to the later maturation of the pubis in females, prolonging the period of growth.[14] It is during this accelerated growth period during adolescence that individuals are vulnerable to poor socio-economic conditions and food deprivation, resulting in limited sexually differential growth. A greater time period for exposure to external factors influencing the shape of the pelvis, could possibly account for a greater variability in females as compared to males.[146]

The pattern of sexual variation differed between ancestral groups and seemed to be greater in the pelvic inlet in SAE and in the outlet in SAA (especially that of the APO). This finding in SAA is in line with what was noted by Msamati[28] and Igbigbi and Nanono-Igibi[47] who found the variation between sexes to be greater in the pelvic outlet than the inlet. When interpreting the shape variations in the pelvic inlet between sex groups, it was noted that the transverse diameter seemed to shift more anteriorly and further away from the sacral promontory in females. In so doing, a more oval/round shape was described as compared to the heart shaped inlet of males. According to Leong[14], the rounded shape is said to be the expected female type, while the heart-shape is often designated a male variant. SAE females presented with similar transverse and AP diameter dimensions transecting approximately in the centre, and a sacral promontory orientated more posteriorly than in males, that could fit in with the described gynaecoid shape.

Unlike the findings of Kuliukas *et al.* who found on multi-detector computer tomography (MDCT) scans that male and female pelves shapes demonstrate two distinct groups with no overlap, in this study some extend of overlap existed in the PC1 vs. PC2 plots.[45] More overlap between the sexes was noted in SAA than in SAE. Nevertheless, the p-value for inter-sex group variation was highly significant at 0.0005 for both SAA and SAE groups. When considering the pelvic inlet, midpelvis and pelvic outlet shapes, a greater degree of overlap was noted, although all intersex comparisons were significant. This was especially true for the pelvic inlet where the p-value for SAA (0.017) was once again greater than in SAE (0.0075). Sexual dimorphism has often been thought to be minimised in SAA for several reasons including socio-economic status and malnutrition.[147] The relative size and orientation of the pelvic inlet, midpelvis and outlet shapes could be important factors contributing to the sexual variation noted in the pelvic canal shape.

The classical male pelvic canal feature of a narrow deep pelvis in comparison to females, was reflected in the greater longitudinal measurements that connect the pelvic inlet, midpelvis or outlet.[22,23,26,32] A relatively greater space between the midpelvis and pelvic outlet rings, though, could be noted in females as compared to males.

As expected, pelvic outlet dimensions were greater in females compared to males, resulting in a wider subpubic angle.[25] An increased distance between the ischial tuberosities found in females will account for a greater subpubic angle, as well as for variations in the ischiopubic rami,[25,55] which correlates with the findings in this study.

Subpubic angles derived from subpubic the triangle 3D-coordinates were greater than the subpubic angles derived from the 3D-coordinates of the urogenital triangle. This finding is in agreement with the appearance of the subpubic angle being an arch, presenting with greater angles closer to the IPS (this was most noticeable in SAE female). These observations are in line with previous morphometric assessments that demonstrated a U-shaped, obtuse angle with strongly everted ishiopubic rami in females, as opposed to V-shaped subpubic angles in males.[60]

5.1.4 Influence of stature

A correlation between stature and the size of the anteroposterior dimension or true conjugate of the pelvic inlet is often used as a measure for favourable obstetric outcomes.[16,37,70,71] In this study, many linear dimensions and variations in shape were found to correlate moderately, significantly and positively with stature especially in SAE, as opposed to SAA, and in females, as opposed to males. A taller stature was associated with a higher and more posteriorly positioned sacral promontory. Although many dimensions correlated with stature (especially female SAE), this might not be a problem, as the pelvic dimensions in this group often exceeded those of the other groups. An important aspect that also needs to be considered is the size of the foetal head, which did not form part of this study.

5.1.5 Influence of aging

Significant and moderate correlations with aging often involved measurements crossing the midline and were more pronounced in SAE and less in female SAA. With aging, the pelvic inlet became flatter and the pelvic cavity wider. These correlations were in line with those of Berger *et al.* on an American CT sample.[13]

5.2. Results of this study compared to the literature researched

Variations in the dimensions of the pelvic canal between population groups are not uncommon (Tables 5.1 – 5.3 and Table 5.5). Both South African ancestral groups considered here are thought to be distinguishable from their European and North American counterparts and, therefore, the results obtained in this study were expected to differ from standards derived from the literature researched.[5,11,37]

It is therefore important for every population to develop its own reference values that are tailored to the unique metric and morphological characteristics of that population when planning or performing surgical procedures or childbirth.

At least some of the variations noted in the pelvic dimensions by previous researchers may be related to the methods used for data acquisition. Metric measurements on radiographs and photographs are not always accurate, as three dimensional shape differences will not always be accurately displayed on X-ray, as it affect the position of the structures. Therefore the distance and angle from the X-ray source to the subject can distort the shape.[50,84,148] Katanozaka[38] and Sonal[39] further comment that measurements are interpreted as radial acoustic shadows observed on radiographs, and this may be prone to subjective error.

The study conducted by Bonneau[111] confirmed a noteworthy effect on the quantitative dimensions of dried bones by reassembling pelves. The variation in the reassemble process is possibly related to the complete absence of cartilaginous tissue on dry bone, and the morphology/ position of the sacroliac joint, resulting in different potential positions of the two sacroiliac surfaces relative to one another. In this study, the shape of the intact pelves were preserved by removing soft tissue only, while keeping the cartilaginous joints intact to negate inaccuracies reported by other researchers. For this reason, the findings of this study should be more relevant to clinical situations.

