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Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications

by

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DECLARATION

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

Jagesur

Suvasha Jagesur

30 day of May 2022

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ABSTRACT

Cephalopelvic disproportion (CPD) is common among South Africans and a major cause of mortality and morbidity. The aim of this study was to explore the variations in pelvic and skull dimensions for their use in forensics and surgical procedures and for a better understanding of CPD and evolutionary processes. This study offered the unique opportunity to explore the variations of the pelvic canal and corresponding skull vault, in cadavers (148 pelves with 33 matching skulls) and on 3D computer tomography models (138 pelves with matching skulls) of black and white South Africans. Metric and geometric morphometric analyses were performed. Maternal and newborn anthropometric data were collected and correlated with birth outcomes (60 vaginal deliveries and 29 caesarean sections). Most linear pelvic canal dimensions were statistically significantly greater in females compared to males, in white compared to black South Africans and in white South Africans than reported in the literature. Biparietal diameter (BPD) and skull circumference were statistically significantly greater in white South Africans, while cranial length was statistically significantly greater in black South Africans. Skull dimensions were greater in males apart from the BPD, which was greater in white South African females. Correlations between skull and pelvic dimensions were more pronounced in females than in males. Contrastingly, to dimensions taken on the skull vault, maternal BPD was statistically significantly greater in black compared to white South Africans, while head circumferences were similar despite a statistically significantly shorter stature. Maternal anthropometrics were greater than reported in the literature. The white South African vaginal delivery group presented with the greatest newborn head circumferences, which were also greater than reported in the literature. Labour was longer in black South Africans. For forensic applications, the skull vault and pelvic canal dimensions delivered high accuracies for population and sex differentiation. Shape analyses of the pelvic canal and skull vault fared better in the prediction of population and sex (for population: pelvis: up to 97.87%; skull: up to 96.38%; for sex: pelvis: 100%; skull: up to 96.38%), when compared to linear dimensions (for population: pelvis: up to 85.33%; skull: up to 94.12%; for sex: pelvis: up to 87.68%; skull: up to 88.24%). Prior identification of population group improved sex discrimination by linear dimensions for both populations (pelvic canal: 89.16% in black South Africans and 96.36% in white South Africans; skull vault: 100% in both groups). Risk factors for CPD could include shorter stature, greater maternal and newborn head circumferences, especially in black South African women. Dietary changes may have worsened the obstetric dilemma by increasing neonatal size without increasing the stature

and pelvic canal. Technically challenging operations may be experienced when performing pelvic or perineal surgery in black South Africans and in men because of the anatomically narrower pelves found in these groups. Future studies could confirm significance of the wider BPD noted in white South African women, whether a correlation between maternal and newborn head circumference exists and in the presence of a shorter stature, duration of labour (a reflection of CPD) is increased.

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LIST OF ABBREVIATIONS

AL	Arcuate line
B	Bregma
BF	Black female
BL	Bilateral
BM	Black male
BPD	Biparietal diameter
C/S	Caesarean section
COC	Coccyx
CPD	Cephalopelvic disproportion
CT	Computer tomography
DC	Diagonal conjugate
EU	Euryon
G	Glabella
GM	Geometric morphometrics
GOF	Greater sciatic notch
IE	Iliopubic eminence
IPS	Public symphysis
IS	Ischial spine/ Interspinous diameter depending on context
ISIJ	Inferior sacroiliac joint
IT	Ischial tuberosity/ Intertuberous diameter depending on context
L	Lambda
MaxCL	Maximum cranial length
MPS	Mid-pubic symphysis
MS	Mid- sagittal
N	Nasion
OC	Obturator canal/ Obstetric conjugate depending on context
OP	Opisthocranion
PO	Anteroposterior dimension of the outlet
S3/4	Sacral joint S3/4 joint
SPR	Sacral promontory
SPS	Pubic symphysis
SSIJ	Superior sacroiliac joint
TC	True conjugate

V/D	Vaginal delivery
WF	White female
WM	White male
WTI	Widest transverse dimension of the pelvic inlet

1. INTRODUCTION

Cephalopelvic disproportion (CPD) is the disproportion of the foetal head size as compared to the size of the maternal pelvis. It and is quite common among Africans and a major cause of maternal and perinatal mortality (Tobias 1974; Merchant et al. 2001; Zahr et al. 2004; Leong 2006). No specific data for infant-mother mortality and CPD in South Africa exists and studies involving the bony pelvis and cranium are limited (Jagesur et al. 2013 [Appendix A]; Patriquin et al. 2005). More specifically, CPD may contribute to prolonged and obstructed labour that can cause neonatal death, cerebral palsy or maternal trauma to the birth canal, and even maternal death (Brabin et al. 2002; Zahr, Wardlaw et al. 2004; Maharaj 2010). A better understanding of the relationship between the shape and size of the birth canal and the shape of the foetal head, as well as other factors such as height and population, may better equip caregivers to predict obstetric risk.

Variations in both pelvic canal and cranial vault dimensions with sex, population, stature and environmental factors, as well as a co-variation between pelvic canal and cranial dimensions within individuals, have been described (Loth and Henneberg 1996; Patriquin et al. 2002; Patriquin et al. 2003; İşcan 2005; Patriquin et al. 2005; Işcan and Steyn 2013). These variations in pelvic canal and cranial dimensions could have implications for deciding on childbirth options and planning pelvic and perineal procedures. Smaller pelvic dimensions in black South Africans not only have far-reaching implications in obstetrics practice, but may also play a role in surgical procedures involving male and female pelvic and perineal structures (Clemans Bushman et al. 1999; Hinoul, Vanormelingen et al. 2007; Zahn, Siddique et al. 2007; Ridgeway, Arias et al. 2008). More specifically, variations in pelvic canal dimensions are important in the planning of pelvic procedures, while pelvic outlet dimensions should be considered in perineal procedures and in incontinence. The diameters which are clinically important include: 1) the true conjugate, 2) the widest diameter of the pelvic inlet, 3) the obstetric conjugate, 4) the narrowest mid-plane dimension and 5) the pelvic outlet dimensions. These diameters and their relationships will not only be helpful in assessing the possibility of a favourable outcome in vaginal deliveries, but also when planning surgical procedures, as a small pelvic canal, for instance, may impede vision, access and space for surgical excision (Hong et al. 2007; Salerno et al. 2007; Killeen et al. 2010).

Population and sex variations in the pelvic canal and cranial vault and co-variations of the pelvic canal and cranial vault could also have forensic anthropological and evolutionary inferences. A pelvis shaped for bipedalism has been considered a compromise for the passage of a foetal head during childbirth and is sometimes referred to as the obstetric dilemma (Rosenberg and Trevathan 1995; Wittman and Wall 2007; Gruss and Schmitt 2015). As larger neonates have a better survival rate, selective pressures will favour larger overall neonatal sizes (Fischer and Mitteroecker 2015). Other evolutionary processes apart from bipedalism have been deliberated and needs to be explored to better understand the influences on the cranial and pelvic dimensions. Betti et al., 2013, for instance, note that the variation in the shape of the pelvis and cranium reflects genetic diversity explained by neutral phenotypic evolution. However, because of obstetrical constraints, dimensions of the pelvic canal are envisaged to show less variation (Betti et al. 2013; Betti 2017). Therefore, although stature is considered an important risk factor for CPD, short women present with relatively larger pelvic dimensions (within and outside the pelvic canal) than taller women (Ricklan et al. 2021).

Variations in pelvic and cranial dimensions also reflect climatic variation, where a narrower pelvis and cranium are found in lower-latitude populations, while the opposite is true for higher latitude populations (Howells 1957; Adadevoh, Hobbs et al. 1989; Keller et al. 2003; Harvati and Weaver 2006; Hubbe et al. 2009; Gruss and Schmitt 2015; Sharma et al. 2016). More recently, changes in diets have been considered more important than bipedalism in the development of CPD. It is thought that improved nutritional status accompanying development in agriculture, may worsen the obstetric dilemma by increasing the size of the neonate without increasing the stature and pelvic canal accordingly. Palaeo-demographic comparisons showed lower rates of perinatal mortality in foragers when compared to agriculturalists (Udosen et al. 2006; Wells et al. 2012; Ricklan et al. 2021).

Variations in the crania and pelvis are useful in forensic anthropological assessments (De Villiers 1968; Fee 1979; Patriquin et al. 2003; Patriquin et al. 2005; Işcan 2013). Krogman (1951), for instance, morphoscopically sexed a sample of 750 adult skeletons (white South Africans and black South Africans, male and female) from the Hamann-Todd Collection, housed at the Cleveland Museum of Natural History. His success rates in identifying the sex correctly were as follows: when the entire skeleton was present (100%), pelvis alone (95%), skull alone (92%), pelvis plus skull (98%), long bones alone (80%), long bones plus pelvis

(98%) (Krogman 1951; Işcan and Steyn 2013). Although it is commonly considered beneficial to first establish the population prior to sex estimation (Steyn and Patriquin 2009; Işcan and Steyn 2013), Kenyhercz et al. 2017 more recently used the morphoscopic method described by Klales et al. and achieved 95.9% classification accuracy for sex estimation without the need for population specific equations. Klales et al. modified the method of Phenice (1969) who used three sex traits related to the pubic bone (ventral arc, subpubic concavity/contour and medial aspect of the ischio-pubic ramus) to capture varying degrees of expression within each trait (Phenice 1969; Klales et.al 2012). Santos et al. 2019, tested Bruzek's non-metric traits for sexing the human os coxae with logistic regressions and obtained an accuracy rate of 99.2% on reconstructed CT models compared to the skeletal sample (98.2%) (Santos et. al 2019).

Metric methods, on the other hand, involve discriminant function analysis and accuracies from 84% to 94% have been achieved for both sex (Dibennardo and Taylor 1983, Işcan 1983, Patriquin and Steyn 2002) and population (or ancestry) estimations on the pelvis (Howells 1957, Patriquin et al. 2005 and Steyn and Patriquin 2009). Accuracies can be enhanced by the performance of geometric morphometrics. Geometric morphometrics allows shape differences to be visualized and quantified. Bytheway and Ross (2010) obtained a near 100% separation between the sexes when assigning 3D landmarks to the pelvis as a whole. On the skull, accuracies for sex estimation with discriminant function formulae ranged from 70% to 99% (Ousley and Jantz, 1996). Although population estimation on the skull is believed to be at least 90% accurate, overlaps between groups do occur, and it is mandatory that the suspected population be represented in the reference sample (Bytheway and Ross 2010, L'Abbé, E.N et al., 2013; Stull et al. 2014; Liebenberg et al. 2015; Liebenberg et al. 2015).

Although the skull is widely used in ancestry and sex estimations by morphoscopic, metric and geometric morphometric methods, less is known regarding the usefulness of the skull vault in both ancestry and sex estimations. By contrast, while sexual dimorphism of the pelvic canal is well known (Boucher 1957; Nwoha 1992; Patriquin, Steyn et al. 2002; Igbigbi and Nanono-Igbigbi 2003; Correia, Balseiro et al. 2005), the usefulness for sex and population estimations in forensic applications is seldom explored.

Furthermore regarding methodology, the use of disarticulated osteological sections invariably leads to unnatural reassembling of bones, which could cause error in measurements crossing joints e.g. the subpubic angle. Ordinary X-rays may also lead to errors, as some landmarks cannot be accurately defined for distances to be measured (Heyns 1947) as well as the lack of standardization in patient positioning. Although craniofacial measurements obtained from medical computer tomography (CT) scans are considered accurate and reproducible (Waitzman et al. 1992), more recently, the findings of Colman et al. indicate different degrees of measurement error. These measurement errors were attributed to differences in size due to misalignment of image slices, as well as segmentation and landmark recognition difficulties (Colman et al. 2019). For these reasons, 3D reconstructed CT models, rather than medical CT scans, were used in this study.

The purpose of this study was to explore the variations of the pelvic canal and cranial vault dimensions on the same individual, when available. Intact cadaver samples, as well as 3D reconstructed CT models of two South African populations were used. Statistical correlations between cranial vault and pelvic canal dimensions (shape and size) were made. Geometric morphometrics were used to statistically analyse shape variations. These findings were brought into context with the clinical situation by collecting retrospective and prospective anthropometric data of mother and baby, and by making correlations with childbirth outcomes.

Lastly, an integrative analysis was made that could provide greater insight to possible predictors of cephalopelvic disproportion in pregnant women in South Africa. The findings of this study could also assist in the planning of perineal and pelvic procedures in both sexes. The co-variation of cranial and pelvic dimensions in South African groups may further contribute to a better understanding of the sources of variation of pelvic and cranial shape and the extent of population history signals and functional pressures related to bipedalism and childbirth (Betti et al. 2014; Huseynov et al. 2016). Analysis of the variations in pelvic and cranial dimensions between sexes and populations could also prove to be useful in forensic anthropological applications.

2. AIMS AND OBJECTIVES

Aim:

The aim of this study was to explore the variations and co-variations in pelvic canal and cranial vault dimensions to a better understand variables involved in CPD and birth outcomes, and the underlying evolutionary processes involved. Implications for surgical procedures and forensic anthropology further be considered.

Objectives:

To evaluate sex and population variations and co-variations in the dimensions (size and shape) of the cranial vault and intact pelvic canal, where the dimensions of the cranial vault and intact pelvic canal were derived from 3D landmarks digitised on:

1. the intact cadaver pelvis and on the cranium, respectively, and where possible, on the same individual. The dimensions on the cranium included: 1) cranial height, 2) biparietal diameter, 3) maximum cranial length, 4) head circumference, 5) BPD/ maximum cranial length and 6) BPD/ head circumference (cadaver sample only). Pelvic dimensions included: 1) the true conjugate, 2) the widest diameter of the pelvic inlet, 3) diagonal conjugate, 4) obstetric conjugate, 5) narrowest mid-plane dimension and 6) anteroposterior dimension of the pelvic outlet, 7) intertuberous diameter and 8) subpubic angle. The co-variation between the linear cranial and pelvic dimensions were determined by regression models, while the shape of the cranial vault and the pelvis (overall pelvic shape, pelvic inlet shape, mid-pelvis shape and pelvic outlet shape, respectively) were correlated by performing two block partial least squares analysis.

2. 3D models of retrospectively collected computer tomography scans (CT) of the cranial vault and pelvic canal of the same individual. The dimensions on the cranium included: 1) cranial height, 2) biparietal diameter, 3) maximum cranial length, 4) head circumference, 5) BPD/ maximum cranial length and 6) BPD/ head circumference (cadaver sample only). Pelvic dimensions included: 1) the true conjugate, 2) widest diameter of the pelvic inlet, 3) diagonal conjugate, 4) obstetric conjugate, 5) narrowest mid-plane dimension and 6)

anteroposterior dimension of the pelvic outlet, 7) intertuberous diameter and 8) subpubic angle. The co-variation between the linear cranial and pelvic dimensions were determined by regression models, while shape of the cranial vault and the pelvis (overall pelvic shape, pelvic inlet shape, mid-pelvis shape and pelvic outlet shape, respectively) were correlated by performing two block partial least squares analysis.

3. To correlate the outcome of childbirth and duration of active labour to the head dimensions of baby and mother considering population and stature. Population, stature of the mother, as well as the head dimensions (circumference and biparietal distance) and available length dimensions of the foetus at various prenatal ages and at birth were recorded, retrospectively. Maternal head dimensions (circumference, biparietal diameter and stature, if not available before) were collected prospectively after informed consent was obtained.

4. To consider the implications of the findings by performing an integrative analysis of cadaver, radiological and patient data. An integrative analysis was achieved by considering the results described in objectives 1 to 3 in a holistic approach, considering the possible limitations and advantages of each part and a) consider the possible inferences for predicting cephalopelvic disproportion, b) application in forensic anthropological processes, c) assist in the planning of perineal and pelvic procedures and d) improve understanding of the possible evolutionary aspects.

3. LITERATURE REVIEW

3.1 Anatomy of the pelvic canal

3.1.1 The bony components

The pelvic canal is a bowl-shaped space bordered by the two coxal bones, each formed by the pubis, ischium and ilium which fuse during development, as well as the sacrum (fused sacral vertebrae) and coccyx (Figure 1 and 2). More specifically, the pelvic canal is a short, curved space bordered antero-inferiorly by the pubic symphysis, bodies of the pubic bones and rami of the pubis, and posteriorly by the concave anterior surfaces of the sacrum and coccyx. Superiorly, the pelvic cavity is bordered by the pelvic brim consisting of the continuous segments of the linea terminalis, which include the iliac arcuate line, pectineal line (pectin pubis) and the pubic crest. The pelvic canal is ± 5 cm deep anteriorly and ± 15 cm deep posteriorly. It encloses parts of the reproductive organs, urinary bladder and rectum (Moore et al. 2013; Betti et al. 2014; Standring 2015).

Fusion of these bones commences in ossification centres found as separate units in each bone. Of particular importance for the pelvic canal is the ossification centres found in the ischial tuberosity, the symphyseal surface of the pubis and in the individual sacral vertebrae. Some of these ossification centres may only completely fuse on or after 25 years of age. Before puberty commences, the bones are kept in place by cartilage (White et al. 2011; Fischer and Mitteroecker 2015; Standring 2015). Individual sacral bodies unite at their margins after the twentieth year, but the central parts, only in midlife (Standring 2015). Females who become pregnant before the age of 25 years, may therefore risk the possibility of a restrictive birth canal, especially due to the anterior and posterior aspects of the pelvic canal which have not yet developed fully.

The ilium, the largest of the three coxal bones, only makes a small contribution to the pelvic canal as the sacropelvic surface, 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 (White et al. 2011; Standring 2015).

The ischium is a U-shaped bone with a body and a ramus. 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 for the 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 (White et al. 2011; Moore et al. 2013; Standring 2015).

The pubis consists of three parts: a superior and inferior ramus and a flat quadrangular body. The superior border consists of the pubic crest and pubic tubercle onto which muscles and ligaments attach. The long, oval medial or symphyseal surfaces of the left and the right pubic bones face each other, and both articular surfaces covered with hyaline cartilage. 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 posteriorly 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) (Scheepers et al. 1999; White et al. 2011; Moore et al. 2013; Standring 2015). The subpubic angle is formed between the inferior pubic rami in an articulated pelvis, below the pubic symphysis. This area is also known as the subpubic arch (Frudinger et al. 2002; Msamati et al. 2005; Moore et al. 2013).

The obturator foramen is located lateral 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 almost entirely 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 distinct (White et al. 2011; Moore et al. 2013; Standring 2015).

The pelvic canal is completed posteriorly by the sacrum which articulates with the coxal bones at the auricular surface of each iliac bone. The five sacral vertebrae fuse to form a large, triangular sacrum. The sacrum is often wider in proportion to its length in females, with the body of the S1 vertebra usually larger in males. The dorsal surface of the sacrum is rough and convex, while the pelvic surface, which contributes to the pelvic cavity, is smooth and concave. The apex of the sacrum tapers inferiorly and has an oval facet for articulation with the coccyx, which is directed downwards and ventrally. The coccyx is small, triangular and often asymmetrical, usually consisting of four variably fused rudimentary vertebrae, although the number varies between three and five (Moore et al. 2013; Standring 2015).

3.1.2 Pelvic joints

The os coxae and sacral bones constitute the pelvic canal, are interconnected by ligaments and muscles which line their inner surfaces (Standring 2015). Joints pertaining to the pelvis are semi-mobile, especially during pregnancy and parturition (Standring 2015). The primary joints of the pelvic girdle are the two sacroiliac joints and the pubic symphysis (White et al. 2011; Işcan and Steyn 2013; Moore et al. 2013; Standring 2015).

Various ligaments are involved in keeping the sacroiliac joint stable. These include the anterior sacroiliac, posterior sacroiliac, iliolumbar, sacrotuberous and sacrospinous ligaments (White et al. 2011; Moore et al. 2013; Standring 2015). 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 complete the pelvic outlet (White et al. 2011; Moore et al. 2013).

The symphyseal 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 than males. The hyaline cartilage is evidently connected to the fibrocartilaginous disc which is held in 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 (White et al. 2011; Moore et al. 2013; Standring 2015).

3.1.3 Horizontal pelvic rings

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 shown in

The pelvic canal, the bony passage through which the baby must pass in females can be quantified by the size, shape and relative orientation of three delineated horizontal rings, namely the pelvic inlet, midpelvis and pelvic outlet, as shown in Figure 1.

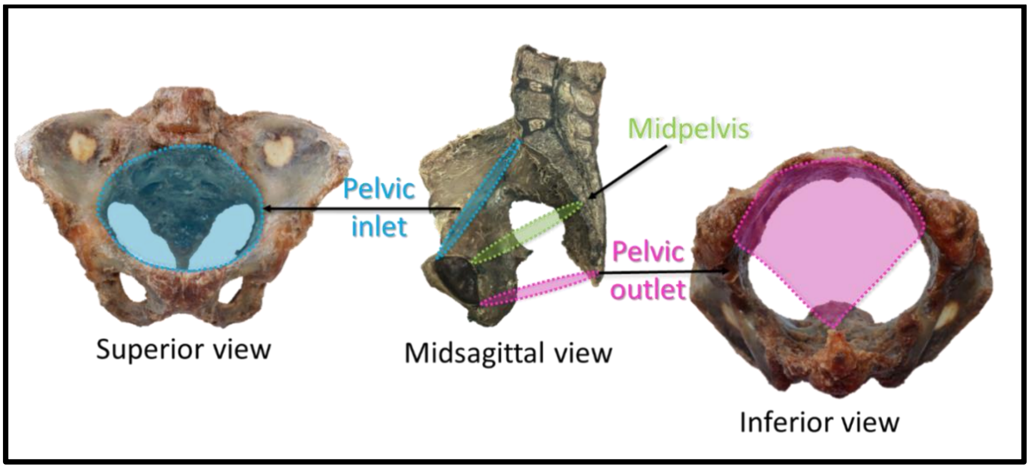


Figure 1. Pelvic rings

3.1.3.1 Pelvic inlet

The pelvic inlet is bordered posteriorly by the sacral promontory, postero-laterally by the sacral alae, laterally by the arcuate and pectineal lines, which, together, form the iliopectineal lines, and anteriorly by the pubic symphysis. The pelvic inlet is also referred to as the entrance of the superior margin of the true pelvis (Figure 1) (Gutman et al. 2005; Moore et al. 2013). The true pelvis is bounded antero-inferiorly by the pubic symphysis and the superior rami of the pubis; postero-superiorly by the sacrum and coccyx; and laterally, by the body and superior ramus of the ischium. It contains the colon, rectum, bladder, and some of the reproductive organs. The false (or greater) pelvis is bounded on either side by the ilium. The false pelvis supports the intestines and transmits part of their weight to the anterior wall of the abdomen (Moore et al. 2013; Standering 2015).

The pelvic inlet is often described by means of dimensions. These dimensions include the antero-posterior diameter of the inlet or true conjugate (TC) and the widest transverse inlet diameter (WTI) (Figures 1, 2 and 3).

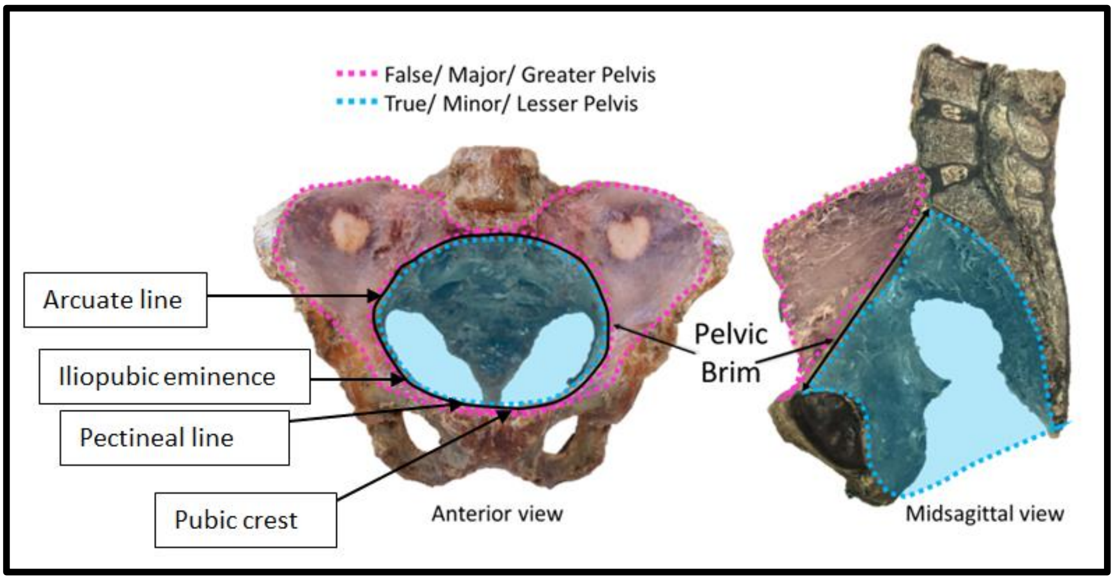


Figure 2. Anterior and midsagittal view of the true and false pelvis

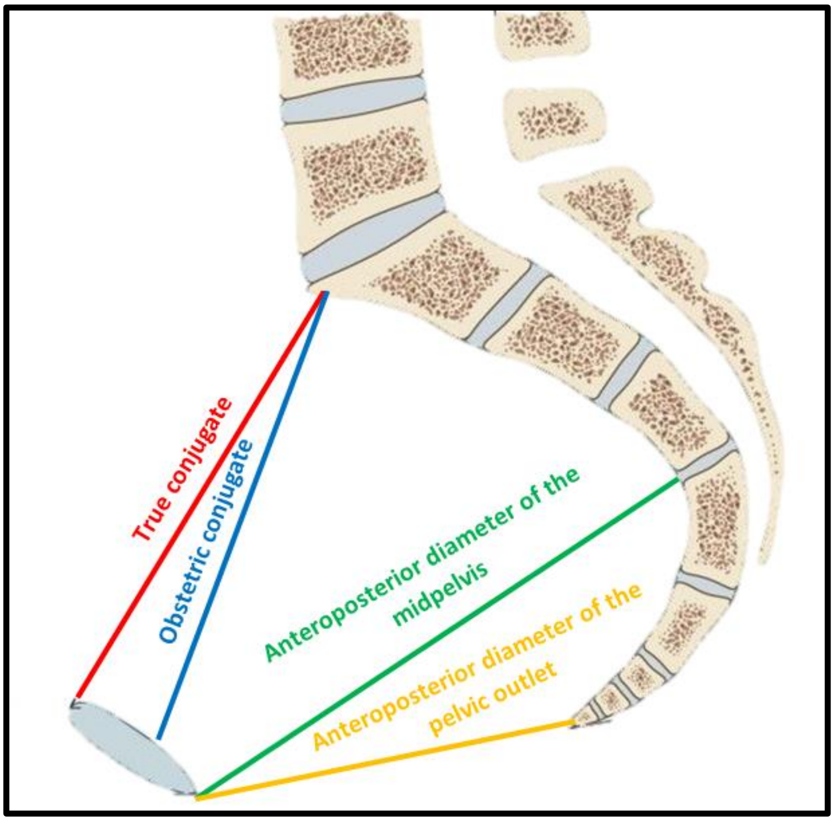


Figure 3. Conjugates considered in the midsagittal plane

The TC is the distance extending from the most supero-anterior point on the sacral promontory to the superior midline point on the dorsal aspect of the pubic symphysis (Figure 3). On average, the TC measures 10 cm in males and 11.2 cm in females according to studies on various population groups (Young and Ince 1940; Gutman et al. 2005; Killeen et al. 2010; Moore et al. 2013; Standring 2015). The TC does not, however, represent the shortest antero-posterior distance for the foetus to pass through during the birth process.

The obstetric conjugate (OC) is the shortest distance from the sacral promontory to the most prominent point on the posterior aspect of the pubic symphysis. The OC measures 10 cm or more in both males and females (Figure 3) (Michel et al. 2002; Louis and Warren 2009; Maharaj 2010; Moore et al. 2013), with Young and Ince (1940) reporting values of 11.83 cm for females and 11.51 cm for male. These values may vary among populations, for instance, a distance of 12.90 ± 0.88 cm was recorded in a representative Japanese sample (Katanozaka et al. 1999), while in an Indian sample, a distance of 11.40 ± 1.07 cm was reported (Sonal et al. 2006). An OC of less than 11.70 cm has been associated with breech presentation of the foetus, resulting in a caesarean section (Joyce et al. 1975). A breech presentation is a polar alignment of the foetus in which the lower pole of the foetus presents to the maternal pelvis (Louis and Warren, 2009).

The widest transverse diameter of the pelvic inlet (WTI) (Figure 4) is considered the greatest transverse width measured across the pelvic inlet. This is an important factor for the engagement of the foetal head in the pelvis and is a co-determiner of the pelvic inlet shape. Standring et al. 2015, as well as other authors (Young and Ince 1940; Tague 1989; Handa et al. 2008), reported an average measurement of 13.10 cm in females and 12.50 cm in males. Louis and Warren (2009) reported an average measurement of 13.50 cm. This measurement may vary among population groups as reported by İşcan (1983), where white North American males measured 12.36 cm, black North American males measured 11.20 cm, white North American females, 13.39 cm and black North American females, 12.06 cm. White, compared to black Americans, therefore, presented with greater dimensions rendering the pelvis not only more spacious, but also wider

Figure 4. Transverse conjugate measurement

According to Greulich and Thomas (1939), pelvic inlet shapes can be classified into four main types, (Figure 5). This classification can be done either by general visual impression of the pelvic shape, or derived from the relative size and position of the transverse conjugate and TC (Turner 1885; Caldwell and Moloy 1933; Greulich et al. 1939; Drake et al. 2009).

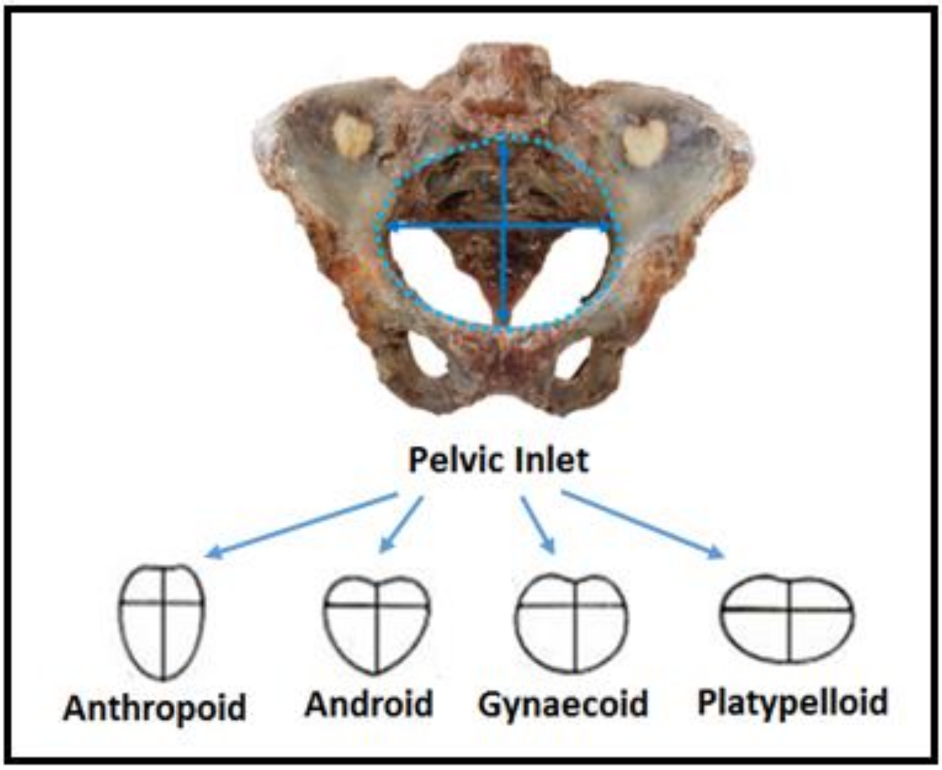


Figure 5. Pelvic inlet shape classification

The gynaecoid pelvis is so called because it has been considered as having the ideal shape for vaginal delivery. The gynaecoid pelvis, as it has been traditionally described, has a round to slightly oval inlet on visual inspection. More objectively, the gynaecoid inlet can be quantified by a TC that measures slightly shorter than the transverse conjugate; with these two measurements intersecting each other approximately in the midline. The android pelvis, on the other hand, has a more triangular or heart-shaped inlet, prominent ischial spines and an angulated pubic arch. The true and transverse conjugates intersect each other posterior to the midline of the TC, which results in the anthropoid pelvis inlet being elongated. The nowadays rarely mentioned platypelloid pelvis has been described to have a flat inlet with a shortened TC or relatively elongated transverse conjugate (Turner 1885; Loth and Henneberg 1996; Kurki 2011).

A more recent study conducted in 2015 by Kuliukas et al. investigated the Caldwell-Moloy (1933) classification system by means of geometric morphometric (GM) analysis (Caldwell and Moloy 1933; Kuliukas et al. 2015). The authors argue that the traditional midwifery teachings of the Caldwell-Moloy system should be reconsidered, as their results show that the shape findings from GM do not correlate with the four distinct pelvic inlet types. Instead, several variations of the shape of the pelvic inlet were observed. They state that it is more helpful to view the pelvic shape as a whole, as it has many components that might affect childbirth.

3.1.3.2 Midpelvis

The interspinous diameter (IS) is described as the distance between the ischial spines (Figure 6). This distance is important for clinicians, as it represents the narrowest part of the pelvic canal through which the infant’s head must pass and, therefore, might be a limiting factor during parturition (Gabbe et al. 2016). According to Maharaj (2010), this distance is assessed by touching both ischial spines simultaneously with two examining fingers on the same hand, and noting the distance between the fingers. She reports that this distance should be at least 10 cm for a successful vaginal delivery (Maharaj 2010; Moore et al. 2013; Standring 2015; Gabbe et al. 2016).

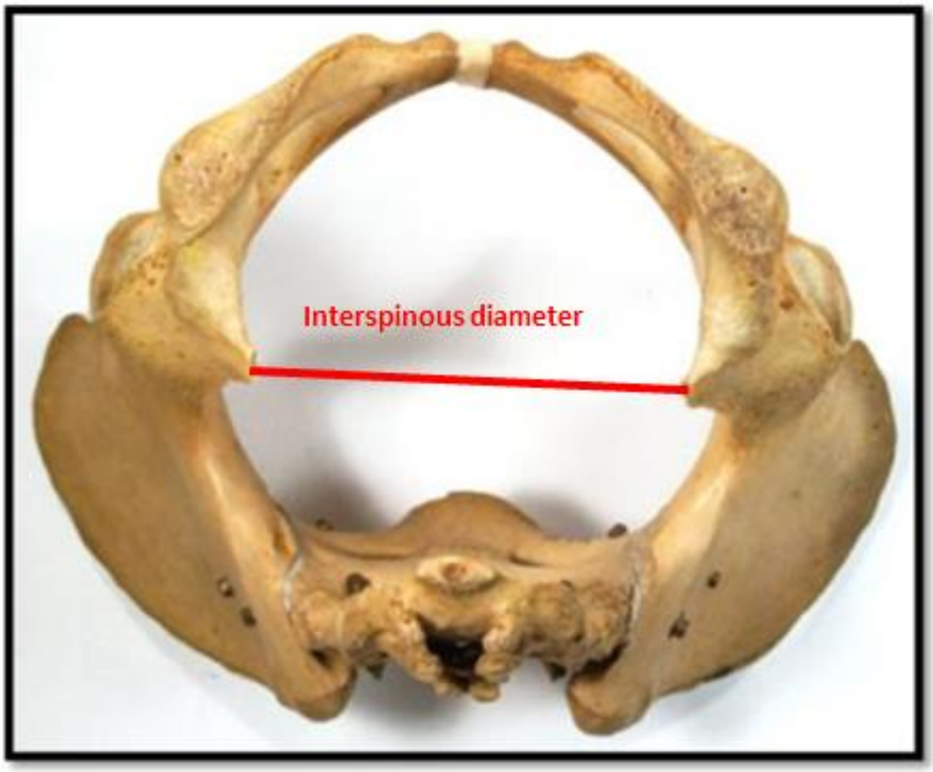


Figure 6. Midpelvis dimensions showing the interspinous distance

Standring et al. (2015) and Gabbe et al. (2016) state that the average IS diameter needed for an adult female is 9.5 cm (Standring 2015; Gabbe et al. 2016).

This smaller diameter, as compared to other conjugates, would allow a foetus with an average foetal head size of 9 cm (fronto-occipital diameter) to pass through the canal. However, this distance is not a fixed dimension. Increased levels of sex hormones, as well as relaxin, have been thought to cause the pelvic ligaments to relax during the latter half of pregnancy, and thus allowing for increased movement of the pelvic joints. Relaxin is a peptide hormone produced by the ovary and the placenta and causes the relaxation of the pelvic ligaments and widening of the cervix during labour (Moore et al 2003). Relaxation of the sacro-iliac joints and the pubic symphysis has been considered to permit increases of between 10-15% in the transverse and interspinous diameters, easing the passage of the foetus (Moore and Lavelle 1974; Moore et al. 2013). The TC diameter, however, remains unaffected by the process (Huerta-Enochian et al. 2006).

Another diameter of the pelvic cavity to be considered, is the antero-posterior diameter of the midpelvis (Figure 7). The descriptions of this dimension are less clear and do not always correspond to the illustrations thereof (Tague 1989; Franciscus 2009; Sigmann et al. 2014). For the purposes of this study, the antero-posterior diameter of the midpelvis is considered as extending from the most inferior point 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 (Standring 2015). This dimension is important, as the long axis of the foetal head is directed against the sacrum during the initial stages of labour (Caldwell et al. 1935).

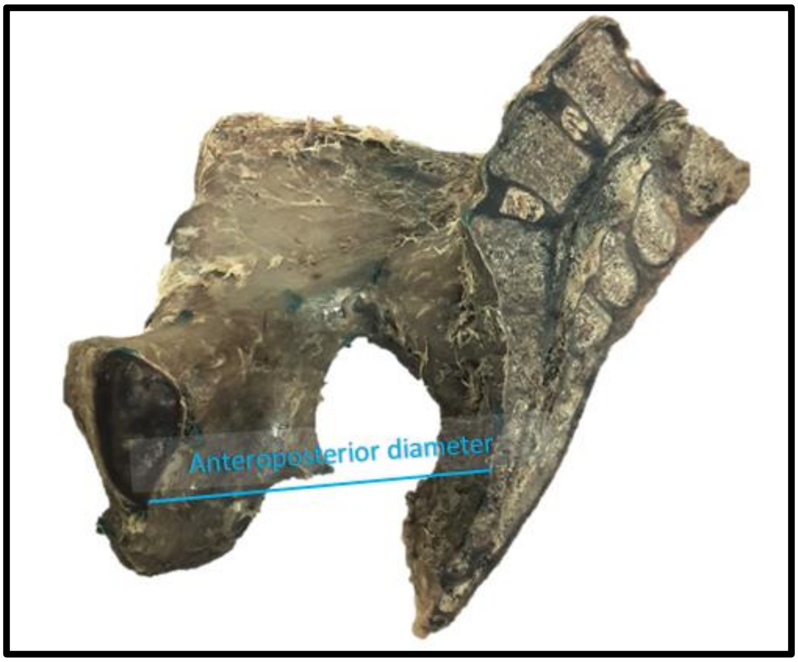
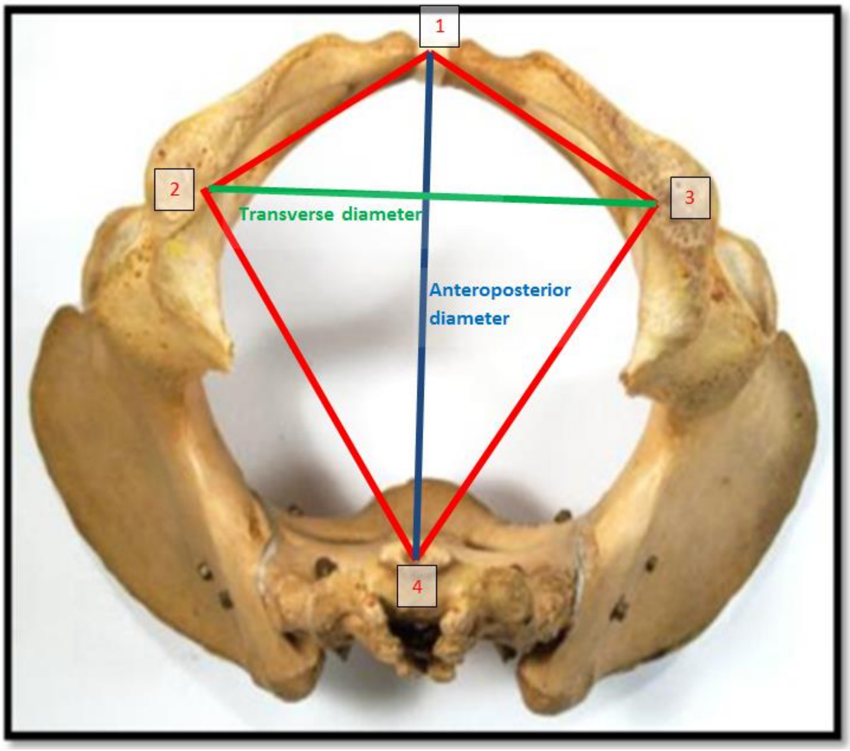


Figure 7. Anteroposterior diameter of the midpelvis

3.1.3.3 Pelvic outlet

The pelvic outlet, or simply the outlet, is outlined antero-inferiorly 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 (Figure 8).

The sacrotuberous ligaments connect the ischial tuberosities and the infero-lateral border of the sacrum bilaterally (Drake et al. 2009; Moore et al. 2013). Together with the ligaments and bony landmarks, the pelvic outlet represents a rhomboidal shape (Standring 2015). The pelvic outlet, therefore, is not a defined rigid structure such as the pelvic inlet, This is especially visible in its posterior half which is completed by ligaments, making the pelvic outlet more a theoretical boundary.



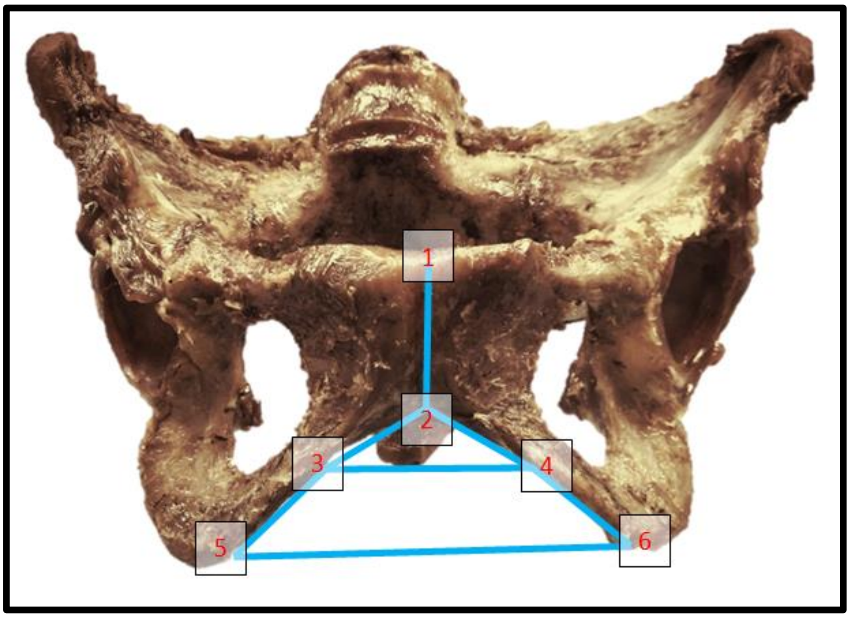
1. Inferior border of the pubic symphysis
2. Medial surface of ischial tuberosity (right)
3. Medial surface of ischial tuberosity (left)
4. Tip of coccyx

Figure 8. Pelvic outlet boundaries and dimensions

The dimensions of the pelvic outlet include the transverse diameter and the antero-posterior diameter of the outlet (PO) (Figure 8). The transverse diameter is commonly referred to as the intertuberous/bituberous diameter, between the medial surfaces of the ischial tuberosities. The intertuberous diameter (IT) is, on average, 8.5 cm in males and 11.8 cm in females. The antero-posterior diameter is, on average, 8 cm in males and 12.5 cm in females (Standring 2015). The closer the ischial tuberosities are to each other, the smaller the subpubic angle and, therefore, the narrower the pelvic outlet (Frudinger et al. 2002) (Figure 9).