5.2.1 Pelvic inlet

The dimensions of the pelvic inlet, as reflected in the anteroposterior dimension of the pelvic inlet/ true conjugate (API) and the transverse dimension of the pelvic inlet (TI), are considered in this section. Ghanaians, as well as the Shona and Zulu groups from South Africa, presented with smaller dimensions. This was especially seen with the true conjugate /API than in the SAA group. The smaller values recorded in the Ghanaian group could be influenced by soft tissue padding the bony landmarks, thereby diminishing the distance between them. The discrepancy with the two other South African studies could have been confounded by the alternative modalities used, namely X-ray and direct/MRI (Table 5.1).

The findings of the first Scottish group, the Omani and the UK sample, were more in line with the SAA sample. The dimensions reported by Loder,[150] Salerno,[151] standards from an obstetrics textbook[36] and Salk[82] groups, were more similar to the SAE group stated in this study. SAE females and males presented with greater values than those given in two widely referred to anatomy textbooks.[22,25]

Table 5.1: Direct measurements of the pelvic inlet in this study compared to researched literature (values in cm)

	Population	Modality	True Conjugate /API	TI
This study, 2016	**South African**			
	SAA Females N=32	Direct cadaveric	11.0	11.6
	SAA Males N=31		10.2	11.2
	SAE Females N=33		12.5	13.3
	SAE Males N=25		11.4	12.6
This study, 2016	**South African**			
	SAA Females N=22	MRI	10.6	12.3
	SAA Males N=21		10.6	11.3
	SAE Females N=14		12.0	13.4
	SAE Males N=20		11.2	13.1
This study, 2016	**South African**			
	SAA Females N=26	CT scan	11.1	12.1
	SAA Males N=21		10.5	11.3
	SAE Females N=18		12.1	12.8
	SAE Males N=27		12.3	12.3
Adadevoh, 1989[37]	**Ghanaian** Total Females N=114	Intra-operative	10.14 ± 0.84 [a]	-
Bernard, 1952[70]	**Scottish**	X - ray		-
	1st Females N=100		10.80	
	2nd group Females N=100		12.7	
Gabbe, 2016[36]	Female	-	12.5	13.0
Gowri, 2010[148]	**Omar** Female N=182	MRI	10.9 ± 0.98 [a]	12.3 ± 0.89 [a]
Keller, 2003[109]	**Zurich, Swiss**	MRI	-	
	Total Females N=781			11.5 ± 1.2 [a]
	Group 1[c] N=100			12.8 ± 0.9 [a]
	Group 2[d] N=130			12.4 ± 0.9 [a]
Killeen, 2010[19]	**United Kingdom** Male N=25	MRI	10.9 – 11.0 [b]	-
Loder, 1993[150]	**Michigan, USA** Female N=6	CT scan	12.5	13.0
Moore, 2010[22]	Female	-	11.2	13.5
	Male		10.0	-
Salerno, 2006[151]	**United Kingdom**	MRI	-	
	Females N=74			13.1
	Males N=112			12.5
Salk, 2015[82]	**Turkey** Female N=203	CT scan		13.6 ± 0.8 [a]
Standring, 2008[25]	Female	-	11.2	12.5
	Male		10.0	12.0
Steward, 1979[71]	**Shona, South African** Female N=82	X-Ray	9.9 – 11.5 [b]	10.6 – 12.0 [b]
Steward, 1979[71]	**Zulu, South African** Female N=34	X -Ray	9.6 – 11.1 [b]	11.6 – 11.8 [b]

[a] Mean value ± standard deviation
[b] Range
[c] Spontaneous vaginal delivery group
[d] CPD groups

5.2.2 Midpelvis

All midpelvic measurements were significantly greater in SAE than in SAA. According to Standring *et al*. the SACHOL male average is 10.5 cm and the female average is 13 cm, which means that the SACHOL in this study is on average, greater for both male groups and SAE female.[25] Average SACHOL in SAA females in this study is 12 cm, which is smaller than the measurements of Stranding. SACHOL values in females of both SAA and SAE were greater than in the groups described by Loder[150] and Gabbe[36] (Table 5.2).

The IS, is the narrowest aspect of the pelvic canal,[36,109] that a foetal head must pass during childbirth. The IS was the greatest in SAE female, followed by SAA female, SAE male and then SAA male. The IS of the SAA group somewhat correlates with that stated by Stranding *et al*. that an average measurement should be 9.5 cm in adult females[25] and is in line with the studies on the Shona and Zulu groups.[71] According to Moore[22] and Gabbe[36], the IS should not be less that 10 cm for a female, which is about midway between the mean values of SAE and SAA in this study. The IS of SAE females is similar to those of the groups reported on by Gowri[149], Keller[109] and Loder.[150]

Table 5.2 Direct measurements of the midpelvis in this study compared to researched literature (values in cm)

	Population	Modality	SACHOL
This study, 2016	**South African**		
	SAA Females N=32		12.0
	SAA Males N=31	Direct cadaver	11.2
	SAE Females N=33		13.3
	SAE Males N=25		12.9
This study, 2016	**South African**		
	SAA Females N=22		12.2
	SAA Males N=21	MRI	11.9
	SAE Females N=14		12.4
	SAE Males N=20		13.9
This study, 2016	**South African**		
	SAA Females N=26		12.2
	SAA Males N=21	CT scan	11.9
	SAE Females N=18		12.9
	SAE Males N=27		12.7
Gabbe, 2016[36]	Female	-	11.5
Loder, 1993[150]	**Michigan, USA**	CT scan	
	Female N=6		11.5
Standring, 2008[25]	Female	-	13.0
	Male		10.5

5.2.3 Pelvic outlet

Apart from the study by Killeen *et al.* on a UK MRI sample[19] and the American CT sample,[150] the pelvic outlet dimensions in this study were much smaller than in other studies. This finding is unexpected and the possibility of the influence of modalities used needs to be taken into consideration. The IT dimension measured by MRI in this study group, approximate some of the values given by other researchers but not so for the APO.

Our results support that, because of an anatomically narrower pelvis found in SAE individuals and males in general, pelvic and perineal procedures might be technically more challenging. With shape analysis, it was found that the ischial tuberosities of SAA were in closer proximity than the SAE, but no significant differences in the pelvic outlet was recorded.

Table 5.3 Direct measurements on the pelvic outlet in this study compared to researched literature (values in cm)

	Population	Modality	IS	APO	IT
This study, 2016	**South African**				
	SAA Females N=32	Direct cadaveric	9.6	8.9	8.8
	SAA Males N=31		8.2	8.0	7.2
	SAE Females N=33		10.6	9.6	9.9
	SAE Males N=25		8.9	8.9	8.2
This study, 2016	**South African**				
	SAA Females N=22	MRI	9.8	9.3	10.6
	SAA Males N=21		8.4	9.0	9.1
	SAE Females N=14		10.7	8.7	11.4
	SAE Males N=20		8.9	8.8	10.0
This study, 2016	**South African**				
	SAA Females N=26	CT scan	10.1	9.1	11.0
	SAA Males N=21		8.5	8.3	9.4
	SAE Females N=18		10.8	9.2	12.1
	SAE Males N=27		9.1	8.4	10.6
Gowri, 2010[148]	**Omar** Female N=182	MRI	10.3 ± 0.98 [a]	10.2 ± 0.86 [a]	10.4 ± 1.1 [a]
Keller, 2003 [109]	**Zurich, Swiss**				
	Total Females N=781	MRI	10.7 ± 1 [a]	11.3 ± 1.1 [a]	11.5 ± 1.2 [a]
	Group 1[c] N=100		11.2 ± 0.8 [a]	11.6 ± 1 [a]	12.6 ± 1.1 [a]
	Group 2[d] N=130		10.5 ± 0.8 [a]	11.1 ± 1 [a]	11.3 ± 1 [a]
Killeen, 2010[19]	**United Kingdom** Male N=25	MRI	-	8.4 – 8.5 [b]	12.0 - 12.3 [b]
Loder, 1993[150]	**Michigan, USA** Female N=6	CT scan	10.5	7.5	10.5
Moore, 2010	Female	-	10.0	-	-
Salk, 2015[82]	**Turkey** Female N=203	CT scan	-	11.5 ± 0.8 [a]	11.7 ± 0.8 [a]
Standring, 2008[25]	Female	-	± 9.5	12.5	11.8
	Male		-	8.0	8.5
Steward, 1979[71]	**Shona, South Africa** Female N=82	X-Ray	8.7 – 9.9 [b]	11.2 – 12.1 [b]	-
Steward, 1979[71]	**Zulu, South African** Female N=34	X -Ray	9.7 – 10.0 [b]	11.3 – 12.2 [b]	-

[a] Mean value ± standard deviation
[b] Range
[c] Spontaneous vaginal delivery group
[d] CPD groups

5.2.4 Subpubic angle

The subpubic angle is an important reflector of the pelvic outlet or perineal space and may therefore be assessed prior to perineal procedures or childbirth.[27,46,152] Despite the seemingly importance of the subpubic angle, relatively few studies exist (Table 5.4). The subpubic angle, especially relevant in obstetrics, was mathematically calculated in previous studies.[27]

Measurements defining a subpubic triangle were obtained from vaginal examinations on actual patients, dried reassembled pelves and from radiographs.[27,50,84] However, during dissections, it was noted that the subpubic angle did not fully describe the subpubic arch in the subpubic triangle, especially in females.[54] The subpubic symphysis is represented as a wedge shape, which could contribute to the wider width of the subpubic arches.[50] The subpubic arches were further found to be consistently asymmetrical.

In this study, greater angles were observed, closer to the IPS, but smaller measurements were recorded when this arch was disregarded and a direct distance from the IPS to the inferior ischial tuberosities was considered. The smaller subpubic angles derived from the borders of the urogenital triangle borders in this study and tabulated in Table 5.4 are more in keeping with the measurements of other researchers, but disregards the concavity of the subpubic arch. Even the subpubic angles so derived were still larger than those reported by other authors.[15,25,52,148] The methodology used may certainly have an influence on these findings. The studies done by Oladipo and Hart[84] on the Ikwerres and Kalabaris tribes of Nigeria are best to the findings of this study. The reason for the relation cannot be ascribed to an ancestral correspondence, since both SAE and SAA groups were represented in the study, but it could relate to the use of different modalities.