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 of the ischial spines in the clinic (Albrich et al. 2015). According to Frudinger et al. (2002), the subpubic angle should be more than 90˚ to avoid complications during delivery (Frudinger et al. 2002; Maharaj 2010). Moore and Dalley (2013) suggest 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 (Moore et al. 2013).

A significant variation in the width of the pubic arch, as reflected in the size of the subpubic angle has been established within the female population (Oladipo et al. 2010). The subpubic angle can be mathematically calculated in the clinic by measuring radiological landmarks, or by palpation of the pubic symphysis and ischial tuberosities. Similar landmarks on dry bones can be used in anthropology (Whiteside and Walters 2004; Reisenauer et al. 2006; Boyles et al. 2007).



1. Superior point on pubic symphysis

2. Inferior point on pubic symphysis

3. Ischiopubic ramus (right)

4. Ischiopubic ramus (left)

5. Ischial tuberosity (right)

6. Ischial tuberosity (left)

Figure 9 Subpubic angle in a female

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 populations (Inuwa 1992; Nwoha 1992; Igbigbi and Nanono-Igbigbi 2003). Igbigbi and Nanono-Igibi (2003) found that the subpubic angle in a Ugandan population ranges from 75˚ to 155˚ (mean of 116.11˚) in females. These subpubic angles were determined by antero-posterior radiographs. However, the values are significantly smaller than the subpubic angles of a Malawian population, with a mean value of 129.07˚ (Msamati et al. 2005). Igbigbi and Nanono-Igibi suggest that these differences are an indication of regional variation of the subpubic angle among African subjects. The variations noted between African subjects emphasise that dimensions should not be expected to be the same in geographically distinct groups. Inter-individual variability should further also be kept in mind.

Brits and co-workers (2012) quantified the subpubic angle in black South African and white South African males and females (Brits et al. 2012). They reconstructed the pelves by using a line 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 that the mean value of the subpubic angle in black South African males and females were 63.98˚ and 84.18˚, respectively. By contrast, white South African males and females were larger, with mean angles of 70.78˚ and 93.98˚, respectively (Brits et al. 2012).

3.2 Anatomy of the foetal skull

For descriptive purposes, the foetal head is divided into regions that aid in defining the lowermost presenting part on vaginal examination during labour. The vertex is the area between the anterior and posterior fontanelles and extends to the parietal eminences on each side. The occiput is the area postero-inferior of the posterior fontanelle. The area of the anterior fontanelle is called the bregma and the area in front of the anterior fontanelle to the root of the nose is known as the brow. The area between the root of the nose and the chin, is the face (Figure 10) (Louis and Warren 2009).

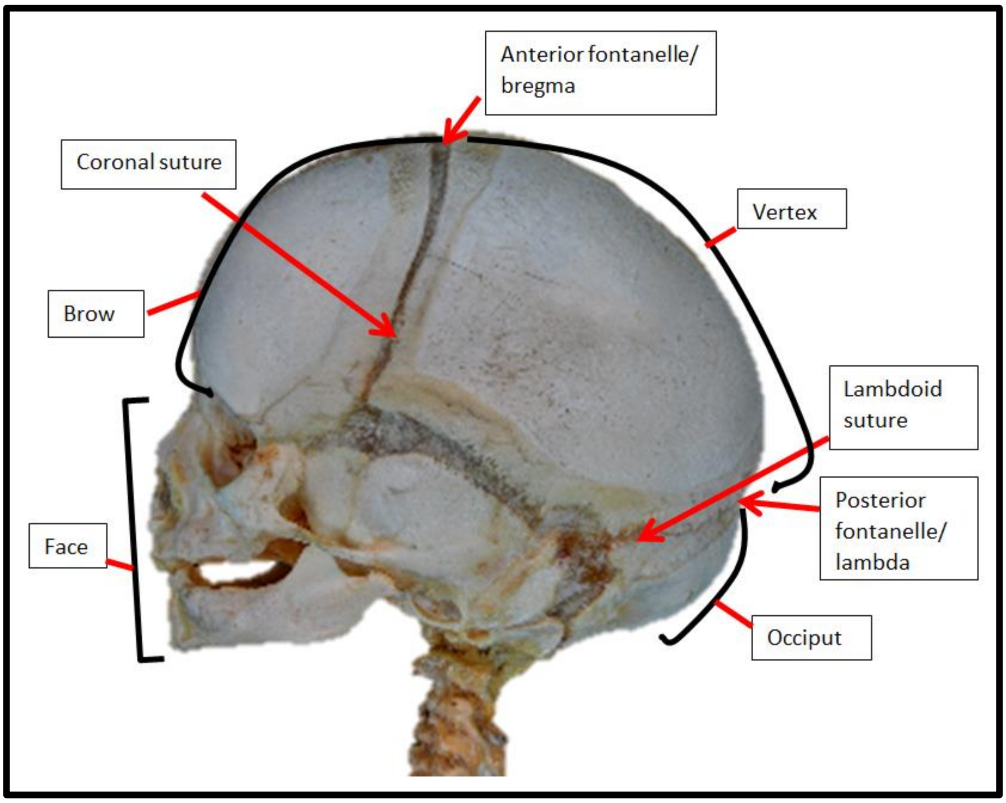


Figure 10. The regions of the foetal skull (Louis and Warren, 2009)

The degree of flexion of the foetal head during labour determines which region of the foetal skull is presenting, and hence it is customary to describe lines that correspond to the diameter of the presenting region of the head (Figure 11) (Louis and Warren 2009). The suboccipito-bregmatic diameter (fully flexed vertex) and the submento-bregmatic diameter (face) are the smallest diameters at 9.5 cm each. The largest diameter is 13.5 cm, which is the mento-vertical diameter of a brow presentation. Other diameters are the suboccipito-frontal (10.5 cm) and occipito-frontal (11.5 cm), both which are seen with deflexed vertex presentations. It is not known whether variations in these diameters exist, as the literature sources does not reflect the population group that was sampled (Louis and Warren 2009; Parente et al. 2010).

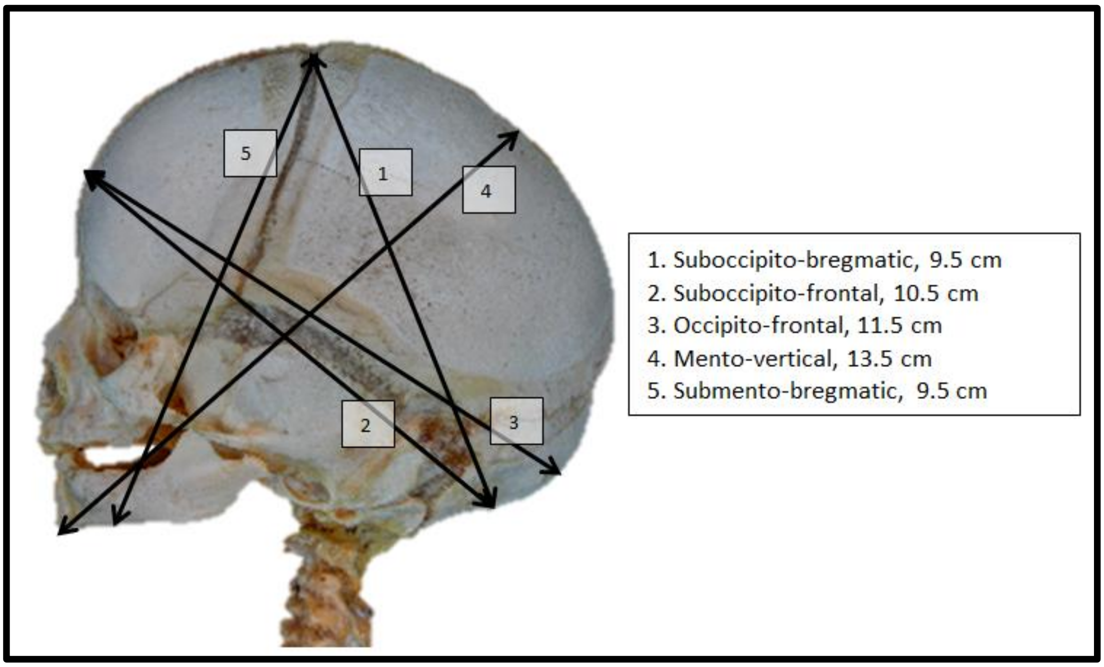


Figure 11. The diameters of the foetal skull according to Louis and Warren (2009) and Parente et al. (2010)

Compared to the adult skull, the foetal skull consists of a large cranium and a relatively small face. The foetal cranium is composed of nine “flat” bones (one occipital, two parietal, two frontal, two temporal, one sphenoid and one ethmoid) (Morriss-Kay and Wilkie 2005; Louis and Warren 2009). The bones are joined by membranes, also called sutures, which allow the skull to expand around the growing brain and to be compressed during birth. The sagittal suture joins the two parietal bones, the frontal suture joins the two frontal bones, while the coronal suture is the junction between between the two frontal and two parietal bones and the lambdoid suture joins the parietal bones and the occipital bone. The frontal suture usually ossifies, but should it persist, it is then referred to as the metopic suture. The diamond-shaped junction where the two coronal sutures meet with the frontal and sagittal sutures is called the anterior fontanelle, whilst the triangular junction between the sagittal suture and the two lambdoid sutures is referred to as the posterior fontanelle (Figures 10 and 12) (Kuliukas et al. 2015).

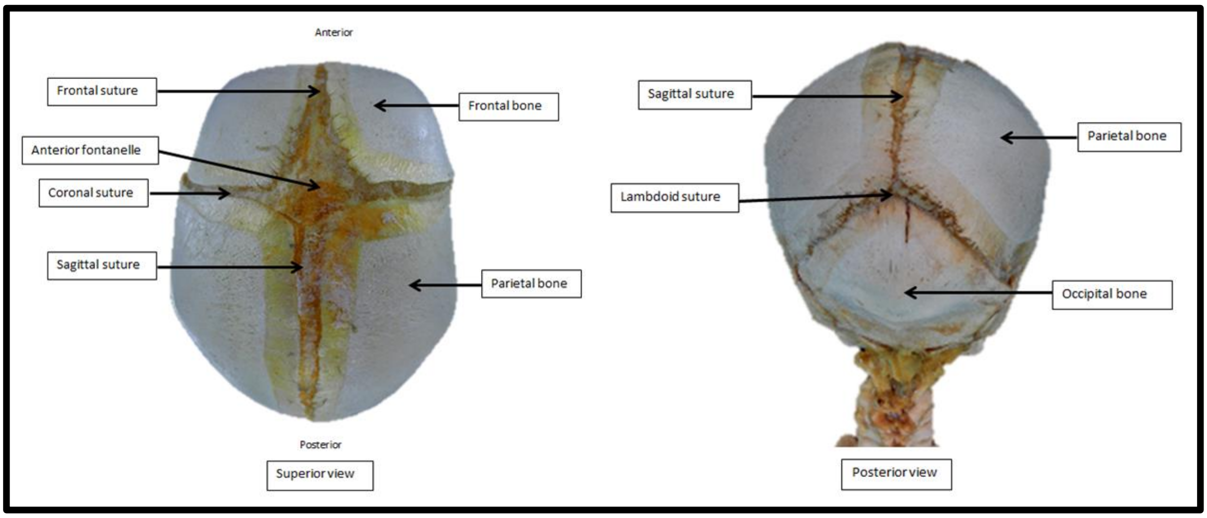


Figure 12. The sutures and fontanelles of the foetal skull

The positions of the sutures overlie areas where brain tissue does not lie close to the surface, i.e. in the midline between the cerebral hemispheres and olfactory lobes (sagittal and metopic sutures) and the area between the cerebral hemispheres and the cerebellum (lambdoid suture). The coronal suture is a flexible joint and in newborn babies with very little hair, the overlapping bones can be seen to slide over each other to widen the suture when the baby cries and intracranial pressure rises (Kurki 2011).

Growth in the sutures is perpendicular to the orientation of the suture, and is normally maintained throughout the period of growth of the brain (Morriss-Kay and Wilkie 2005). The growth regions between the bones of the skull base are cartilaginous and are referred to as synchondroses. Bony fusion does not normally occur until an advanced age in the human skull, after the major part of growth in breadth of the forehead has taken place; an exception is the metopic suture, which begins to fuse at around 18 months of age (Morriss-Kay and Wilkie 2005). The ability of the neocortex to expand within its protective casing made evolution of human intelligence possible. Similarly, the development of full mental capacities in the growing child depends on long term expansion of the skull to allow free growth of the brain (Kurki 2011).

3.2.1 Moulding

The movement and overlapping of the cranial bony plates at the sutures during labour, is referred to as moulding (Louis and Warren 2009). It is the process whereby the anatomical relationship between the cranial bones changes as a response to external pressures or forces. During labour, moulding occurs to a varying degree as the foetal head descends, allowing the foetal head to adjust to the geometry of the birth canal (McPherson and Kriewall 1980; Louis and Warren 2009). This process involves the overlapping of the parietal bones over other cranial bones and is often more marked when there is a partially contracted pelvis, as moulding reduces the diameter of the presenting part of the foetal head and helps descent and progress towards a vaginal delivery. Moulding may be considered a normal part of labour, however, excessive moulding with subsequent cerebral trauma has been linked to conditions ranging from subtle psycho-neurological disabilities to cerebral palsy, dural membrane injury, intercranial hypertension and even death (McPherson and Kriewall 1980; Lapeer and Prager 2001).

Extreme moulding in the full-term foetus is prevented by the mechanical interactions of adjoining skull bones. As moulding progresses and extremes are reached, the frontal bones and occipital bones interlock at the metopic suture and lambdoidal sutures, respectively. In addition, the parietal bones interlock at the sagittal suture. Thus, the head, after optimally adapting to the conformation of the birth canal, begins to act as a more rigid body in protracted labours, preventing further moulding and protecting the brain (McPherson and Kriewall 1980).

In a premature foetus, the skull bones are not well ossified, especially at the margins, which results in the sutures being wider. The interlocking mechanism therefore does not create as rigid a structure and the premature infant is thus at greater risk of birth trauma (McPherson and Kriewall 1980). This may explain why pre-term infants are at a higher risk of cerebral trauma during parturition than are full-term infants. In the pre-term foetus, the lower value of the elastic modulus, coupled with the thinner structure of the cranial bones, allow much greater deformation of its head. This conclusion may be a contra-indication for the use of forceps to “protect” the pre-term foetal head during delivery. Inadvertent pressure from forceps application may create the situation that the forceps intended to prevent (McPherson and Kriewall 1980).

3.3 Mechanism of labour

The mechanism of labour, or its cardinal movements, describes the series of changes in the position of the foetal head required to navigate its passage through the birth canal enabling the largest dimensions of the foetal head and shoulders to align with the largest dimensions of the maternal pelvis as labour progresses (Wittman and Wall 2007; Louis and Warren 2009; Parente et al. 2010). Active labour commences when the cervix dilates from 6 cm to 10 cm and is a possible reflection of the progress of labour which could be influenced by CPD (Philpott and Castle 1972; McGuinness and Trivedi 1999; Stephansson et al. 2016).

The dimensions of the pelvis at the plane of the pelvic inlet, midpelvis and outlet, alone, and in combination, determine whether vaginal birth of a fetus of average size is possible, and also the mechanism by which the fetus may pass through the birth canal (Salk et al. 2016). The pelvic inlet, or entrance to the birth canal, is larger transversely (mediolaterally) than antero-posteriorly (Tague and Lovejoy 1986; Rosenberg and Trevathan 2002; Weaver and Hublin 2009). Further down the birth canal however, at the pelvic midplane and outlet, humans have larger POs. This results in a twisted birth canal in humans, in which the largest dimension is first transverse and then antero-posterior (Merchant et al. 2001).

As a result of the constricted birth canal, the foetus must be oriented so that the largest dimensions of its head and shoulders align with the most spacious parts of the birth canal, to be able to pass through it successfully. Consequently, a human foetus enters the birth canal facing sideways, so that its larger antero-posterior head dimensions align to the wider transverse dimensions of the inlet. On entering the midplane at the level of the ischial spines, the foetus rotates so that its head length is aligned antero-posteriorly to lie in the wider antero-posterior diameter of the pelvic outlet. The foetus continues in this way until it reaches the outlet. One final rotation then occurs to enable the foetus's shoulders to pass antero-posteriorly through the midplane and outlet. Typically, the foetus exits the birth canal facing posteriorly of its mother, because its occiput tends to pass alongside the more spacious anterior part of the outlet (Weaver and Hublin 2009).

The degree of flexion of the foetal head will determine the presentation and thus, a deflexed head for example, may result in a brow or face presentation. This presentation can be in relation to an easily definable reference point, usually a bony prominence of the maternal pelvis. The ‘denominator’ for the vertex is the occiput (O). For the face, the denominator is the chin (mentum) (M) and for the shoulder, the acromion (A), although, for practical reasons, the back is taken as reference. The denominator for the breech presentation is the sacrum (S). Full-term babies generally present by the vertex.

The sequential changing positions of the foetal head presenting in the normal vertex position, and rotating to lie occipito-anteriorly during childbirth, is set out below and involves the following stages: (1) engagement, (2) descent, (3) flexion, (4) internal rotation and (5) extension (Louis and Warren 2009; Parente et al. 2010).

3.3.1 Engagement

Engagement is the mechanism whereby the BPD of the foetal head enters the ‘true’ pelvis. The foetal head is engaged when it is well flexed and its maximum diameters (suboccipito-bregmatic and biparietal (Figure 10) have passed the pelvic inlet. On engagement, the BPD lies at the level of the TC, while the vertex is 1 cm above the ischial spines (Louis and Warren 2009) and can be noted as the -1 position (Figure 13A). The sagittal diameter is aligned either obliquely, or along the transverse plane of the pelvis (Wittman and Wall 2007).

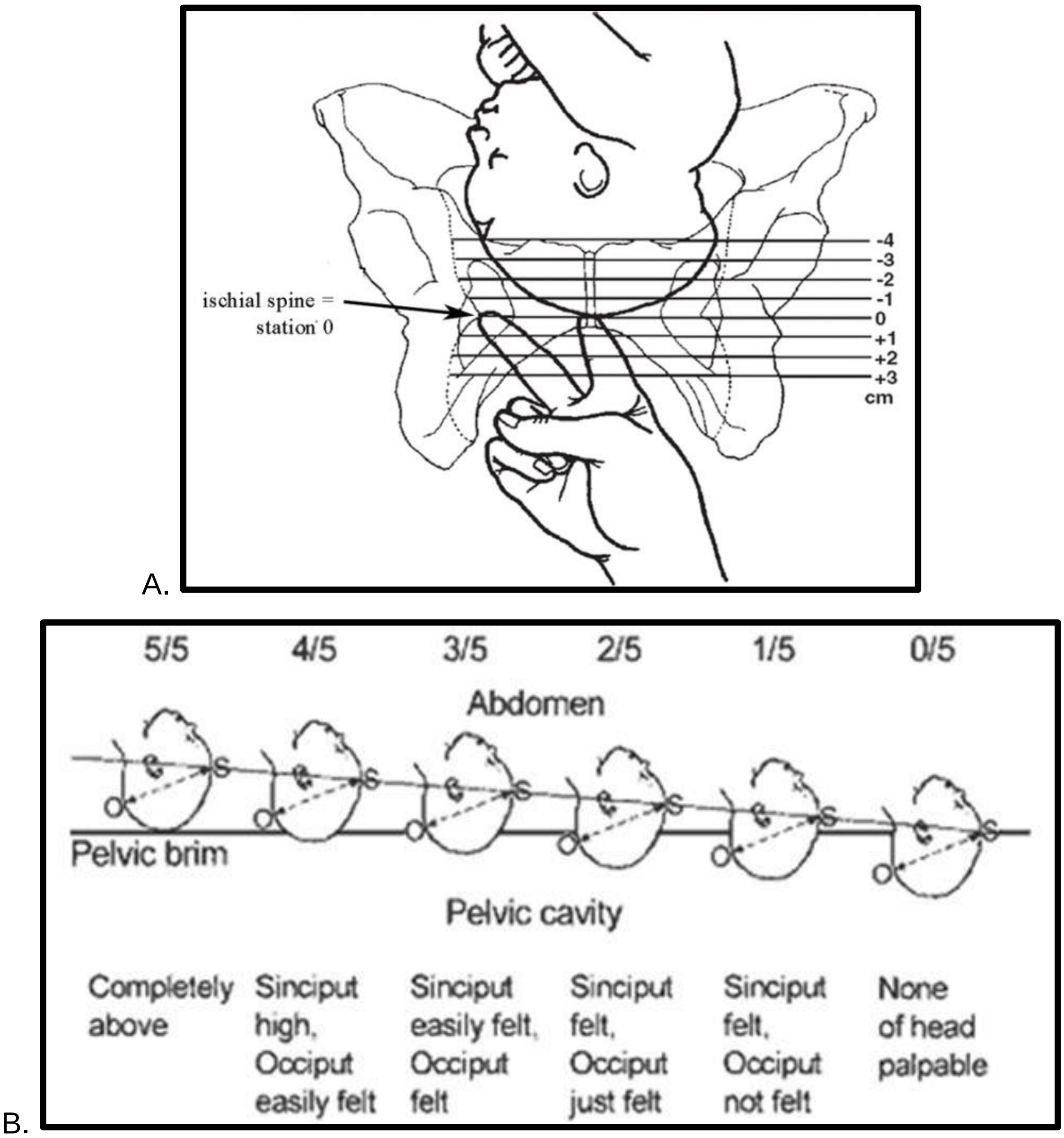


Figure 13. Foetal head engaged in the maternal pelvis and illustrating the descent stages: A: by stations and B: by fifths (Louis and Warren, 2009)

3.3.2 Descent

The downward movement of the foetal head in the pelvis is referred to as the descent, which is usually described by the number of fifths of the presenting part that is still palpable above the pelvis, and by the station. These divisions represent centimeters above and below the ischial spines. Thus, as the presenting foetal part descends from the inlet toward the ischial spines, the designations are –5, –4, –3, –2, –1 and 0 stations. Below the ischial spines, the presenting foetal part passes +1, +2, +3, +4, and +5 stations to delivery (Parente et al. 2010).

This is shown in Figure 13B (Louis and Warren 2009). As the foetal head descends through the midpelvis, it must rotate so that its sagittal plane is aligned with the sagittal plane of the pelvis (Wittman and Wall 2007).

3.3.3 Flexion

Uterine contractions and resistance from the cervix will usually cause flexion of the foetal head forwards, as it is pressed against the lower segment of the uterus, the pelvic side walls and pelvic floor. This results in the foetal chin coming into contact with the foetal chest as the smallest diameter (suboccipito-bregmatic diameter, in the case of a fully flexed head) continues to pass through the birth canal (Louis and Warren 2009; Parente et al. 2010).

3.3.4 Internal rotation

Internal rotation involves the gradual turning of the foetal head (which usually enters the pelvis with the sagittal suture in the transverse plane) so that the occiput turns to become situated behind the symphysis pubis (occipito-anterior) (Louis and Warren 2009).

3.3.5 Extension

As the foetal head descends to the level of the pelvic outlet, the base of the occiput will come into contact with the inferior margin of the symphysis pubis where the birth canal curves upward and forward. The head is then delivered through the maternal vagina by extension from the flexed position. First to deliver is the occiput, then, with further extension, the vertex, bregma, forehead, nose, mouth and finally, the chin (Louis and Warren 2009).

3.4 Cephalopelvic disproportion (CPD)

Humans are predisposed to develop cephalopelvic disproportion (CPD) and obstructed labour. Obstructed labour is a most dangerous complication in obstetrics and claims an average of 17% globally (85 000 lives that are lost) (Kwast 1989; Kwast 1992; Zahr et al. 2004). Data on mortality from obstructed labour may be concealed as deaths resulting from a ruptured uterus which may have been reported most often, following a neglected obstructed labour (Kwast 1992).

The relatively high risk of obstructed labour, as a complication of human childbirth, is due to mechanical factors such as the dimensions of the mother's pelvis, which are relatively small compared to the foetal head.

The most common cause of obstruction in CPD is due to a contracted pelvis. This usually results from stunted growth due to malnutrition, rickets, untreated infection in childhood and/or adolescence, trauma, or as a result of a post- operative complication. Another cause for a contracted pelvis during childbirth may be due to teenage pregnancy, soon after the menarche and before the growth of the pelvis is complete (Camilleri 1981; Liselele et al. 2000; Brabin et al. 2002).

Maternal height can be used as an indicator of pelvic size (Hughes et al. 1987). A tall stature is generally considered to be advantageous, particularly regarding childbirth (Hughes et al. 1987). Baird (1949) was among the first researchers to correlate the health and physique of women with their reproductive efficiency. He found that babies of shorter women have higher rates of perinatal mortality and low birth weight, and are subjected to operative delivery (Baird 1949; Kwast 1992; Van Roosmalen and Brand 1992).

Shorter women within a population continue to carry a higher risk of neonatal low birth weight, caesarean section and problematic obstetric outcomes (Camilleri 1981). The obstetric significance of a particular height is related to the patient's genetic background and is population specific, hence different cut-off points are to be used for different populations (Van Roosmalen and Brand 1992). Overall foetal size has also been shown to increase with the height of the mother (Hughes et al. 1987), however, foetal size was only slightly affected by the height of the father (Cawley et al. 1954).

Assessment of external pelvimetry and maternal height as predictors of CPD, revealed that women who had CPD were shorter than those having a normal delivery (Liselele et al. 2000). A study conducted in Zaire (Democratic Republic of Congo) suggested using a cut-off value of 159 cm for maternal height, as this reduced the referral rate to a limit that may be more suitable in a resource-restricted setting, as opposed to 150 cm, proposed by previous authors (Van Roosmalen and Brand 1992; Dujardin et al. 1996).

The majority of external pelvic measurements were smaller in women having CPD than in women with uncomplicated vaginal delivery. These measurements included the intercrestal, interspinous and intertrochanteric diameters which are used to determine pelvic shape and transverse capacity. The intertrochanteric diameter was found to be the best predictor of CPD. The intertuberous diameter (IT) was not related to CPD, as this distance may be related to outlet dystocia which poses as a high risk factor for larger babies (Rosenberg and Trevathan 1995; Liselele et al. 2000).

Clinically, dissimilarities in pelvic anatomy may be used to predict obstetric outcomes. The size and shape of the pelvis, for instance, often described at the three horizontal planes along the birth canal, are important criteria to consider when contemplating vaginal delivery. These criteria are used to predict how the foetus will move from the pelvic inlet through the midpelvis and the pelvic outlet (Salk et al. 2016). The pelvic shape can influence the type of foetal presentation and mechanism of labour (Young and Ince 1940). 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. Variations in the dimensions of the pelvic canal, including the size and shape, need to be taken into consideration when planning childbirth options (Young and Ince 1940; Rosenberg 1992; Rosenberg and Trevathan 2002; Chan and Lao 2009).

Accurate prediction of women at risk for CPD would permit early referral to district hospitals for trial of labour under safe conditions. If CPD is not predicted by health centres which are not equipped to perform a caesarean section, long distances to better equipped centres and poor local transport may lead to obstructed labour and uterine rupture which may be a cause of maternal death (Kwast 1992; Liselele et al. 2000). At present, the prediction for CPD, prenatally, is performed by manual pelvimetry (Camilleri 1981; Liselele et al. 2000).

3.5 Evolutionary aspects

The investigations of the human pelvis have been of immense interest to biological anthropologists because of atypical evolutionary responses of a human pelvis to accommodate erect posture (Sharma et al. 2016). This favoured a narrow pelvis that increases locomotor efficiency (Rosenberg 1992; Gruss and Schmitt 2015), while simultaneously, meeting the competing demand of obstetrical requirements. In order to maintain adequate space for a safe delivery of a large skull sized foetus, the female requires a wide sacrum tilted backward (Washburn 1949), a wider bi-acetabular diameter (Lovejoy 2005) and more elongated pubic rami (Patriquin et al. 2003) to reduce the risk of obstructed labour.

The action of these two antagonistic evolutionary selection pressures resulted in the difficult childbirth process in humans due to a large-brained neonate, despite having a birth canal space constrained by bipedality. It was called a “scar of evolution” by Krogman (1951) and Washburn (1960) described it as an “obstetric dilemma” (Washburn 1949; Krogman 1951), making midwifery obligatory to facilitate childbirth.

Gruss and Schmitt (2015) have estimated that the narrow, anatomically modern pelvis, with a circular birth canal and further encephalised (larger brains) neonate, which requires foetal rotation during birth, and with narrow body shape to enhance locomotion and to meet thermoregulatory demands, evolved about 200,000 years ago in Africa and the Middle East (Gruss and Schmitt 2015). The different functional requirements in males and females in relation to the intensity of obstetrical selection pressures, have often been emphasised to account for the observed sexual dimorphism in the pelvis (Patriquin et al. 2003; Salerno et al. 2007). This sexual dimorphism has been described as females having decreased height and increased lateral breadth of the pelvis compared to males (Patriquin et al. 2005).

The evolutionary background explaining why humans are predisposed to develop CPD and obstructed labour, may be ascribed to the evolutionary trend in an increase in brain size of the neonate versus the effects of biomechanical pressures of bipedal posture on the pelvic cavity. The reduced dimensions of the human birth canal likely mandated by the mechanical requirements of upright bipedal locomotion and the evolution of progressively larger human brains (encephalisation), are often referred to as the obstetric dilemma (Wittman and Wall 2007). Bipedal locomotion and encephalisation have, therefore, placed competing demands on the human pelvis and selection has favoured compromises between these often contradictory selective pressures.

In the erect posture, the ability to balance the upper body on long extended limbs, necessitated certain changes in the pelvic anatomy. The lumbar lordosis and the sacral kyphosis help to balance the upper body over the pelvis. Because of these curvatures, the sacrum forms a bony posterior/superior boundary of the pelvic canal constricting it in the antero-posterior plane, superiorly. The result is a pelvic inlet that is wider transversely than antero-posteriorly. In compensation, the antero-posterior dimension in the midplane and the pelvic outlet is expanded, especially in females (Rosenberg and Trevathan 1995; Gruss and Schmitt 2015).

Conflicting selective pressures acted on the pelvis in early *Homo:* while a greater overall width was beneficial for non-rotational parturition, a narrower pelvis was more advantageous in terms of both locomotor efficiency and thermoregulation in hot climates. In Australopithecines, a broad pelvis may have provided the important benefit. These locomotor changes had important consequences with regard to the way that early hominids gave birth. Its greater bi-acetabular diameter allowed more forward movement of the lower limb for each degree of rotation, especially in short-legged individuals. However, greater mobility for running, especially, required improvements in locomotor efficiency in early *Homo,* and was accompanied by a narrower pelvis and longer lower limbs, especially that of the leg (Rosenberg and Trevathan 1995; Rosenberg and Trevathan 2002; Wittman and Wall 2007).

Obstetric considerations likely played a relatively minor role in the changes in pelvic shape until the evolution of hominins in general, and *Homo sapiens sapiens*, specifically. The close relationship between the size and shape of the maternal birth canal and the size and shape of the infant skull means that in humans, the mechanism of birth can be inferred from the morphology of the bony birth canal (Rosenberg and Trevathan 1995). The platypelloid birth canal in these hominins suggests that they retained the presumed primitive non-rotational birth mechanism similar to that of the Australopithecines. Non-rotational birthing of a relatively larger brained and larger-shouldered infant would explain the continued need for the transversely broad true pelvis (Gruss and Schmitt 2015).

To investigate the evolution of human childbirth, Weaver and Hublin (2009) reconstructed the size and shape of a Neanderthal birth canal from the fragmentary pelvic remains of the Tabun C1 skeleton that was discovered during Garrod's 1929–1934 excavation of a site at Mugharet et-Tabun, Israel. Computed tomography (CT) scans of the original pelvic fragments were taken and mirror images were created using a computer algorithm (Weaver and Hublin 2009).

As adequate maternal pelvic areas are crucial for successful childbirth, the pelvic inlet and outlet area of the Tabun C1 skeleton was compared to those of 231 human samples. Their findings showed that Tabun's inlet area (21,485 mm^2, based on antero-posterior and transverse diameters of 104 mm and 131 mm, respectively) was nearly the same as the human female mean inlet area. The Tabun's outlet area (19,176 mm^2, based on antero-posterior and transverse diameters of 93 mm and 132 mm, respectively) is slightly smaller than the human female mean outlet area, but well within one standard deviation of it (Weaver and Hublin, 2009.

The results showed that unlike humans, who have an antero-posteriorly oval outlet (Figure 14A), Tabun has a transversely oval outlet (Figure 14B). Tabun's midplane also appears to be transversely oval, but poor preservation of the ischial spines leaves the possibility that the outlet could either be round or perhaps antero-posteriorly oval. Nevertheless, because foetal rotations are mediated by physical resistance within the birth canal, this transversely oval outlet indicates that Tabun had a different birth mechanism than modern humans. On reaching the outlet, a foetus passing through Tabun's birth canal would likely have aligned its antero-posterior head dimensions transversely, leading to an occiput transverse exit position (Weaver and Hublin 2009).

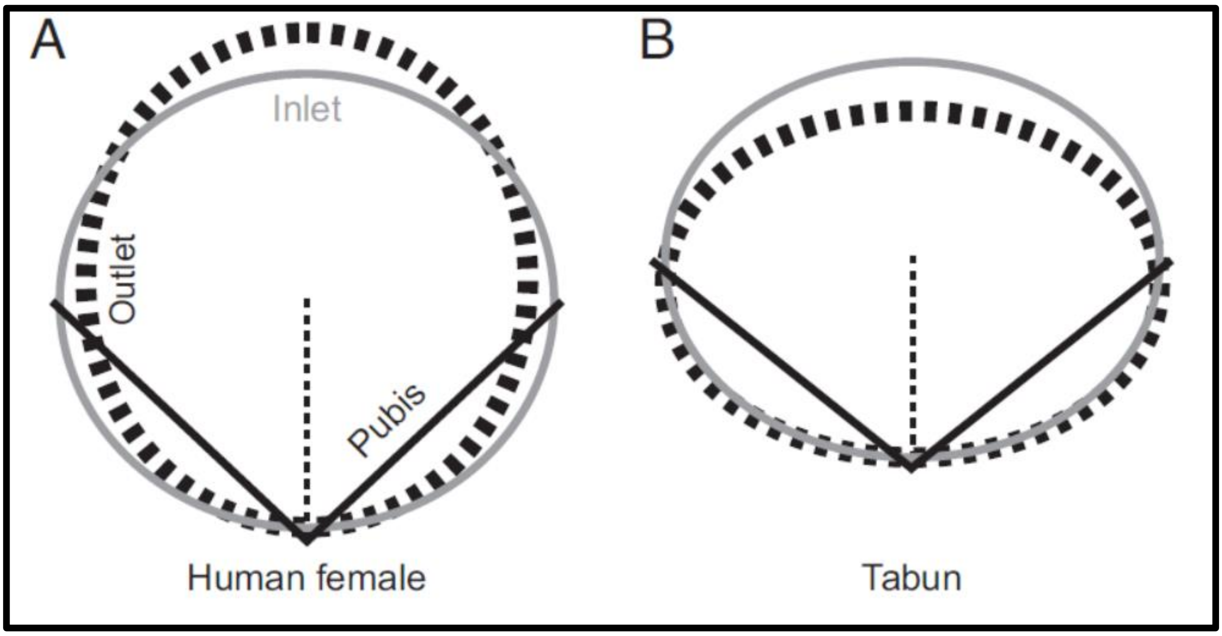


Figure 14. Schematic comparison of the mean birth canal shape in A: Humans and B: Tabun. The grey and dashed black ovals depict pelvic canal inlet and outlet shapes respectively based on the pelvic indices found. (Modified from Weaver and Hublin, 2009)

Although Tabun and the modern human examples had similar pelvic areas, their birth canal shapes differed considerably. Both female and male humans typically have transversely oval inlets (pelvic inlet index <1) and antero-posteriorly oval outlets (pelvic outlet index >1, but human females tend to have lower inlet and outlet indices than males, meaning that the transverse diameter is relatively larger than the antero-posterior dimension, as compared to males (Weaver and Hublin 2009).

Tabun had quite a low inlet index of 0.79 compared to both female and male humans. Tabun's extremely low outlet index of 0.70 is completely outside the range of variation of the comparative sample of 231 humans. Unlike humans, who have a transversely oval inlet and an antero-posteriorly oval outlet, Tabun had both a transversely oval inlet and outlet.

For successful childbirth, both modern human and Neanderthal females require transversely wider inlets than males, which can be achieved either by having pubic bones that are about the same length as those in males, but oriented in such a way as to open up the pelvic inlet, or by having pubic bones oriented similar to those in males, but longer (Weaver and Hublin 2009).

Modern human females follow the second option of having elongated pubic bones as compared to males, whereas Tabun's pelvis suggests that Neanderthals follow the first option of changing the orientation of the pubic bone. Part of the reason for this could be that a twisted birth canal makes the first option infeasible for humans. The sexual adaptation of changing the angulation of the pubic bone to open up the pelvic inlet and increasing the transverse inlet dimensions also decreases the antero-posterior outlet dimensions by moving the pubic symphysis closer to the sacrum. The only way to increase both transverse inlet and antero-posterior outlet dimensions is to increase pubic length, so with a contorted birth canal, females must have longer pubic bones than males (Weaver and Hublin 2009). Therefore, the modern female pelvis has a pelvic inlet that is wider transversely than antero-posteriorly with expanded antero-posterior dimensions in the midplane and the pelvic outlet.

Variations in pelvic and cranial dimensions also reflect climatic variation, where a narrower pelvis and skull are found in lower-latitude populations living in colder conditions, while the converse is true for higher latitude populations living in warmer conditions (Howells 1957; Adadevoh et al. 1989; Keller et al. 2003; Harvati and Weaver 2006; Hubbe et al. 2009; Gruss and Schmitt 2015; Sharma et al. 2016). These findings also align with the ecogeographic rules of Bergmann's stating that larger-bodied variants are found in colder parts and smaller-bodied variants in warmer parts. Allen's "Rule", on the other hand, states that short extremities will be found in colder climates, which in this context could perhaps relate to a shorter pelvic canal (Ruff 1994).

3.6 Possible determinants of the dimensions of the pelvic canal

3.6.1 Sex

The pelvis is the most sexually dimorphic bony region in the human body (Işcan 1983; Tague and Lovejoy 1986; Rosenberg 1992; Patriquin et al. 2005; Fischer and Mitteroecker 2015; Moffett 2017). Morphological differences in sex can be determined as early as foetal life (Boucher 1957; Coleman 1969). The pelvic dimensions during infancy are greater in males than in females, with female pelvic cavity size remaining larger until about 22 months (Fischer and Mitteroecker 2015). In adults, sex differences correlate to functionality, namely the requirements of childbirth and differences in robusticity (Huseynov et al. 2016). Robusticity, as well as child bearing modifications, play important roles in producing metric and non-metric manifestations of sexual dimorphism in the pelvis (Correia et al. 2005; Patriquin et al. 2005).

Numerous morphological differences between male and female pelves have been reported (Işcan 1983; Scheepers et al. 1999; Drake et al. 2009; Maharaj 2010; White et al. 2011; Işcan and Steyn 2013; Moore et al. 2013). A brief summary of the main differences between the male and female pelves are shown in Figure 15a and Figure 15b, respectively.

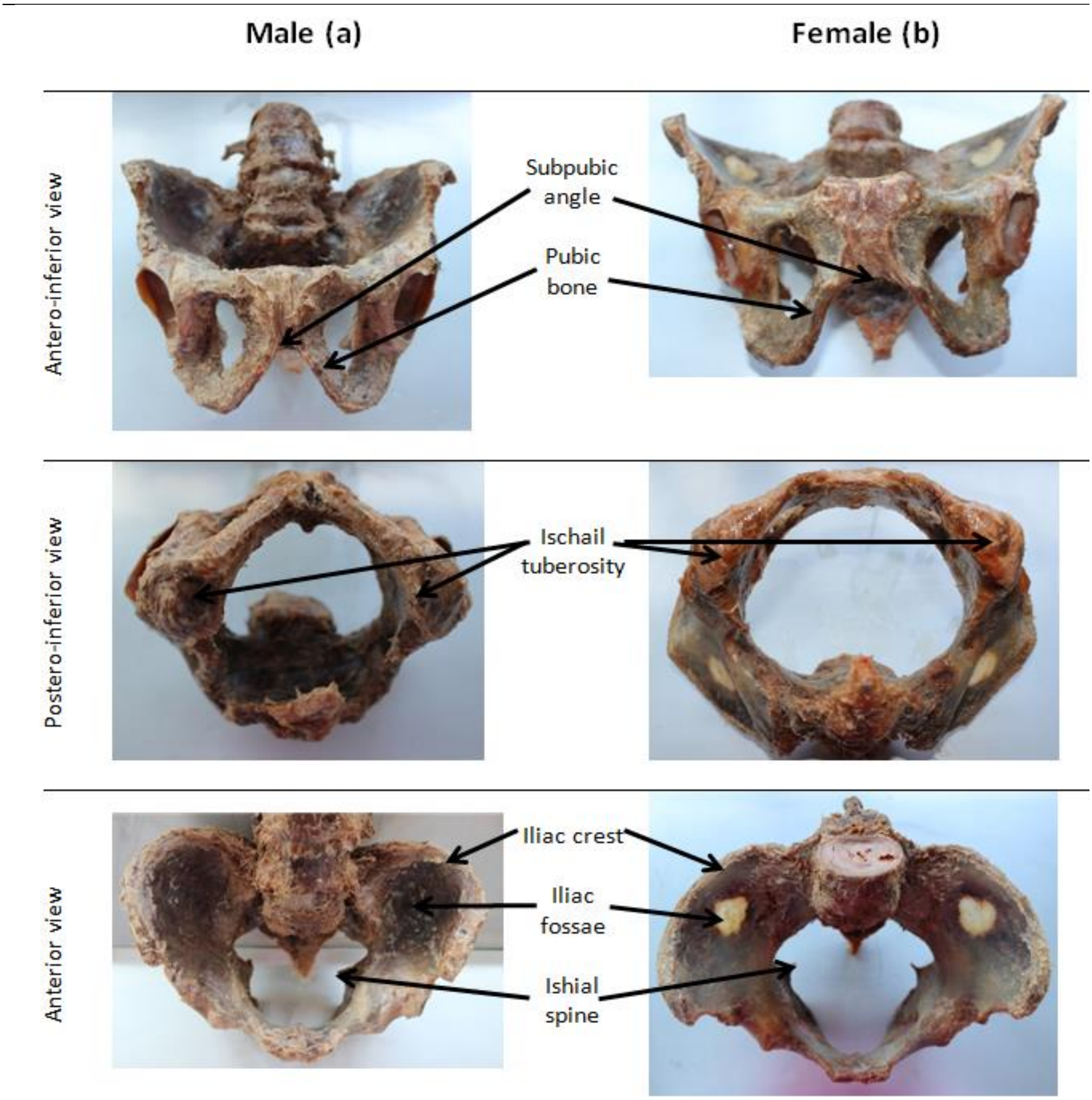
The female pelvis appears broader, yet more gracile and lighter, with more slender bones, in comparison to the male pelvis which has a more robust appearance with more prominent muscle attachments. Metric measurements for males exceed most corresponding measurements for females (Işcan 1983; Patriquin et al. 2005; Maharaj 2010; Işcan and Steyn 2013; Moore et al. 2013).

As males are more muscular and more heavily built, the overall dimensions of the pelvis are greater than in females. Markings for muscles are more pronounced in males and the general architecture is relatively stouter than in females, with the iliac crests being more rugged and curved more medially at the anterior ends. 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 with the pectin pubis oriented more vertical in females. The pubic bone shape in males is more triangular, whereas for females, it is more rectangular. In males, the ischial spines are closer together, being classically inverted, thus rendering the IS smaller than in females. The sciatic notch in females is much wider than in males. (Maharaj 2010; White et al. 2011; Işcan and Steyn 2013; Moore et al. 2013; Standring 2015).