Frudinger[27] used a similar methodology on a female UK sample and reported similar subpubic angles of 60˚ - 128˚ with a mean of 104˚ than found on SAE females of this study on intact cadaver pelves, MRI and CT scans.[27] The subpubic angles determined in other African studies were much larger with a wider range. Igbigbi and Nanono-Igibi[47] found that the subpubic angle in a Ugandan population ranged from 75˚ to 155˚ (mean of 116.11˚) in females. These subpubic angles were determined by anteroposterior radiographs. However, the values are significantly smaller than the subpubic angles of a Malawian population, with a mean angle of 129.07˚.[28] Igbigbi and Nanono-Igibi suggest that these differences are indicative of regional variation of the subpubic angle among 'black' subjects.[47]

Studies on disarticulated pelves[50,148] possibly neglected the asymmetric wedge shape of the pubic symphysis and its contribution towards the subpubic area. Further studies, which included geometric morphometrics described the pubic symphysis as essential, especially to elucidate overall pelvic shape and angle impressions.[110]

The subpubic angle measured from the IPS to both the LIIT and RIIT are more in line with the findings of Jagesur *et al.*[153] than those of Small *et al.*[50], who measured the subpubic angles on reconstructed pelves. Jagesur *et al*.[153] measured the subpubic angles on non-disarticulated pelves (Table 5.4).

Table 5.4 Comparison of subpubic angle findings in degrees (˚) between various authors.

	Population	Modality	Subpubic angle (IPS to RIIT/LIIT)	Subpubic angle (IPS to RIPR/LIPR)
This study, 2016	**South African** SAA Females N=32 SAA Males N=31 SAE Females N=33 SAE Males N=25	Direct cadaveric	89.3 ˚ 74.0 ˚ 87.6 ˚ 74.3 ˚	106.2 ˚ 79.2 ˚ 108.7 ˚ 83.4 ˚
This study, 2016	**South African** SAA Females N=22 SAA Males N=21 SAE Females N=14 SAE Males N=20	MRI	-	112.8 ˚ 91.2 ˚ 120.7 ˚ 92.1 ˚
This study, 2016	**South African** SAA Females N=26 SAA Males N=21 SAE Females N=18 SAE Males N=27	CT Scan	-	103.5 ˚ 84.1 ˚ 114.8 ˚ 88.9 ˚
Frudinger *et al.*, 2002[27]	**United Kingdom** Females N=132	Vaginal examination	104˚ 60˚ - 128˚[b]	-
Igbigbi & Nanono-Igibi, 2003[47]	**Ugandan** Combined Total N=205 Females Males	X - Rays	116.1 ˚ ± 17.8 ˚[a] 93.9 ˚ ± 21.1 ˚[a]	-
Jagesur *et al.*, 2016[153]	**South African** SAA Females N=20 SAA Males N=20 SAE Females N=20 SAE Males N=20	Direct cadaveric	88.0 ˚ 68.1 ˚ 87.3 ˚ 77.2 ˚	-
Msamati, 2005[28]	**Malawian** Females N=46 Males N=73	X - Ray	129.07 ˚ ± 14.19 ˚[a] 99.16 ˚ ± 15.73 ˚[a]	-
Oladipo *et al.*, 2010[84]	**Ikwerre, Nigeria** Females N=173 Males N=85	X - Ray	119.38 ˚ ± 3 ˚[a] 100.25 ˚ ± 7.8 ˚[a]	-
Oladipo *et al.*, 2010[84]	**Kalabaris, Nigeria** Females N=213 Males N=129	X - Ray	125.0 ˚ ± 3.2 ˚[a] 105.63 ˚ ± 3.9 ˚[a]	-
Small *et al.*, 2012[50]	**South African** SAA Females N=33 SAA Males N=44 SAE Females N=25 SAE Males N=43	Reassembled Dry bones	84.1 ˚ ± 8.9 ˚[a] 63.9 ˚ ± 11.1 ˚[a] 93.9 ˚ ± 11.2 ˚[a] 70.7 ˚ ± 9.4 ˚[a]	-
Standring, 2008[25]	Females Males	-	80 ˚ – 85 ˚[b] 50 ˚ - 60 ˚[b]	-
Youssef, 2016[152]	**Bologna, Italy** Female N=145	Ultra Sound	-	123.7 ˚ ± 9.6 ˚[a]

[a] Mean and standard deviation
[b] Range

5.2.5 Conjugates and dimensions connecting the pelvic inlet and outlet

The conjugates were originally described as dimensions estimated by palpation. The obstetrical conjugate, by manual palpation, is calculated by subtracting 1.5 to 2.0 cm from the diagonal conjugate, since the obstetric conjugate cannot be measured directly during a pelvic examination (Table 5.5). This limitation could be overcome by MRI or ultrasound. The values in female SAE for the diagonal conjugate by direct measurements on intact cadaver pelves in this study, were similar to those reported by Moore[22] and Standring,[25] but the obstetric conjugate, however, was much smaller. The obstetric conjugate in this study was more similar to what was observed by ultrasound studies.[38,39,46] The possible reason for this could be that these anatomical textbooks mention values derived from manual examinations, which are less accurate than by other means, such as MRI and CT scans.