The subpubic angle has been shown to be one of the most sexually dimorphic dimensions of the pelvis (Igbigbi and Nanono-Igbigbi 2003). Both quantitative and qualitative approaches have been used to assess the variability of the subpubic angle (Young and Ince 1940; Brits et al. 2012; Moore et al. 2013). An increased distance between the ischial tuberosities in females will account for a greater subpubic angle, as well as variations in the ischiopubic rami (Standring 2015). The subpubic angle is more angular, or acute, in males than in females, whereas in females, it is more rounded or obtuse. In females, a significant variation in the degree of openness of the pubic arch has been established (Igbigbi and Nanono-Igbigbi 2003; Harmanli et al. 2004; Brits et al. 2012; Moore et al. 2013; Standring 2015).

Reproductive adaptations in females, particularly, affect the pelvic canal and, to a variable degree, the proportions and dimensions of the greater pelvis. Modern human females give birth to large neonates relative to maternal body and birth canal size (Weaver and Hublin 2009). The hypothesis that the female pelvis is adapted to the selective pressures of giving birth to such large neonates is well-supported (Tague 1989; Lovejoy 2005; Moffett 2017).

The true pelvis is on average larger and more spacious in females than in males, contrary to other parts of the skeleton, which are greater in males than in females (Turner 1885; Caldwell and Moloy 1933; Greulich et al. 1939; Işcan 1983; Correia et al. 2005; Kurki 2011; Işcan and Steyn 2013; Moffett 2017). Across human populations, females have larger circumferences of the pelvic inlet, midplane and outlet than males, both absolute and relative to body size (Young and Ince 1940; Tague 1989; Gutman et al. 2005; Killeen et al. 2010; Işcan and Steyn 2013; Moore et al. 2013; Standring 2015). Females also have mediolaterally wider midplanes (Caldwell et al. 1935; Standring 2015; Gabbe et al. 2016) and outlets (Işcan 1983; Correia et al. 2005; Standring 2015) than males, relative to body size.



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˚

Figure 15. A brief summary of the main differences between the male (a) and female (b) pelvis as shown from anterior, inferior and superior (Maharaj 2010; Standering 2015; Moore et al 2013)

The way in which the obstetrics demands influences variation between males and females is unclear. The evolutionary theory would suggest that there should be sexual dimorphism in the variability of pelvic morphology, with variation in the size and shape of the female birth canal limited by obstetric demands (Gruss and Schmitt 2015) more specifically the “obstetric dilemma” (Moffett 2017). The “obstetrical dilemma” is thought to alter the timing of birth so that humans have a shortened gestational period, consequently giving birth to neonates with a smaller proportion of brain growth completed, compared to other apes (Washburn 1949).

Research indicates that the obstetric dilemma may not exist in humans (Moffett 2017) and that the wider inter-acetabular distance in females may not pose an energetic cost, compared to males. Maternal metabolic constraints, rather than pelvic constraints, may alter the timing of birth in humans. The prevalence of CPD in modern humans might be the result of the transition to agricultural subsistence and increased nutrition during pregnancy.

The presence of dimorphism may not be due only to obstetric demand, but it is possible that the magnitude of dimorphism in birth canal size and shape is greater among species with large cephalopelvic proportions, compared to those with small proportions (Ridley 1995; Maharaj 2010). The existence of pelvic dimorphism among anthropoids with small cephalopelvic proportions means that there must be factors other than parturition, including potentially overall body size or body size dimorphism, that influence pelvic dimorphism in anthropoid primates. In anthropoid species with high levels of body size dimorphism, females have exceptionally large birth canals. It is possible that the magnitude of dimorphism in birth canal size is affected by both body size dimorphism and cephalopelvic proportions, such, that species with both large cephalopelvic proportions and high levels of body size dimorphism, also have the most dimorphic pelves.

Moffetti et al. (2017) investigated the degree of dimorphism in the birth canal size and shape of large and small cephalopelvic samples. He found that birth canal dimorphism is common among anthropoids, regardless of cephalopelvic proportions, but species with large cephalopelvic proportions have a higher magnitude of dimorphism than those that give birth to relatively small-headed neonates. Furthermore, modern humans have exceptionally high levels of dimorphism that cannot be explained on the basis of large cephalopelvic proportions alone (Moffett 2017).

Sexual dimorphism in the pelvic inlet may be due to the later maturation of the pubis in females, prolonging the period of growth (Leong 2006). During the accelerated growth period in adolescence, some individuals are exposed to poor socio-economic conditions and food deprivation so that growth, in for instance, the pubic symphysis, is limited. These socio-economic factors could be contributing factors for stunted growth in the pubic symphysis in South Africans females (Bernard 1952). In cases where the height of the individual is also affected, the pelvic inlet transverse diameter may be diminished as well. It might, therefore, be of value to take the height in black South African females into account before contemplating normal vaginal delivery.

3.6.2 Population variation in South Africa

Measurable differences exist in the size and proportions of the skeletal components of the pelvis between populations, including black South African and white South Africans (Loth and Henneberg 1996; Patriquin et al. 2002; Igbigbi and Nanono-Igbigbi 2003; Patriquin et al. 2005).

In the South Africa context, Patriquin et al (2003) demonstrated a significant difference ($p<0.001$) in the pelvic measurements between black South African and white South African males and females (Igbigbi and Nanono-Igbigbi 2003; Patriquin et al. 2003). The pelvic dimensions were larger in white South Africans than in black South Africans, with the exception of the anterior width of the greater sciatic notch, which was larger in black South African males than in white South African males. These findings on the inter-population variations of the pelvic diameters correspond with previous studies that demonstrated a difference in other parts of the skeleton for both black South Africans and white South Africans. Kurki (2013) examined skeletal remains from various global locations by analysing the size and shape of the pelvic canal in relation to the body size (Kurki 2013). Kurki found that black South Africans had a unique pelvic shape due to a rather small and petite body shape, as reported by other researchers (Loth and Henneberg 1996; Patriquin et al. 2005).

Pelvic shape differences also reflect climatic variation in body build and proportions. The transverse breadth of the birth canal may be constrained by climate, with lower-latitude populations having relatively narrower dimensions, while the antero-posterior breadth of the birth canal appears freer to vary, in order to maintain obstetric capacity (Gruss and Schmitt 2015).

The differences between sexes and populations are greater in the inferior aperture than the pelvic brim (Igbigbi and Nanono-Igbigbi 2003; Msamati et al. 2005). Patriquin et al. (2005) suggest that to some extent, the shape of the pelvis may correlate with that of the skull, since the skull has to pass through the pelvis during the birth process (Patriquin, Steyn et al. 2005). In black South Africans, the pelvic shape consisted of a small pelvic inlet relative to an elongated lower pelvic canal, antero-posteriorly (Jagesur et al. 2013 [Appendix a]; Kurki 2011). This finding supports the view that every population should have its own standards that are tailored to the unique metric and morphological characteristics of that population (Adadevoh et al. 1989; Patriquin et al. 2002; Patriquin et al. 2005).

The smaller pelvic inlet diameters in black South African females (Panday et al. 2009) could be associated with an inability of the foetal head to engage or the overriding of the vertex during parturition (Standring 2015). Furthermore, it was found that the length of the pubic symphysis in black South African females is shorter than in other South African groups (Jagesur et al 2013 [Appendix A]), rendering the pelvic cavity shallower and smaller, anteriorly.

As the interspinous distance is normally the narrowest part of the pelvic canal through which the foetal head must pass during birth, diameters less than 100 mm could be a risk for midpelvic arrest (Keller et al. 2003; Moore et al. 2013). The interspinous distance was sometimes smaller than 100 mm in black South African females, and was also stature dependent (Jagesur et al. 2013 [Appendix A]).

On the other hand, Kurki (2013) relates population specific variations in the pelvic canal to genetic factors. His findings on an archaeological collection were in line with those reported here (Kurki 2013). South African females displayed small pelvic inlets relative to a larger lower canal in antero-posterior diameters. Cephalopelvic disproportion might be negated if population specific variations in foetal head size and shape are expected to be accommodated by the population specific pelvic canal size and shape. Further research in this regard is necessary to improve the understanding of the relationship between the shape and size of the foetal head and pelvis.

Although variations between populations have been described and may be expected, studies considering the extent of these differences when childbirth options are planned, are limited (Tobias 1974).

3.6.3 Stature

Although birth canal proportions in modern humans are considered by some researchers such as Gruss and Schmitt (2015) to not necessarily correlate with body proportions, others correlated some of the pelvic dimensions with the stature of an individual (Kurki et al. 2010; Kurki 2013; Gruss and Schmitt 2015).

Stature is often used in obstetric practice as an early warning for possible CPD (Kurki 2007; Kurki et al. 2010). A more spacious pelvic canal is found in adults with larger body size, which also has an effect on the gestational period and foetal weight (Rosenberg 1992; Rosenberg and Trevathan 2002). According to Kurki (2013), a complex relationship exists 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 (Kurki 2013).

The impression that the antero-posterior inlet dimension is related to the height of the individual was confirmed in black South African females (Jagesur et al. 2013 [Appendix A]), but was confirmed in white South Africans, as statistically no correlations were found, or were not specifically investigated (Bernard 1952; Stewart et al. 1979; Adadevoh et al. 1989; Merchant et al. 2001). A critical height for white South African females could therefore not be predicted. Contrarily, the associated height of even up to 161.46 cm may be a risk factor for CPD in black South African females (Jagesur et al. 2013 [Appendix A]). This height is taller than what is associated with CPD in three other African populations (Adadevoh et al. 1989). It should be cautioned, however, that both AP diameter and stature were derived values and not direct measurements. Although data collection techniques differed, regardless of stature, the mean pelvic inlet diameters of black South African females were often associated with CPD by other researchers (Stewart et al. 1979; Adadevoh et al. 1989; van Dillen et al. 2007).

A study by Kurki (2013) on an archaeological collection, found that South African females displayed small pelvic inlets relative to an elongated lower pelvic canal in antero-posterior lengths (Jagesur et al. 2013 [Appendix A]). The reasons for these differences could be related to genetic differences, as selective pressures may differ among populations (Kurki 2013). Socio-economic factors and poor nutrition should be considered as well. Bernard (1952) suggested that women with poor nutrition are shorter in stature and have smaller pelvic brims than women with better nutrition (Bernard 1952).

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3.6.4 Co-variation with dimensions of the head

As recent studies suggested that pelvic canal shape shows significant correlations with head circumference (Relethford et al. 1994; Huseynov et al. 2016), factors that influence cranial shape should be taken into consideration for a better understanding of CPD. While consensus has emerged in recent years that global patterns of cranial shape variation can be explained to a large extent on the basis of a neutral theory for population diversification, previous research emphasized that a response to modifications in climate change, as well as in masticatory behaviours, could significantly influence overall skull morphology (Relethford et al. 1994; Noback and Harvati 2015).

3.7 Possible determinants of the dimensions of the cranium

To understand the factors determining the appearance of the skull, an overview of the growth of the various parts is given. The cranial base (basicranium), vault (neurocranium) and face (splanchnocranium) are derived from embryologically distinct regions that grow in a morphologically integrated manner. These interactions occur as the result of many morphogenetic (e.g., neural) and functional (e.g., masticatory, respiratory) stimuli. Developmentally, the basicranium differs from the neurocranium and splanchnocranium in several important aspects. Unlike the rest of the skull, which develops intramembranously from neural crest-derived tissue, the basicranium mostly grows from endochondral ossification processes (Lieberman et al. 2000; Moore et al. 2013; Standring 2015).

The basicranium is the first region of the skull to reach adult size (Moore and Lavelle 1974; Lieberman et al. 2000), and it is the structural foundation of many aspects of craniofacial architecture. The cranial base forms the platform upon which the rest of the skull grows and attaches, and it provides and protects the crucial foramina through which the vessels and nerves of brain are transmitted to the face, neck and the rest of the body (Lieberman et al. 2000; Moore et al. 2013; Standring 2015). These aspects of cranial base growth and function may account for its apparent morphological and developmental conservatism in mammals compared to other regions of the skull. In humans, facial growth is about 95% complete by 16–18 years, at least 10 years after the majority of the neuro-basicranial complex has reached adult size (Lieberman et al. 2000).

Growth of the skull tends to proceed in an anterior-posterior direction, with growth of the brain in a transverse and upward direction. The joint effect of these two factors in particular, determine the general form of the skull i.e. dolichocephaly v brachycephaly. The cephalic index is described by Fee (1979) as the ratio of the maximum breadth of the skull to its maximum length multiplied by 100. Skulls with a relatively large cephalic index (round skulls) are termed brachycephalic, while those with a small cephalic index (long skulls) are dolichocephalic. The author further describes the skulls of European women and children as being brachycephalic and those of European males, as dolichocephalic (Fee 1979). Beyond these two factors are secondary effects adding to the adjustment to size and probably to muscle pull. The cranial vault responds to various forces and genetic factors which further modify not only its “cranial ratio”, but also its specific shape (Howells 1957).

Patterns of variation in modern humans on a worldwide scale show that the overall cranial variation is mainly geographically structured (Howells 1957) and probably related with random processes — some cranial traits are associated with environmental variables such as temperature (Harvati and Weaver 2006; Hubbe et al. 2009). Different cranial regions are thought to be more or less susceptible to these processes. The size and shape of the face and neurocranium have been related to climate differences (Adadevoh et al. 1989; Keller et al. 2003).

The human face (splanchnocranium), for instance, takes longer to develop than the rest of the skull. External influences such as masticatory stresses have a longer timespan to exert an effect on facial morphology compared with to other cranial components (cranial base (basicranium) and the vault (neurocranium) (Freidline et al. 2015). These factors could be important to shape the patterns of morphological variation among human populations (Beals et al. 1983; Roseman and Weaver 2004; Menéndez et al. 2014). On the other hand, the shape of the basicranium has been proposed to be the most genetically determined and evolutionarily conservative aspect of the cranium, and is thought to be minimally influenced by environmental factors (Stewart et al. 1979; Kurki 2013). As such, it has been argued that the cranial base, and particularly the basal aspect of the temporal bone, preserves a stronger signal of phylogeny and population history (Washburn 1949; Stewart et al. 1979; Weise et al. 2001; Kurki 2007).

Variation in diet is another environmental factor that could have an influence on the variation of the shape of the skull. Diet plays a fundamental role in craniofacial variation due to both the effect of the nutritional status, which is the type and amount of nutrients consumed on the skeletal growth, and the localised effects of masticatory forces (Menéndez, et al. 2014). Several studies at regional scales have also noted the association of craniofacial variation with broad diet categories, with hunter-gatherers having bigger and more robust skulls than farmers (Carlson and Van Gerven 1977; Stynder et al. 2007). This has been attributed to differences in masticatory force, or loading, due to the consumption of items that differ in their mechanical properties, with farmers relying on softer and more processed diets than hunter-gatherers.

The bite force needed to break down food items depends on the material properties of the food. Tough foods cost a lot of muscle power to break down because they need to be sheared and thus require more energy to propagate cracks, whereas tender foods are easily broken down by mastication (Noback and Harvati 2015). A reduction in the mechanical loading will result in an underdevelopment of masticatory muscles and the associated cranial structures. Others have stressed the role of diet composition as a factor with systemic effects on the skull (Stynder et al. 2007).

Despite various factors involved in the development of the different parts of the skull, they do interact and influence the growth of each other. A study done by Lieberman et al. (2000) investigated the extent to which variations in the major dimensions of the cranial base (length, breadth and flexion) might influence several aspects of the shape of the face and cranial vault in humans from various diverse geographical populations. His sample included populations from Australia, East Asia, Europe, North Africa and sub-Saharan Africa. The neuro-basicranial complex (NBC) explained by these authors describes the growth of the basicranium and neurocranium in tandem, forming a morphological unit. This model of cranial growth assumes that overall shape of the NBC has two primary influences: the shape of the brain and the shape of the basicranium (Lieberman et al. 2000).

According to Enlow et al. (1990), individuals with absolutely narrow NBCs (primarily dolicho-cephalics) tend to have more flexed cranial bases, longer anterior cranial bases and narrower faces than individuals with absolutely wider NBCs (primarily brachycephalics). According to this model, individuals with narrower NBCs will have proportionately narrower and antero-posteriorly longer faces than individuals with broader NBCs (Figure 16) (Enlow and Bhatt 1984; Enlow 1990).

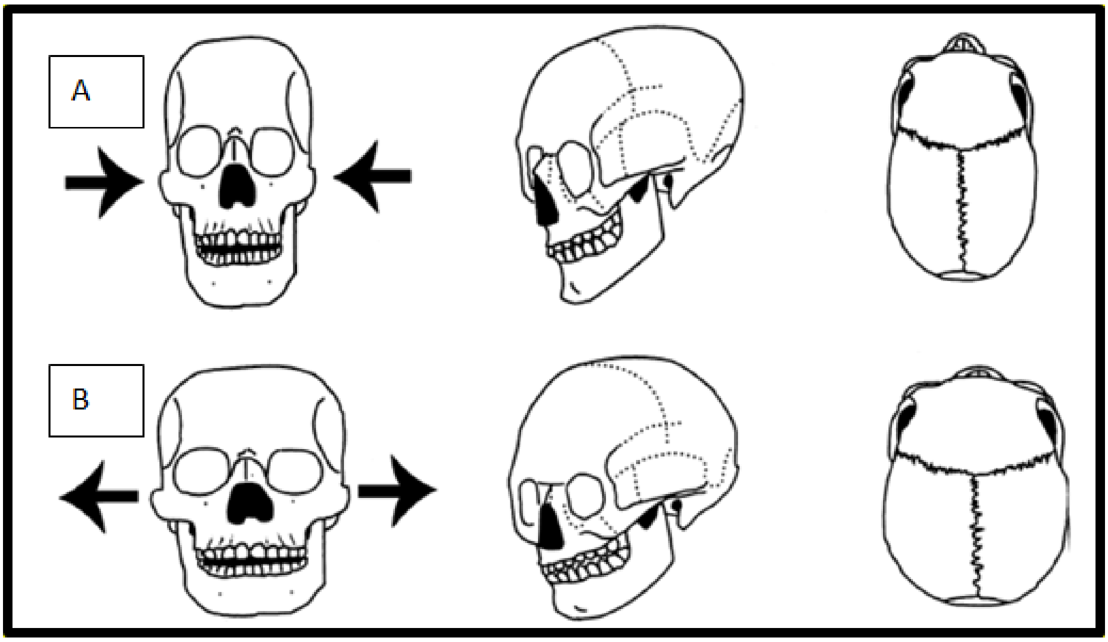

Figure 16. Enlow's (1990) model of differences in facial form between (A) dolichocephalic and (B) brachycephalic individuals

The results of the study by Lieberman et al. (2000) weakly support Enlow's (1990) model, in that individuals with absolutely and relatively narrower NBCs tend to have proportionately longer (antero-posteriorly) and narrower faces than individuals with wider NBCs, as the trend may be largely the result of variation within and between populations. In particular, Italian and Chinese individuals tend to have relatively high values for the facial ratio and a broad neurocranium, while Australian and, to a lesser extent, Ashanti individuals tend to have a low facial ratio and a narrow neurocranium (Enlow 1990; Lieberman et al. 2000). When compared to Western Europeans, black South Africans present with a smaller neurocranial size, taller vaults in frontal view, narrower cranial bases and frontal flatness (Sardi and Ramírez Rozzi 2012).

3.8 Forensic implications for variations in the pelvic canal dimensions

The noted variations between population and sex in the dimensions of the pelvis can be employed in forensic anthropological assessments for sex and ancestry estimations. Traditionally, the methodological approaches to sexing skeletal remains involved morphological and metric methods.

3.8.1 Sex estimation

The pelvis is the most sexually dimorphic bone of the human skeleton and has been studied extensively with regard to estimating sex from unknown skeletal remains. (Işcan 1983; Tague and Lovejoy 1986; Rosenberg 1992; Correia et al. 2005; Patriquin et al. 2005; Fischer and Mitteroecker 2015; Moffett 2017).

Morphoscopic methods

The morphological approach is based on the classification of morphological traits in a descriptive manner. Descriptions of morphological traits focus on the shape of the bony configurations that are macroscopically visible. These methods have been extensively applied to the pelvis. Morphoscopic methods make use of morphological traits to sex the skeleton. These traits show much variation, a large degree of overlap between sexes and much variance between the findings of different researchers, and may be used in isolation or in combination. The ventral arc, subpubic concavity and medial aspect of the ischiopubic ramus, for instance, delivered a correct estimate of about 96% for both sexes and all populations for the researcher who original described this combination of traits (Phenice 1969), while others found this method less accurate with lower percentages, e.g. 59% (MacLaughlin and Bruce 1990) and 80% (Bruzek 2002). By including a greater number of traits, the accuracy of sex estimation seems to improve to more than 90% (Işcan and Steyn 2013). The accuracies of many of the morphological traits in isolation have also been studied: Patriquin et al. (2003) found that the pubic bone shape and subpubic concavity, in isolation, had an average accuracy of 88% in white South Africans, while in black South Africans, the greater sciatic notch shape presented the highest accuracy of 87.5%, followed by pubic shape with an accuracy of 84.5% (Patriquin et al. 2003). Klales et al. modified the method of Phenice (1969) to capture varying degrees of expression within each trait (Phenice 1969; Klales et al. 2012). Klales et. al reached a mean correct classification rate of 94.5% for sex estimation with low intra- and interobserver error in trait scoring. Santos et al. 2019 tested Bruzek's nonmetric traits for sexing human os coxae with logistic regressions and found an accuracy rate of 99.2% on reconstructed CT models, compared to the skeletal sample (98.2%). Although it is commonly considered beneficial to first establish the population prior to sex estimation (Steyn and Patriquin 2009; Işcan and Steyn 2013), Kenyhercz et al. (2017) more recently used the morphoscopic method described by Klales et al. and achieved classification accuracy of 95.9% for sex estimation without the need for population specific equations.

Metric methods

By comparison, metric methods are more repeatable than morphoscopic methods but not ideal to describe shape differences, as it primarily reflects variations in size (Işcan and Steyn 2013).

Earlier studies focused on the overall pelvic shape and classified it according to indices, for example, Turner's (1886) pelvic index classified the pelvic inlet as follows: platypellic, mesatipellic and dolichopellic (Turner 1885). Greulich and Thoms (1939) further modified the classification by including the brachypellic shape. According to these authors, white South African females most commonly presented with a mesatipellic (44.7%) or brachypellic (31.8%) pelvis, while white South African males were 78.2% dolichopellic. Other indices are also described, including the ischiopubic index with an accuracy of about 66% (Greulich et al. 1939).

Howells (1957) used discriminant function on four measurements and found accuracies greater than 90%. A study conducted by Patriquin (2005), using nine measurements on the os coxa, found ischial length, the most sexually dimorphic dimension in white South Africans averaged 86% accuracy, while acetabulum diameter was most diagnostic in black South Africans (averaged 84% accuracy) (Patriquin, Steyn et al. 2005). The highest accuracy which included all dimensions averaged 95.5% correct classification in white South African and 94% in black South Africans. Steyn and Patriquin (2009) used seven measurements from the os coxa and also found accuracies greater than 90% on South Africans (Steyn and Patriquin 2009).

Geometric morphometrics

Accuracies for sex estimation can be enhanced by performing geometric morphometrics on an isolated trait or on 3D landmarks describing a greater area of the pelvis, or the entire pelvis. Gonzalez et al. (2009), for instance, found a greater than 90% separation accuracy using semi-landmarks by assessing the greater sciatic notch (Gonzalez et al. 2009). Bytheway and Ross (2010) obtained a near 100% separation accuracy between the sexes when assigning 36 three-dimensional landmarks to the pelvis as a whole (Bytheway and Ross 2010). Steyn and Patriquin (2009) state that populations differ with regard to robusticity, degree of sexual dimorphism and body size, thus applying measurements from one population to another unreliable (Steyn and Patriquin 2009). These studies demonstrate that it is necessary to also distinguish between populations for sexing purposes using GM

3.8.2 Population affinity

Metric methods:

The pelvis has evolved to adapt to climate factors to maintain a stable body temperature (Wood and Harrison 2011). Todd (1928), for instance, described the brachypellic white South African pelvis as a wide basin for a broad torso, and the dolichopellic black South Africans pelvis as a pedestal for a narrow torso (Todd and Lindala 1928). The study undertaken by Krogman and Isçan, however, demonstrate that the pelvis may be of limited use for estimating population affinity, reporting accurate results in only 70%–75% of cases) (Krogman and Isçan 1986). Considerable variation has since been demonstrated in the pelves of various populations of black South Africans and white South Africans. It is also well known that there is metric and morphologic variation in the expression of sexual dimorphism between populations (Patriquin et al. 2003). İşcan (1983) used discriminant function analyses on three dimensions: bi-iliac breadth, antero-posterior inlet diameter and transverse breadth and found accuracies as high as 88%, with females yielding higher accuracies than males (Işcan 1983). Patriquin and Steyn (2002) also published discriminant functions to distinguish between South Africans and white South Africans, using measurements on disarticulated pelvic bones and found that pubic length and iliac breadth were the best discriminators (Patriquin et al. 2002). Accuracies of 88% for males and 85% for females were found. Some studies combined measurements of the pelvis with those of other bones. Dibennardo and Taylor (1983), for instance, used 15 measurements from the pelvis and femur and found accuracies as high as 97% (Dibennardo and Taylor 1983).

3.9 Forensic implications of the variations in the skull

3.9.1 Sex estimation

Morphoscopic methods:

Traditionally, the sexing of skulls has been done on a morphological basis whereby skeletal features are described, rather than metric dimensions. Morphological traits can provide sex estimation that may be as accurate as that of metric methods. (Franklin et al. 2013; Işcan and Steyn 2013). When sexing a skull, the initial impression is often the deciding factor, i.e. a large, robust skull is generally that of a male and a small, gracile skull, that of a female. Moreover, the female skull is usually rounder than that of the male, so that the cranial index is greater in females than in males (Işcan and Steyn 2013). Further, the female craniofacial skeleton may be relatively more gracile with relatively larger orbits. Variation of other facial features may clinch the initial impression, e.g. features of the mandible, nasal aperture, orbits, cheekbones, supra-orbital ridges, glabella, forehead contour, mastoid process, supramastoid crest, occipital region, palate and teeth, and the base of the skull (Işcan and Steyn 2013). Buikstra and Ubelaker (1994) used five skull traits in sex estimation: robusticity of the nuchal crest, size of the mastoid process, sharpness of the supra-orbital margin, prominence of the glabella and projection of the mental eminence (Gonzalez et al. 2011; Işcan and Steyn 2013). Other researchers used various other combinations of skull traits with varying results. Williams and Rogers (2006) achieved 96% accuracy and 92% precision when using a combination of 20 traits. (Krüger et al. 2015; Walker 2008) assessed the five traits outlined by Buikstra and Ubelaker (1994) and the combinations of these traits correctly classified the sex in 77.9%–88.4% (Graw et al. 1999; Williams and Rogers 2006; Ryan et al. 2008; Işcan and Steyn 2013).

Metric methods

Since the 1950s, there have been many studies employed dealing with metric methods for sexing the skull. Giles and Elliot were the first to use a discriminant function technique for the determination of population from the skull. In their initial study, they analysed differences between American Whites (108 males, 79 females) and black South Africans (113 males, 108 females) from the Hamann-Todd and Terry Collections. For their assessment, Giles and Elliot used 8 cranial measurements (cranial length, maximum cranial breadth, basion-bregma height, basion-prosthion length, basion-nasion length, bizygomatic breadth, prosthion-nasion height, and nasal breadth) (Giles and Elliot 1962). Discriminant function formulae have so been established for various populations with different accuracies to estimate sex, ranging from 70% to 99%. The Fordisc 3.1 programme uses discriminant function formulae to not only assess sex, but also population (Ousley and Jantz 1996). Guyomarc'h and Bruzek (2011), however, assessed the reliability of sex determination using the Fordisc 3.1 programme and found a low accuracy for sex estimation in the populations they studied of only 52.2%–77.8% (Guyomarc'h and Bruzek 2011; L'Abbé, E.N et al., 2013; Stull et al. 2014; Liebenberg et al. 2015; Liebenberg et al. 2015).

Geometric morphometrics

Geometric morphometrics have been used in many other studies for sex estimation of the skull (Rosas and Bastir 2002; Pretorius et al. 2006; Kimmerle et al. 2008; Green and Curnoe 2009). Kimmerle et al. 2008, for instance, used 16 craniofacial landmarks and achieved and accuracy of 73.3% for females and 80.0% for males when only using shape, but when shape and size are used, the accuracy increased to 90.0% and 83.3% respectively.

3.9.2 Population affinity

According to Krogman (1986), the skull is the most useful in estimating population, and can be assigned correctly through metric and morphological assessment in 85%–90% of cases (Krogman and Isçan 1986; Işcan and Steyn 2013).

Morphoscopic methods:

Morphoscopic traits appear to have a geographic pattern, however, inter-individual variation is sometimes considerable, rendering it not useful for estimating population. The variability between populations is thought to be accentuated in the mid-facial region. Rhine (1990) described 45 population specific morphoscopic traits. Hefner and Ousley (2006) examined six of these traits and found that only 17% to 58% of individuals have all expected traits (Hefner and Ousley 2006). Hefner (2009) and L'Abbé et al. (2011) found that in South Africans, these characteristics did not necessarily conform to traditional assumptions and showed large variability and overlap between groups. No individual had all the expected traits. Both Hefner (2009) and L'Abbé et al. (2011) concluded that it is not possible to visually differentiate between populations using these traits, unless a suitable multivariate statistical model is used (Hefner 2009; L'Abbé et al. 2011).

Metric methods:

It is thought that if enough variables are used, it may be possible to predict a geographical group from the skull. However, fewer, but well-selected measurements are preferred in differentiating between populations (Johnson et al. 1989; Işcan and Steyn 2013). İşcan and Steyn (1999) developed discriminant functions using a samples of skulls and mandibles of modern white South African and black South Africans and achieved accuracies above 95% (Işcan and Steyn 1999). Burris and Harris (1998) used measurements of the palate and found an accuracy of 83% (Burris and Harris 1998). To determine sex, the Fordisc 3.1 statistical programme is used to create discriminant functions based on the variables available used by many forensic anthropologists. Although accuracy for population assignment is believed to be at least 90%, overlaps between groups do occur and it is mandatory that the suspected population be represented in the reference sample (L'Abbé et al. 2013; Stull et al. 2014; Liebenberg et al. 2015a; Liebenberg et al. 2015b).

Geometric morphometrics

Geometric morphometrics have been used in many other studies for sex estimation of the skull (Rosas and Bastir 2002; Pretorius et al. 2006; Kimmerle et al. 2008; Green and Curnoe 2009). Kimmerle et al. (2008), for instance, used 16 craniofacial landmarks and achieved and accuracy of 73.3% for females and 80.0% for males when only using shape, but when shape combined with size were used, the accuracy increased to 90.0% and 83.3% respectively.

3.10 Surgical implications for the variations in the pelvic canal dimensions

As pelvic dimensions in South African populations have been shown to differ (Loth and Henneberg 1996; Patriquin et al. 2002; Patriquin et al. 2003; İşcan 2005; Patriquin et al. 2005; Işcan and Steyn 2013), specific dimensions relating to the pelvic canal and perineum could also have implications for pelvic and perineal procedures. The following examples of pelvic and perineal procedures are explored: radical retropubic prostatectomy (RRP), surgical procedures for rectal cancer and procedures for stress urinary incontinence respectively and sacrospinous colpopexy.

3.10.1 Pelvic procedures

Radical retropubic prostatectomy (RRP)

Radical retropubic prostatectomy (RRP) is regarded as the treatment of choice for curative therapy of localised prostate cancer. Hong et al. (2007) suggested that this procedure may be performed with greater ease in a wider and shallower pelvis. They found that variations in the pelvic dimensions, such as the narrowest distance between the tips of the ischial spines and the intertuberous distance, are important factors in performing RRP (Greene 1983; Hong et al, 2007). A wide pelvis is regarded as one that presents with a large transverse diameter, a large interspinous distance and a large external diameter. A narrow pelvis has a shorter true conjugate. In the current era of laparoscopic and robot-assisted retropubic prostatectomy, pelvic dimensions, such as the pelvic depth and height, could be important, since the instruments are manipulated in a confined space and there is limited freedom of movement during laparoscopic pelvic surgery (Hong et al. 2007).

Von Bodman (2010) found that there are population variations in the pelvimetric measurements, which have an impact on the surgical margins during RRP. He found that African-American males have significantly smaller pelvic inlets and subpubic angles than males of European ancestry (von Bodman et al. 2010).

Surgical procedures for rectal cancer

Pelvic surgery for rectal cancer and laparoscopic surgery is also complicated by a prominent sacral promontory and a deep, narrow pelvis (Salerno et al. 2007) particularly in the transverse plane. These pelves could represent anatomical bottlenecks in which access and vision are both restricted by the pelvic anatomy. The space in which instruments can be manipulated is restricted as explained by Killeen (Killeen et al. 2010) and the relative size of the tumour to the pelvic dimensions could further complicate the procedure (Killeen et al. 2010; Salerno et al. 2007). A deep narrow pelvis therefore could hinder operations involving the resection of rectal cancers, which require adequate vision, maximum retraction and access to the depth of the pelvis via the pelvic inlet.

3.10.2 Perineal procedures

Stress urinary incontinence (SUI) and the surgical procedures involved

Stress urinary incontinence (SUI) is defined as the involuntary loss of urine associated with activities that increase the intra-abdominal pressure in combination with intrinsic sphincter deficiency (Bonnet et al. 2005; Lee et al. 2008; Magon et al. 2011). It is repoted to affect between 4% and 35% of adult women worldwide and can lead to a deterioration in the quality of life of affected women (Moore 2008). This dysfunction is caused by structural or functional damage to the urethra, which renders it unable to resist the increased abdominal pressure as an expulsive force, e.g. coughing, sneezing and laughing (Delmas 2005; Winters et al. 2000; Okorocha et al. 2005; Lee et al. 2008; Ridgeway et al. 2008; Trost and Elliott 2012). Several procedures have been developed to alleviate stress urinary incontinence.

According to Handa et al. (2003), most pelvic floor disorders in women, including urinary incontinence, are associated with parity because the levator ani and pelvic floor muscles may be injured at the time of vaginal delivery (Delorme et al. 2004; Handa et al. 2003). Stav and others found that metric pelvic inlet and outlet dimensions were significantly larger in incontinent females (Stav et al. 2007). In males, detrusor instability may play a role, however, malfunction of the internal urethral sphincter appears to be the primary reason for male stress incontinence after radical retropubic prostatectomy (RRP) (Schaeffer et al. 1998; Schaeffer 2002; Bauer et al. 2005; De Leval and Waltregny 2008; Christine and Knoll 2010).

When conservative methods fail to alleviate SUI, as a result of more severe forms of incontinence in both sexes, bone anchors or sling placements may be considered. The obturator foramen, ischiopubic ramus and the body of the pubis are involved in the placement of bone anchors and urethral slings (Rapp et al. 2007; Zahn et al. 2007; De Leval and Waltregny 2008). Although the dimensions of these components of the pelvis may vary between populations, bone anchors and urethral slings use instrumentation with fixed dimensions and prescribed distances from identified landmarks are given. Neither the dimensions of the instruments, nor the guideline distances, take into account the variability in the relevant pelvic dimensions observed in the different populations (Van der Walt et al. 2015; Van der Walt et al. 2017). Misplacement of bone anchors used for the treatment of SUI in both sexes, may result from using fixed measurements, as individual body variations are not taken into account (Madjar et al. 2000). Misplacement may lead to trauma, ischaemia, nerve entrapment, infection and osteomyelitis (Madjar et al. 2000; Winters et al. 2000; Madjar et al. 2001; Frederick et al. 2004; Goldberg et al. 2004; Riveros et al. 2004).

Apart from bone anchors, variation in pelvic and perineal dimensions between individuals, or populations, could also affect other incontinence procedures. Other sling procedures include the bulbo-urethral sling (e.g. Clemens et al. 1999; Fernandez et al. 2008; Moore 2008; Ridgeway et al. 2008), trans-obturator tape (TOT) (e.g. De Leval and Waltregny, 2008; Lee et al. 2008; Moore 2008; Ridgeway et al. 2008; Grise et al. 2009; Hazewinkel et al. 2009; Houwert et al., 2009; Magon et al. 2011), the outside-in TOT approach (e.g. Lee et al., 2008) and the “Four -Armed” or Quadratic male sling system (Grise, 2009; Trost and Elliott 2012).

Sacrospinous colpopexy

Transvaginal sacrospinous colpopexy is currently used by reconstructive pelvic surgeons to repair varying degrees of vaginal vault prolapse (Gutman et al. 2005; Verdeja et al. 1995). This involves placing a stitch from the vaginal cuff to the sacrospinous ligament, approximately 2 cm medial to the ischial spine, to correct the defect. This may be associated with injury to the pudendal artery and nerve (pudendal complex) and sciatic nerve if the procedure is not carefully performed. (Verdeja et al. 1995).

Gutman emphasises the importance of the measurement of the pelvic outlet diameter (distance between the ischial spines) (Gutman et al. 2005). Verdeja advocates the use of the obstetric conjugate and the distance from the ischial spine to the midpoint of the lateral border of the sacrum (this distance is consistent with the length of the sacrospinous ligament) during this procedure (Verdeja et al. 1995). These authors noted that, after dissection of 24 female cadavers, there was a correlation between the length of the sacrospinous ligament and the obstetric conjugate. They established that the longer the obstetric conjugate, the longer the sacrospinous ligament, and vice versa. The distance from the ischial spine to the sciatic nerve also correlated with the length of the obstetric conjugate.

4. MATERIALS AND METHODS

Direct linear measurements on intact cadaver pelves and PET CT scans (Positron Emission Tomography - Computer Tomography) were used to assess the variations between sex-ancestral groups.

4.1 Materials

4.1.1 Cadaver sample

Intact cadaver pelves of two South African populations (black South Africans and white South Africans) of both sexes were collected and where possible, their matching crania. The cranial sample consisted of 8 black South African females, 8 white South African females, 11 black South African males and 6 white South African males. The pelvic sample size consisted of 34 black South African females (with 9 corresponding crania), 42 white South African females (with 8 corresponding crania), 34 black South African males (12 corresponding skulls) and 40 white South African males (6 corresponding crania), as represented in Table 1 below.

Table 1. Sample distribution of cadaveric pelvic and corresponding skulls

	Pelves for black South Africans	Pelves for white South Africans	**Total pelves**	Corresponding crania for black South Africans	Corresponding crania for white South Africans	**Total crania**
Females	34	42	**76**	8	8	16
Males	33	39	**72**	11	6	17
Total	**67**	**81**	**148**	**19**	**14**	**33**

Cadaveric remains are grouped as black South African or white South Africans; according to the group, they most likely identified themselves with during life. Assignment to a particular population group was previously enforced, while currently, individuals freely choose to indicate their ancestral affinity (L'Abbé et al. 2005). In the context of this study, definitions of these particular population (cultural) groups are according to phenotypical or external physical characteristics. Four main groups are recognised, namely black South Africans, white South Africans, Coloureds, Asian and Indian (Hubbe et al. 2009). For the purposes of this study only South African males and females of African ancestry (known as black South Africans) and of European ancestry (known as white South Africans) were considered, because of the underrepresentation of the other two groups in the cadaver collection, scan and patient collections.

Historically, black South Africans originally descended from western and central Africa and migrated throughout sub-Saharan Africa (Tishkoff and Williams 2002; Ribot 2004; Liebenberg et al. 2015). White South Africans are mostly of European descent, primarily from the Netherlands, France, Germany, Great Britain and Portugal (Patriquin et al. 2002; Patriquin et al. 2005).

The black South African group has long been the predominant people of the South Africa population (80.9%) (Statistics South Africa, 2021) and, therefore, they are the main ancestral group to consider when dealing with forensic cases in the country (L'Abbé et al. 2011). Black South Africans, as described by Tobias (1974), were previously considered as broadly alike in genetic constitution with similar cranial size and shape and significantly different from other African groups (Tobias 1974; Loth and Henneberg 1996).

Representatives of European ancestry arrived mainly from 1652 as a direct result of European settlement in South Africa (Patterson et al. 2010). White South Africans have their origin from the Netherlands, but later also from France, Germany and Britain, as well as smaller additions from other countries (L'Abbé et al. 2011, L'Abbé et al. 2021). However, as a result of temporal change, founder's effect and admixture, the white South African group has become osteologically distinguishable from both their European and North American counterparts (Patriquin et al. 2005; Işcan and Steyn 2013).

Cadavers housed at the Departments of Anatomy of the Faculty of Health Sciences, University of Pretoria (UP) and the Anatomy and Histology Department, Sefako Makgatho Health Sciences University (SMU) were used. Under the National Health Act No. 61 of 2003, cadavers for the purpose of medical teaching and research originate from either donations or unclaimed bodies from various hospitals. Unclaimed bodies forming part of the cadaver collection at UP, generally come from local hospitals in Pretoria such as Mamelodi, Kalafong and Steve Biko (Patriquin et al. 2002; L'Abbé et al. 2005; Patriquin 2005; L'Abbé et al. 2021), while those at SMU originate from a wider area in Gauteng, as well as some areas in the North West Province of South Africa. It should be noted that the cadaver sample used in this study did not originate from the associated bone collections at University of Pretoria (UP) (Pretoria Bone Collection) (L’Abbé et al. 2021) and the Sefako Makgatho Health Sciences University (SMU) (Human Osteological Research Collection), but in time, and after maceration, will be included in these respective collections. The individuals originating from the cadaver sample used in this study were studied within a year or two after their death and are therefore from a more recent period than those housed in the Pretoria Bone Collection (L’Abbé et al. 2021).

Negation of the cost of a burial or cremation could be the motivation for donating remains and may be representative of a lower socio-economic group (Patriquin et al. 2002, L’Abbé et al. 2021). Although these individuals are suspected to be of a low socioeconomic status, little else is known regarding their nutritional status and personal disease histories. In light of this poor health is implied. Nevertheless, it is important for this study to include these individuals as they are applicable to the South African situation and are likely a representative sample. Notwithstanding, pelves or skulls demonstrating disease, trauma or surgery were excluded.

4.1.2 Radiological sample

One hundred and thirty eight computer tomography scans (CT) of skulls and pelves of the same individual, representative of two groups (Black South African and white South Africans) belonging to both sexes, with a wide age range were collected retrospectively from the Radiology Department of the Steve Biko Academic Hospital. These full body CT scans of crania and pelves on the same person were feasible to collect retrospectively as prior to PET scanning; patients routinely have screening CT scans of other areas of the body.

The sample distribution between the groups is represented in Table 2. The CT sample consisted of 52 black South African females, 33 white South African females, 31 black South African males and 22 white South African males. Care was taken not to include crania and pelves with evidence of pathology or with fractures. Slice thickness of the scans ranged between 2 and 2.5 mm.

Table 2. Sample distribution of CT scans (pelvis and crania)

	Black South Africans	**White South Africans**	**Total**
Females	52	33	**85**
Males	31	22	**53**
Total	**83**	**55**	**138**

The CT scan data (and not PET scans) were loaded onto MeVisLab software and analysed to create 3D points. MeVisLab software allows advanced image processing with a special focus on medical imaging. (Heckel et al. 2009). MeVisLab includes advanced software modules for segmentation, registration, volumetry, as well as quantitative morphological and functional analyses (Heckel et al. 2009).

4.1.3 Patient sample

Following approval, retrospective patient data were collected from a private obstetrics practice, a state run Community Health Centre and a private birthing clinic in Pretoria and the surrounding area, Gauteng Province (Annexures C and D respectively).

White and black South Africans mothers and their babies originating from the greater Pretoria area were included in the sample. Historically, black South Africans originally descended from western and central Africa and migrated throughout sub-Saharan Africa (Tishkoff and Williams 2002; Ribot 2004; Liebenberg et al. 2015). White South Africans are mostly of European descent, primarily from the Netherlands, France, Germany, Great Britain and Portugal (Patriquin et al. 2002; Patriquin et al. 2005).

From the mothers, data on population, age, height, head circumference, BPD, duration of active labour (when available) and mode of delivery were collected. The duration of labour was recorded where available, as a possible reflection of the progress of labour, which could be influenced by CPD (Albers et al. 1999; Philpott and Castle 1972; Stephansson et al. 2016). The maternal head circumference and BPD, age and stature, if needed, were taken prospectively with due informed consent (Annexure E). From the baby, the following data were collected: pre- and/or postnatally, head circumference, BPD, maximum cranial length, length, gestational age as applicable, as well as the history regarding childbirth outcomes. The distribution is represented in Table 3.

Table 3. Sample distribution of patient data

Mode of delivery→ Population group↓	**Vaginal**	**Caesarean section**	**Total**
Black South Africans	40	9	49
White South Africans	20	20	40
Total	**60**	**29**	**89**

In an attempt to correct for gestational age differences, the foetal adjusted ratio were used where both the BPD and head circumference were represented as a fraction of the expected standard for the particular gestational age (Hadlock et al. 1984).

4.2 Methodology

This study comprises a cadaver based part, a radiological (CT scan) part and a patient based part derived from retrospective and prospective records. Circumference measurements were taken directly on the exposed cadaveric crania, while all other dimensions were derived from 3D landmarks. Landmarks were taken on both the cadaveric and the radiological sample for linear (size) and shape analyses. Seven standard cranial landmarks and twenty-two pelvic landmarks were chosen. These findings were brought into a clinical context by retrospective and prospective patient records.

4.2.1 Collection of landmarks

Cadaver sample

Standard craniometric landmarks were identified and digitised on cadaver crania and intact pelves in order to explore the relationships between cranial and pelvic dimensional variations in the same individual, and to assess the effects of sex, age and population affinity. In this study, an intact pelvis refers to a pelvis that was previously dissected and partially defleshed in preparation to be macerated and skeletonised without disarticulating the pelvis to facilitate the identification of bony landmarks. Homologous landmarks were obtained on each crania and intact pelvis using an Immersion 3D Microscribe digitiser (Immersion Corporation, San Jose Ca, USA) (Işcan and Steyn 2013). The MicroScribe® G2 digitiser is a registered trademark of the Immersion Corporation and delivers spatial information regarding a 3D object to a computer system.

The MicroScribe® G2 digitiser delivers spatial information regarding a 3D object to a computer system. It consists of mechanically linkages ending in a stylus that allows the user six degrees of motion in a three dimensional space. This is the ability to move forward/backward, up/down, and left/right (i.e. x, y and z positions). This is combined with three perpendicular axes (roll, pitch and yaw orientations). As the movement along each of the three axes is independent of each other, and independent of the rotation about any of these axes, the motion has six degrees of freedom (Rosenberg et al. 1998; Nagasaka et al. 2003).

The stylus is used as a probe device to trace over the surface of the 3D object and thereby provide the spatial coordinate data of the object to the host computer system via a standard RS-232 serial port. The computer is then able to receive the precise data points at different spatial coordinates. The position and orientation of the stylus is uniquely determined by the configuration of the five-linkage arm. The arm can be assembled by placing the joints of the arm in joint fixtures at the desired distance and angle apart. The stylus is fixed to one end of a series of mechanical linkages, while the other end of the linkage chain is connected to a base, fixed to a stationary surface (Rosenberg et al. 1998; Nagasaka et al. 2003).

Sensors are included in the joints of the linkage chain to sense the relative orientation of linkages, and therefore where the stylus is located in relation to the base. The angle data read by the sensors can be converted into coordinate data by the microprocessor. The sensors of the probe apparatus are zeroed by placing the probe apparatus in the only possible home position (Rosenberg et al. 1998; Nagasaka et al. 2003).

In this way, 3D repetitive landmarks of an object in this study were determined by the MicroScribe® G2 digitiser with a click-of-the-hand switch. The x-, y- and z- coordinates of each 3D landmark were then imported to the connected computer in a Microsoft Excel spread sheet. Thereafter, calculation of linear distances, as well as shape analyses were performed on all the non-disarticulated cadaver pelves by means of a free software package PAlentological Statistics (PAST) v4.03.

Radiological (CT scan) part

CT scan data were loaded onto MeVisLab software and analysed to create 3D points. MeVisLab software allows for advanced image processing and development with a special focus on medical imaging. MeVisLab has advanced software modules for segmentation, registration and volumetry, as well as for quantitative morphological and functional analyses, allowing fast integration and testing of new algorithms and the development of clinical application prototypes. (Heckel et al. 2009).

Figure 17 outlines the methodology followed for image processing leading to the creating of a WEM file. This file consists of 3D points corresponding to each landmark taken. The x-, y- and z- coordinates of each 3D landmark were then imported to the PAlentological Statistics (PAST) v4.03 software programme for calculation of linear distances, as well as shape analyses.

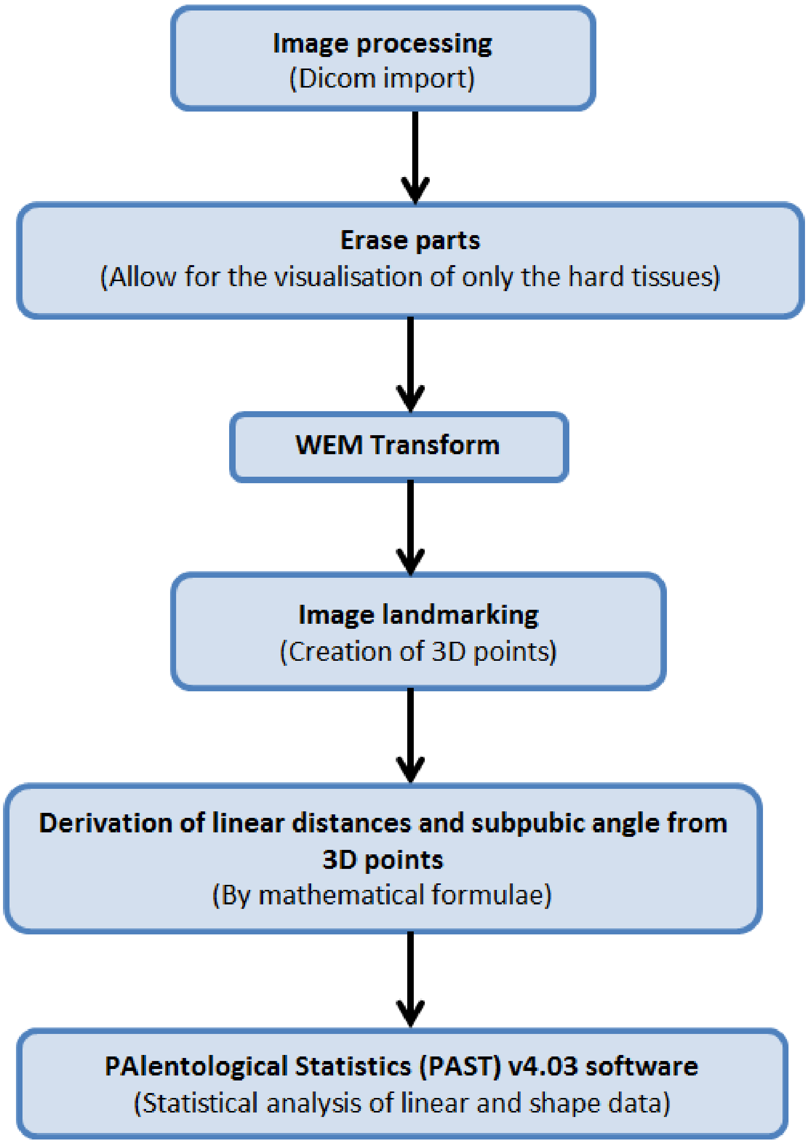

Figure 17. Methodology used from MevisLab image processing

During the first step which is image processing, patient Dicom files were loaded onto the MeVisLab Segmentation module. The IsoSurface of the TIFF files was adjusted to eliminate all soft tissue and to visualise only the bony elements (pelvis and cranium) of the scans. All IsoSurface values ranged between 1100 and 1130. This was followed by the "Erase parts" module. Here, the WEM files were altered to erase all irrelevant components of the scan area, except for the cranium and the pelvis. Images were saved as a secondary WEM file.

These WEM files were then imported to a WEM Transform module before landmarking. A landmarking template was created and applied to all the scans to mark the same seven standard cranial landmarks and twenty-two pelvic landmarks that were taken on the cadaveric sample. These created files consisted of the x-, y- and z- coordinates of each 3D landmark which was then imported into PAST v4.03 for calculation of linear measurements as well as for shape analyses.

4.2.1.1 Landmarks taken on pelves

Twenty-two pelvic landmarks that reflect the overall pelvic shape were selected on both the cadaveric and the radiological samples. These landmarks were chosen to represent the pelvic inlet, midpelvis and pelvic outlet. The list of landmarks taken, and definitions of landmarks that were used on the pelves, are shown in Tables 4 - 6 and Figures 18 and 19.

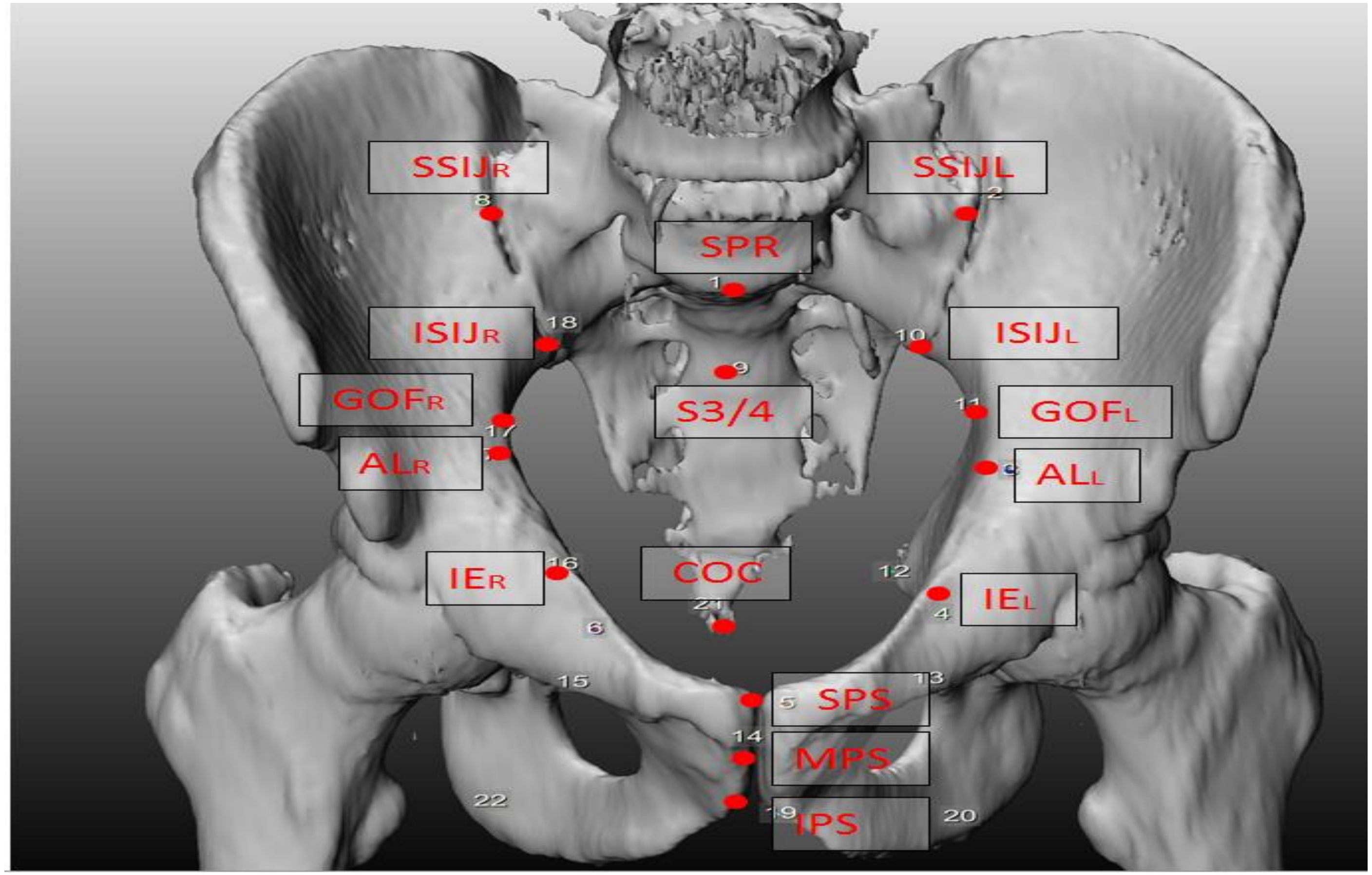

Figure 18. Landmarks taken on anterior and superior view of pelvic CT scans

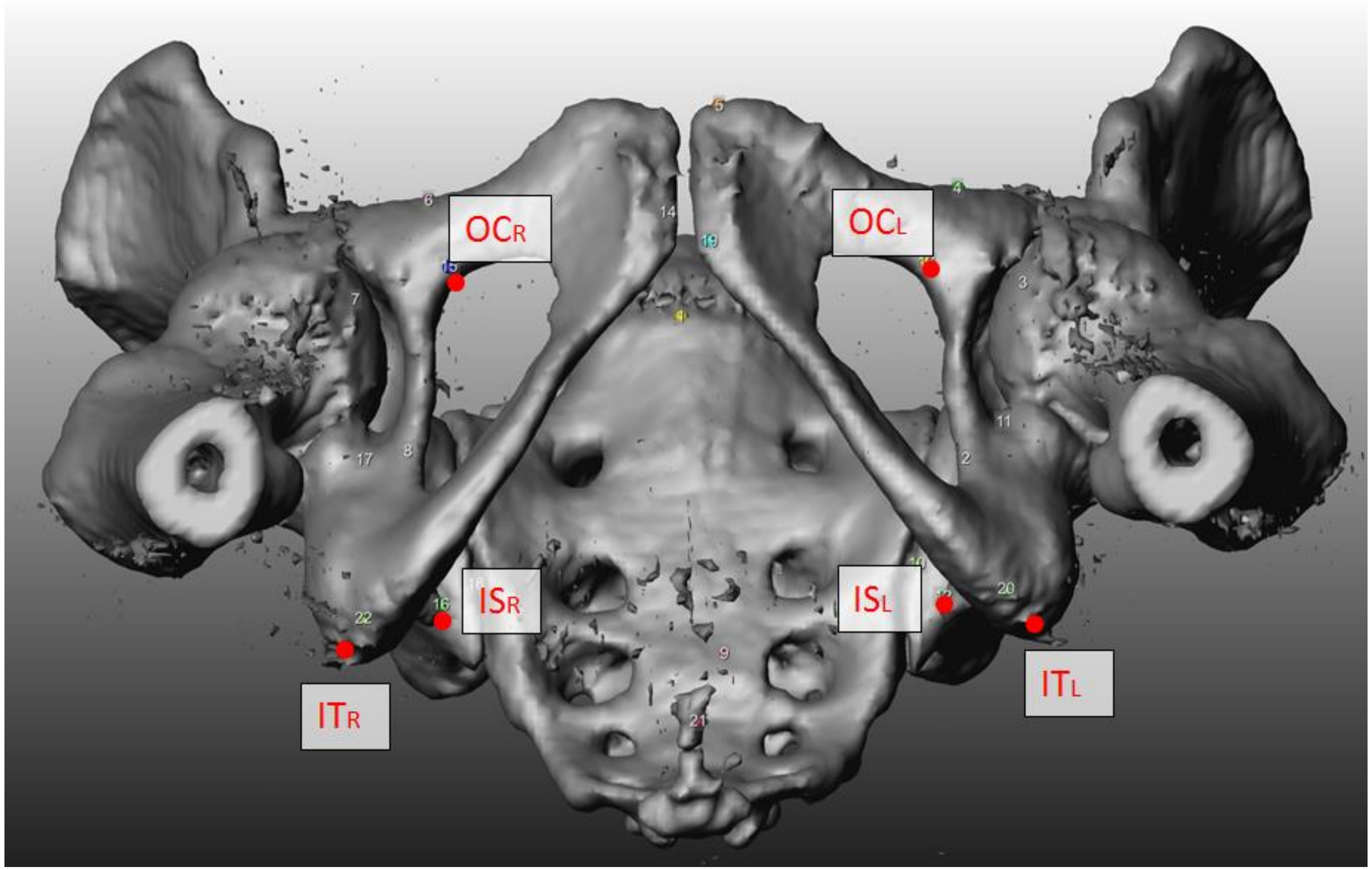

Figure 19 . Landmarks taken on anterior and inferior view of pelvic CT scans

Table 4. Definition of landmarks on the pelvic inlet used for pelvic measurements

Abbreviation	Landmark	Bilateral (BL) OR Mid-sagittal (MS)	Definition/ Description
SPR	Sacral promontory	MS	Most anterosuperior point on sacral promontory
SPS	Pubic symphysis	MS	Most superior point on the pubic symphysis
AL	Arcuate line	BL	Point of maximum curvature of the arcuate line of the ilium (most lateral point)
SSIJ	Superior sacroiliac joint	BL	Most anterosuperior point at the junction of the sacrum and ilium, where the arcuate line meets the auricular surface
IE	Iliopubic eminence	BL	Most medial point on the iliopubic eminence where the arcuate and pectinate lines meet

Table 5. Definition of landmarks on the pelvic midplane used for pelvic measurements

Abbreviation	Landmark	Bilateral (BL) OR Mid-sagittal (MS)	Definition/ Description
MPS	Mid-pubic symphysis	MS	Midpoint of the posterior aspect of pubic symphysis. (most prominent point)
S3/4	Sacral joint S3/4 joint	MS	Midpoint on junction of sacral joints S3/4 in midsagittal plane
ISIJ	Inferior sacroiliac joint	BL	Most inferior point at the junction of the sacrum and ilium
GOF	Greater sciatic notch	BL	Point of maximum curvature in the greater sciatic notch
IS	Ischial spine	BL	Tip of the ischial spine
OC	Obturator canal	BL	Superior point on the obturator canal

Table 6. Definition of landmarks on the pelvic outlet used for pelvic measurements

Abbreviation	Landmark	Bilateral (BL) OR Mid-sagittal (MS)	Definition/ Description
COC	Coccyx	MS	Most inferior point on the tip of the coccyx
IPS	Public symphysis	MS	Most inferior point in the midline of the pubic symphysis
IT	Ischial tuberosity	BL	Most inferior point on the ischial tuberosity

4.2.1.2 Landmarks taken on all crania

Seven cranial landmarks (Table 7) that reflect the overall neurocranial shape were chosen. These points were taken on both the cadaveric and the radiological samples and are shown in Figure 20. The list of landmarks taken, and definitions of landmarks that were used on the crania, are shown in Table 7.

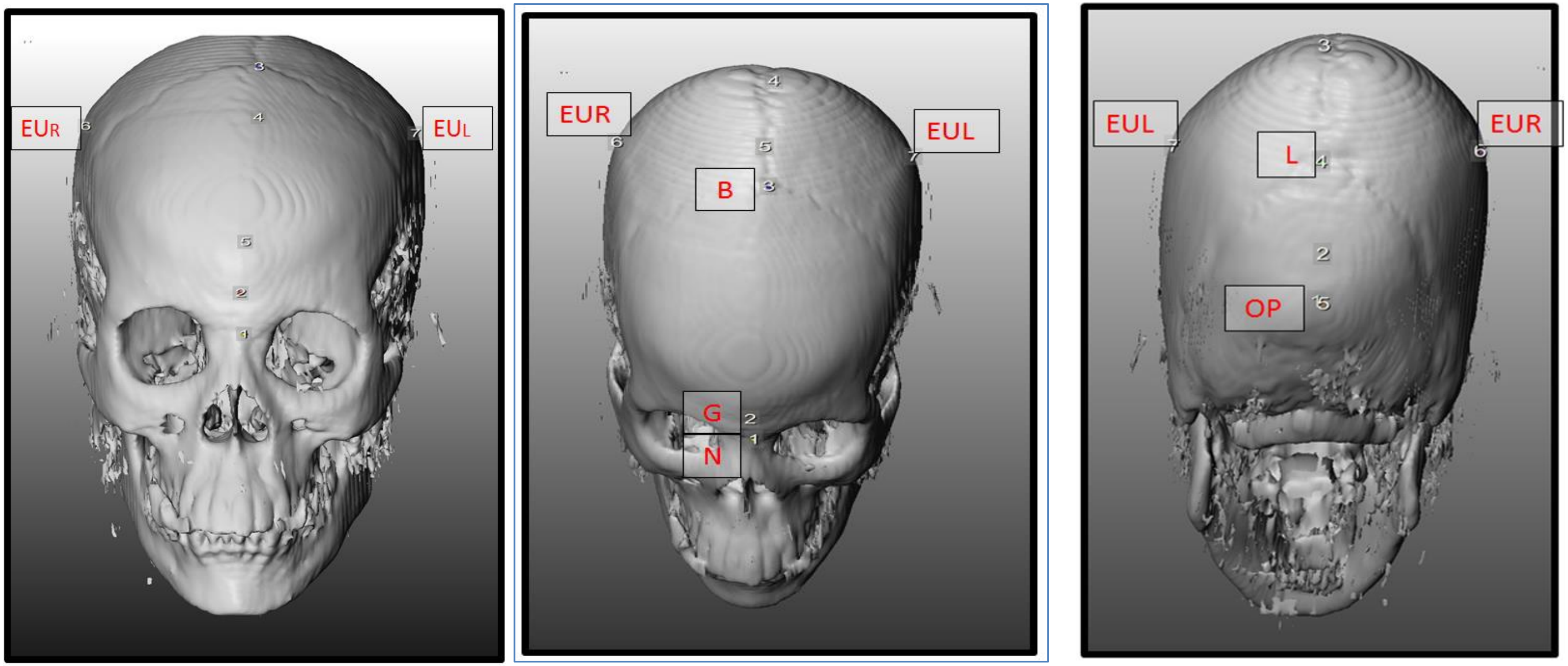

Figure 20. Landmarks taken on anterior and superior view of cranial CT scans

Table 7. Definition of landmarks on the crania used for cranial measurements

Abbreviation	Landmark	Bilateral (BL) OR Mid-sagittal (MS)	Definition/ Description
EU	Euryon	BL	Most lateral point on the parietal or temporal bone
N	Nasion	MS	The point at the intersection of the nasal bones and the frontal bones
G	Glabella	MS	Most anterior projecting point at the lower margin of the frontal bone , just superior to the nasal root and between the superciliary arches
OP	Opisthocranion	MS	Most posteriorly protruding point at the back of the braincase, maximum distance from the glabella
B	Bregma	MS	Located at the intersection of the coronal and sagittal sutures
L	Lambda	MS	Located at the intersection of the lambdoid and sagittal sutures

4.2.2 Calculation of subpubic angle and linear distances pelves

Subpubic angle

Three 3D points namely left ischial tuberosity (ABC), pubic symphysis (DEF) and right ischial tuberosity (GHI) were used to determine the subpubic angle using the following formula:

=DEGREES(ACOS((((D-A)*(D-G)) + ((E-B)*(E-H)) + ((F-C)*(F-I))) / ((SQRT((D-A)^2 + (E-B)^2 + (F-C)^2)) * (SQRT((D-G)^2 + (E-H)^2 + (F-I)^2)))))

Linear distances

Linear distances, reflecting the overall shape of the birth canal, were calculated from the twenty-two digitised 3D points taken on intact articulated pelves. The list of landmarks taken and definitions of these landmarks are shown below. The landmarks were digitised and 3D points were created. From these 3D points, absolute distances were calculated using the following formula, where a particular 3D point is represented by X1, Y1 and Z1 and another by X2, Y2 and Z2:

=DEGREES(ACOS((((D-A)*(D-G)) + ((E-B)*(E-H)) + ((F-C)*(F-I))) / ((SQRT((D-A)^2 + (E-B)^2 + (F-C)^2)) * (SQRT((D-G)^2 + (E-H)^2 + (F-I)^2)))))

Points and corresponding measurements were grouped into those pertaining to the pelvic inlet (Table 8 and Figure 21), midpelvis (Table 9 and Figure 22) and pelvic outlet (Table 10 and Figure 23).

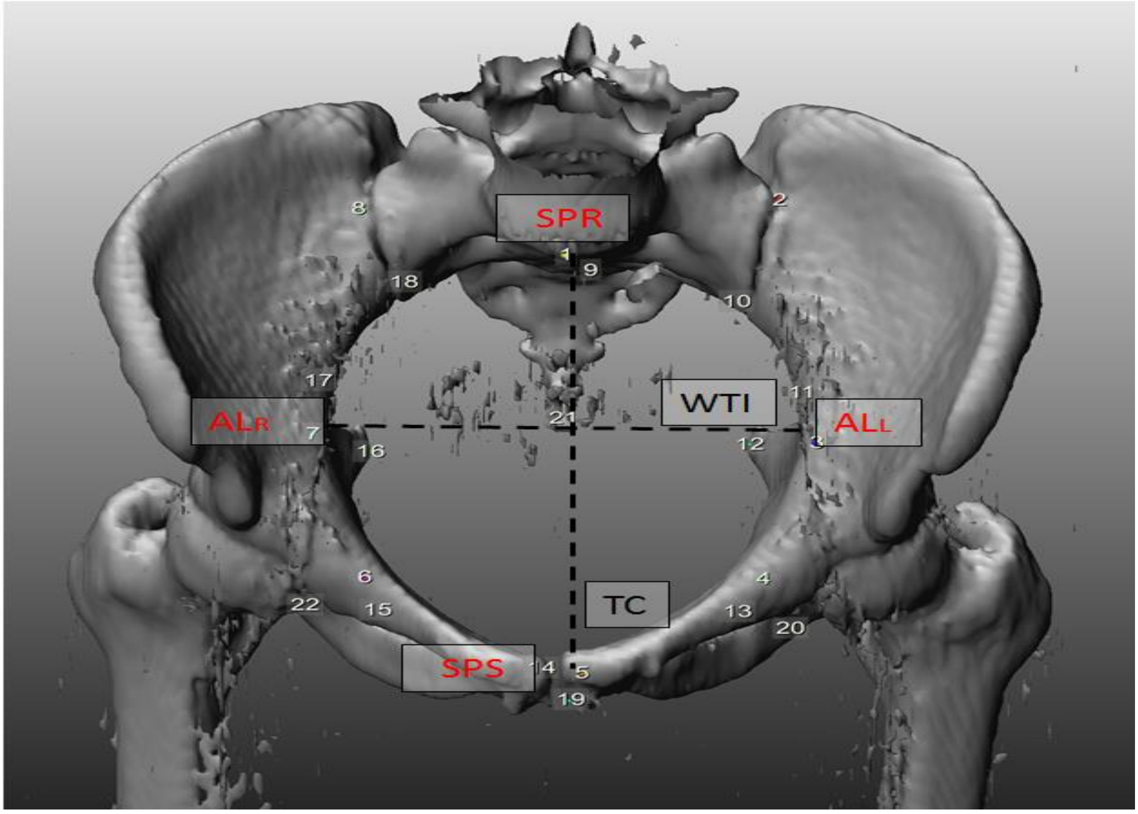

Figure 21 Absolute measurements related to the pelvic inlet

Table 8. Absolute measurements related to the pelvic inlet

Abbreviation	Measurement	Description
TC	Anteroposterior dimension of the pelvic inlet (TC)	Most anterosuperior point on sacral promontory (SPR) to dorsomedial aspect of superior most point on pubic symphysis (SPS)
WTI	Widest transverse dimension of the pelvic inlet	Maximum distance between iliopectineal lines (ALR- ALL). This diameter is visually aligned to be perpendicular to the anteroposterior diameter of the inlet
DC	Diagonal dimension of the pelvic inlet (taken by obstetricians and midwives)	Most anterosuperior point on sacral promontory (SPR) to inferior most point on pubic symphysis (IPS)

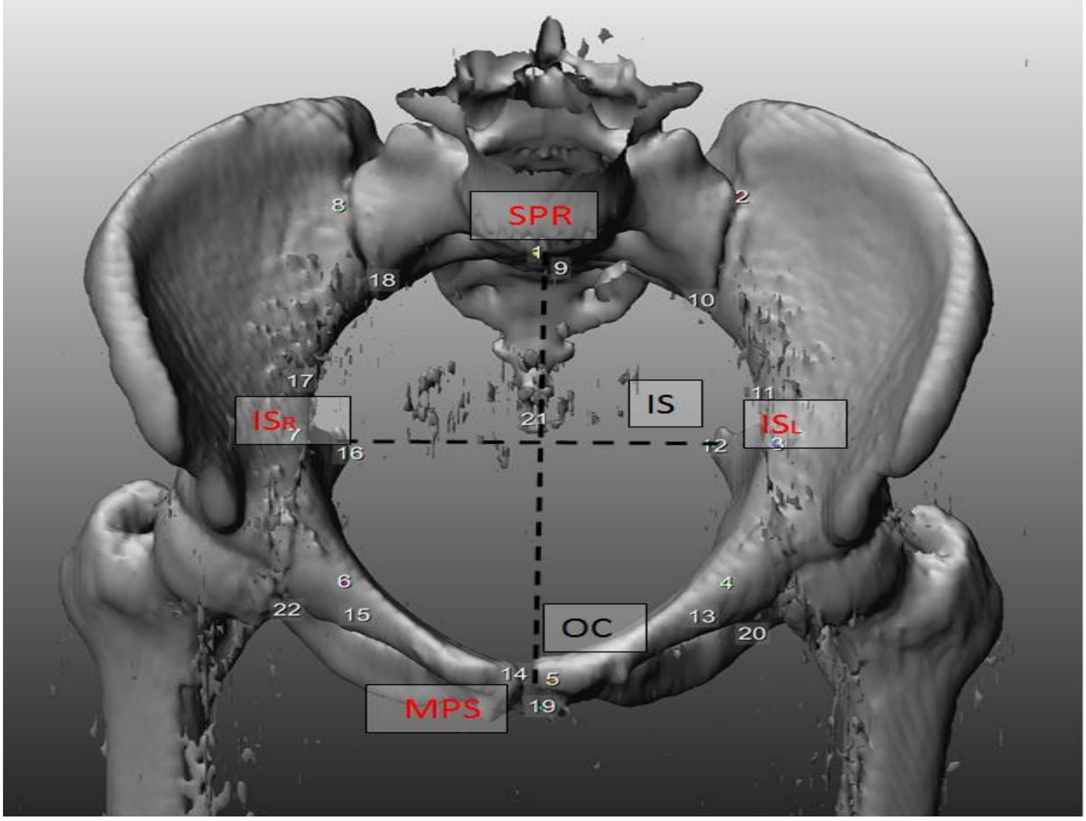

Figure 22. Absolute measurements related to the midpelvis

Table 9. Absolute measurements related to the midpelvis

Abbreviation	Measurement	Description
OC	Obstetric conjugate	Most anterosuperior point on sacral promontory (SPR) to the midpoint of the posterior aspect of pubic symphysis (MPS). (most prominent point)
IS	Narrowest transverse midpelvic dimension (interspinous diameter)	Distance between tips of the left and right ischial spines (ISL-ISR)

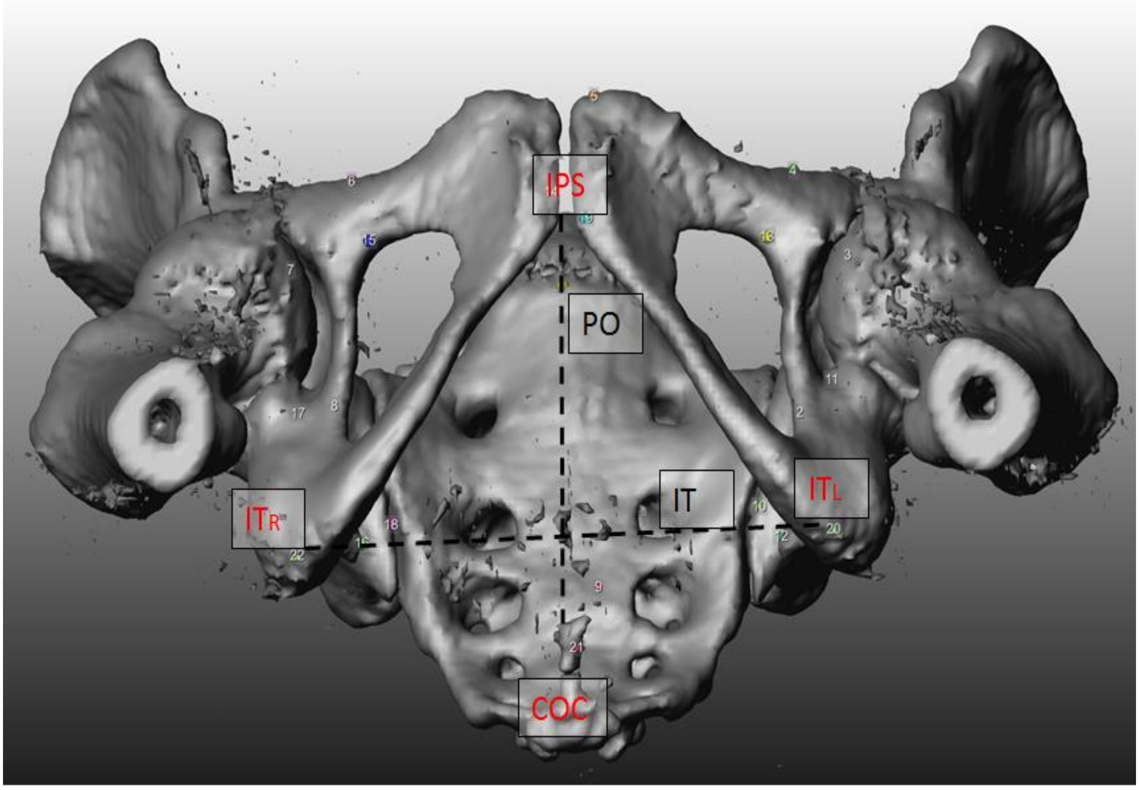

Figure 23. Absolute measurements related to the pelvic outlet

Table 10. Absolute measurements related to the pelvic outlet

Abbreviation	Measurement	Description
PO	Anteroposterior dimension of the outlet	Tip of coccyx (COC) to most inferior point on the dorsomedial aspect of most inferior point on pubic symphysis (IPS)
IT	Transverse dimension of the pelvic outlet (intertuberous diameter)	Distance between the most inferior points of the left and right ischial tuberosities (ITL-ITR)
Subpubic angle	Angle formed at the inferior pubic ramus between the inferior pubic ramus on each side	Angle calculated from the two tangent lines on the inferior border of the pubic rami

4.2.3 Calculation of linear distances on crania

From the seven cranial landmarks that reflect the overall cranial shape, two absolute distances were calculated using the following formula.

SQRT((A2-D2)^2+(B2-E2)^2+(C2-F2)^2):

These absolute distances include: the BPD ($EUR_L – EUR_R$) and the maximum cranial length (G- OP) (Figure .42). The list of landmarks taken, and definitions of landmarks as well as the absolute distances between them are shown in Figure 23 and Table 11. The head circumference was also taken directly on the crania with a measuring tape.

Cranial ratios were calculated to provide an idea of the head size as well as for correlations with the pelvic dimensions. The following ratio were calculated from the cadaveric sample: widest distance of the skull / head circumference (BPD / Head circumference) while the second ratio: widest distance of the skull / greatest cranial length (BPD / MaxCL) was calculated from the radiological sample.

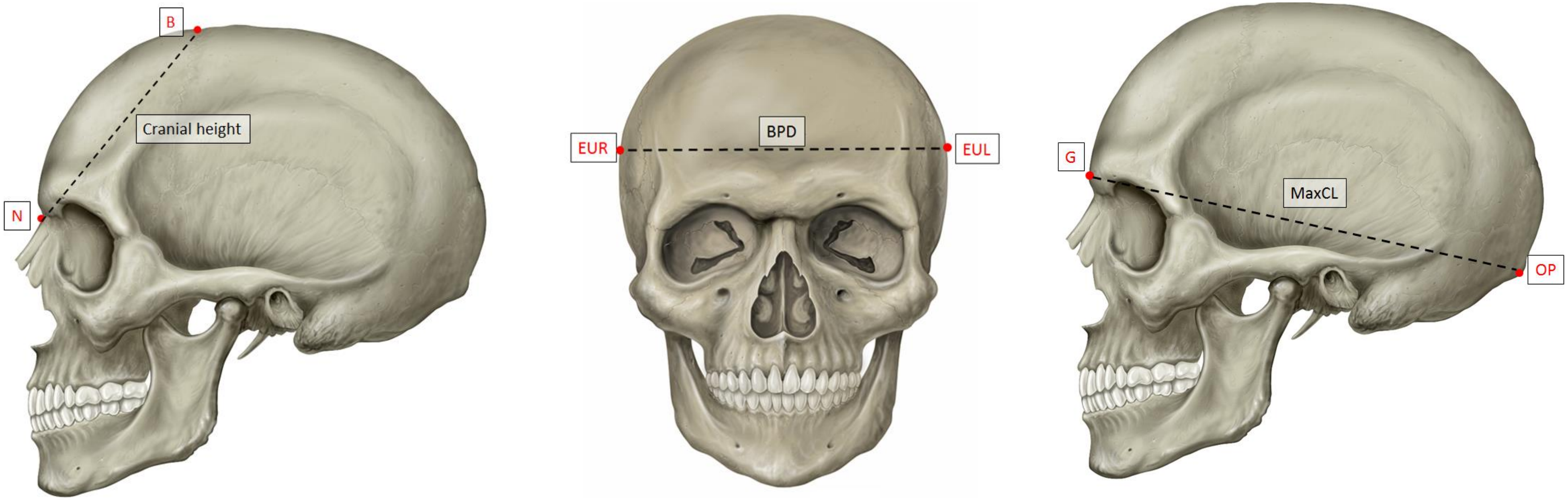

Figure 24 Absolute measurements related to the maximum cranial dimensions

Table 11. Absolute measurements and ratios related to the cranium

Abbreviation	Measurement	Description
Cranial height (N-G)	Longest vertical distance of the cranium	Distance between nasion (N) and bregma (B)
Biparietal diameter (BPD)	Most lateral points on the parietal or temporal bone)	Widest diameter on the parietal bone taken between the left and right euryon (EUR-EUL)
Maximum cranial length (MaxCL)	Greatest cranial length	Maximum distance between the glabella (G) and the opisthocranion (OP)
Head circumference	Measurement of the head around its largest area	Maximum distance around the cranium from the glabella (G) anteriorly to the Opisthocranion (OP) posteriorly
Ratio: BPD / Head circumference (calculated from cadaveric sample)	Widest distance of the skull / head circumference	
Ratio: BPD / MaxCL (calculated from radiological sample)	Widest distance of the skull / greatest cranial length	

4.2.4 Statistical analysis of linear measurements

Using the PAST v4.03 software, intra-class correlation for intra-observer error on all dimensions of the cadaver pelvis, cadaver crania, pelvic scans and cranial scans were performed, respectively. Inter-observer error was performed on all dimensions of the scan data. Inter-observer error on the cadaver data could not be performed because of the lack of availability of this sample. This was followed by a univariate analysis of each dimension within the sex-population groups to determine the means and standard deviation. Normality testing was used to determine whether a data set is well-modelled by a normal distribution, and to compute how likely it is for a random variable underlying the data set, to be normally distributed.

Normality tests were performed and where a normal distribution was found, a one way ANOVA, accompanied by Tukey's pairwise comparisons were performed to evaluate p-values between pairs. If the distribution was not normal, non-parametric tests such as Kruskal Wallis were performed to evaluate p-values. Finally, discriminant analyses were performed to explore the potential application for forensics. A flow chart of statistical tests performed is shown in Figure 25.

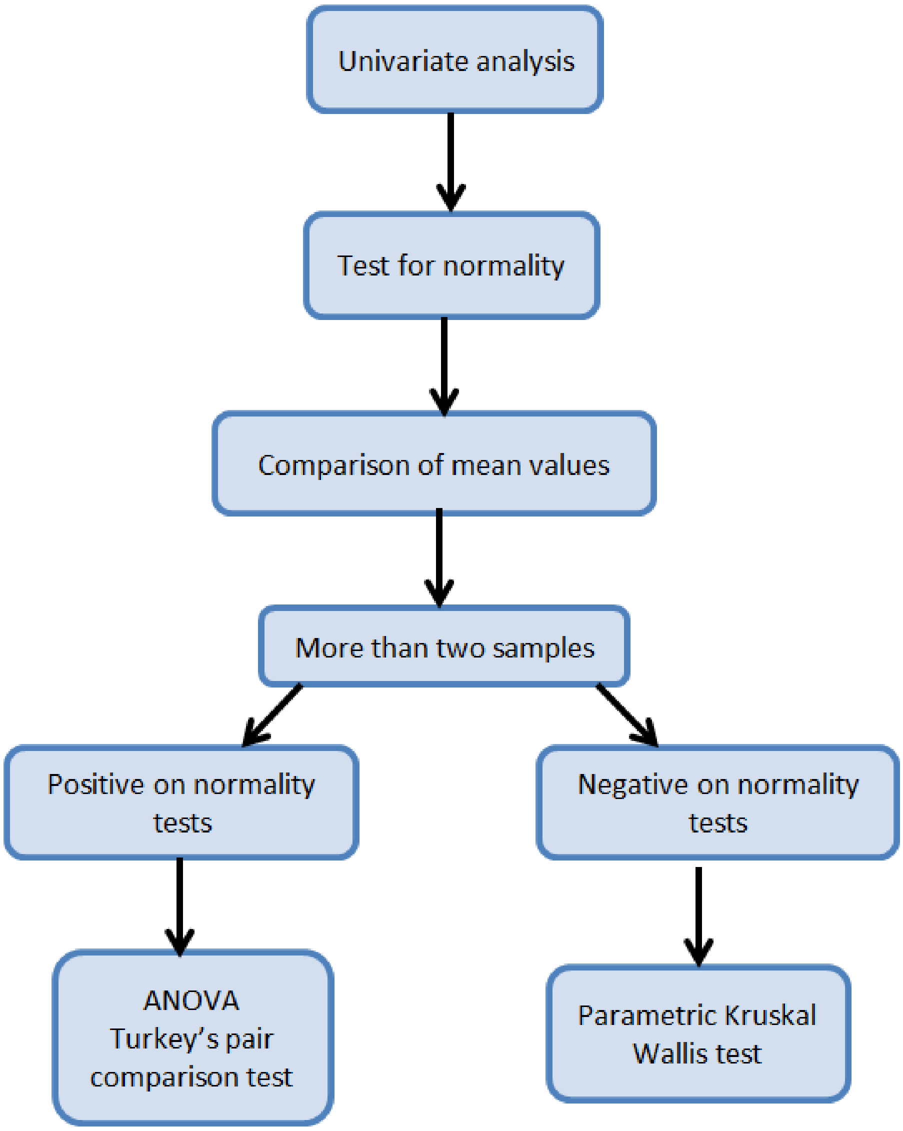

Figure 25. Statistical tests for linear measurements performed

To test the relationship between cranial linear dimensions and the pelvic canal linear dimensions, (i.e. to assess how skull dimensions (5 independent variables) predict the pelvic canal dimensions (8 dependent variables)), multivariate linear regressions were performed using the PAST v4.03 software. This function allows a visual representation of the relationship between the variables tested.

For the scan data ages of the individuals could be collected for further statistical analysis. In these cases linear regressions were performed to assess the variation in cranial or pelvic measurements with age, respectively.

4.2.5 Statistical shape analysis of cadaver and CT crania and pelves

Shape analyses, using geometric morphometrics (GM) on established standard landmarks of the cranium and pelvis in the cadaver and CT samples, were performed. Standard geometric morphometric methods were applied in order to (i) analyse the pattern of variation of size and shape components intra- and inter-group, (ii) test the co-variation between cranial and pelvic canal and cranial size on the shape variations of the crania and pelvis.

The main advantages of geometric morphometrics are its statistical power and the ability to visualise shape deformations, which is not possible with traditional methods (Mitteroecker and Gunz 2009). The pattern of shape variation and morphological differences have been examined with principal components analysis (PCA) in the case of two groups and canonical variate analysis (CVA) in the case of more than two groups, as well as discriminant analysis (Hammer et al. 2001).

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 shape space. In addition to a visual image, values are created that can be statistically compared. Multivariate statistics can then be applied to investigate morphological variations with direct reference to the anatomical context of the structure involved, thus quantifying the morphological characteristics (Mitteroecker and Gunz 2009).

Shape analysis of the complete intact pelvic shape, pelvic inlet, midpelvis, pelvic outlet and cranial shape were performed, stepwise, by means of the PAST v4.03 software programme. A flow chart of statistical tests performed is shown in Figure 26.