The sacral length in this study was found to be longer than in the Shona group.[71] SAE females had a sacral length of 12.2 cm, compared to SAA females with 11.6 cm, while the sacral length of the Shona group was between 9.7 -10.8 cm. However, the SAA females' sacral length more closely related to the Zulu females (10.1 cm) and Shona female (10.5 cm) in the study by Steward.[71] Shona and Zulu females have shorter pubic symphyseal lengths of 3.7 cm and 3.6 cm respectively, compared to SAA females averaging 1 cm longer.[71]

Table 5.5 Direct measurements of the pelvic outlet in this study compared to researched literature (values in cm)

	Population	Modality	Diagonal Conjugate	Obstetric Conjugate	LPS	SL
This study, 2016	**South African**					
	SAA Females N=32	Direct cadaveric	11.1	12.2	4.4	11.6
	SAA Males N=31		10.6	11.3	4.5	11.8
	SAE Females N=33		12.8	13.0	4.5	12.2
	SAE Males N=25		12.2	12.1	4.9	13.1
This study, 2016	**South African**					
	SAA Females N=22	MRI	-	-	-	10.9
	SAA Males N=21					11.9
	SAE Females N=14					11.9
	SAE Males N=20					12.6
This study, 2016	**South African**					
	SAA Females N=26	CT scan	-	-	-	11.4
	SAA Males N=21					11.9
	SAE Females N=18					11.4
	SAE Males N=27					12.5
Gabbe, 2016[36]	Female	-	12.5	11.0	-	-
Katanozaka, 1999[38]	**Japan** Female N=209	Ultra sound	-	10.7 – 15.1 [b] 12.90 ±0.88 [a]	-	-
Keller, 2003[109]	**Zurich, Swiss** Total Females N=781 Group 1[c] N=100 Group 2[d] N=130	MRI	-	11.7 ± 1.6 [a] 12.2 ± 0.9 [a] 11.4 ± 1 [a]	-	-
Moore, 2010[22]	Female	-	13.0	>11.0	-	-
Salk, 2015[82]	**Turkey** Female N=203	CT scan	-	10.9 ± 1.0 [a]	-	-
Sonal, 2006[39]	**Indian** Females N=55	Ultra sound	-	11.4 ± 1.07 [a]	-	-
Steward, 1979[71]	**Shona, South Africa** Female N=82	X-Ray	-	-	3.4 – 3.7 [b]	9.8 – 10.8 [b]
Steward, 1979[71]	**Zulu, South African** Female N=34	X -Ray	-	-	3.5 -3.6 [b]	9.7 -10.1 [b]

[a] Mean value ± standard deviation
[b] Range
[c] Spontaneous vaginal delivery group
[d] CPD groups

5.3. Clinical Implications

Discrepancies between the dimensions of the groups studied and the standards reported in the literature might have implications for procedures involving the pelvic canal and perineum, as well as for the tendency to develop certain conditions. Intergroup variation, as well as their correlations with aging and stature, might further necessitate adjustments when planning surgery or making decisions regarding childbirth options.

Procedures and conditions, including childbirth, to be considered, are stress urinary incontinence, inferior pubectomy in posterior urethroplasty, rectal incontinence, radical retropubic prostatectomy, as well as intra-pelvic applications such as rectal cancer procedures, hysterectomy, sacrospinous colpopexy and obstetrics. Table 5.6 represents the procedures and the clinically relevant dimensions.

Table 5.6: Applied dimension to clinical situations

	API	APO	OBS-CONJ	TI	IS	IT	LPS	ANG	LDTP RDTP
Stress urinary incontinence[52,88-90,92]							✓	✓	
Inferior pubectomy in posterior urethroplasty[96,97]						✓		✓	
Rectal incontinence[154-157]			✓	✓				✓	
Radical retropubic prostatectomy[20,99,100]				✓	✓	✓	✓	✓	✓
Rectal cancer[19,21]				✓	✓	✓			✓
Hysterectomy[57,104]								✓	
Sacrospinous colpopexy[34,105,106]					✓		✓		
Obstetrics[27,31,36,78,81,82,85]	✓		✓	✓	✓	✓		✓	

5.3.1 Stress urinary incontinence

Variations in pelvic anatomy could possibly be associated with the occurrence of pelvic floor disorders. It was found that a narrow transverse inlet and wider obstetrical conjugate pose a lower risk for SUI.[88,90,92] Stav[89] determined that women with SUI have significantly larger pelvic inlet and -outlet dimensions. In this study, the pelvic inlet size of SAE females and the widest inlet distance were significantly larger than those of the other ancestral groups, and should thus predispose SAE females to incontinence. Further, as the pelvic outlet size has also been related to the incidence of incontinence, SAE females will be implicated[89]. Other factors apart from the absolute pelvic dimensions also play a role in continence and should be considered.

5.3.2 Inferior pubectomy in posterior urethralplasty

When inferior pubectomy is contemplated for posterior urethralplasty, pre-operative pelvimetry, and especially the determination of the subpubic angle, is essential. The subpubic angle can easily be measured by X-ray, MRI, ultrasound and CT scans. According to previous studies,[96,97] the standard size of the subpubic angle measured at the IPS between the two ischiopubic rami should be 50° – 60° for males and 70°- 80° for females[25]. The subpubic angles measured in this study were larger than these reported values and, therefore, should not pose a challenge to perineal procedures in this regard. The values of the subpubic angle reported in this study could also serve as a reference when interpreting the extent of deformation caused by the healing of a fractured inferior pubic ramus. The modality and technique used should be taken into consideration when comparing the findings in this study to those of other studies (Table 5.6).