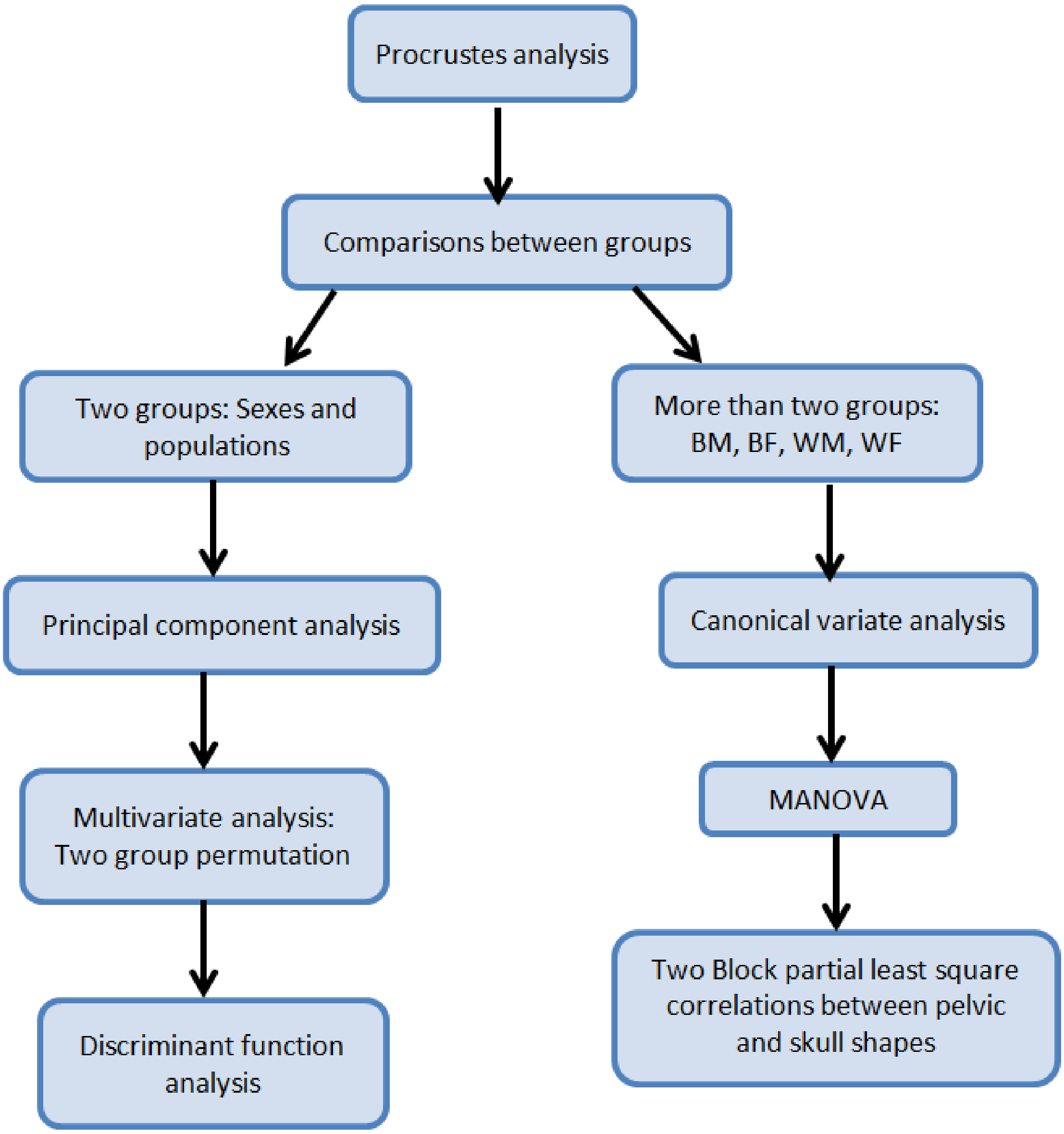

Figure 26. Statistical tests used for shape analyse

Generalised Procrustes Analysis (GPA) was the first step in the GM methods applied, and was conducted on the raw 3D coordinate data in PAST v4.03 (Hamme et al. 2001). In PAST v4.03, the raw coordinates were given a procrustes fit and converted to procrustes coordinates by using the centroid of the entire sample to translate and scale the landmark's raw coordinates, and then to rotate the entire sample to minimise the squared distances between landmarks. Through this approach, shape analysis could follow, independent of size. The pattern of shape variation and morphological differences were then examined with principal components analysis (PCA), generating principal component scores.

Principal component analysis was used when only two groups were compared for instance black South Africans males and black South Africans females, white South Africans males and white South Africans females, black South Africans and white South Africans, followed by multivariate analysis: two-group permutation in order to test for significance when comparing groups. Discriminant function analysis, as applicable to forensic anthropology, were performed for prediction of population affinity and sex. In this context, the following groups were compared: black South African males (BM) and black South African females (BF), white South African males (WM) and white South African females (WF), as well as black South Africans and white South Africans.

Where sex-population groups were compared (BM, BF, WM, WF), canonical variate analysis was performed followed by MANOVA using Hotelling's p-values. Finally, covariance between pelvic and cranial shape was determined by performing two block partial least squares within sex-population groups (BM, BF, WM, WF). Average wireframe shapes were created for illustrative and description purposes (Figures 27-31).

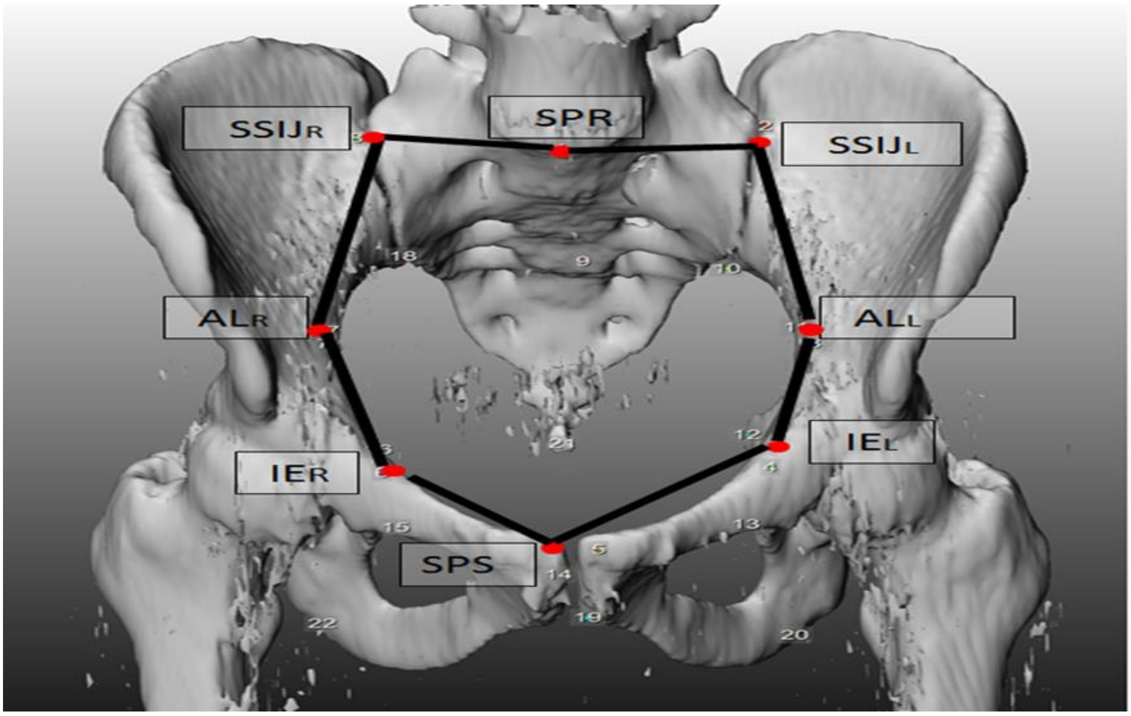

Figure 27. Wireframe connecting landmarks representing the pelvic inlet

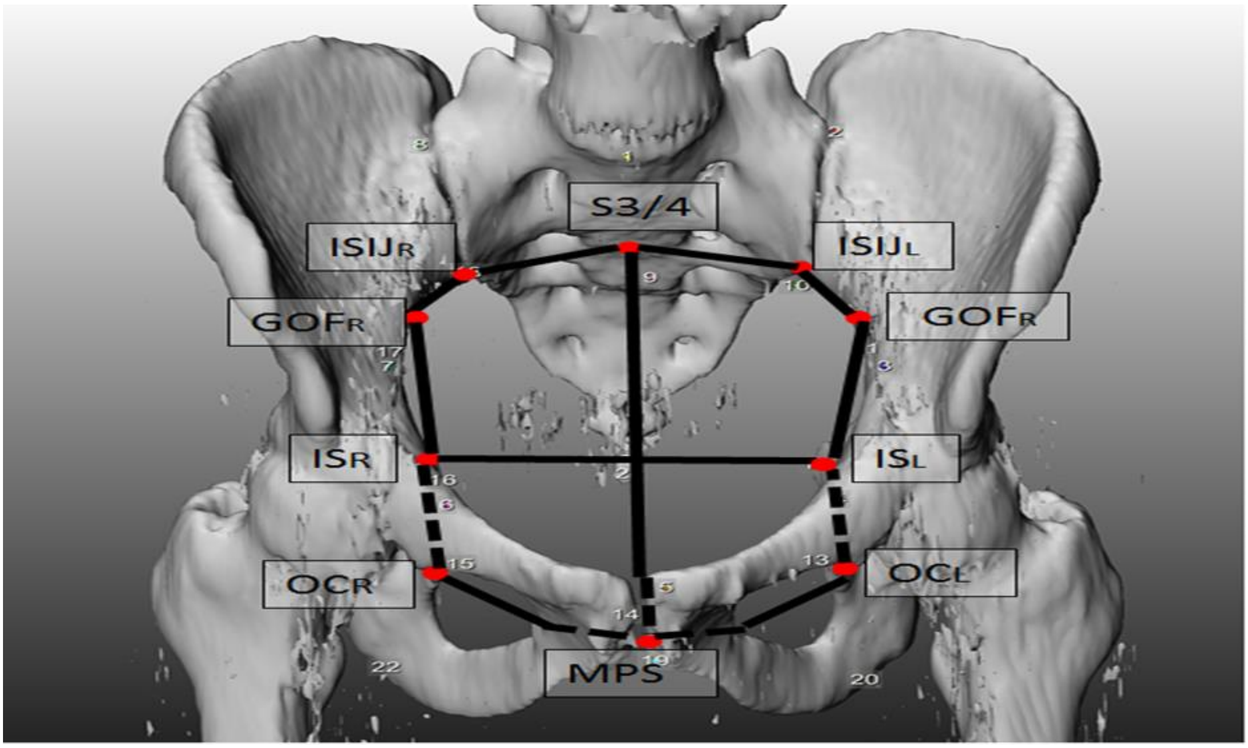

Figure 28. Wireframe connecting landmarks representing the midpelvis

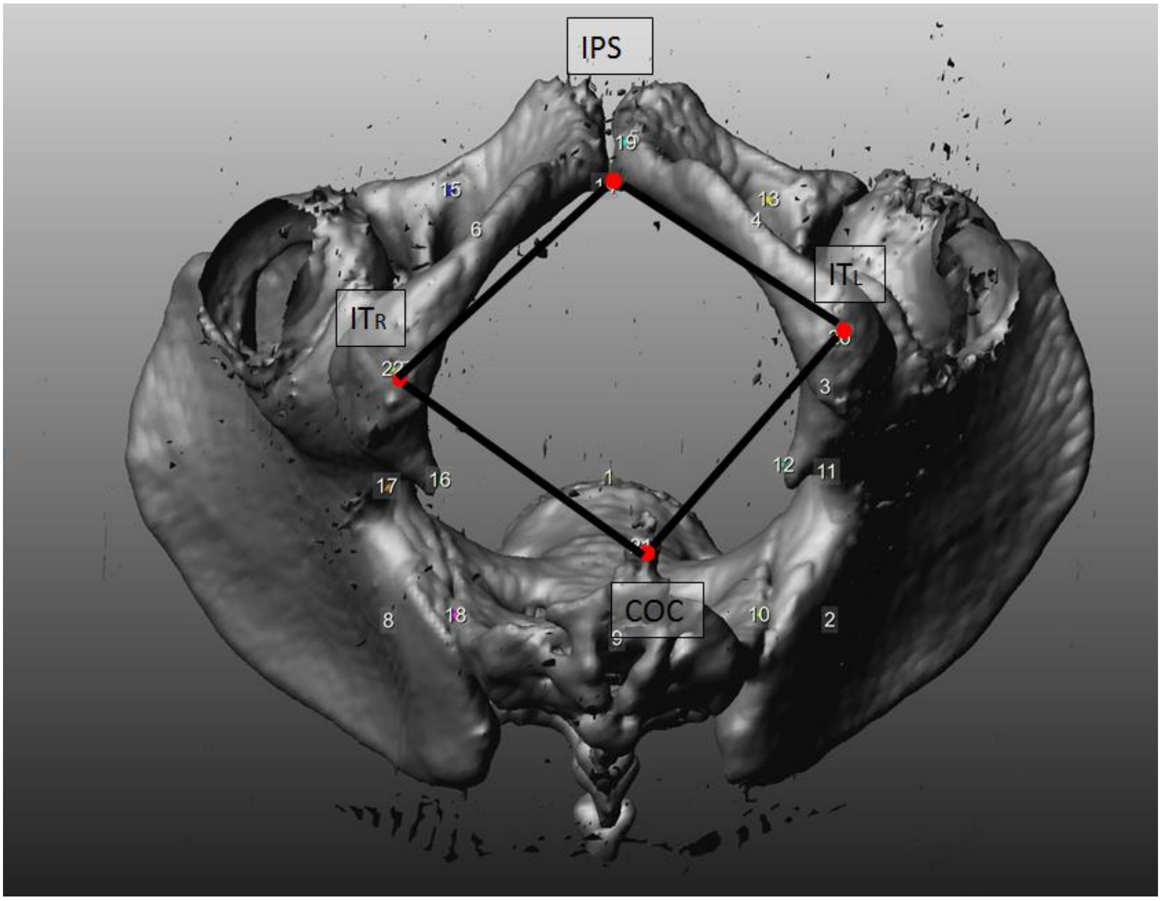

Figure 29. Wireframe connecting landmarks representing the pelvic outlet

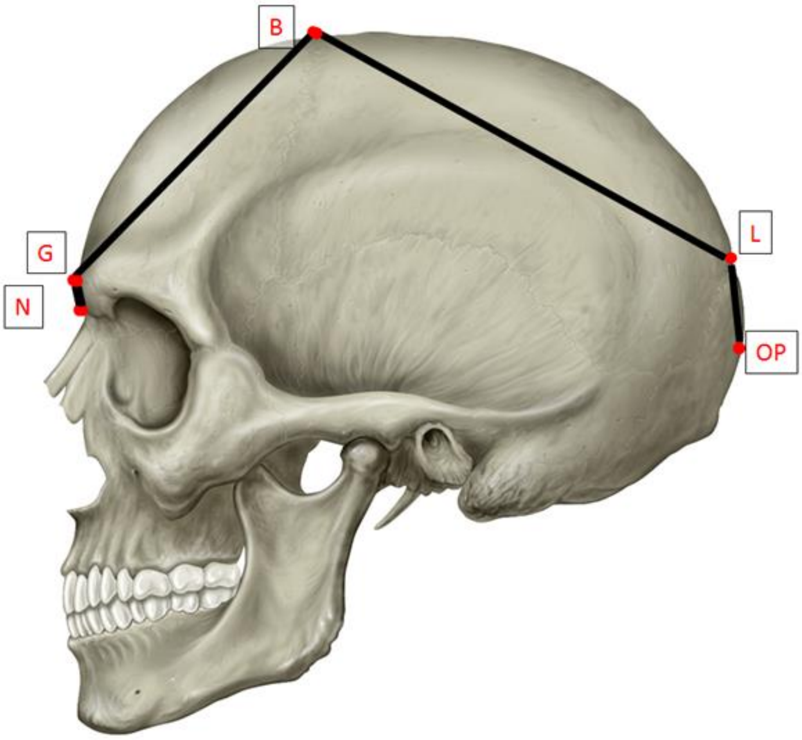

Figure 30. Wireframe connecting landmarks representing the overall cranial length

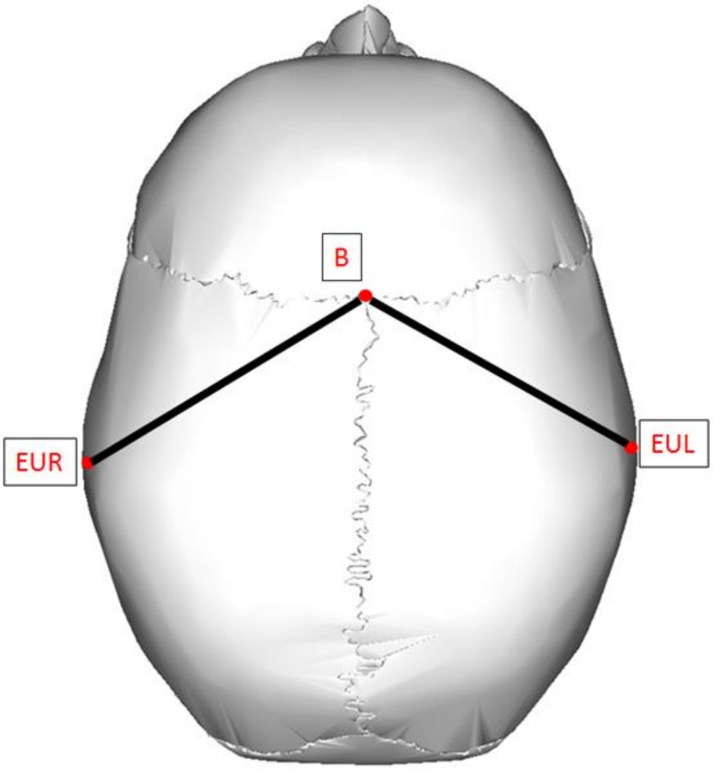

Figure 31. Wireframe connecting landmarks representing the overall cranial breadth

4.2.6 Correlation between linear and shape data

Covariances between linear cranial and pelvic measurements, as well as pelvic shape, were calculated by linear regression models in an effort to simulate the clinic situation. These linear regressions were performed within the sexes and populations, as well as sex-population groups individually (BM, BF, WM, WF). The linear cranial measurements included the cranial height (N-G), BPD (EUR_L – EUR_R) and the maximum cranial length (MaxCL) (G- OP), the ratio between the BPD and MaxCL and the ratio between BPD and head circumference in the cadaver sample only, correlated to the overall pelvic shape, pelvic inlet shape, midpelvis shape and pelvic outlet shape, respectively. The shape of the cranial and the pelvis (overall pelvic shape, pelvic inlet shape, midpelvis shape and pelvic outlet shape, respectively) were also correlated by performing two block partial least squares analyses within the sexes and populations, as well as sex-population groups individually (BM, BF, WM, WF).

4.2.7 Collection and statistical analysis of patient data

Research design:

Quantitative, descriptive, cross sectional study on prospective and retrospective data

Sampling: Convenience sampling technique was used

Ethical clearance was originally obtained for the entire PhD study including the patient sample with a further amendment when the data of a private birthing centre was included. These certificates can be found at Annexure A and B respectively. In the case of prospective data, mothers were fully informed regarding the procedures and the purposes of this study and were asked to sign a consent form for their voluntary participation. The consent form can be found [Annexure E] data were further anonymised to protect the identity of the mother and baby.

The patient data were grouped according to the two main populations represented in the collection: black South African females and white South Africans females, and also according to mode of delivery into a caesarean section group and a normal vaginal delivery group. These groupings were extended by including both criteria so that four groups could be analysed, namely: black South African vaginal delivery, black South African caesarean section, white South African vaginal delivery and white South African caesarean section. Comparisons between population groups and birth mode were made.

The flow of statistical tests performed are summarised in Figure 32. Using the PAST v4.03 software programme, univariate analyses were performed to determine the means and standard deviation. In order to compare the means between the mentioned groups, normality tests were performed. When the data were distributed normally in the case of two groups being compared, a Student’s t-test was performed and when more than two groups were compared, a one-way ANOVA accompanied by Tukey’s pairwise comparisons were performed to evaluate p-values between pairs. When the distribution was not normal, non-parametric tests such as Mann Whitney for two group comparisons were performed and Kruskal Wallis, for more than two groups to evaluate p-values.

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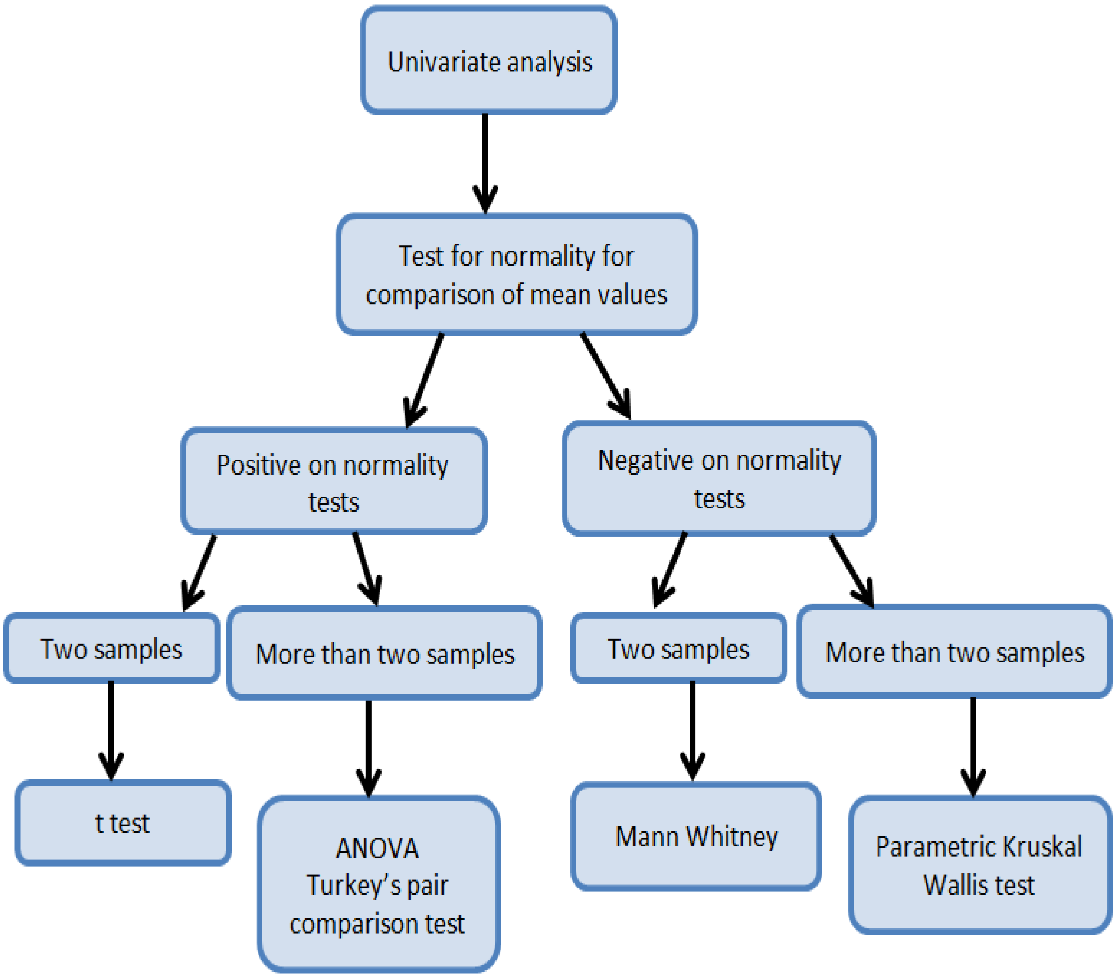


Figure 32. Statistical tests performed on patient data

Validity and reliability could not be assessed as it is not part of the routine practice to repeat anthropometrics either by the main caregiver or another person before or after the delivery.

4.2.8 Integrative analysis and possible implications of the findings

Consideration of anthropometric parameters of the mother (e.g. her age, stature or population group) and its influences on the shape of her pelvis may provide better insight when making childbirth decisions. An integrative analysis of all data (cadaver, scans and patient data) may be helpful to the clinician when deciding on birthing options to possibly negate cephalopelvic disproportion, as well as when planning pelvic and perineal procedures. An integrative analysis of the variations in the linear distances of the crania and pelvis, as well as the subpubic angle and shape variations between groups, will give insight into the geographical trends and functional pressures in evolutionary processes. Correlations found between the pelvic dimensions and with sex may provide a better and improved understanding of the sexual adaptations of the pelvis and provide more insight on the evolutionary and anthropological aspects. As a corollary, variations observed in the skull and pelvis between populations and sexes, might have implications for forensic anthropology.

5. RESULTS

5.1 Cadaver sample

5.1.1 Analysis of linear dimensions on the intact pelvis

Measurements relating to the birth canal were taken on intact cadaver pelves. These measurements were grouped into conjugates pertaining to the three pelvic rings, namely the pelvic inlet, midpelvis and the pelvic outlet. The dimensions of the pelvic inlet are described by the TC, the WTI dimension of the pelvic inlet and the conjugate taken by midwives known as the DC of the pelvic inlet (Table 4). The dimensions of the midpelvis are described by the OC and the narrowest transverse midpelvic dimension known as the distance between the ischial spines (IS) (Table 5), and lastly, the dimensions of the pelvic outlet are described by the anteroposterior diameter of the pelvic outlet, the IT and the subpubic angle (Table 6). Intra-class correlation for intra-observer error on all dimensions of the cadaver pelvis showed excellent reliability, as the lowest value was 0.966 and that on the subpubic angle.

Table 12. Linear measurements taken on intact pelves on cadaveric sample

Parameter	BF n = 34	WF n = 42	BM n = 3	WM n = 39	Black South Africans n = 68	White South Africans n = 82	South African females n = 76	South African males n = 74
Pelvic inlet								
True Conjugate [TC] (SPR - SPS)	**112.77** ^{ad} *9.16* (99.81 - 135.86)	**127.06** ^{ac} *10.41* (90.70 - 147.46)	**105.20** ^{bd} *10.75* (82.46 - 126.63)	**120.17** ^{bc} *10.97* (96.364 - 157.23)	**109.17** ^{e} *10.58* (82.46 - 135.86)	**123.67** ^{e} 11.11 (90.70 -157.23)	**120.66** ^{f} *12.13* (90.70 - 147.46)	**113.43** ^{f} *12.99* (82.46 -157.23)
Widest transverse inlet diameter [WTI] (AL$_L$ - AL$_R$)	**119.15** ^{ad} *8.20* (106.44 - 136.71)	**135.28** ^{ac} *7.44* (121.79 - 151.51)	**114.97** ^{bd} *6.67* (101.58 - 126.29)	**128.49** ^{bc} *9.66* (112.25 - 152.86)	**117.01** ^{e} *7.69* (101.58 - 136.71)	**132.05 e** *9.15* (112.25 - 152.86)	**128.06** ^{f} *11.19* (106.44 - 151.51	**122.32** ^{f} *10.80* (101.58 - 152.86)
Diagonal conjugate [DC] (SPR – IPS)	**126.86** ^{a} *11.14* (105.06 - 151.35)	**133.85** ^{a} *18.42* (63.94 - 156.84)	**122.31** ^{b} *10.42* (93.89 - 136.96)	**134.99** ^{b} *12.72* (113.52 - 176.34)	**124.75** ^{e} *10.92* (93.89 - 151.35)	**133.30** ^{e} *18.63* (44.33 -176.34)	**130.72** *15.88* (63.94 - 156.84)	**128.09** *16.40* (44.33 - 176.34)
Midpelvis								
Obstetric conjugate [OC] (SPR – MPS)	**110.38** ^{ad} *11.22* (91.07 - 141.46)	**128.26** ^{ac} *17.44* (97.56 - 185.54)	**105.87** ^{bd} *15.35* (71.27 - 148.67)	**120.85** ^{bc} *18.46* (92.83 - 193.31)	**108.23** ^{e} *13.41* (71.27 - 148.68)	**125.02** ^{e} *18.34* (92.83 - 193.32)	**120.26** ^{f} *17.37* (91.07 - 185.54)	**114.48** ^{f} *18.83* (71.27 - 193.32)
Interspinous diameter [IS] (IS$_L$ –IS$_R$)	**94.26** ^{d} *9.84* (68.81 - 112.81)	**106.34** ^{c} *11.12* (83.64 - 136.19)	**83.40** ^{bd} *9.33* (59.17 - 03.75)	**89.97** ^{bc} *7.712* (71.36 - 107.81)	**88.15** ^{e} *12.58* (37.10 - 112.82)	**99.27** ^{e} *14.54* (71.36 -165.04)	**100.94** ^{f} *12.12* (68.81 - 136.19)	**87.34** ^{f} *14.04* (37.10 - 165.04)
Pelvic outlet								
Anteroposterior dimension of the pelvic outlet [PO] (COC – IPS)	**89.43** *9.16* (73.58 - 110.72)	**96.25** *9.15995* (55.212 - 120.21)	**84.41** *9.01* (69.06 - 06.36)	**91.96** *9.80* (66.19 - 113.35)	**87.53** ^{e} *10.40* (69.06 - 125.39)	**94.78** ^{e} *12.84* (55.21 - 143.42)	**93.20** ^{f} *11.88* (55.21 - 120.21)	**89.74** ^{f} *12.57* (66.19 - 143.42)
Intertuberous diameter [IT] (IT$_L$ – IT$_R$)	**108.49** ^{d} *10.72* (85.16 - 125.33)	**125.94** ^{c} *12.63* (99.86 - 150.20)	**97.04** ^{bd} *12.10* (75.25 - 126.43)	**107.87** ^{bc} *13.02* (85.26 - 144.80)	**102.65** ^{e} *12.72* (75.25 - 126.43)	**117.52** ^{e} *15.76* (85.26 - 150.20)	**118.13** ^{f} *14.63* (85.16 - 150.20)	**103.23** ^{f} *14.24* (75.25 - 144.81)
Subpubic angle (degrees)	**87.63** ^{d} *9.35* (70.51 - 109.80)	**91.52** ^{c} *11.42* (75.61 - 145.26)	**76.71** ^{d} *8.57* (62.72 - 96.75)	**79.46** ^{c} 11.58 (62.20 – 120.01)	**82.17** *10.46* (62.72 - 109.80)	**85.64** *12.94* (62.20 -145.26)	**89.78** ^{f} *10.66* (70.51 - 145.26)	**78.19** ^{f} *10.33* (62.20 -120.09)

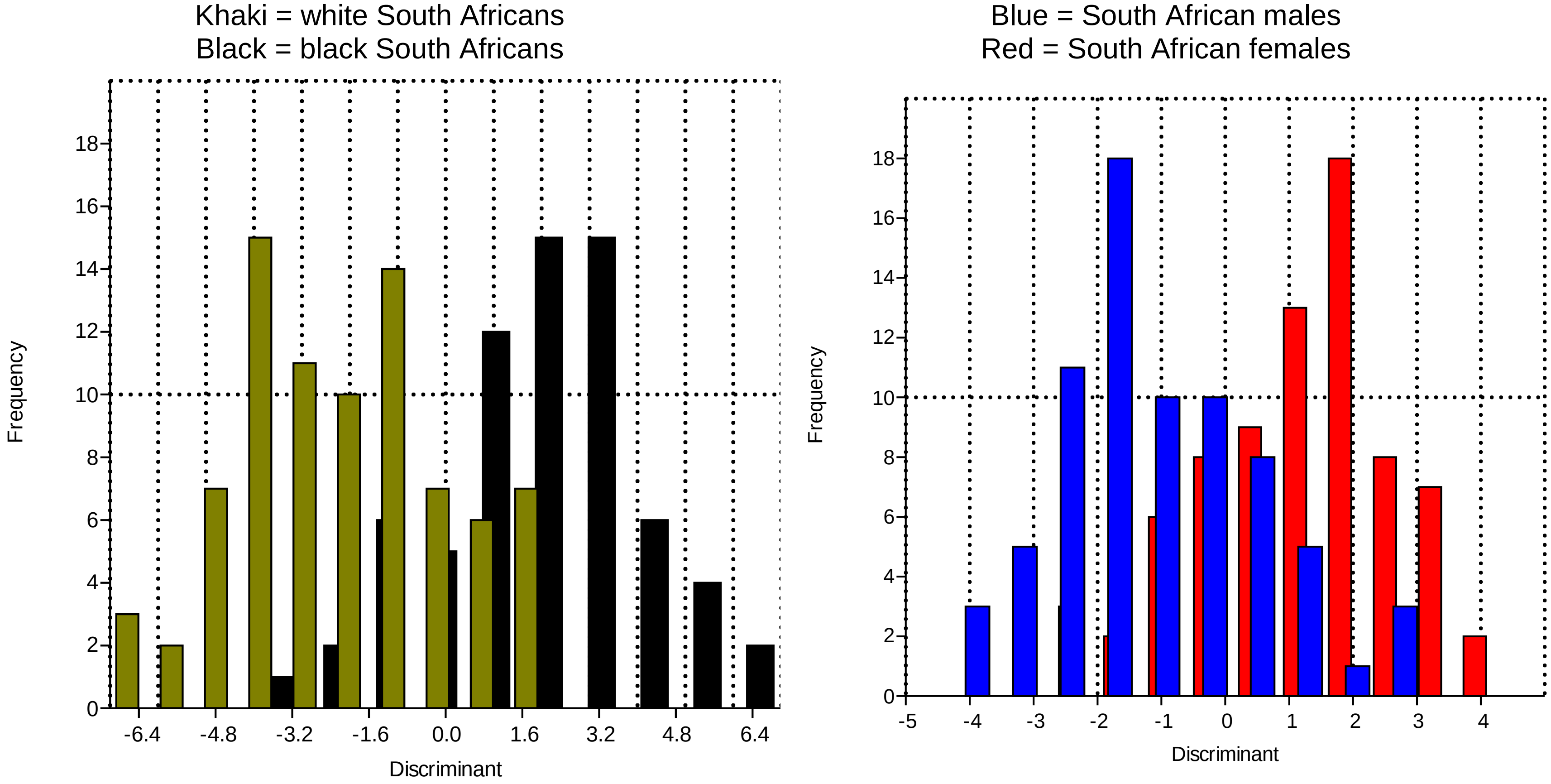
The number per group is indicated by n values. The mean values (mm) are indicated in **bold.** The standard deviation is indicated in *italics and* the range is shown within the round (brackets).

a Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African females
b Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African males
c Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the white South Africans
d Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the black South Africans
e Indicates a significant difference in the mean values ($p \leq 0.05$) between South African populations
f Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes

5.1.1.1 Comparisons between populations and sexes in the complete sample

All linear dimensions were greater in females than in males, and greater in white South Africans as compared to black South Africans. All relationships were statistically significant when considering the sexes, apart from the DC of the pelvic inlet. All comparisons between populations were statistically significant, apart from the subpubic angle. The TC, WTI diameter of the inlet, DC of the pelvic inlet and outlet, as well as the OC of the midpelvis, were the greatest in white South Africans as compared to black South Africans, males or females, whereas IS, IT and the subpubic angle were the greatest in females, as compared to white South Africans, black South Africans and South African males.

Discriminant function analysis were performed to determine whether the size of the pelvis was effective in predicting population and sex. The results revealed 85.33% accuracy when predicting population and 78.00 % accuracy when predicting sex (Figure 33).



Khaki = white South Africans
Black = black South Africans

Blue = South African males
Red = South African females

Discriminant function analysis: 85.33% correctly classified

Discriminant function analysis: 78.00% correctly classified

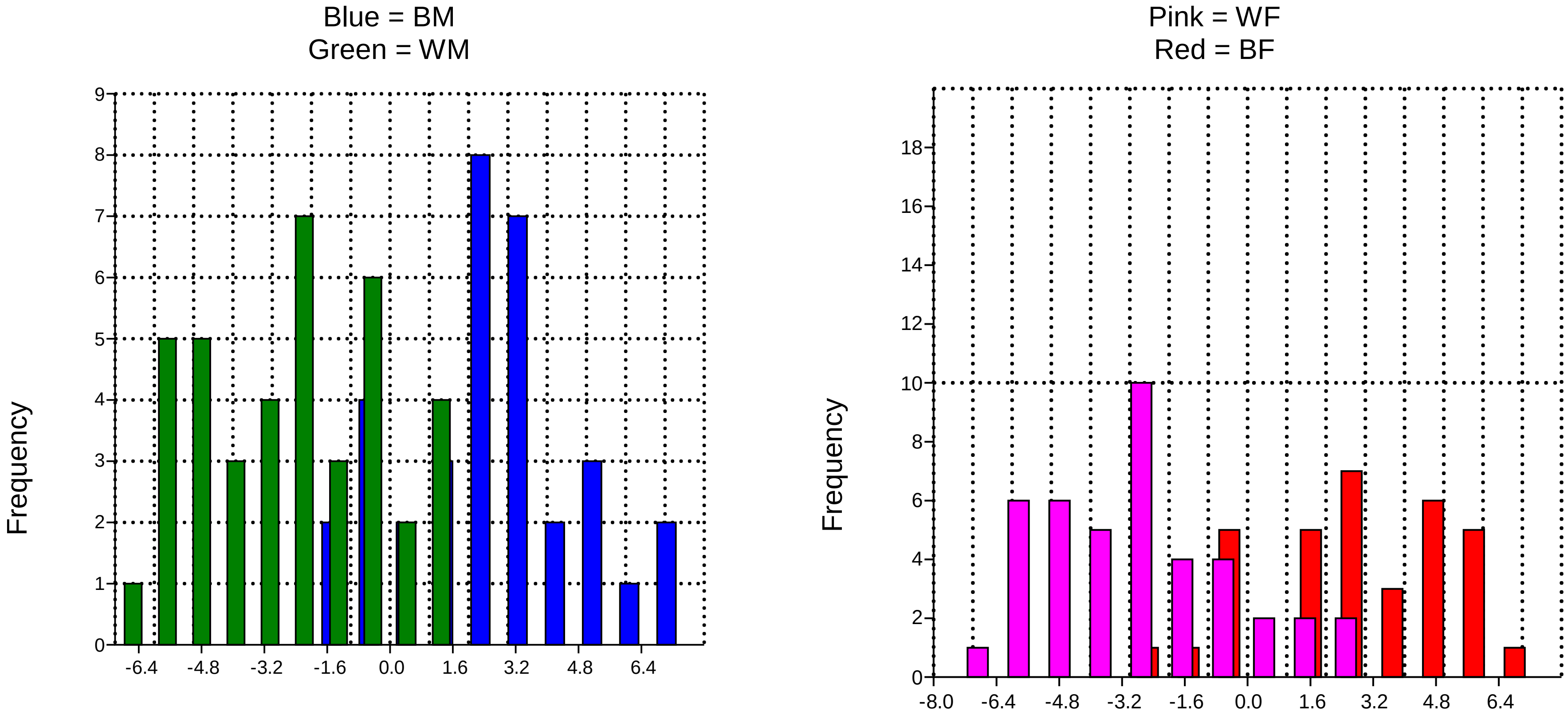
Figure 33. Discriminant function analyses of the linear pelvic dimensions between populations and sexes in the cadaveric sample

5.1.1.2 Comparisons between populations within sexes

All mean conjugate values, as well as the subpubic angle for white South African females were greater than those of black South Africans females. Three of the eight measurements were significantly larger in white South African females ($p \leq 0.05$). Two of these are found on the pelvic inlet: the TC and the DC of the pelvic inlet (PI), and one on the midpelvis: the OC.

Black South African males presented with the smallest mean values in all dimensions. White South African males presented with significantly larger dimensions in five of the eight distances. Similar to white South African females, two of these measurements are found on the pelvic inlet: the TC and the DC of the pelvic inlet .In addition, both midpelvic dimensions in white South African males, as well as the intertuberous distance on the pelvic outlet, were statistically significantly larger than in black South African males.

Discriminant function analysis were performed to determine whether the size of the pelvis was effective in predicting the population group within the sex group. Discrimination function analyses (Figure 34) revealed 86.49% accuracy when predicting the population group in the male sex group and 85.53% accuracy when predicting the population group in the female sex group



Discriminant function analysis: 86.49 % correctly classified

Discriminant function analysis: 85.53% % correctly classified

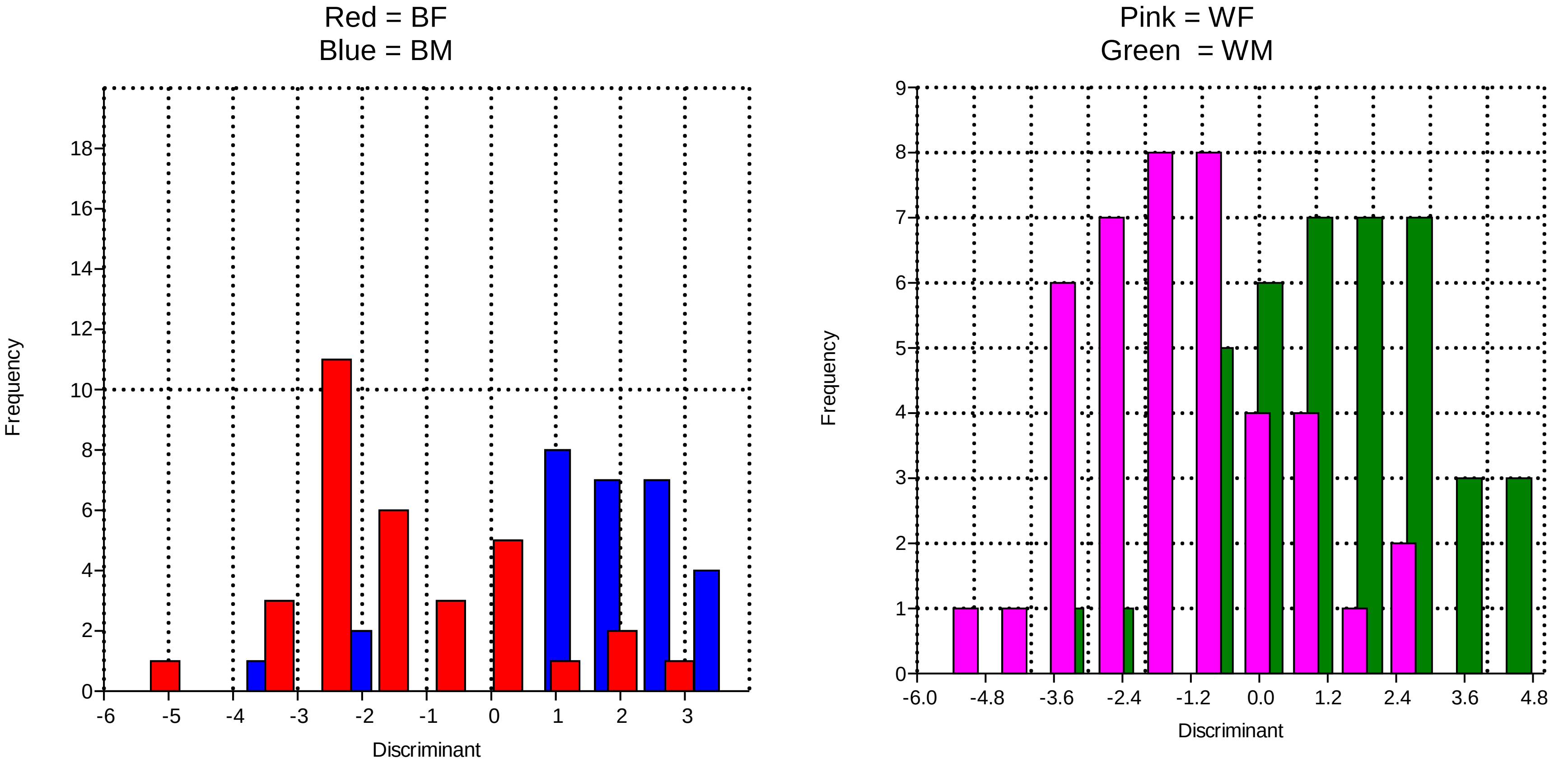
Figure 34. Discriminant function analyses of the linear pelvic dimensions between populations within the sexes in the cadaveric sample

5.1.1.3 Comparisons between sexes within a population

White South African females presented with larger overall dimensions when compared to all and also white South African males, except regarding the DC of the pelvic inlet, where males presented with a mean value of 134.99 mm and females with a mean value of 133.85 mm. White South African females have significantly wider WTI and longer TC than white South African males. They also present with a statistically larger midpelvis and IT dimension.

Black South African females presented with larger overall dimensions when compared to black South African males. White South Africans and black South African females had a statistically significant wider WTI and longer TC than black South African males. They also presented with a statistically larger midpelvis and IT dimension.

Discrimination function analyses were performed (Figure 35) separating the sexes within the black South African population with 85.07% accuracy, and the sexes within the white South African population with 82.93% accuracy.



Discriminant function analysis: 85.07 % correctly classified

Discriminant function analysis: 82.93 % correctly classified

Figure 35. Discriminant function analyses of the linear pelvic dimensions between sexes within populations

Summary of sex and population group variations in linear cadaver pelvic dimensions

All pelvic linear dimensions were statistically significantly greater in females than in males and in white compared to black South Africans, with the exceptions of the DC and the subpubic angle, respectively. Prediction of population affinity was more accurate (85.33%) than sex (78.00%), when considering the entire sample.

All pelvic linear dimensions were greater in white South African females than those of black South African females and were statistically significant for the pelvic inlet dimensions and for the OC of the midpelvis. Similarly, pelvic linear dimensions were greater in white South African males than those in black South African males and were statistically significant, except for the anteroposterior pelvic outlet dimension and subpubic angle. Discriminant function analysis within a sex group for different populations were similar to the entire sample with 86.49% accuracy for males and 85.53% for females.

When comparing the sexes within a population group, both white South African females and black South African females presented with statistically significant greater dimensions when compared to white South African males and black South African males, respectively, except for the DC of the pelvic inlet and outlet (PO). The DC was smaller in white South African females than in white South African males, but greater in black South African females compared to black South African males. The PO was greater in females compared to males within a population. Sex discrimination improved when considering populations separately, with 85.07% within the black South African population group and 82.93% accuracy within the white South African population group.

5.1.2 Analysis of linear dimensions on the crania

Intra-class correlation for intra-observer error on all linear dimensions of the cadaver crania showed excellent reliability, as the values were greater than 0.91, except for the cranial length (opisthocranion to glabella) of 0.769, which was still moderately good agreement.

The mean values, the standard deviations and range of each linear dimension are presented in Table 13. Comparisons between sex-population groups were performed and significant p-values ($p \leq 0.05$) are indicated by the superscripts a–f. Thereafter, a discriminant analysis was performed between the two populations and sexes (Figure 35), secondly, between populations within the sex groups (Figure 36) and thirdly, between the sexes within the populations (Figure 37).

Table 13. Linear measurements taken on crania on cadaveric sample

Parameter	BF n = 8	WF n = 8	BM n = 11	WM n = 6	Black South Africans n = 19	White South Africans n = 14	South African females n = 16	South African males n = 17
Cranial height (N – B)	**110.76** *7.68* (100.16 - 120.66)	**112.28** *5.54* (104.38 -123.30)	**114.43** *5.98* (104.92 -127.34)	**117.28** *6.90* (105.22 -25.25)	**112.89** *6.80* (100.16 -127.34)	**114.42** *6.44* (104.38 -125.25)	**111.52** *6.52* (100.16- 23.30)	**115.44** *6.26* (104.92 - 27.34)
Greatest cranial length [MaxCL] (G - OP)	**181.27** *7.74* (169.52 - 192.03)	**178.39** [c] *2.96* (174.05 - 181.78)	**188.97** *7.72* (179.34 - 99.84)	**190.81** [c] *5.59* (182.76 196.58)	**185.73** *8.47* (169.53 - 99.84)	**183.71** *7.58* (174.05 -196.58)	**179.83** [f] *5.86* (169.53 192.03)	**189.62** [f] *6.92* (179.34 -199.84)
Biparietal diameter [BPD] (EU$_L$ - EU$_R$)	**105.52** [a] *9.54* (88.53 - 116.19)	**119.80** [a] *8.21* (105.38 - 128.72)	**108.71** *6.48* (93.30 - 117.23)	**111.63** *10.26* (196.22 125.1)	**107.37** [e] 7.83 (88.53 - 117.23)	**116.30** [e] 9.72 (96.22 - 128.72)	**112.66** *11.33* (88.53 - 128.72)	**109.74** *7.83* (93.30 - 125.10)
Ratio: BPD / MaxCL	**0.58** [a] 0.05 (0.46-0.64)	**0.67** [a c] 0.04 (0.61-0.71)	**0.58** 0.03 (0.52-0.65)	**0.59** [c] 0.06 (0.50-0.68)	**0.58** [e] 0.04 (0.47-0.65)	**0.63** [e] 0.07 (0.51-0.71)	**0.63**[f] 0.06 (0.46-0.71)	**0.58**[f] 0.05 (0.51-0.68)
Head circumference*	**519.14** *19.09* (490.00 - 549.00)	**533.38** *31.21* (484.00 -571.00)	**524.11** *11.31* (505.00 -543.00)	**546.00** *9.59* (531.00 556.00)	**521.94** [e] *14.85* (490.00 -449.00)	**538.79** [e] *24.53* (484.00 571.00)	**526.73** *26.40* (484.00 571.00)	**532.87** *15.14* (505.00 556.00)
Ratio: BPD / Head circumference*	**0.20** *0.02* (0.17 -0.22)	**0.23** *0.02* (0.20 - 0.25)	**0.20** *0.01* (0.18 - 0.22)	**0.20** *0.02* (0.18 - 0.23)	**0.20** *0.01* (0.17- 0.22)	**0.22** *0.02* (0.18 - 0.25)	**0.22** *0.02* (0.17 - 0.25)	**0.20** *0.02* (0.18 - 0.23)

The number per group is indicated by n values. The mean values (mm) are indicated in **bold.** The standard deviation is indicated in *italics and* the range is shown within the round (brackets).

a Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African females
b Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African males
c Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the white South Africans
d Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the black South Africans
e Indicates a significant difference in the mean values ($p \leq 0.05$) between South African populations
f Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes

Head circumference and Ratio: BPD / Head circumference could not be performed on 2 black South African males and 1 black South African female

5.1.2.1 Comparisons between populations and sexes

Black South Africans had a statistically significantly smaller cranial height, BPD, head circumference and BPD/MaxCL ratios, but a longer cranial length (MaxCL). Females presented with a smaller cranial height, cranial length and head circumference, but a greater BPD and ratios when compared to males. In the comparison between the sexes, the cranial length was statistically significantly different, as was the BPD/MaxCL ratio. Discrimination function analyses (Figure 35) revealed 94.12% accuracy when predicting population and 88.24% accuracy when predicting sex.

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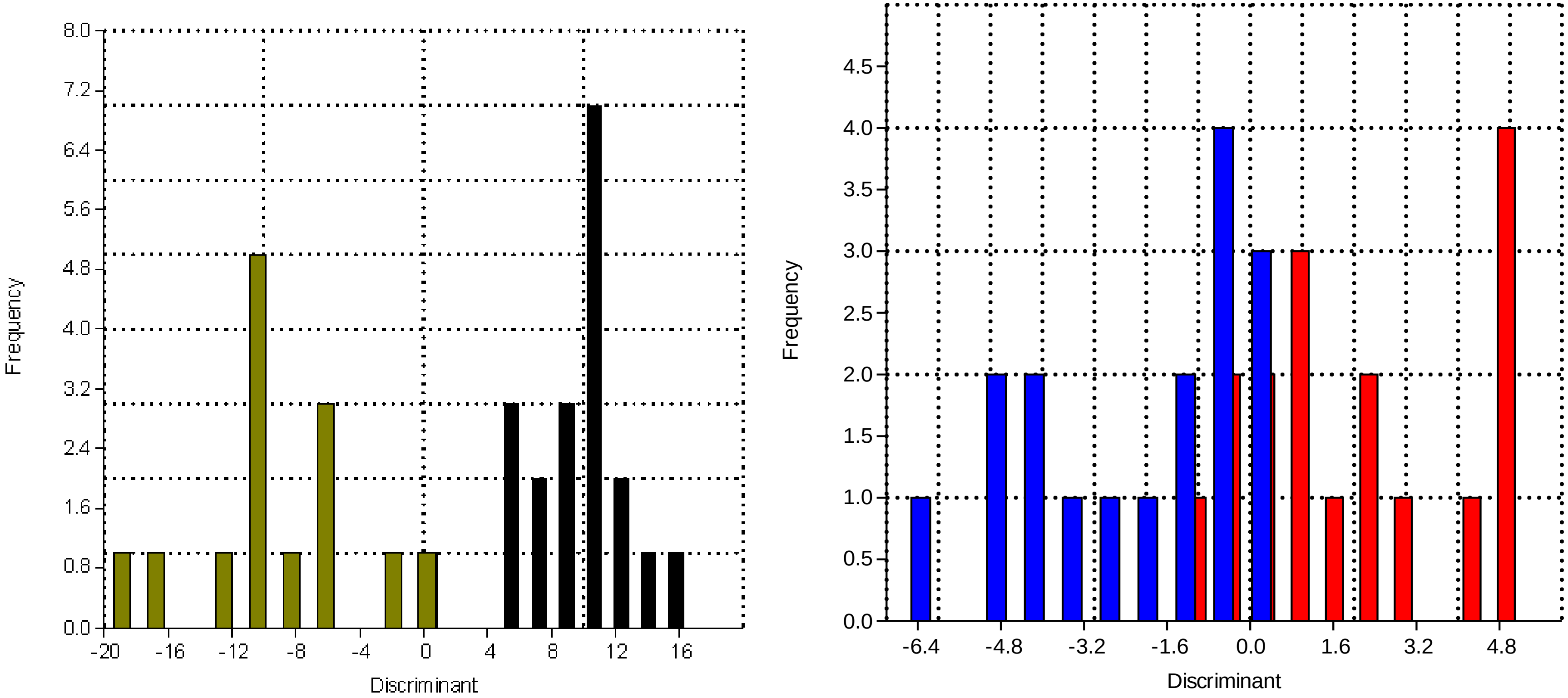


Khaki = White South Africans
Black = Black South Africans

Blue = South African males
Red = South African females

Discriminant function analysis: 94.12% correctly classified

Discriminant function analysis: 88.24% correctly classified

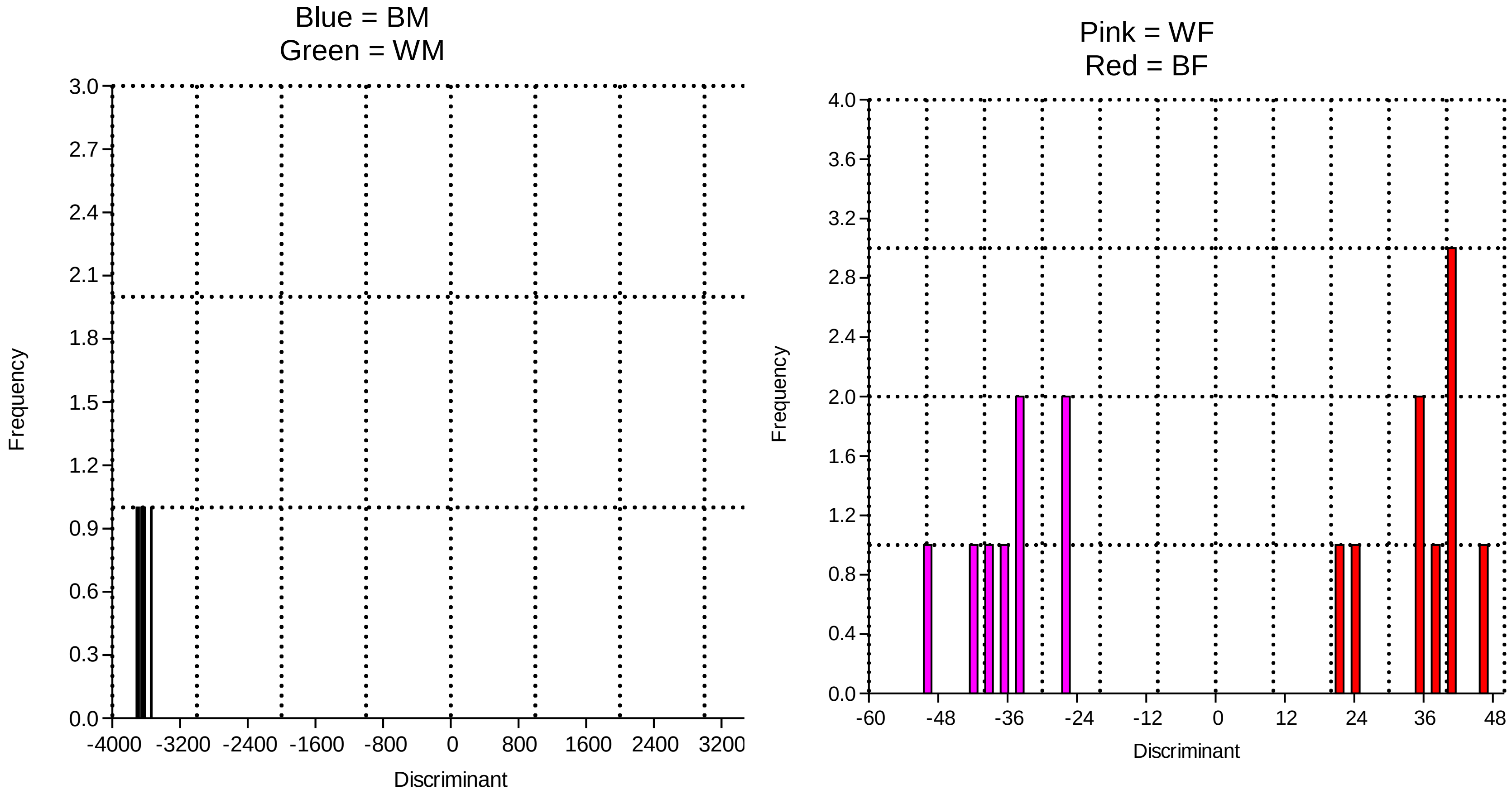
Figure 35. Discriminant function analyses of the linear cranial dimensions between populations and sexes in the cadaveric sample

5.1.2.2 Comparisons between populations within sexes

White South African males presented with larger distances in all cranial dimensions when compared to black South African males, although the BPD/Head circumference ratio was the same. Similarly, white South African females presented with greater distances in all cranial dimensions and ratios when compared to black South African females except for one, which is the greatest cranial length. White South African females presented with a smaller mean MaxCL (178.39 mm) than black South African females (181.27 mm), while the BPD was statistically significantly greater in white (119.80 mm) compared to black South African females (105.52 mm). The different behaviour of these two measurements is reflected in the larger ratios seen in white South African females which was statistically significant for BPD/MaxCL.

The black South African males and females had longer (anteroposterior), narrower (transversely) and smaller (supero-inferior) crania when compared to white South African males and females.

A discrimination function analyses were performed (Figure 36) and separated populations within both the male and females groups with 100% accuracy.



Discriminant function analysis: 100% correctly classified

Discriminant function analysis: 100% correctly classified

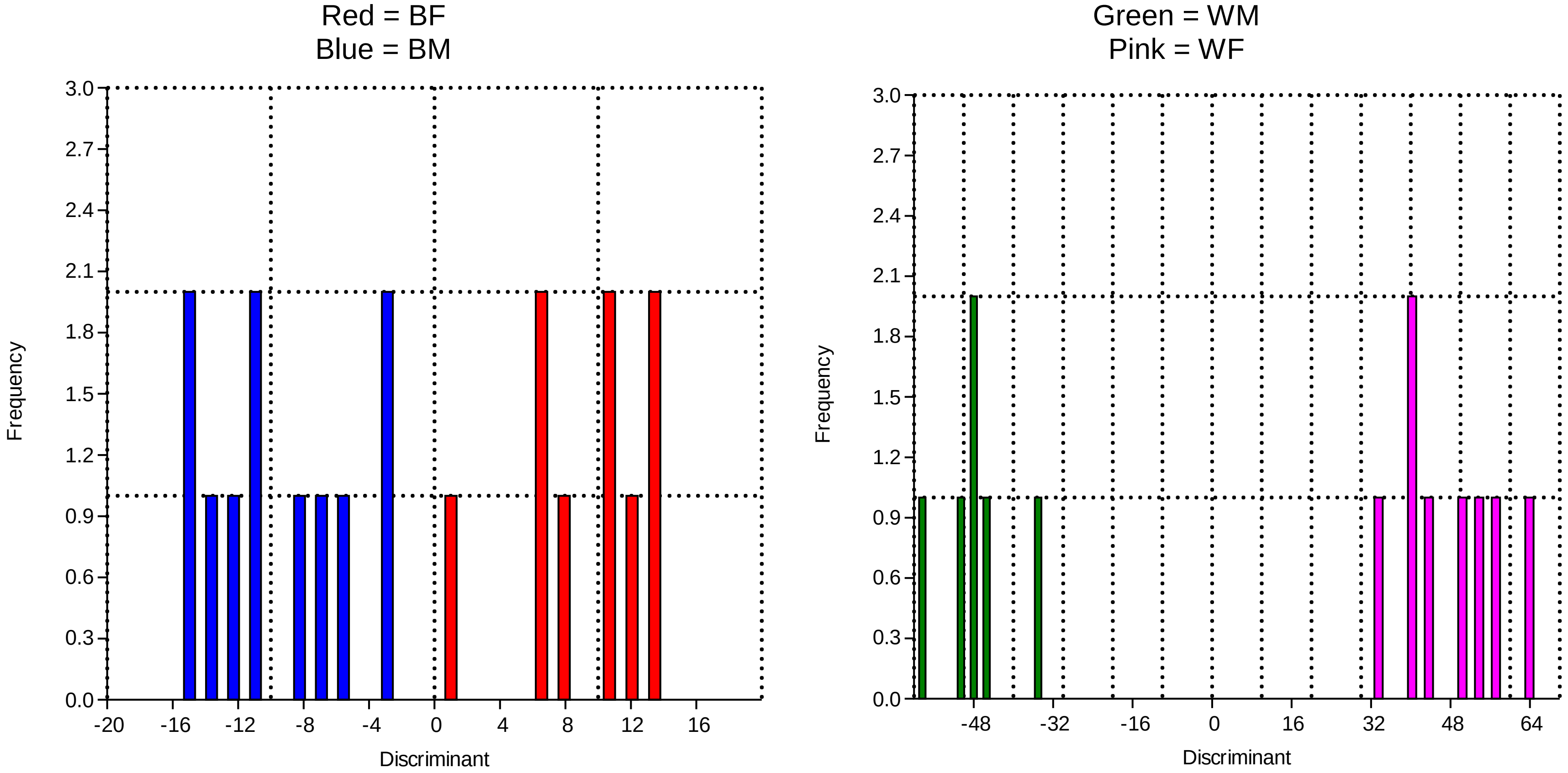
Figure 36. Comparison of linear cranial dimensions between populations within sexes in the cadaveric sample

5.1.2.3 Comparisons between sexes within population groups

Black South Africans males displayed overall non-significantly larger cranial linear dimensions, but similar BPD/MaxCL and BPD/Head circumference ratios when compared to black South African females.

White South Africans males presented with the largest cranial dimensions, except for the BPD, where white South African females (119.80 mm) were larger. White males, however, showed a significantly longer MaxCL when compared to white South African females. A shorter cranial length, paired with a significantly larger BPD in white South African females, suggests a more globular shaped head. This is evident in the significantly larger ratios of BPD/MaxCL noted in white South African females compared to males.

Discrimination function analyses were performed (Figure 37) and separated the sexes within both populations with 100% accuracy.



Discriminant function analysis: 100% correctly classified

Discriminant function analysis: 100% correctly classified

Figure 37. Discriminant function analyses of the linear cranial dimensions between sexes within populations

Summary of sex and population group variations in linear cadaver cranial dimensions

Black South Africans presented with smaller cranial dimensions and BPD/MaxCL (cranial) ratios but a longer cranial length when compared to white South Africans. Females presented with smaller cranial dimensions but greater BPD/MaxCL (cranial) ratios when compared to males. Head circumference and BPD were statistically significantly different between populations, while the cranial length was statistically significantly different between sexes. Prediction of population was more accurate (94.12%) than for sex (88.24%) when considering the entire sample.

White South African males presented with larger distances in all cranial dimensions and BPD/MaxCL (cranial) ratio when compared to black South African males, although the BPD/Head circumference ratio was the same. Similarly, white South African females presented with greater distances in all cranial dimensions and BPD/MaxCL (cranial) ratios when compared to black South African females, except for the greatest cranial length as reflected in the larger BPD/Head circumference ratio and significantly larger BPD/MaxCL seen in white South African females. Black South African males presented with non-significantly larger distances throughout than black South African females, as reflected in the similar BPD/Head circumference ratio observed between the two groups. White South African males presented with the largest cranial dimensions, except for the BPD and the BPD/MaxCL ratio, which were greater in white South African females.

Discrimination function analyses completely (100%) separated sexes within population groups and population groups within sex groups. Black South Africans have longer, narrower and shorter shaped crania when compared to white South Africans, especially white South African females, which presented with a more globular shaped cranium.

5.1.3 Shape analyses for intact pelves

Shape variation of the overall pelvic shape, pelvic inlet, midpelvis and pelvic outlet are presented here as principal component analysis (PCA) scatter plots, where principal component 1 (represented on the X-axis) contributed to the greatest shape difference and principal component 2 (represented on the Y-axis) to the second greatest variation. Statistical significant variations in shape between sexes, population groups and sex-population groups were determined by two group permutation multivariate statistical analysis in the PAST v4.03 software programme on the principal component scores. In addition, discriminant function analyses were performed and a classification accuracy of each comparison given.

5.1.3.1 Overall pelvic shape

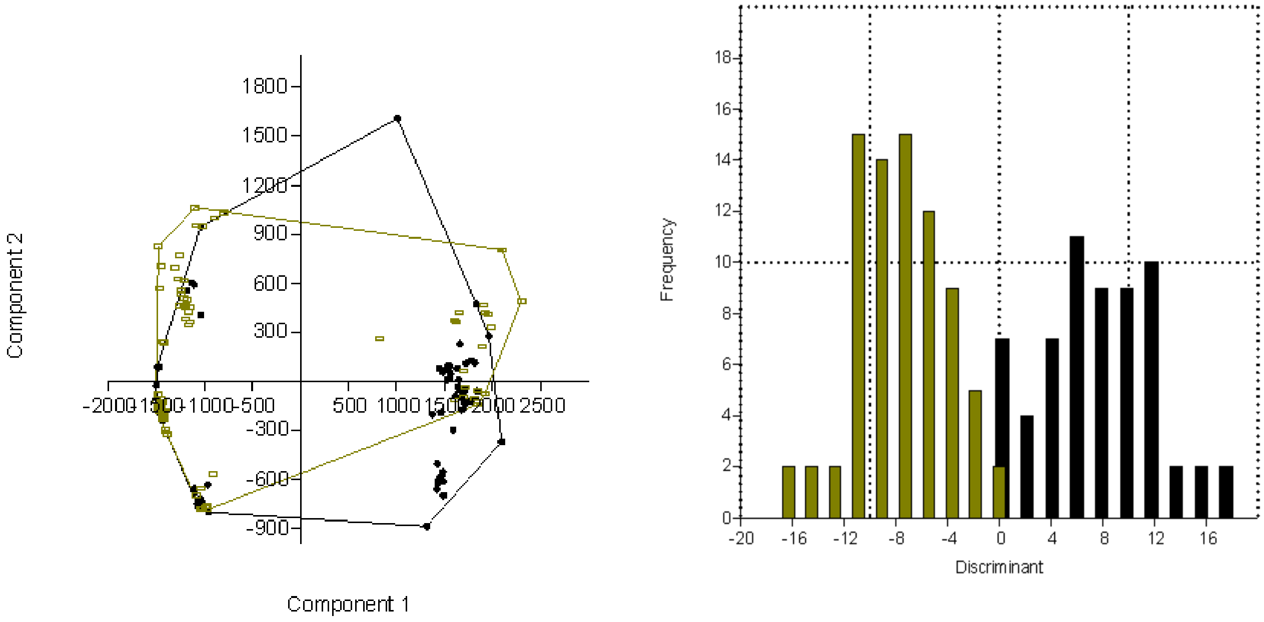
In the analysis of overall pelvic shape, PCA graphs of principal component 1 and 2, p-values, percentages correctly scored by discriminant function analyses, as well as bar charts, are displayed in Figure 42 for the comparison between populations and sexes, and in Figure 39 for the comparison between sexes within each population group.

5.1.3.1.1 Comparison between populations and sexes

Although the groups did not visually clearly separate on the PCA graphs where principal component 1 and 2 were considered, the variations of the overall pelvic shape for the entire sample based on the principal component scores, were statistically significant ($p = 0.0070$ between population groups and $p = 0.0005$ between sexes). The discriminant analysis separated the population groups with a 97.87% accuracy and the sexes with a 94.67% accuracy.

Comparison of the overall pelvic canal shape between populations within the entire sample:

Khaki = White South Africans
Black = Black South Africans

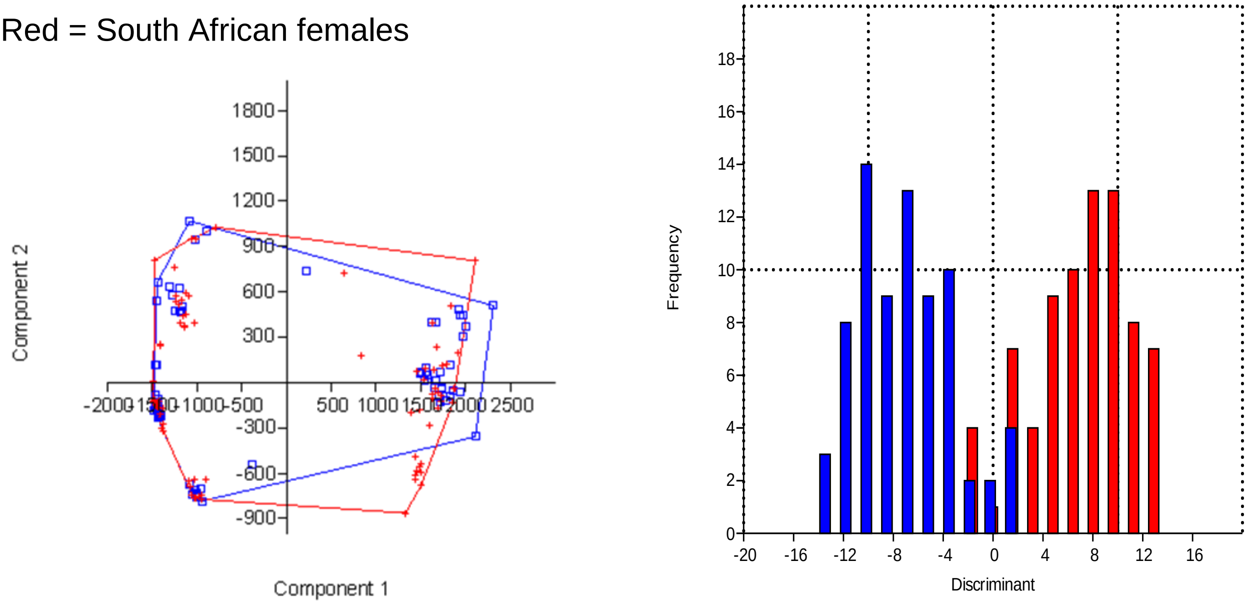


PCA: p = 0.0070

Discriminant function analysis: 97.87% correctly classified

Comparison of the overall pelvic canal shape between sex groups within the entire sample:

Blue = South African males
Red = South African females



PCA: p = 0.0005

Discriminant function analysis: 94.67% correctly classified

Figure 38. Comparison of overall pelvic shape between populations and sexes in the cadaveric sample

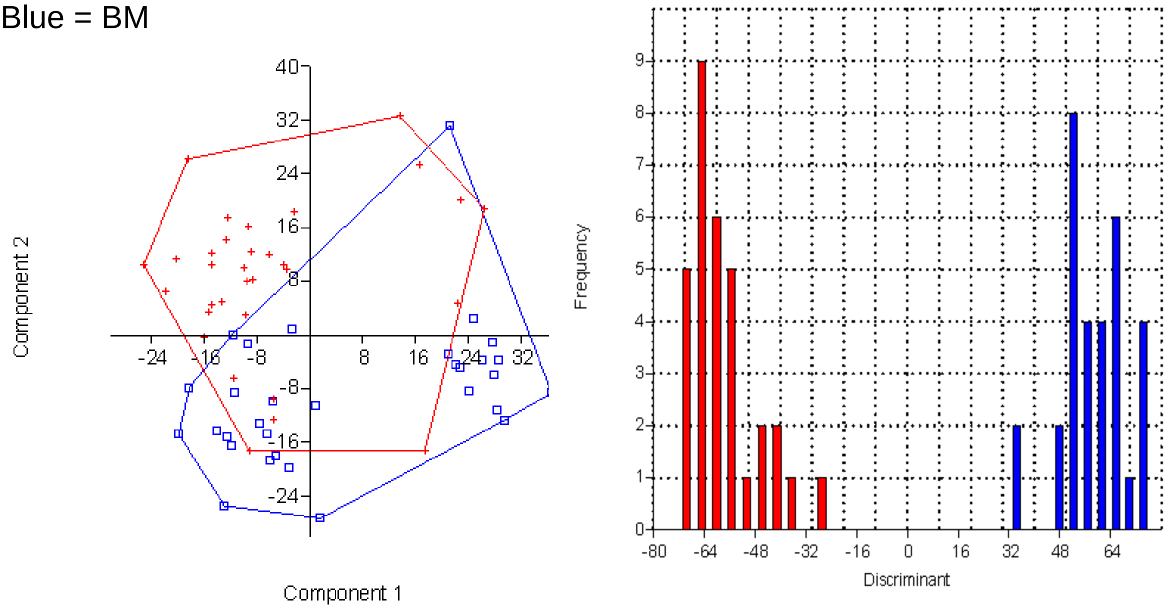
5.1.3.1.2 Comparison between sexes within population groups

The groups showed some separation on the PCA graphs and were statistically significant between the sexes for the overall pelvic shape in each population group. In addition, overall pelvic shape discriminated 100% between the sexes within each population group.

Comparison of the overall pelvic canal shape between black South African males and females:

Red = BF

Blue = BM



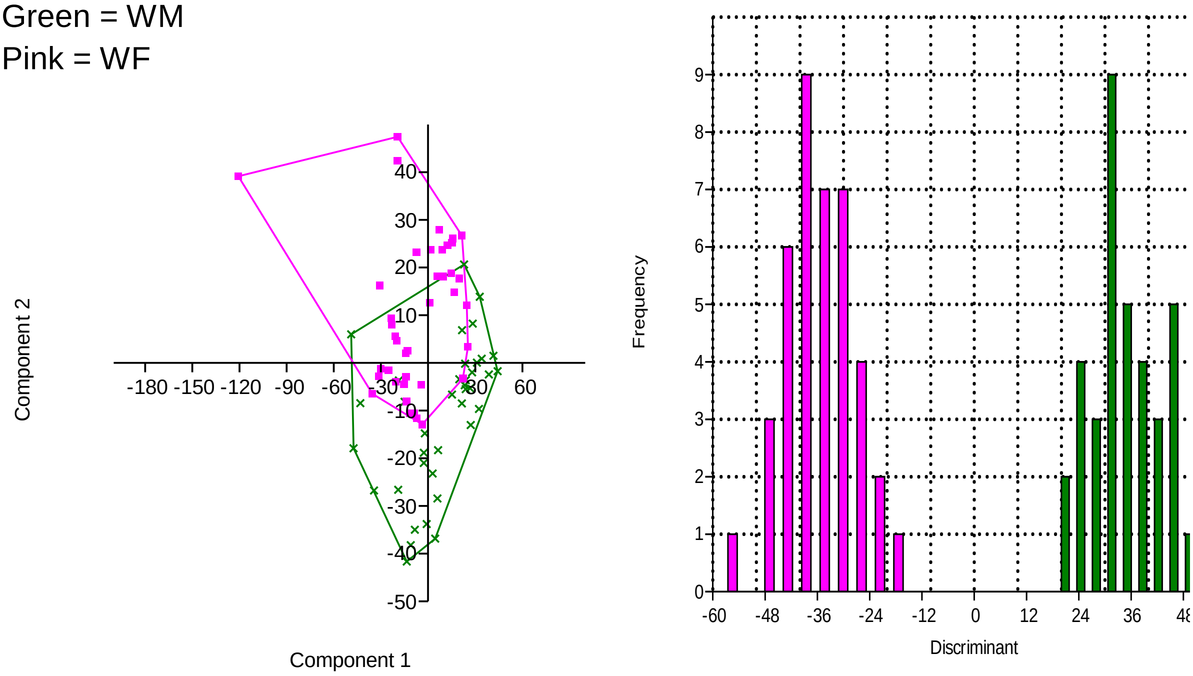
PCA: p = 0.0005

Discriminant function analysis: 100% correctly classified

Comparison of the overall pelvic canal shape between white South African males and females:

Green = WM

Pink = WF



PCA: p = 0.0005

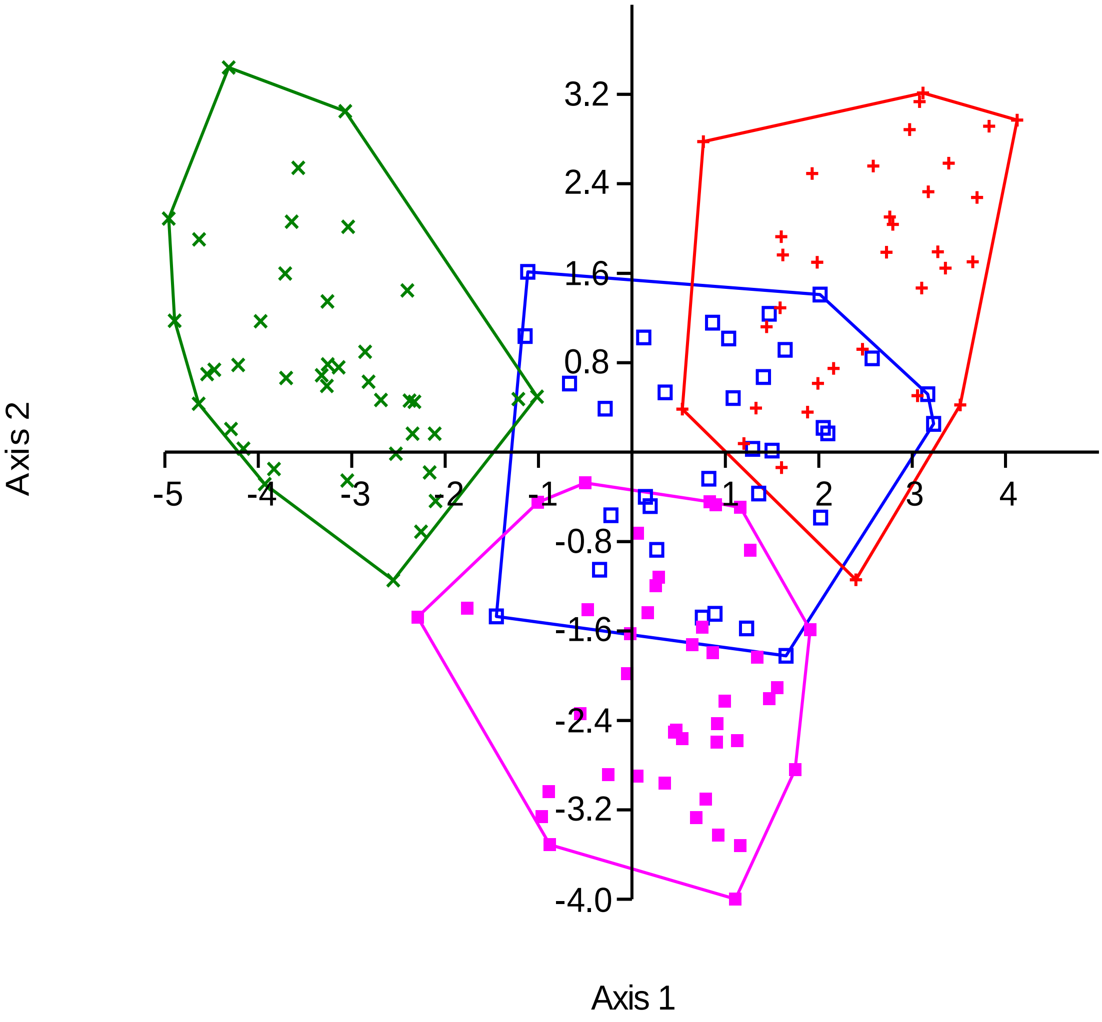
Discriminant function analysis: 100% correctly classified

Figure 39. Comparison of overall pelvic shape dimensions between sexes within populations on the cadaveric sample

5.1.3.1.3 Comparison between sex-populations

Figure 40 displays the graphs of the canonical variate analysis (CVA) with p-values between sex- population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.0000

Figure 40 Comparison of the overall pelvic canal shape between sex-population groups

The relationship between each sex-population group for pelvic shape was not statistically significant (Table 14).

Table 14. MANOVA pairwise comparisons between sex-population groups for the overall pelvic shape

	BM	BF	WM	WF
BM	0	Fail	0.8765	0.9701
BF	Fail	0	0.6084	0.8724
WM	0.8765	0.6084	0	0.3214
WF	0.9701	0.8724	0.3214	0

Significant differences (< 0.05) between groups are indicated in **bold**

In addition, the Mahalanobis distances failed when performing the MANOVA pairwise comparisons between black South African female and black South African male groups for the overall pelvic shape, because of the small number of individuals compared to the number of landmarks. However, as can be noted in the confusion matrix (Table 15), sex-population groups were seldom misclassified (BF: 0/31; WF: 3/45; BM: 2/34; WM: 2/40).

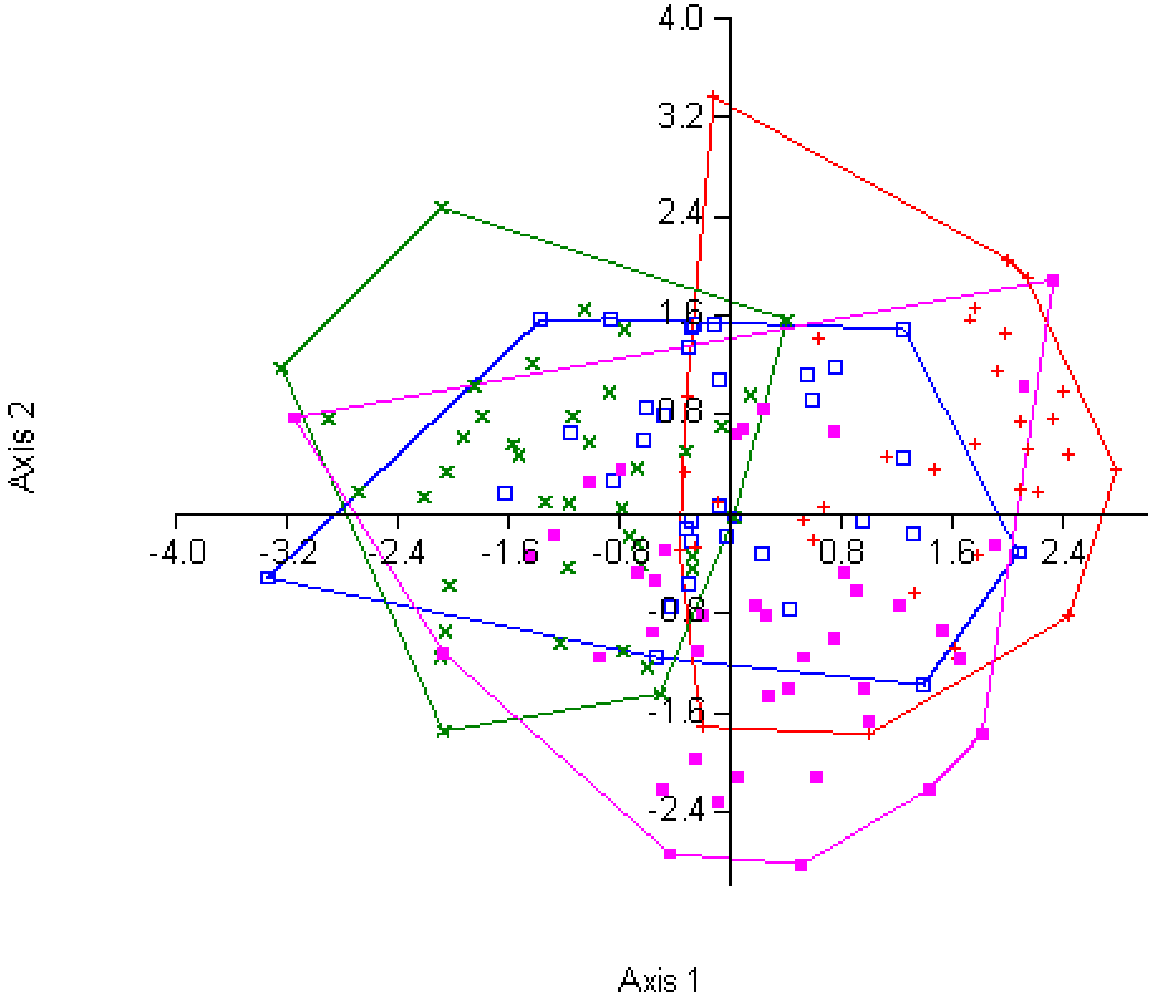
Table 15. Confusion matrix for overall pelvic shape between sex-population groups

Given groups→ Predicted groups↓	BF	WF	BM	WM	Total
BF	31	1	2	0	34
WF	0	42	0	0	42
BM	0	0	32	2	34
WM	0	2	0	38	40
Total	**31**	**45**	**34**	**40**	**150**

5.1.3.2 Pelvic inlet

Figure 41 displays the graphs of the canonical variate analysis (CVA) with p-values in the comparison of sex- population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.0000

Figure 41. Comparison of the pelvic inlet shapes between sex-population groups

Although the populations overlap to a great extent, black South African females tend to represent the extremes on the right half of the graph, while white South African males tend to represent the extremes on the left half of the graph. This separation noted in the CVA graphs between black South African females and white South African males representing the combination of population and sex variations, is also reflected in the significant difference for the pelvic inlet shape noted with pairwise comparisons (Table 16). Black South African females showed a significant difference in the shape of the pelvic inlet when compared to white South African males. These differences are visually represented in Figure 42.

Table 16. MANOVA pairwise comparisons between sex-population groups for pelvic inlet

	BM	**BF**	**WM**	**WF**
BM	0	0.3212	1	0.8429
BF	0.3213	0	**0.0003**	0.2761
WM	1	0.0003	0	0.0678
WF	0.8429	0.2761	0.0678	0

Significant differences (< 0.05) between groups are indicated in **bold**

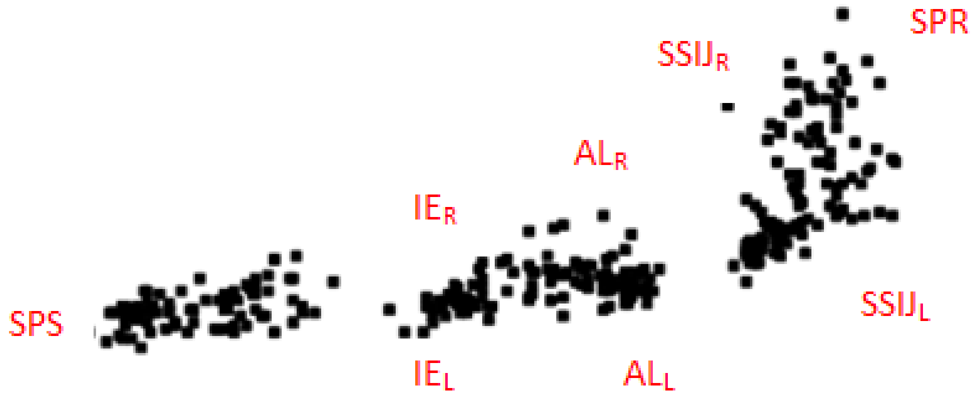
These differences can also be noted in the confusion matrix (Table 17). Black South African females were seldom classified as white South African males (1/37 times) and so were white South African males seldom classified as black South African females (1/40), while other sex-population groups were often misclassified (BF: 13/37; WF: 17/41; BM: 13/33; WM: 11/39).