5.3.3 Radical retropubic prostatectomy and rectal cancer

Regarding surgical procedures for RRP and the excision of rectal cancer, Hong[20] and Salerno[21] support the notion that a wider and shallower pelvis would allow for easier performance of procedures than narrower and deeper pelves.[100]

When considering the RPR procedure in males, SAE males present with not only greater width measurements (TI, IS and TO), but also greater depth measurement (LDTP/RDTP, SL and LPS). The overall pelvic canal is more spacious, which would facilitate procedures. The LHTP/RHTP (most medial point of the iliopubic eminence approximately perpendicular to the lowest point of the ischial tuberosity), however, is the greatest in SAA males, which would afford the narrow pelvic cavity noted in this group to be deeper and less accessible.

Regarding resection for rectal cancer in both sexes, resection in females should be facilitated by the wider dimensions in this group, especially in SAE female. The depth dimensions were, however, smaller in SAA females, contributing to a more shallow pelvis. Once again, the SAE group will have a more spacious pelvic cavity regardless of width and depth ratios and, therefore, procedures should be easier. In general, the SAE pelvic diameters, especially those of female SAE, compare favourably with the largest diameters reported in the literature. No extra precautions are thus deemed necessary. SAA diameters are similar to other African groups, but when performing procedures, it should be kept in mind that the dimensions in general are smaller than those of the SAE group.

5.3.4 Hysterectomy

The larger capacity of the pelvic cavity in female SAE with greater widths and depths vs. female SAA, should be taken into consideration when planning an abdominal approach for the performance of a hysterectomy.

During a perineal approach for the removal of the uterus, a wide subpubic angle is preferred, thus, more than 90˚.[57,104] As SAE and SAA females in general, presented with wider subpubic angles, a perineal approach should not be limited by a small subpubic angle. However, the SAE and SAA females at the lower end of the spectrum (minimum value for SAE females 75° and SAA females 80°) could present with insufficient space for the performance of this procedure. Assessing the subpubic angle when planning the hysterectomy could prove useful.

5.3.5 Sacrospinous colpopexy

Authors use various guidelines when placing a suture (Richter's stitch) into a sacrospinous ligament for the sacrospinous colpopexy. Giberti[158] and Guner[159] described the placement of the stitch as two fingers breadth medial to the ischial spine. Goldberg[160] explained that lateral suspension of the suture, which is roughly placed 2 cm medial to the ischial spine, allows for safeguarding of the pudendal nerve and vessels. Van der Walt *et al.* concluded that to minimise the risk of nerve damage or entrapment,[94] he Richter's stitch should be placed more than 20 mm from the ischial spine.[161] It is suggested that this recommended area should be revised for different population groups.

The length of the sacrospinous ligament (the distance between the ischial spine and the attachment of the sacrospinous ligament onto the inferior lateral border of the sacrum) is therefore important to estimate for the correct placement of the stitch. Verdeja[106] noted a correlation between the obstetric conjugate and the length of the sacrospinous ligament. The larger the diameter of the obstetric conjugate, the longer is the sacrospinous ligament. The results of this study indicate that SAE females have a larger obstetric diameter, though not significantly. Therefore, a longer sacrospinous ligament is beneficial for the safe placement of the stitch.

5.3.6 Parturition

During parturition, knowledge of the dimensions of the pelvic canal is essential, especially to avoid CPD. Factors to consider in the case of CPD do not only entail the size and shape of the maternal pelvic canal, but also the size of the foetal skull. Considerable variations have been validated in the pelves among individuals of different ancestral groups.[3,4,66,162,163] Recent studies suggest that the shape of the outlet may reflect the size of the skull passing through the birth canal.[164]

Metric measurements of the pelvic inlet, midpelvis and pelvic outlet were statistically greater in SAE females as compared to SAA, while SL, obstetric conjugate and the measurements involving the pubic symphysis and the subpubic angle, did not differ significantly. Statistical analyses of the variations in the shape of the pelvic inlet and midpelvis in females of the different ancestral groups, were highly significant, as opposed to the pelvic outlet, which were not. The smaller pelvic inlet diameters, shorter pubic symphyseal length and smaller anterior pelvic inlet space in SAA females might be associated with an inability of the foetal head to engage, or overrides of the vertex during parturition.

The interspinous distance is normally the narrowest part of the pelvic canal through which the foetal head must pass during birth and should be greater than 10 cm.[22,109] When the foetal head enters the pelvic midplane (between the ischial spines), it is compressed by the narrowing lateral walls of the passage and consequently rotates so that its long axis lies anteroposteriorly.[31] Individuals with an IS below 10 cm, especially SAA females with an average below 10 cm, could therefore be at risk for midpelvic arrest during parturition.

The impression that the API dimension is related to the height of the individual was confirmed in SAE, but not in SAA in this study.[16,37,70,71] Many other dimensions of both SAE and SAA were dependent on stature and it therefore seems valuable to take stature into account when contemplating childbirth options. While a short stature may predict a small pelvic cavity, it is uncertain how stature and pelvic canal size predicts foetal head size or CPD in these study groups. Merchant *et al.* suggests that shorter women, however, tend to have smaller babies, some of whom will show signs of intra-uterine growth restriction, raising the possibility that this biological relationship might protect shorter women from suffering of delivery complications.[16]

5.4. Possible limitations

This study could be improved by creating a MRI or a CT scan for each of the non-disarticulated cadaver pelves thus, correlating the direct measurements with those of the scanned images, noting any discrepancies. The clinical implications considered should be verified in the clinical context.

Increasing the data base for MRI and CT scans will lend more accuracy to the reference values determined in this study.