Table 17. Confusion matrix for pelvic inlet shapes between sex-population groups

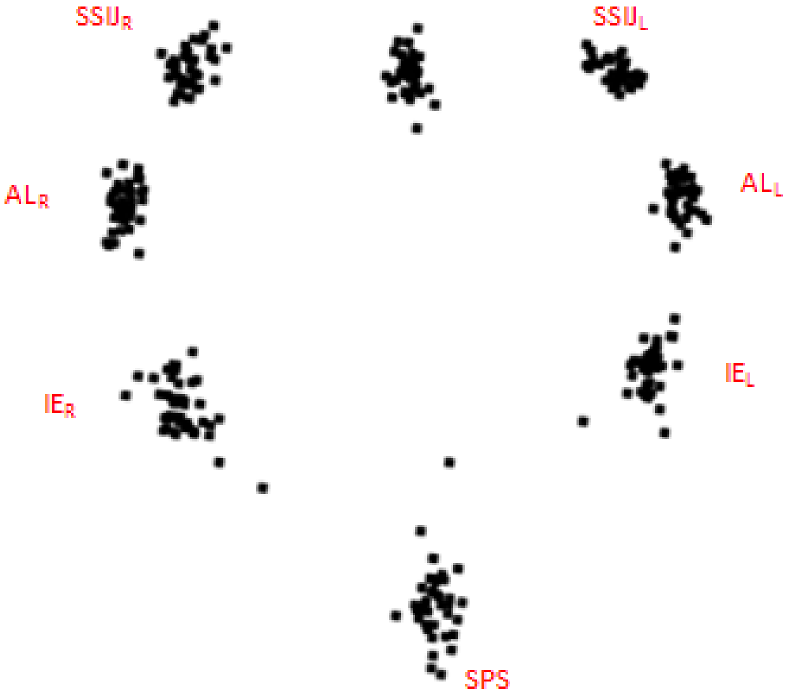
Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	24	5	3	2	34
WF	7	24	5	6	42
BM	5	6	20	3	34
WM	1	6	5	28	40
Total	**37**	**41**	**33**	**39**	**150**

The clustering of the landmarks representing the shape of the pelvic inlet in all individuals is illustrated in Figure 46. Both the lateral and anterior views are shown.

The points used to outline the pelvic inlet are listed in Table 4. Clustering of the pelvic inlet shape 3D points for each sex-population group is represented in Figure 42.



Lateral view



Anterior view

Figure 42. Visual representation of the clustering of the shape of the pelvic inlet in all groups (Table 4)

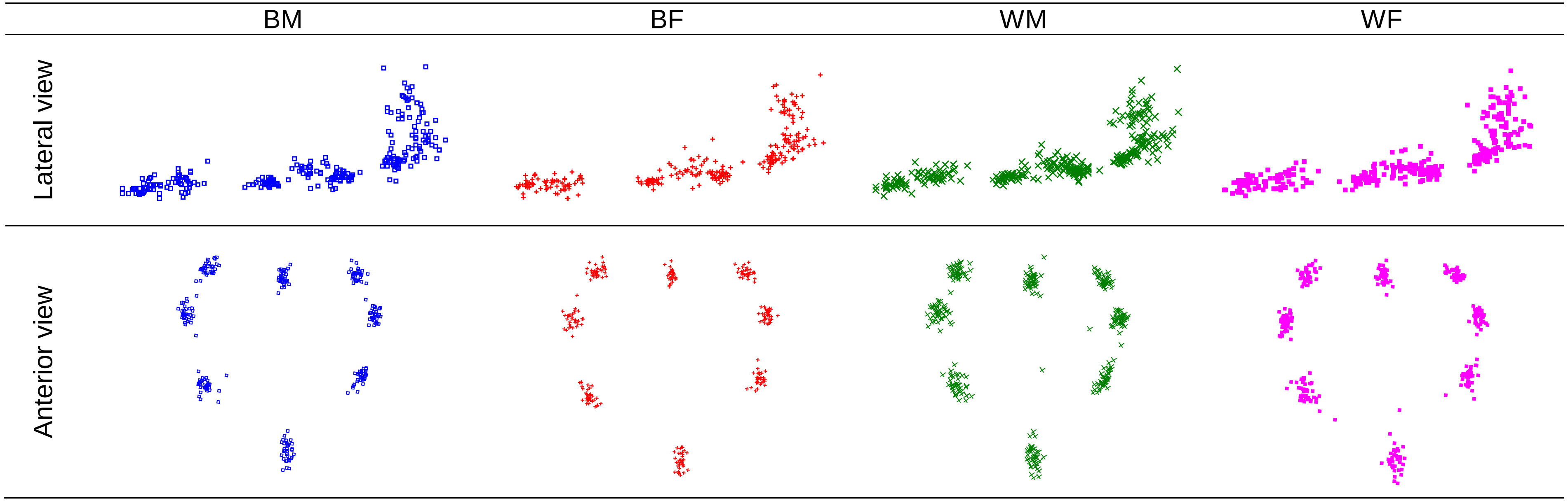


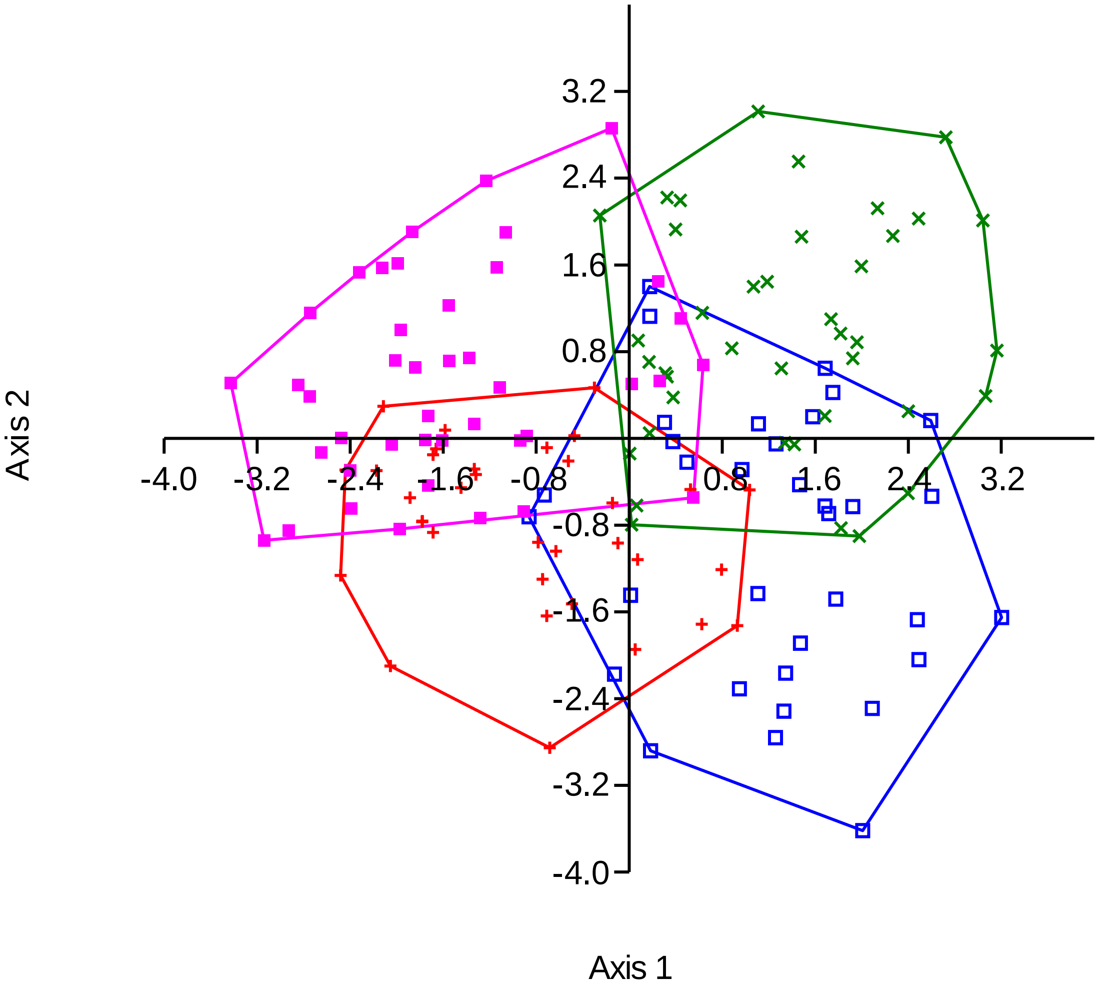
Figure 43. Clustering of pelvic inlet shapes landmarks in the sex-populations groups

From the clustering of pelvic inlet 3D points, the following variations were noted in females compared to males: a more posteriorly located midpoint on the sacral promontory with the WTI diameter situated relatively more anteriorly than in males. The noted variations were accentuated in white South African females. Transversely narrower pelvic inlets with the greatest transverse diameter at a more posterior position possibly denoting a relatively smaller anterior pelvis in males in general, but especially in black South African males, as compared to white South African males. These variations between sex-population groups could also be described and supports the notion of a more rounded pelvic inlet in females and a heart-shaped pelvic inlet in males

5.1.3.3 Midpelvis

Figure 44 displays the graphs of the canonical variate analysis (CVA) along with p values when comparing sex- population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.0001

Figure 44. Comparison of the midpelvic shape between sex-population groups

The groups showed some separation on the CVA graphs as reflected in the significant difference noted for the midpelvic shape in all sex-population group pairwise comparisons, except for black South African females compared to white South African females (Table 18). The shape of the midpelvis in black South African males showed a statistically significant difference when compared to all groups. White South African males showed a statistically significant difference when compared to females of both populations.

Table 18. MANOVA pairwise comparisons between sex-population groups for the midpelvis

	BM	**BF**	**WM**	**WF**
BM	0	**0.0193**	**0.0290**	**< 0.0001**
BF	0.0193	0	**0.0002**	0.0927
WM	0.0290	0.0002	0	**< 0.0001**
WF	< 0.0001	0.0927	< 0.0001	0

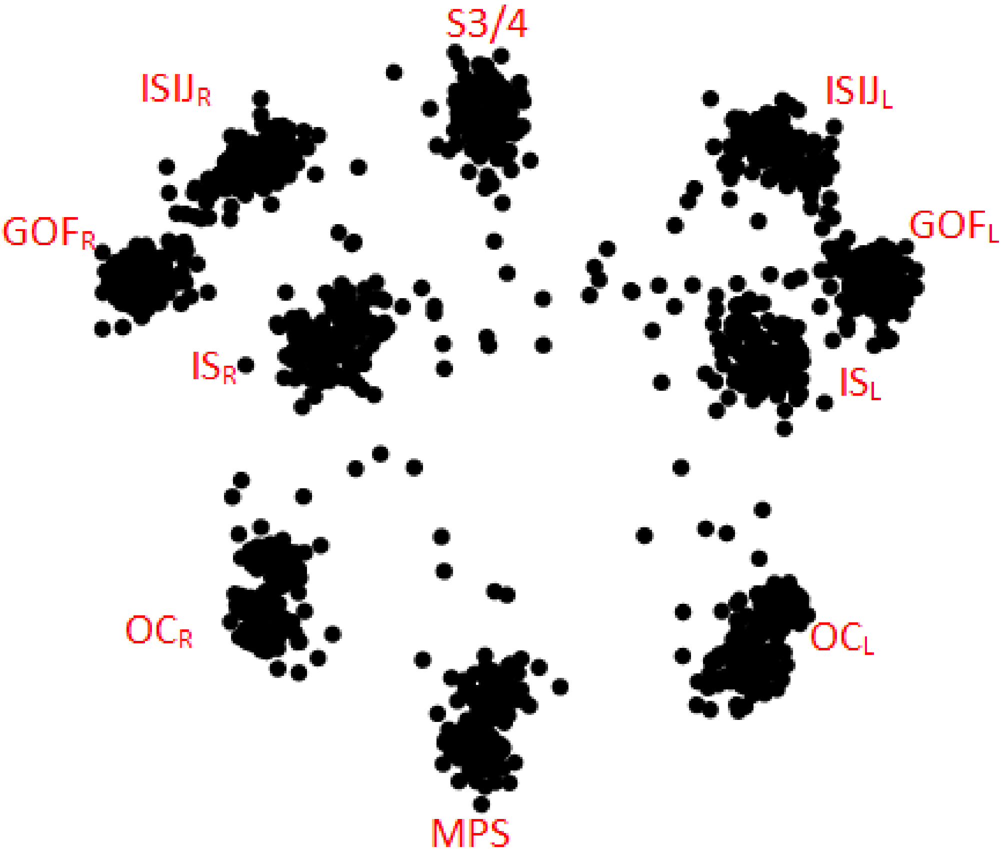
Significant differences (< 0.05) between groups are indicated in **bold**

These differences are also reflected in the confusion matrix (Table 19). Sex-population groups were often correctly classified (BF: 26/34; WF: 33/43; BM: 25/33; WM: 31/40).

Table 19. Confusion matrix for the midpelvic shapes between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	26	5	3	0	34
WF	4	33	1	5	43
BM	3	1	25	4	33
WM	4	1	4	31	40
Total	**37**	**40**	**33**	**40**	**150**

The average shape of the midpelvis is visually represented by 3D points taken as illustrated in Figure 45. The superior view is shown. The points used to outline the midpelvis are listed in Table 5. Clustering of the midpelvic shape for each sex-population group is represented in Figure 46.



Superior view

Figure 45. Visual representation of the clustering of the shape of the midpelvis in all individuals (Table 5)

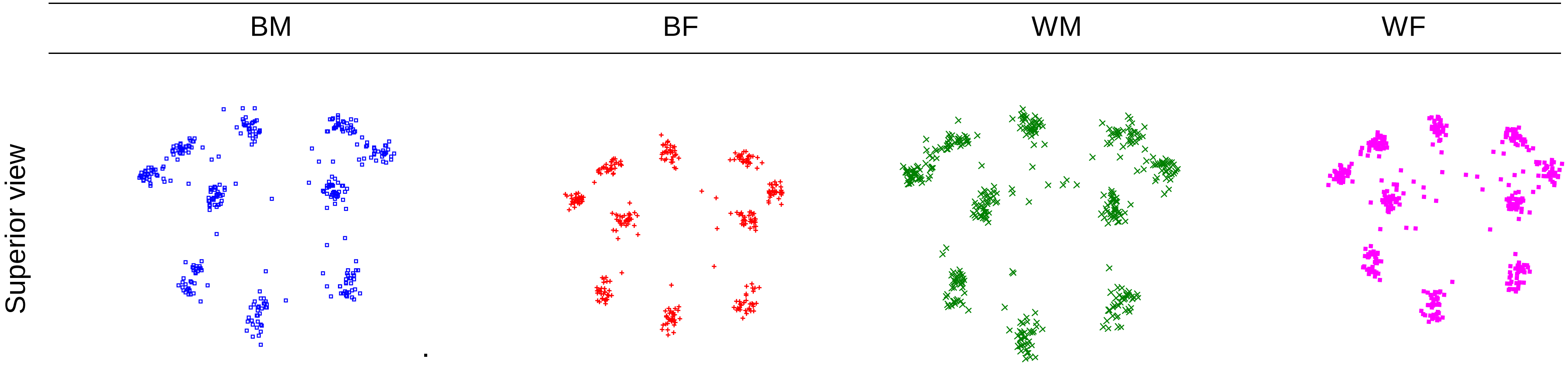


Figure 46. Clustering of midpelvic landmarks in the sex-populations groups

The midpelvic shapes of both population groups showed a great variation of the posterior aspect of the midpelvic shape. The posterior aspect reflects the degree of concavity of the sacrum. A more prominent sacral hollow and a relatively more spacious posterior aspect between the sacral notch and the sacro-iliac joint were noted in females, as compared to males, especially black South African males. Males further also presented with a narrower transverse shape than females due to the bilaterally encroaching ischial spines.

The anterior part of the pelvis in males demonstrated a more acute angulation at the posterior part of the symphysis pubis, as if it was encroaching into the pelvic cavity anteriorly. Females presented with a less angulated appearance anteriorly.

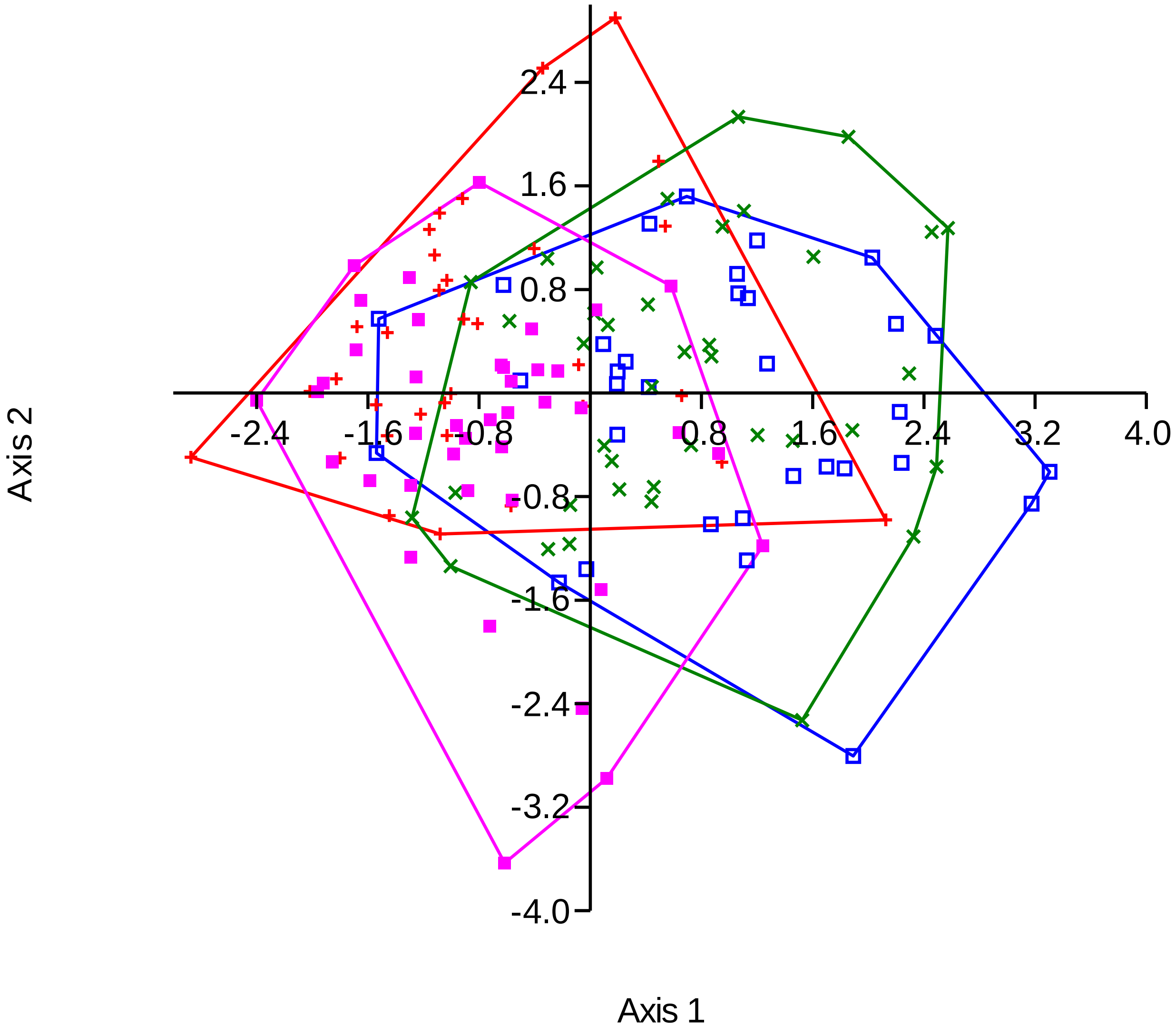
White South African females, however, often presented with wider midpelvic shapes than black South African females, which could partly be responsible for the associated wider angle noted in the anterior portion of the midpelvic shape. The anterior aspect of the midpelvis of the white South African female also appeared to be greater than that of the black South African female.

In summary, a relatively wider midpelvis, a more prominent sacral hollow, a flatter inner aspect of the pubic symphysis and a relatively greater space in the 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 white South African females and accumulatively contribute to a relatively even wider appearance of the midpelvic shape as compared to the narrower midpelvic shape of males.

5.1.3.4 Pelvic outlet

Figure 47 displays the graphs of the canonical variate analysis (CVA). Although the groups showed almost no separation on the CVA graphs, a statistically significantly variation was noted ($p = 0.0002$). The black South African male and white South African male groups seemed to differ the least.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.0002

Figure 47. Comparison of the pelvic outlet shape between sex-population groups

MANOVA pairwise comparisons for the pelvic outlet shape between each sex-population group were highly significantly different (Table 20).

Table 20. MANOVA pairwise comparisons between sex-population groups for the pelvic outlet

0	**BM**	**BF**	**WM**	**WF**
BM	0	**< 0.0001**	**0.0088**	**< 0.0001**
BF	< 0.0001	0	**< 0.0001**	**< 0.0001**
WM	0.0088	< 0.0001	0	**< 0.0001**
WF	< 0.0001	< 0.0001	< 0.0001	0

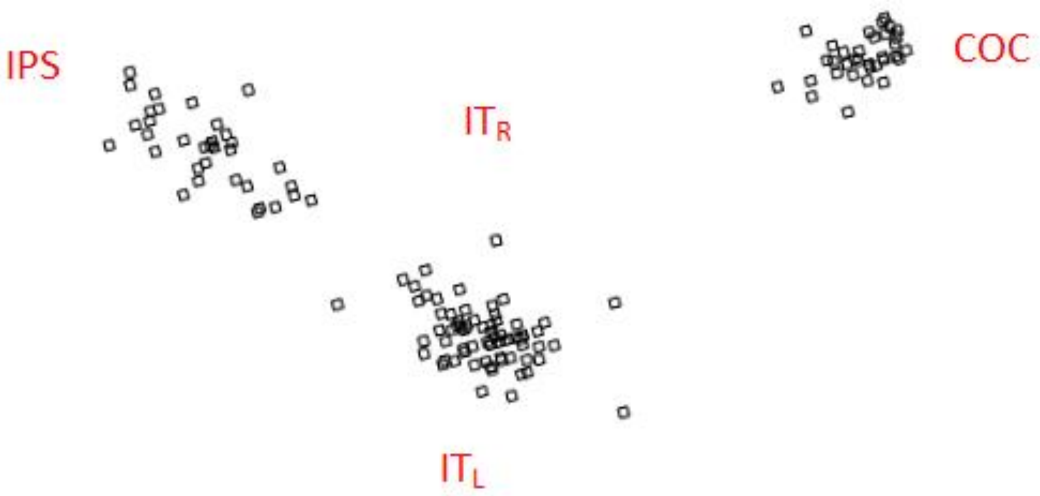
Significant differences (< 0.05) between groups are indicated in **bold**

This overlap in shape of especially males is reflected in the confusion matrix, where black South African males were often classified as white South African males (8/34) and white South African males as black South African males (7/40) (Table 21). Correct classifications for each sex-population group were: BF: 29/34, WF: 33/42, BM: 23/34 and WM: 23/40..

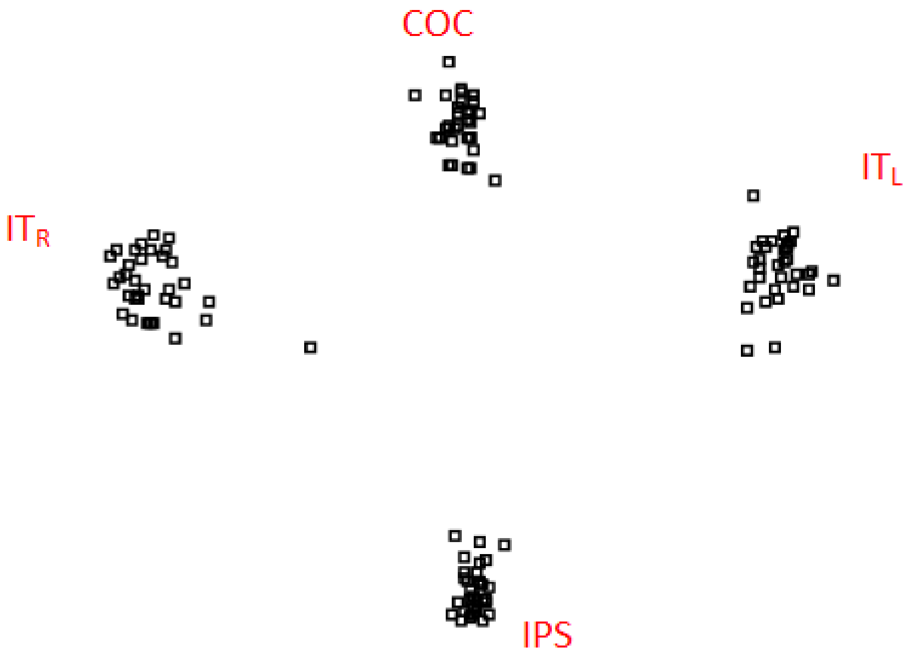
Table 21. Confusion matrix for the pelvic outlet shapes between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	29	2	0	3	34
WF	4	33	2	3	42
BM	0	3	23	8	34
WM	3	7	7	23	40
Total	**36**	**45**	**32**	**37**	**150**

The shape of the pelvic outlet is visually represented by 3D points taken and is illustrated in Figure 48. Both lateral and superior views are shown. The points which outline the pelvic outlet taken are listed in Table 6. Clustering of the pelvic outlet shapes for each sex-population group is represented in Figure 49.



Lateral view



Inferior view

Figure 48. Visual representation of the clustering of the shape of the pelvic outlet in all individuals (Table 6)

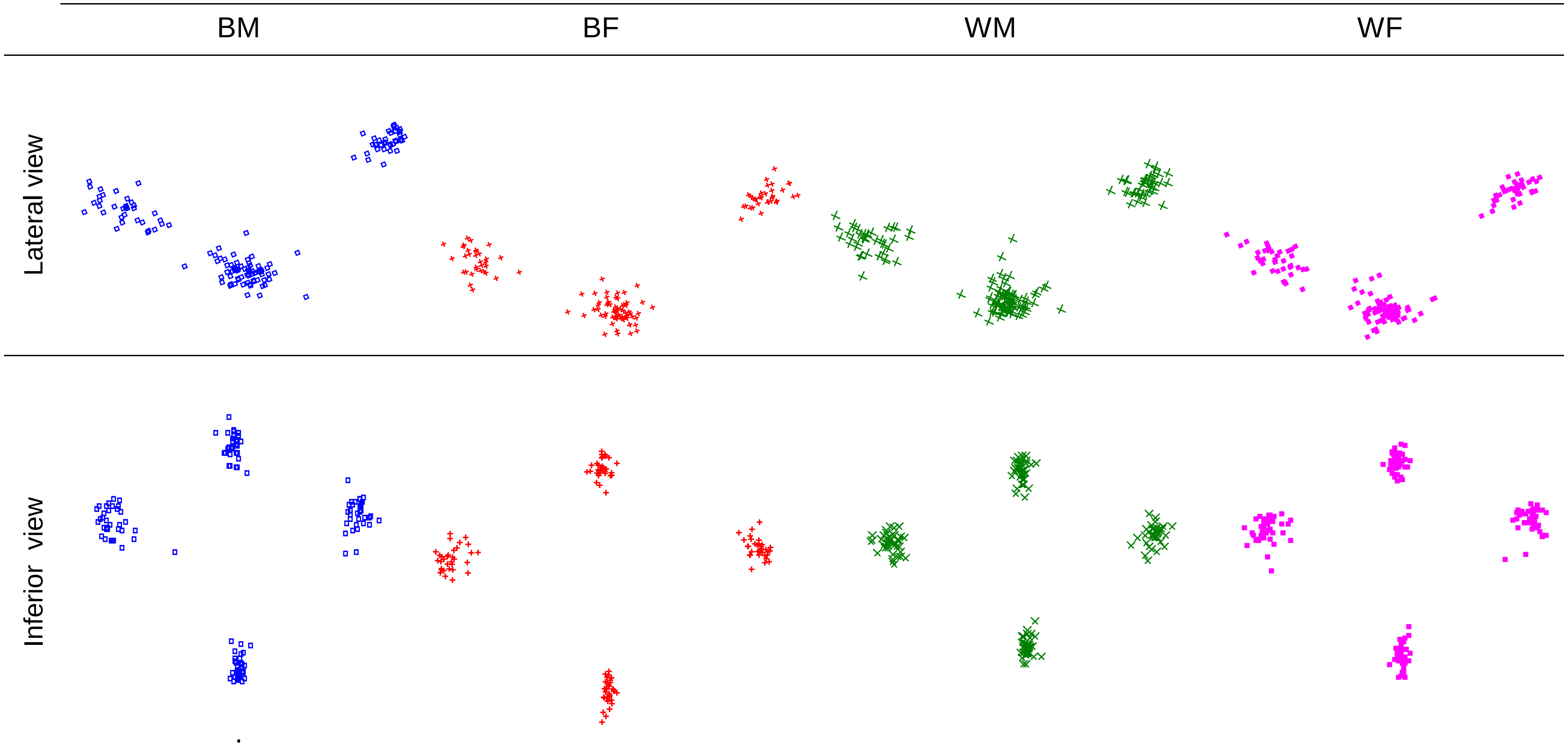


Figure 49. Clustering of pelvic outlet landmarks in the sex-populations groups

From a lateral view, black South African females presented with a relatively further distance from the pubic symphysis to the ischial tuberosity as compared to white females. From the lateral view, the coccyx was directed more posteriorly and downwards than other groups. White South African females, compared to other groups, presented with a generally wider shape and a relatively more anteriorly placed widest diameter, meaning that the IT is placed relatively more anteriorly. Females, in general, had a shorter distance from the pubic symphysis to the ischial tuberosity, with the angle directed more vertically. White South African males presented with an almost symmetrical diamond shape on inferior view, as reflected in the size of the urogenital triangle, approximating that of the anal triangle. Black South African males presented with a relatively more inferiorly placed ischial tuberosity, as noted on the lateral view.

In summary, the greatest transverse outlet diameter is relatively wider and located more anteriorly in females than males. White South Africans of both sexes presented with relatively wider pelvic outlet shapes than black South Africans. The greatest transverse outlet diameter appears to be situated more posteriorly in white South African males, compared to black South African males, who presented with a more inferiorly placed ischial tuberosity.

Summary of sex and population variations in the shape analysis of intact cadaver pelves:

Sex and populations in the complete sample, as well as for the population and sex groups, separately, were highly statistically significant. The discriminant analysis were 97.87% accurate for population groups and 94.67% accurate for the sexes for the complete sample and improved to 100% accuracy between sexes and populations when considering, respectively, populations and sexes separately. When considering each sex-population individually, groups separated on the CVA graphs and were seldom misclassified but were not significantly different for the overall pelvic shape.

Significant differences for the pelvic inlet shape were noted with CVA and with pairwise comparisons between black South African females and white South African males, representing the extremes between population and sex group. Females, especially white South African females, presented with more posteriorly located midpoints on the sacral promontory with the WTI diameter situated relatively more anteriorly than in males (round vs. heart shaped inlets). The heart shaped pelvic inlet in males presented with transversely narrower pelvic inlets, with the greatest transverse diameter at a more posterior position, possibly denoting a relatively smaller anterior pelvis in males, especially in black South African males.

A significant difference was noted for the midpelvic shape between black South African females and black South African males, black South African females and white South African males and between black South African males and white South African males, but not between black South African females compared to white South African females. A more prominent sacral hollow and a relatively more spacious posterior aspect between the sacral notch and the sacro-iliac joint, wider placed ischial spines and a wider angle between the symphysis pubis and the obturator canal were noted in females as compared to males, especially black South African males.

For the pelvic outlet, all sex-population comparisons were highly statistically significant although some misclassification between black South African males and white South African males were present. From an inferior view, black South African females presented with a relatively further distance from pubic symphysis to ischial tuberosity, as compared to white South African females. From the lateral view, the coccyx was directed more posteriorly and downwards than in other groups. White South African females presented with a generally wider shape and a relatively more anteriorly placed widest diameter. Females, in general, had a shorter distance from pubic symphysis to ischial tuberosity directed more vertically. White South African males presented with an almost symmetrical diamond shape on inferior view, as reflected in the size of the urogenital triangle approximating the anal triangle. Black South African males presented with a relatively more inferiorly placed ischial tuberosity, as noted on lateral the view.

5.1.4 Shape analyses for crania

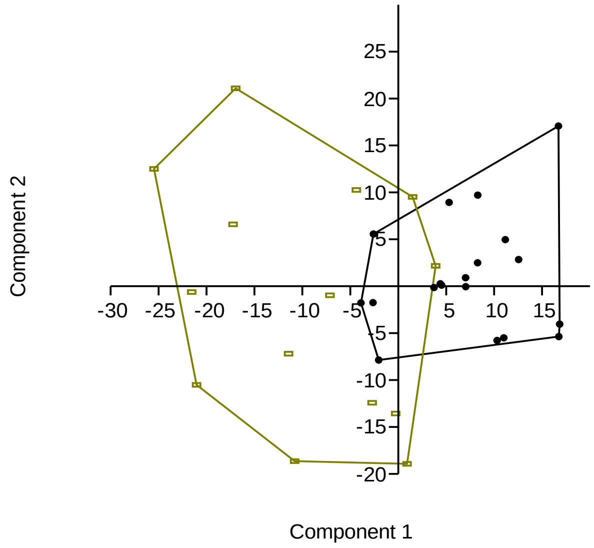
The overall shape of the cranium was analysed by standard geometric morphometric methods and discriminant function analysis to visualise the pattern of intra and inter-group variations and to test for statistical significance.

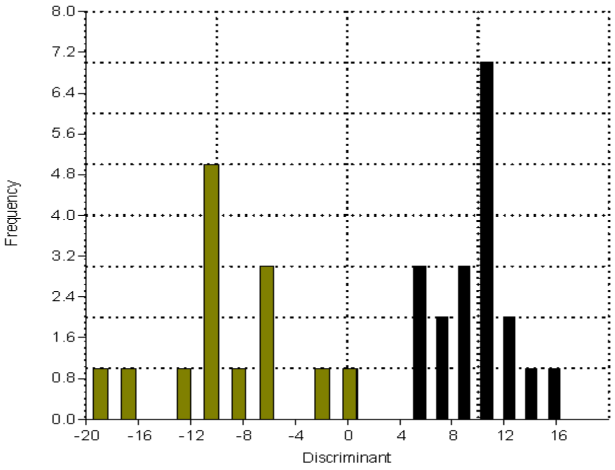
5.1.4.1 Comparison between populations and sexes

Figure 50 displays the graphs of the principal component analysis (PCA) with p-values, as well as the discriminant analysis with classification accuracy of each comparison within the entire sample, as indicated. There was a distinct separation of the population groups on the PCA graphs, while the sexes did not visually clearly separate. The variations of the overall cranial shape between the populations were highly statistically significant with a discriminant analysis separation of 94.12% accuracy. The variations between the sexes were not significant, but discriminant analysis separated the sexes with 100% accuracy.

Comparison of the overall cranial shape between populations within the entire sample:

Khaki = South African Whites
Black = South African Blacks



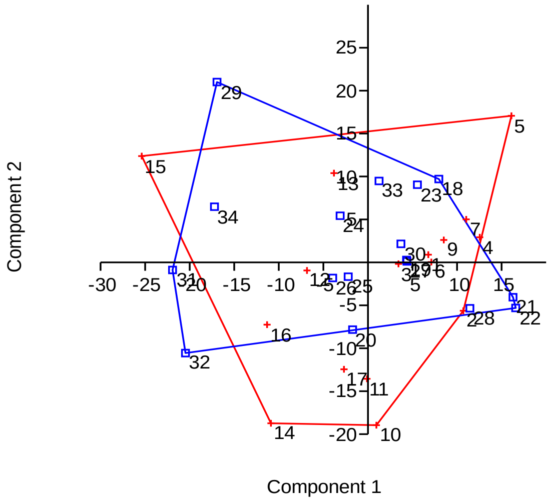


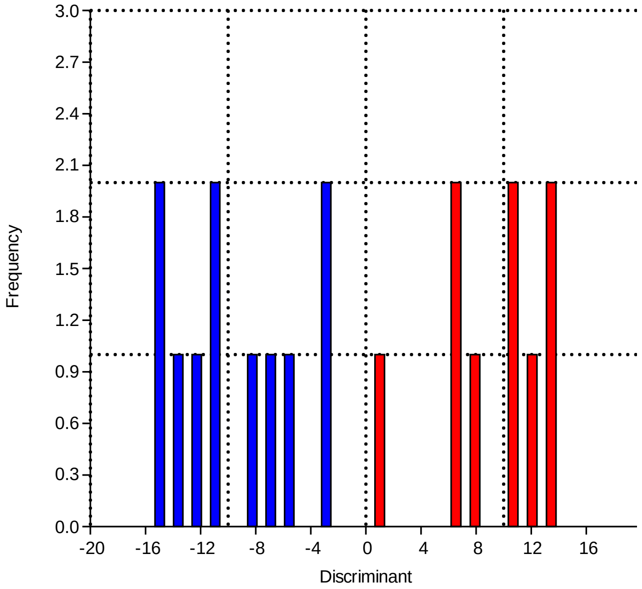
PCA: p = 0.0005

Discriminant function analysis: 94.12% correctly classified

Comparison of the overall cranial shape between sex groups within the entire sample:

Blue = South African males
Red = South African females



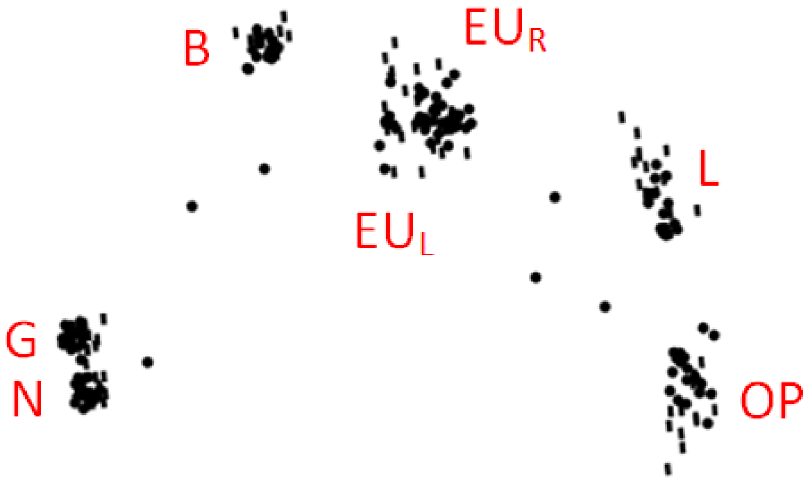


PCA: p = 0.2005

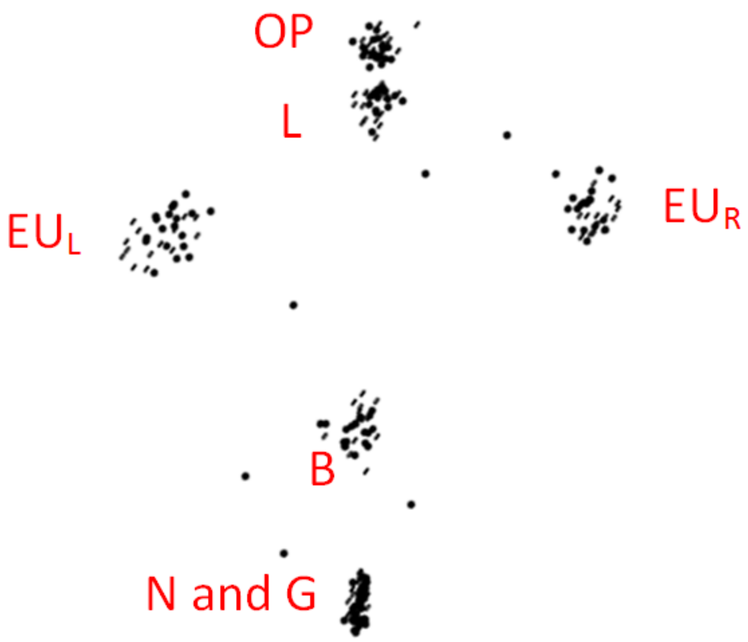
Discriminant function analysis: 100% correctly classified

Figure 50. Comparison of the cranial shape dimensions between populations and between sexes on a cadaveric sample

Visual representation of the clustering of the landmarks representing the cranial shape in all individuals is illustrated in Figure 51, and in Figure 52, landmarks are colour-coded to indicate the comparison between sexes and populations, respectively. Both lateral and superior views are shown. The points used to outline the cranial shape are listed in Table 7.



Lateral view



Superior view

Figure 51. Visual representation of the clustering of the landmarks representing cranial shape in all individuals (Table 7)

Khaki = South african Whites
Black = South African Blacks
Blue = South African males
Red = South African females

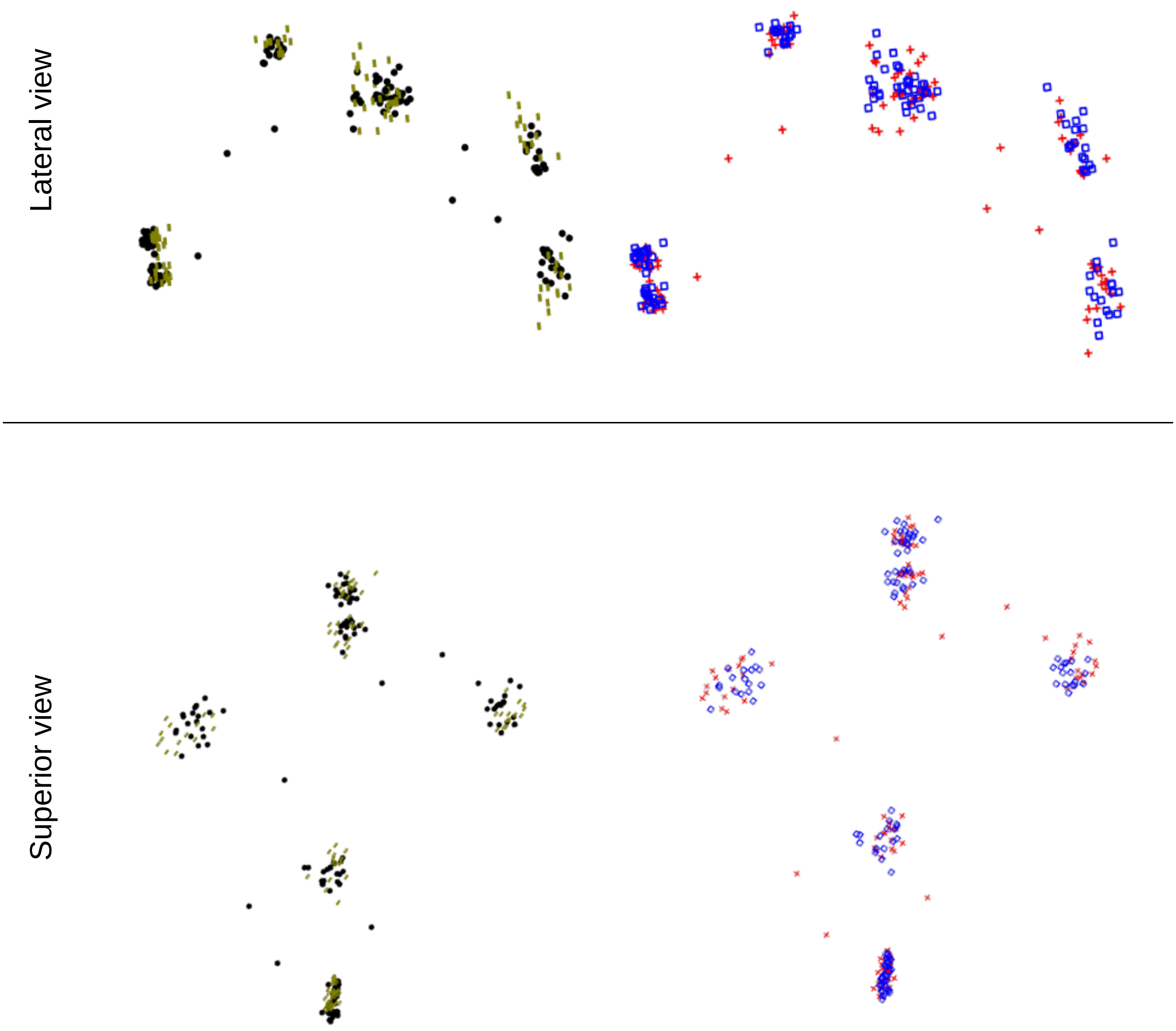


Figure 52. Comparison of the overall cranial shape between populations and sexes

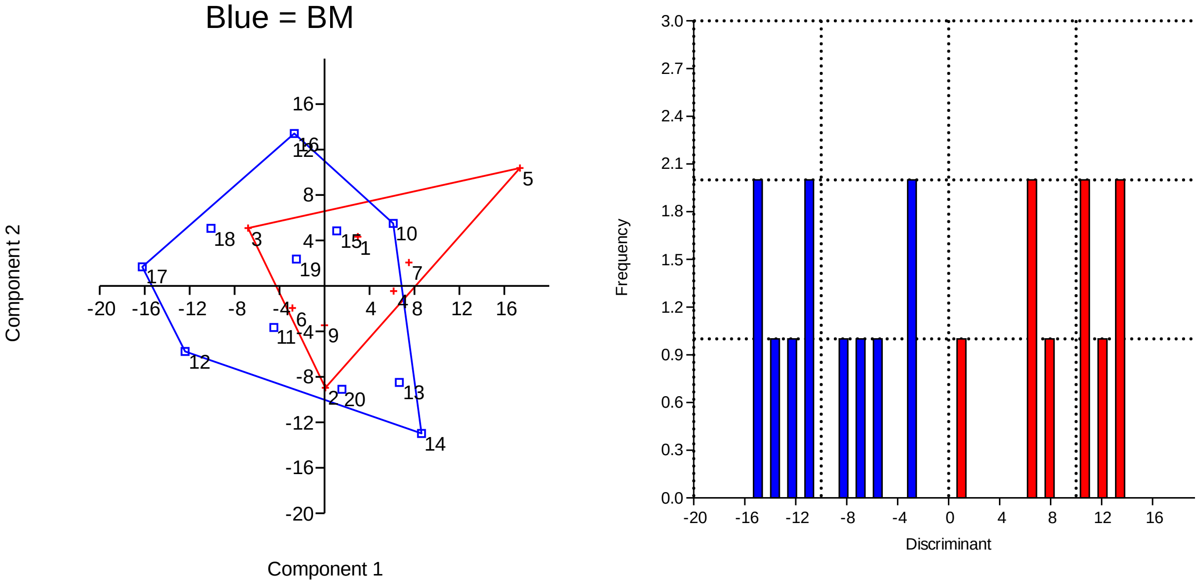
Figure 52 indicates that the nasion and glabella were placed more posterior while the bregma, euryon and lambda landmarks were placed higher, whereas the opisthocranion, lower and more anterior in white South Africans than in black South Africans, creating a relatively higher but shorter cranium. The white South African population group also presented with a wider cranium with euryons placed further apart. From a lateral view, males presented with a longer cranial height and length when compared to females, while the females presented with a relatively wider cranium.