6. CONCLUSION

In this study the shape and size variations of pivotal dimensions of the pelvic canal in South Africans were recorded by four modalities: direct measurements and geometric morphometric shape analyses on intact cadaver pelves, CT- and MRI scanning. Variations were noted and the possible implications reflected upon.

6.1. Metric measurements on intact cadaver pelves

All conjugates and dimensions of the pelvic canal rings, as well as the length of the inferior pubic rami and the subpubic angles, were significantly greater in SAE females than in the other groups and correlated with the greatest dimensions found in the literature. Dimensions of SAA females corresponded to other African groups and were larger than in SAA males. Females of both ancestral groups presented as expected with a significantly more spacious pelvic canal shape compared to their male counterparts. Longitudinal dimensions were the greatest in SAE males, apart from the true height of the pelvis, which was greater in SAA males.

6.2. Shape analysis

The antero-posterior diameters of the pelvic canal rings differed at a higher level of significance than the transverse diameters between sexes and/or ancestral groups, as reflected in statistically wider pelvic canal shapes in females and SAE. Wider diameters were associated with a more anterior placement in the pelvic inlet, creating greater anterior pelvic spaces and subpubic regions in SAE and females. However, the shorter length of the pubic symphysis in SAA females diminished this space longitudinally compared to SAA females. The pelvic outlet shape variations were, on the other hand, not statistically significant between ancestral groups.

6.3. Stature and age correlations

Pelvic dimensions correlated more with stature, which presented with a general increase in dimensions, than with aging, that presented with a widening of dimensions. Stature correlations were more evident in SAE and females, while aging correlations were more obvious in SAE and males.

6.4. Variations between modalities

Variations between groups were more similar when taken by direct measurements on intact cadaver pelves than with CT, but less constant with MRI. Horizontal dimensions were affected to a greater extent when comparing modalities, especially when considering MRI values. Difficulty of identifying landmarks and inadequate Z-plane representation on MRI images seem to be implicated.

6.5. Implications

During parturition, taller SAE women may present with larger dimensions, that may facilitate the passage of the foetus. Stature should, therefore, be considered when contemplating childbirth options. The smaller inlet and anterior pelvic space in SAA women might be associated with obstructed labour. However, the associated foetal head might also be smaller.

As a small pelvic canal may impede vision, access and space for surgical excision, consideration of pelvic dimensions are important when planning intrapelvic procedures. An anatomically narrower pelvis was found in SAA and in males in general, which may lead to technical difficulties. The perineal space was smaller as a result of smaller subpubic angles and IT diameters in males and more specifically SAA males, which might influence the ease of performing of perineal procedures.

Pre-operative pelvimetry by MRI or CT scanning for comparison with population specific reference values could be useful when considering childbirth options or other procedures eg.

inferior pubectomy for posterior urethroplasty. Care should be taken when interpreting the transverse diameters on MRI scans.

6.6. Future prospects

6.6.1 All predicted adaptations to procedures or during parturition based on pelvic variations should be verified by further studies in the clinical setting.

6.6.2 Increasing the data base will improve the applicability of the reference values created for South African populations.

6.6.3 The variations between groups could have physical anthropological relevance and should be considered.

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APPENDIX A

Appendix A: Correlations of the dimensions with stature

				African ancestry				European ancestry			
Dimension		**All**		**Female**		**Male**		**Female**		**Male**	
API	r	0.00		0.29		0.53		0.51		0.47	
	r^2	0.00		0.09		0.29	p=0.0072	0.26	p=0.0311	0.22	
SACHOL	r	0.25		-0.04		0.22		0.16		0.49	
	r^2	0.06	p=0.0295	0.00		0.05		0.02		0.24	
APO	r	0.04		-0.07		0.20		0.50		0.46	
	r^2	0.00		0.01		0.04		0.25	p=0.0360	0.21	p=0.0051
TI	r	0.16		-0.07		0.20		0.50		0.44	
	r^2	0.03		0.01		0.04		0.25	p=0.0360	0.20	
IS	r	-0.14		-0.20		0.23		0.18		0.59	
	r^2	0.02		0.04		0.05		0.03		0.35	P=0.0416
IT	r	-0.14		-0.09		0.06		0.34		0.38	
	r^2	0.02		0.01		0.00		0.12		0.17	
SL	r	0.37		0.52		0.22		0.36		0.19	
	r^2	0.13	p=0.0013	0.27	p=0.0163	0.05		0.13		0.04	
LIPL	r	0.15		0.38		0.31		0.33		0.29	
	r^2	0.02		0.15		0.10		0.11		0.09	
RIPL	r	0.18		0.36		0.45		0.41		0.20	
	r^2	0.04		0.13		0.20	p=0.0270	0.17		0.04	
LDTP	r	0.29		0.62		0.26		0.53		0.33	
	r^2	0.09	p=0.0110	0.39	p:0.0023	0.07		0.29	p=0.0224	0.10	
RDTP	r	0.27		0.58		0.25		0.42		0.41	
	r^2	0.07	p=0.0195	0.34	p:0.0057	0.06		0.17		0.16	
LOI	r	0.10		-0.07		0.62		0.34		0.60	
	r^2	0.01		0.01		0.38	p=0.0013	0.11]		0.36	p=0.0387
ROI	r	0.09		-0.20		0.52		0.37		0.65	
	r^2	0.01		0.04		0.27	p=0.0087	0.13		0.42	p=0.0234
LHTP	r	0.51		0.62		0.09		0.37		0.30	
	r^2	0.26	p<0.0001	0.39	p=0.0027	0.01		0.14		0.08	
RHTP	r	0.51		0.50		0.07		0.52		0.33	
	r^2	0.26	p<0.0001	0.25	p=0.0225	0.01		0.28	p=0.0254	0.11	
OBS_CONJ	r	0.06		0.45		0.34		0.15		-0.20	
	r^2	0.00		0.20	p=0.0409	0.12		0.02		0.04	
DIA_CONJ	r	0.11		0.22		0.16		0.09		0.19	
	r^2	0.01		0.05		0.03		0.01		0.03	
LPS	r	0.47		0.28		0.26		0.47		0.41	
	r^2	0.22	p<0.0001	0.08		0.07		0.23	p=0.0467	0.17	p=0.0200
TDIPS	r	-0.16		0.09		0.44		0.36		0.27	
	r^2	0.03		0.01		0.20	p=0.0307	0.13		0.07	
TDSPS	r	-0.21		-0.26		0.05		-0.38		0.19	
	r^2	0.05		0.07		0.00		0.15		0.04	
ANG	r	-0.26		-0.03		0.28		0.28		-0.07	
	r^2	0.07	p=0.0262	0.00		0.08		0.08]		0.00	
LRIPR	r	-0.23		-0.21		0.47		0.09		0.06	
	r^2	0.05	p=0.0490	0.04		0.22	p=0.0271	0.01		0.00	
LIPR_IPS	r	-0.14		-0.34		0.19		0.09		0.29	
	r^2	0.02		0.12		0.03		0.01		0.08	
RIPR_IPS	r	-0.15		-0.34		0.05		0.07		0.26	
	r^2	0.02		0.11		0.00		0.00		0.07	

APPENDIX B

Appendix B: Correlations of the dimensions with age

		All		African ancestry			European ancestry			
Dimension				**Female**	**Male**		**Female**		**Male**	
API	r	0.09		-0.15	-0.32		-0.21		-0.21	
	r^2	0.01		0.02	0.10		0.05		0.04	
SACHOL	r	0.32		0.01	-0.19		-0.06		0.08	
	r^2	0.10		0.00	0.04		0.00		0.01	
APO	r	0.11		-0.02	0.02		0.06		0.03	
	r^2	0.01		0.00	0.00		0.00		0.00	
TI	r	0.52		0.19	-0.22		0.15		0.49	
	r^2	0.27	p=0.0000	0.04	0.05		0.02		0.24	p=0.0125
IS	r	0.23		0.13	0.32		0.13		0.03	
	r^2	0.05		0.02	0.10		0.02		0.00	
IT	r	0.06		0.10	-0.08		0.15		0.11	
	r^2	0.00		0.01	0.01		0.02		0.01	
SL	r	0.06		0.02	-0.26		0.36		0.15	
	r^2	0.00		0.00	0.07		0.13	p=0.0428	0.02	
LIPL	r	0.29		0.11	-0.24		0.08		0.01	
	r^2	0.08	p=0.0007	0.01	0.06		0.01		0.00	
RIPL	r	0.29		0.16	-0.18		0.09		0.04	
	r^2	0.08	p=0.0022	0.03	0.03		0.01		0.00	
LDTP	r	0.07		-0.19	-0.24		0.24		0.16	
	r^2	0.00		0.04	0.06		0.06		0.02	
RDTP	r	0.06		-0.16	-0.32		-0.24		0.21	
	r^2	0.00		0.02	0.11		0.06		0.04	
LOI	r	0.33		0.24	0.01		0.03		0.05	
	r^2	0.11	p<0.0001	0.06	0.00		0.00		0.00	
ROI	r	0.37		0.26	0.12		0.16		0.11	
	r^2	0.14	p<0.0001	0.07	0.02		0.03		0.01	
LHTP	r	0.39		0.07	0.12		0.11		0.57	
	r^2	0.15	p<0.0001	0.00	0.01		0.01		0.33	p=0.0028
RHTP	r	0.39		0.02	0.14		0.29		0.37	
	r^2	0.16	p<0.0001	0.00	0.02		0.09		0.14	
OBS_CONJ	r	0.01		0.09	-0.20		0.41		0.23	
	r^2	0.00		0.01	0.04		0.17	p=0.02	0.05	
DIA_CONJ	r	0.11		0.11	-0.35		0.15		0.19	
	r^2	0.01		0.01	0.13	p=0.05	0.02		0.04	
LPS	r	0.37		0.23	0.07		0.37		0.32	
	r^2	0.05	p<0.0001	0.05	0.00		0.14	p=0.038	0.10	
TDIPS	r	-0.05		0.11	-0.16		0.24		0.03	
	r^2	0.00		0.01	0.03		0.06		0.00	
TDSPS	r	-0.06		0.34	-0.15		0.25		0.33	
	r^2	0.00		0.11	0.02		0.06		0.11	
ANG	r	-0.07		0.03	-0.21		0.30		0.39	
	r^2	0.00		0.00	0.05		0.09		0.15	
LRIPR	r	-0.00		0.08	-0.30		0.25		0.13	
	r^2	0.00		0.01	0.09		0.06		0.02	
LIPR_IPS	r	-0.01		0.09	-0.28		-0.21		0.05	
	r^2	0.00		0.01	0.08		0.04		0.00	
RIPR_IPS	r	-0.06		0.15	-0.38		-0.22		-0.04	
	r^2	0.00		0.02	0.14		0.05		0.00	