5.1.4.2 Comparison between sexes within population groups

Figure 53 displays the graphs of the principal component analysis (PCA) and the discriminant analysis with classification accuracy of each comparison between sexes within each population group as indicated. For both PCA's Mahalanobis distance failed when performing the two group permutation tests because of the small number of individuals compared to the number of landmarks. The groups showed some separation on the PCA graphs and were highly significant between the sexes for the overall cranial shape in each population group. In addition a discrimination of 100% was noted between the sexes within each population group.

Comparison of the cranial shape between black South African males and females:

Red = BF
Blue = BM

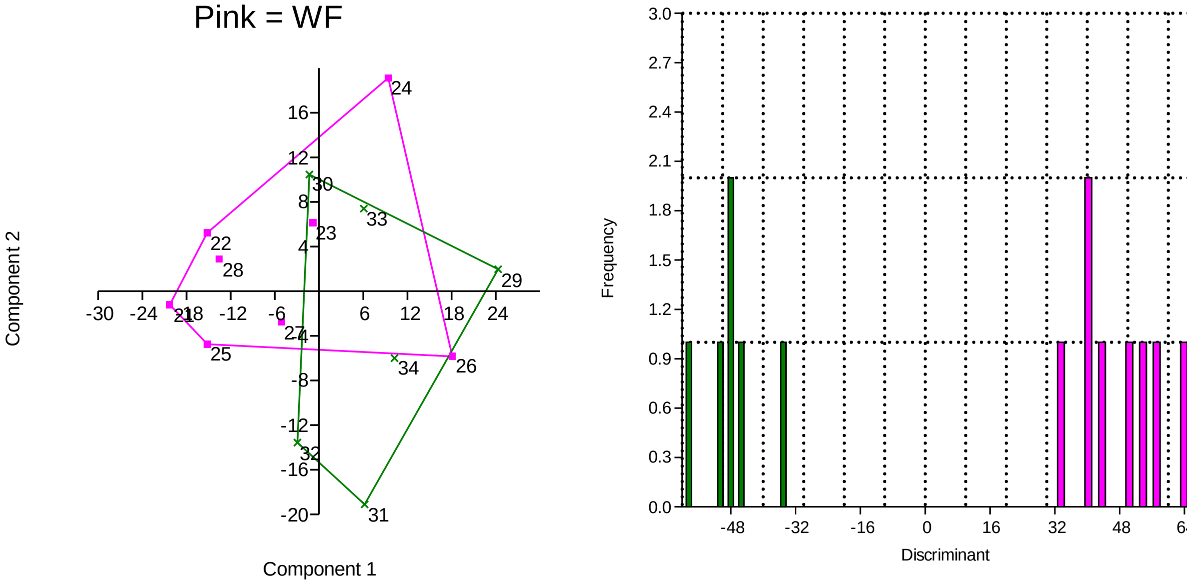


PCA: p = 0.0005

Discriminant function analysis: 100% correctly classified

Comparison of the cranial shape between white South African males and females:

Green = WM
Pink = WF



PCA: p = 0.0005

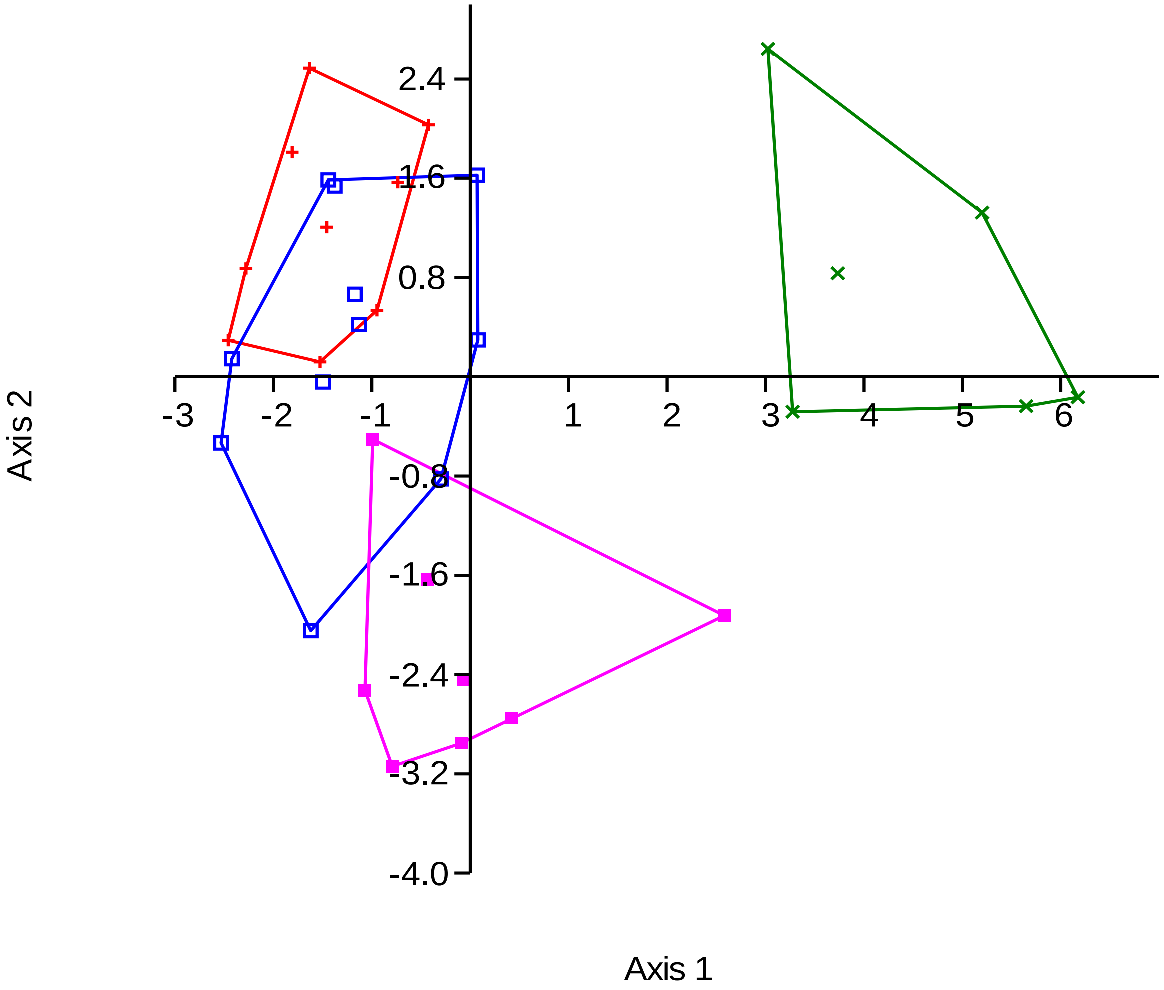
Discriminant function analysis: 100% correctly classified

Figure 53. Comparison of cranial shape dimensions between sexes within populations on the cadaveric sample

5.1.4.3 Comparison between sex-population groups

Figure 54 displays the graphs of the canonical variate analysis (CVA) with p values between sex- population groups as indicated. The groups showed complete separation on the CVA from the White South African males group.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.000

Figure 54. Comparison of the cranial shape between sex-population groups

The overall cranial shape did not differ significantly between each sex- population group with pairwise comparisons (Table 22).

Table 22 .MANOVA pairwise comparisons between sex-population groups for the cranial shape

0	**BM**	**BF**	**WM**	**WF**
BM	0	0.6128	0.4212	0.4267
BF	0.6128	0	0.3755	0.1546
WM	0.4212	0.3755	0	0.7435
WF	0.4267	0.4267	0.7435	0

Significant differences (< 0.05) between groups are indicated in **bold**

However, as can be noted in the confusion matrix (Table 23), sex-population groups were seldom misclassified (BF: 2/11; WF: 0/8; BM: 0/9; WM: 0/6)

Table 23. Confusion matrix for overall cranial shape between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	9	0	0	0	9
WF	0	8	0	0	8
BM	2	0	9	0	11
WM	0	0	0	6	6
Total	**11**	**8**	**9**	**6**	**34**

Clustering of cranial landmarks in the sex-populations groups can be noted in Figure 55. It is evident that black South African males presented with a relatively narrower cranium as compared to its width, while the widest distance across the cranium was placed more posteriorly in black South Africans than in white South Africans. White South African females presented with a more globular cranial shape.

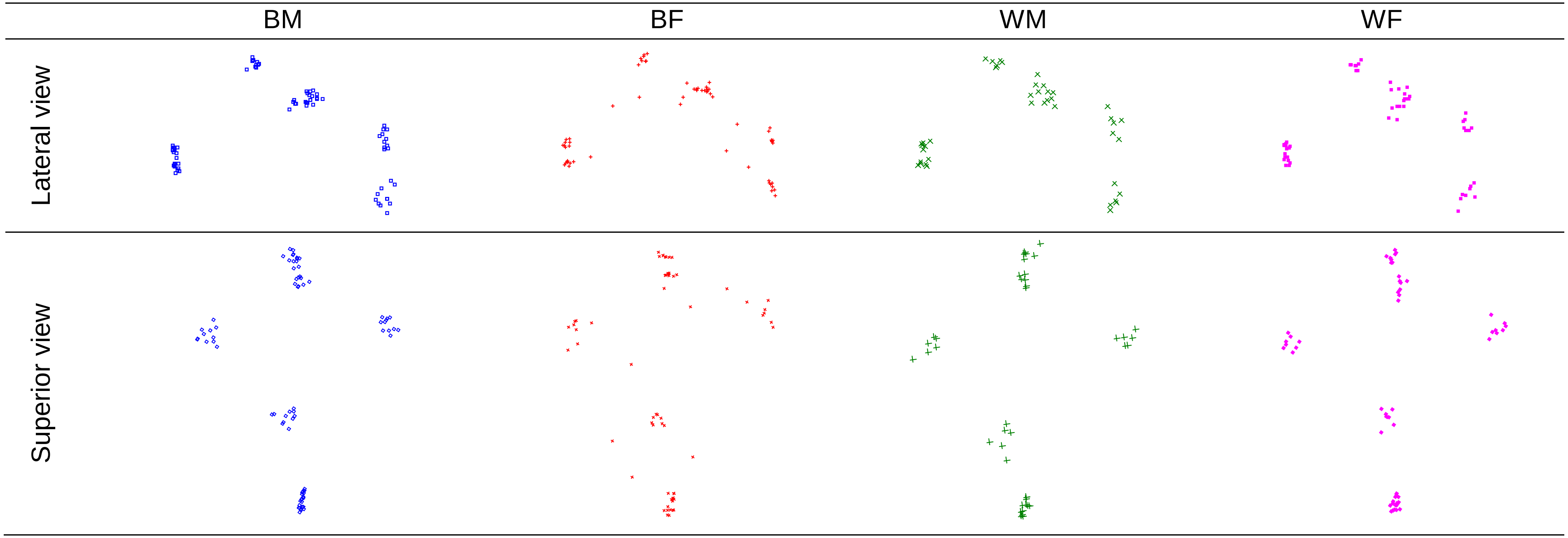


Figure 55. Clustering of cranial landmarks in the sex-populations groups

Summary of sex and population variations in the shape analysis of cadaver crania:
The variations of the overall cranial shape between the populations were highly statistically significant with a discriminant analysis of 94.12% accuracy. South African whites have a relatively higher and wider but shorter cranium. The variations between the sexes were not significant in the complete sample. However, within the population groups in isolation with a 100% discriminant accuracy. Females presented with a relatively wider cranium.

CVA was statistically significant between sex- populations and separated white South African males from the other groups. Cranial shape, however, did not differ significantly between each sex- population group with pairwise comparisons, but from the confusion matrix, sex-population groups were seldom misclassified. Black South African males presented with a relatively narrower cranium as compared to its width, while the widest distance across the cranium was placed more posteriorly in black South Africans than in white South Africans. White South African females presented with a more globular cranial shape.

5.1.5 Correlation between cranial and pelvic data

5.1.5.1 Linear cranial dimensions vs linear pelvic dimensions

Least square regressions were performed for pelvic and cranial linear dimensions to demonstrate a relationship in each sex-population group. The correlation coefficient (r) and the coefficient of determination (r^2) may range from -1 for a perfect negative relationship to +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 shape. The main purpose of finding a relationship is that the knowledge of the relationship may enable events to the predicted to a specified degree.

All linear cranial and pelvic dimensions in each sex-population group, population and sexes, were correlated by means of ordinary least squares regressions. Moderate to strong positive or negative correlation ($r \geq 0.5$) and/or significant p-values ($p < 0.05$) are reported in Table 24.

Table 24. Correlations between linear cranial dimensions and linear pelvic dimensions

	Pelvic inlet			**Midpelvis**		**Pelvic outlet**		
Linear pelvic dimensions→ Linear cranial dimensions ↓	**TC**	**Widest transverse distance**	**Diagonal conjugate**	**Obstetric conjugate**	**Interspinous diameter**	**Anteroposterior distance**	**Intertuberous distance**	Subpubic angle
Cranial height	**0.56**	**0.52** **0.57**	**0.70**	**0.51** **0.53**	**0.67** **0.55**	**0.69** **0.55** **0.60***		
MaxCL	**0.62**			**0.58**	**0.83***		**0.67**	**0.71**
Biparietal diameter	**0.64***		**0.57***	**0.66***			**0.63***	
Head circumference	**0.83*** **0.77*** **0.80** **0.64*** **0.72***	**0.68***	**0.67** **0.70** **0.54*** **0.69***	**0.82*** **0.69*** **0.63** **0.62*** **0.61***	**-0.58** **0.57**	**0.74** **0.70***	**0.73** **0.60*** **0.60***	**0.75** **0.53*** **0.49**
BPD/ Head circumference	**-0.60**			**-0.72**	**-0.64**			

BF, WF, BM, WM, Black South Africans, White South African, South African males, South African females
r values are indicated in **bold**
p > 0.05 is indicated with *

When interpreting the r- and p-values as presented in Table 24, certain patterns were noted in each sex, population or sex-population group. In females, as a group, moderate and statistically significantly positive relationships existed between the BPD and head circumference on the one hand, and the TC, DC, OC and the intertuberous distance on the other hand. In addition, in females, head circumference had a moderate but not significant relationship with the subpubic angle.

In black South African females, the cranial height and length had a moderate correlation with the TC and OC. Head circumference in black South African females had a strong statistically significant relationship with the TC, a moderate correlation with the DC and a strong statistically significant relationship with the OC. In white South African females, the cranial height had a moderately positive not significant correlation with the WTI and DC of the pelvic inlet, as well as the OC, IS and anteroposterior distance of the pelvic outlet. White South African females had a moderately negative not significant correlation with the BPD/Head circumference ratio on the one hand, and the TC and OC, as well as the IS on the other hand.

In males as a group, head circumference was moderately and statistically significantly correlated to all pelvic dimensions, apart from the interspinous distance. The only correlation noted in black South African males was the moderate negative but not statistical significant correlation between the head circumference and the interspinous distance. White South African males had a strong correlation, but not statistically significant, between head circumference and all pelvic dimensions, apart from the WTI distance and DC of the pelvic inlet. In addition, cranial height in white South African males was moderately but not significantly correlated with IS and anteroposterior distance of the pelvic outlet, while the cranial length was moderately but not significantly correlated with the IS, intertuberous distance and the subpubic angle.

In white South Africans as a group, the cranial height was moderately and statistically significantly related to the anteroposterior distance of the pelvic outlet. There were no correlations between linear cranial and pelvic dimensions in black South Africans as a group.

5.1.5.2 Linear cranial dimensions vs. pelvic shapes

All cranial and pelvic dimensions between each sex-population group, population and sexes were correlated by means of ordinary least squares regressions. Only r-values that showed a moderate to strong positive or negative correlation (r≥0.5) and significant p-values ($p < 0.05$) were reported in Table 25.

Table 25. Correlations between pelvic shape and cranial linear dimensions

Pelvic shap → Linear cranial dimensions↓	Overall pelvic shape	Pelvic inlet	Midpelvis	Pelvic outlet
Cranial height		**0.60** **-0.56**	**0.77*** **0.54***	**0.58** **0.68**
MaxCL		**0.72***	**-0.51**	**0.52*** **0.63**
Biparietal diameter	**-0.68**		**-0.51*** **-0.53**	
Head circumference		**0.70** **0.70** **0.46***	**-0.64** **0.66**	**0.63*** **0.75*** **0.62** **0.48**
BPD/ Head circumference	**-0.64**		**0.53**	

BF, WF, BM, WM, Black South Africans, White South Africans, South African Males, South African females
r values are indicated in bold
p > 0.05 is indicated with *

When understanding the r- and p-values as presented in Table 25, certain trends were noted in each sex, population or sex-population group. In females, as a group, strong and mild positive relationships were noted between the head circumference and the pelvic inlet and outlet shapes, respectively.

In the black South African female group, the cranial height and head circumference each had a moderate to strong positive correlation to the shape of the pelvic inlet and the pelvic outlet; with the head circumference showing a significant relationship to the pelvic outlet. The cranial length showed a strong positive statistically significant relationship to the shape of the pelvic inlet and a moderate relationship to the pelvic outlet. A moderate negative not significant relationship was observed in white females between the shape of the midpelvis and the cranial length and BPD. A positive moderate correlation was noted between the head circumference and the midpelvic shape. The cranial height showed a moderate negative relationship to the shape of the pelvic inlet.

In males, as group, mild positive statistically significant correlation existed between the head circumference and the pelvic inlet shape, and the cranial height and the midpelvic shape. The shape of the midpelvis displayed a strong positive significant correlation to the cranial height and a mild positive correlation to the BPD/Head circumference in black South African males. Furthermore, the head circumference was moderately correlated to the midpelvis and pelvic outlet, negatively and positively, respectively.

The BPD and BPD/Head circumference in white South African males was moderately negatively correlated to the overall pelvic shape. The cranial height showed a moderate positive correlation to the pelvic outlet shape.

As a group, white South Africans showed a mild negative not significant relationship between the BPD and the midpelvis only, while black South Africans showed statistically significant moderate positive correlations between the cranial length and head circumference to the pelvic outlet.

5.1.5.3 Shape of crania vs. shape of pelvis

Lastly the shape of the cranium versus the shape of the pelvis was correlated by two block partial least squares analysis and the squared covariance percentage recorded (Table 26).

Table 26. Summary of two block partial least squares analysis between cranial shape and overall pelvic shape recording squared covariance percentage

Pelvic shape dimensions→ Cranial shape ↓	**Overall pelvic shape**	**Pelvic inlet**	**Midpelvis**	**Pelvic outlet**
BF	**35.33** *36.74*	**40.35** *29.73*	**42.51** *33.57*	**28.74**[e] *24.60*[f]
WF	**88.71** *54.81*	**82.32** *53.02*	**83.49** *50.73*	**80.01** *59.83*
BM	**38.76** *31.46*	**34.44** *25.96*	**38.32** *31.83*	**34.09** *28.84*
WM	**29.29** *39.23*	**38.87** *31.39*	**54.22** *37.14*	**57.84** *36.01*
South African Blacks	**28.23** *24.96*	**27.66** *20.60*	**29.35** *23.71*	**24.74** *20.39*
South African Whites	**55.02** *36.74*	**43.56** *31.67*	**54.24** *36.57*	**54.03** *38.19*
South African males	**39.84** *28.94*	**36.63** *27.40*	**38.01** *28.43*	**33.83** *27.77*
South African females	**35.91** *32.77*	**33.85**[a] *29.51*[b]	**36.20**[c] *28.20*[d]	**29.81** *23.63*

The variance- covariance matrix (VC) is indicated in **bold**
The correlation matrix (C) is indicated in *italics*
Squared covariance percentage values > 50.0 are indicated in red

The statistical significant covariances noted were as follows and confined to female groups:
a: axis 2 accounting for 40.98% of the co-variation, p value = 0.02
b: axis 2 accounting for 35.59% of the co-variation. p value = 0.05
c: axis 2 accounting for 39.27% of the co-variation, p value = 0.04
d: axis 2 accounting for 39.53% of the co-variation. p value = 0.01
e: axis 2 accounting for 40.41% of the co-variation, p value = 0.05
f: axis 2 accounting for 39.53% of the co=variation, p value = 0.05

As can be noted, white South Africans, as a group, presented with moderately high squared covariance percentages: white South Africans for the overall pelvis, midpelvis and pelvic outlet and white South African males for the midpelvis and pelvic outlet both in the variance-covariance matrix. More importantly, white South African females presented with high squared covariance percentages in the variance-covariance matrix for all pelvic shape components and moderately covariance percentages in the correlation matrix.

The statistical significant covariances noted were confined to female groups: for the pelvic inlet and in the midpelvis in a variance-covariance and in a correlation matrix, while in the black South African females group for the pelvic outlet in a variance-covariance and a correlation matrix.

5.2 Radiological sample

5.2.1 Analysis of linear dimensions on the pelves

Measurements relating to the birth canal were taken on the CT scans. As with the measurements taken on the intact cadaver pelves, these measurements were grouped into conjugates pertaining to the three pelvic rings, namely the pelvic inlet, midpelvis and the pelvic outlet. The dimensions of the pelvic inlet are described by the TC, the widest transverse dimension of the pelvic inlet (WTI) and the conjugate taken by midwives – the DC of the pelvic inlet (PI) (Table 4 above). The dimensions of the midpelvis are described by the OC and the narrowest transverse midpelvic dimension – the IS (Table 5). Lastly, the dimensions of the pelvic outlet are described by the anteroposterior diameter of the pelvic outlet (PO), the IT and the subpubic angle (Table 6).

Regarding intra-observer errors on pelvic scans, all dimensions showed excellent repeatability being >0.9, apart from PO (0.5456), IT (0.6827) and subpubic angle (0.6889) which presented with moderately good repeatability. These results indicate that there was some inaccuracy in identifying the lowest point of the ischial tuberosity and the coccyx on scans. When considering inter-observer errors, three dimensions namely the WTI, IS and PO showed good repeatability with intra-class correlation (ICC) of > 0.8. The subpubic angle and IT, as for the intra-observer ICC, showed moderately repeatability with ICC > 0.5, while measurements involving the promontory (OC, DC and TC) showed poor repeatability with ICC < 0.1.

Basic descriptive statistics of the linear dimensions on the pelvic scans are summarised in Table 27. Comparisons between sex-population groups were performed and significant p-values ($p \leq 0.05$) are indicated by the superscripts a–f.
Discriminant function analyses were performed between the two population groups and sexes (Figure 60), between populations within the sex groups (Figure 56) and thirdly, between the sexes within the population groups (Figure 57).

Table 27. Linear measurements taken on pelves in the radiological sample

Parameter	BF n = 52	WF n = 33	BM n = 31	WM n = 22	Black South African n = 83	Whites South Africans n = 55	South African females n = 85	South African males n = 53
Pelvic inlet								
True Conjugate [TC] (SPR - SPS)	**116.28** [a] *12.50* (94.94 - 146.02)	**129.55** [a] *11.15* (106.60 - 163.23)	**112.44** *9.44* (89.24 - 128.28)	**121.02** *8.24* (107.49 - 137.57)	**114.85** [e] *11.55* (89.24 - 146.02)	**126.13** [e] *10.86* (106.60 -163.23)	**121.43** [f] *13.58* (94.94 - 163.23)	**116.00** [f] *9.85* (89.24 - 137.57)
Widest transverse inlet diameter [WTI] (AL$_L$ - AL$_R$)	**127.55** [a d] *10.73* (94.12 - 148.84)	**142.79** [a c] *11.54* (117.31 - 166.52)	**120.91** [d] *9.81* (102.47 - 139.16)	**129.13** [c] *9.50* (100.30 - 143.51)	**125.07** [e] *10.83* (94.12 -148.84)	**137.33** [e] *12.64* (100.30 - 166.52)	**133.47** [f] *13.28* (94.12 - 166.52)	**124.32** [f] *10.43* (100.30 - 143.51)
Diagonal conjugate [DC] (SPR – IPS)	**130.94** *11.38* (106.53 - 158.81)	**142.15** *11.88* (117.80 - 168.71)	**133.43** [b] *9.86* (114.20 - 164.87)	**141.07** [b] *9.55* (124.69 - 159.12)	**131.87** [e] *10.84* (106.53 - 164.87)	**141.72** [e] *10.93* 117.80 - 168.71)	**135.29** *12.75* (106.53 - 168.71)	**136.60** *10.36* (114.20 -164.87)
Midpelvis								
Obstetric conjugate [OC] (SPR – MPS)	**114.62** *12.44* (91.43 - 144.01)	**128.28** *12.03* (104.22 - 154.15)	**113.53** 9.68 (93.29 - 135.78)	**122.25** *8.91* (108.86 - 138.35)	**114.21** [e] *11.44* (91.43 - 144.01)	**125.87** [e] *11.20* (104.22 - 154.15)	**119.92** *13.92* (91.43 - 154.15)	**117.15** *10.24* (93.29 - 138.35)
Interspinous diameter [IS] (IS$_L$ –IS$_R$)	**104.31** [d] *10.66* (64.95 - 121.14)	**107.85** *9.74* (91.62 - 130.84)	**86.24** [d] *8.42* (67.57 - 105.67)	**89.12** *9.61* (67.28 - 104.99)	**97.56** *13.19* (64.95 - 121.14)	**100.36** *13.34* (67.28 -130.84)	**105.68** [f] *10.40* (64.95 - 130.84)	**87.44** [f] *8.96* (67.28 -105.67)
Pelvic outlet								
Anteroposterior dimension of the pelvic outlet [PO] (COC – IPS)	**120.11** *13.66* (86.58 - 147.06)	**126.42** *12.20* *(*91.23 - 155.54)	**112.98** *10.40* (86.00 - *133.39)*	**117.50** *11.65* (87.22 - 137.18)	**117.44** [e] *12.95* (86.00 - 147.10)	**122.85** [e] *12.67* (87.22 - 155.54)	**122.56** [f] *13.40* (86.58 - 155.54)	**114.85** [f] *11.06* (86.00 - 137.18)
Intertuberous diameter [IT] (IT$_L$ – IT$_R$)	**129.13** [d] *11.24* (94.08 - 146.82)	**137.29** *11.98* (108.01 - 165.78)	**112.39** [d] *10.92* (90.30 - 134.62)	**122.64** *9.92* (100.69 - 142.97)	**122.88** [e] *13.73* (90.29 -146.88)	**131.43** [e] *13.26* (100.69 - 165.78)	**132.30** [f] *12.14* (94.08 - 165.78)	**116.64** [f] *11.60* (90.29 -142.97)
Subpubic angle (degrees)	**86.62** [d] *6.43* (76.84 - 100.52)	**87.45** [c] *7.49* (70.13 - 100.67)	**75.12** [d] *9.19* (57.13 - 93.88)	**78.13** [c] *6.08* (63.41 - 87.68)	**82.32** *9.38* (57.13 - 100.52)	**83.72** *8.30* (63.41 -100.67)	**86.94** [f] *6.83* (70.13 - 100.67)	**76.37** [f] *8.12.* (57.13 - 93.88)

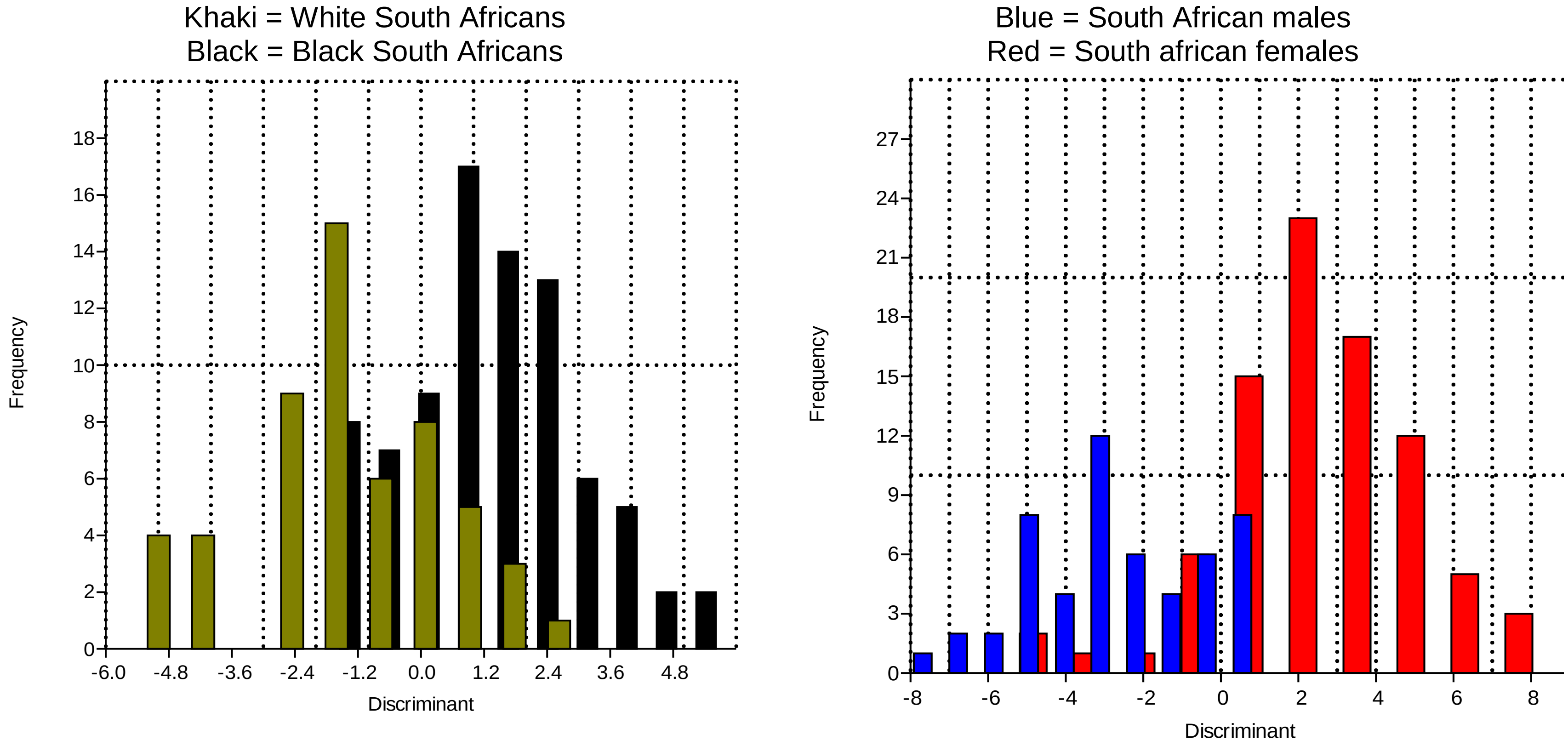
The number per group is indicated by n values. The mean values (mm) are indicated in **bold.** The standard deviation is indicated in *italics and* the range is shown within the round (brackets).

a Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African females
b Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African males
c Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the white South Africans
d Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the black South Africans
e Indicates a significant difference in the mean values ($p \leq 0.05$) between South African populations
f Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes

5.2.1.1 Comparisons between populations and sexes in the complete sample

All values in the white South African group overall were statistically significantly larger than that of the black South African group, apart from the subpubic angle. In general, females overall presented with statistically significantly greater dimensions than males.

Discriminant function analysis were performed to determine whether the size of the pelvis was effective in predicting population group and sex. Discrimination function analysis (Figure 56) revealed 80.43% accuracy when predicting population group and 87.68% accuracy when predicting sex in the complete sample.



Discriminant function analysis: 80.43% correctly classified

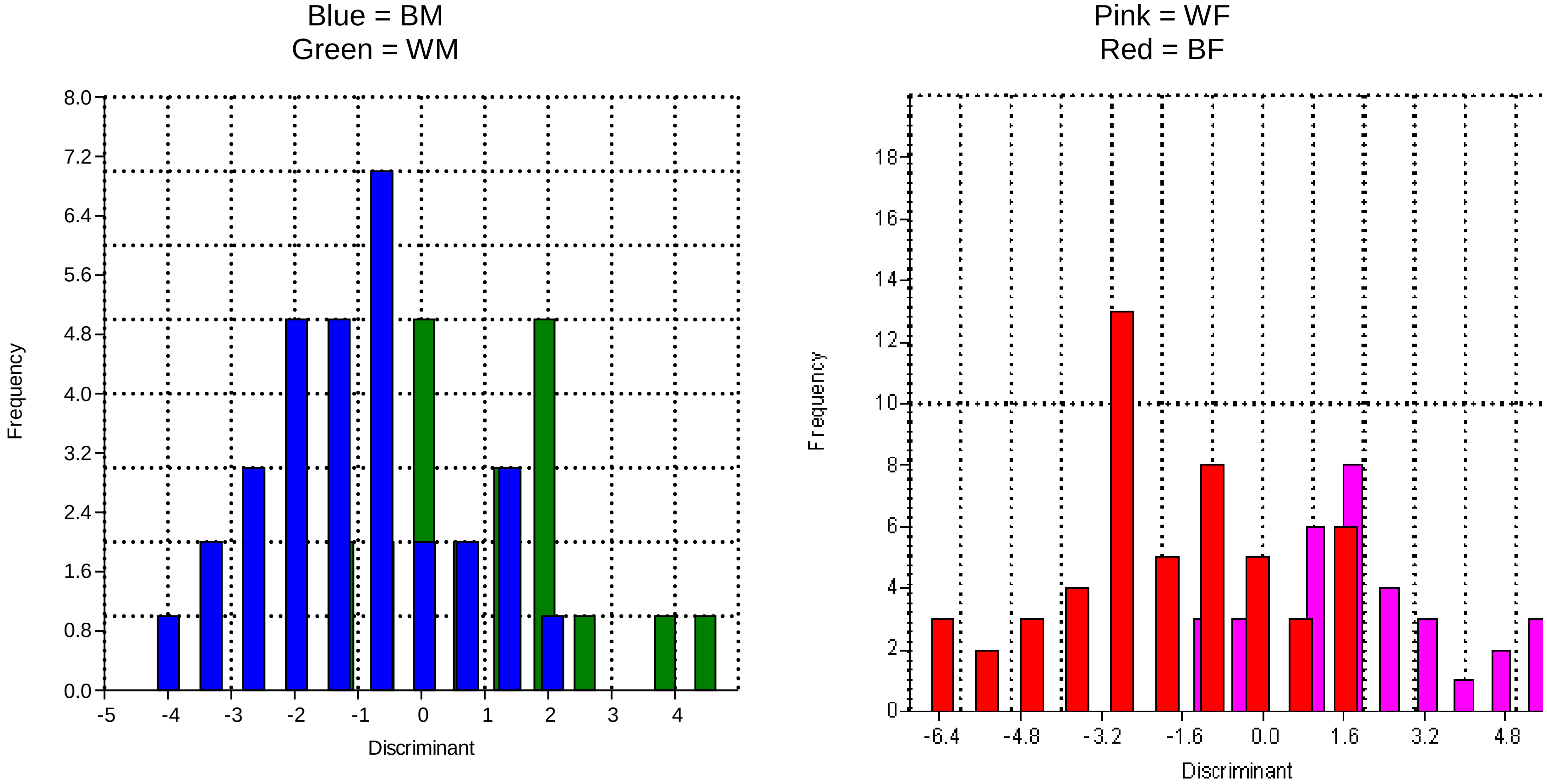
Discriminant function analysis: 87.68% correctly classified

Figure 56. Comparison of pelvic linear dimensions between populations and between sexes on the radiological sample

5.2.1.2 Comparisons between populations within sexes

All dimensions were larger in white South African females as compared to black South African females, and white South African males as compared to black South African males, respectively. Two of the eight measurements were significantly larger in white South African females ($p \leq 0.05$) compared to black South African females and were found on the pelvic inlet – the TC and the WTI diameter. White South African males presented with a significantly larger DC as compared to black South African males.

Discriminant function analyses were performed to determine whether the size of the pelvis was effective in predicting population group within the sex group. Discrimination function analyses within sex groups were performed (Figure 57) and separated the male groups with 79.25% accuracy, and the female groups with 83.53% accuracy.



Discriminant function analysis: 79.25 % correctly classified

Discriminant function analysis: 83.53 % correctly classified

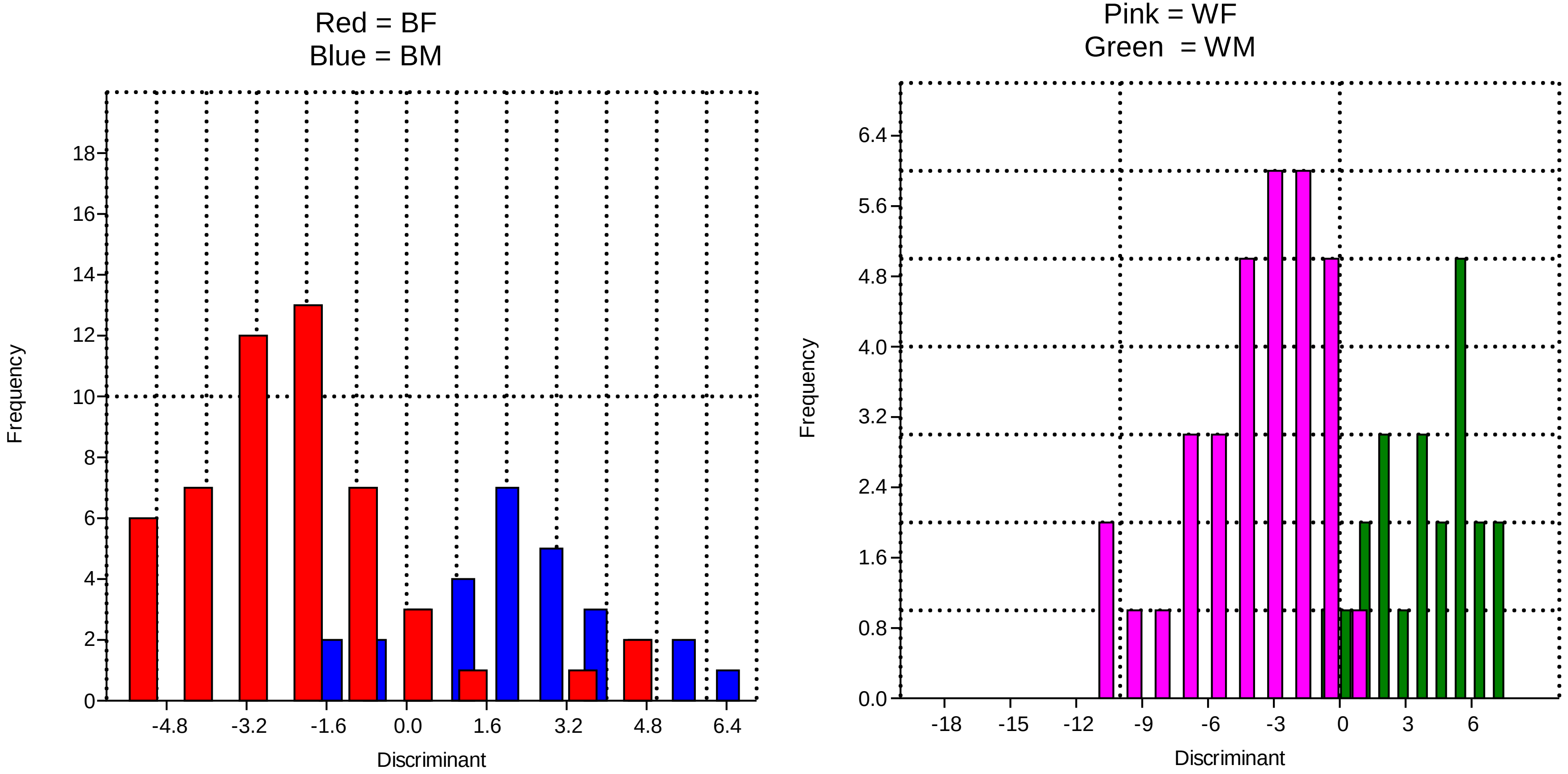
Figure 57. Comparison of pelvic linear dimensions between population groups within sexes on the radiological sample

5.2.1.3 Comparisons between sexes within population groups

White South African females presented with larger overall dimensions when compared to white South African males. The WTI inlet dimension and the subpubic angle were significantly larger in white South African females than in white South African males.

Similarly, black South African females presented with larger overall measurements when compared to black South African males. Black South African males presented with the smallest measurements throughout, apart from the DC at 130.94 mm, which was the smallest in black South African females. Black South African females had a significantly larger WTI diameter, IS, IT and subpubic angle than black South African males.

Discriminant function analyses were performed to determine whether the size of the pelvis was effective in predicting sex within a population group. A discriminant function analysis was performed (Figure 61) and separated the black South African group with 89.16% accuracy and the white South African group with 96.36% accuracy.



Discriminant function analysis: 89.16 % correctly classified

Discriminant function analysis: 96.36 % correctly classified

Figure 58. Comparison of pelvic linear dimensions between sexes within populations on the radiological sample

Summary of sex and population group variations in linear radiological pelvic dimensions:

Similar to the cadaver sample, all pelvic linear dimensions were statistically significantly greater in females than in males and in white South Africans as compared to black South Africans, apart from the DC which was greater in males, while the OC was greater in females, but not significantly so, and the subpubic angle which showed no statistically significant variations between populations. Prediction of sex was more accurate (87.68%) than populations (80.43%) when considering the entire sample.

All pelvic linear dimensions were greater in white South African females than those in black South African females and were statistically significant for the pelvic inlet dimensions: the TC and the WTI distance. Similarly, all pelvic linear dimensions were greater in white South African males than those in black South African males, with the DC significantly so. Discriminant function analyses within sex groups for a population was slightly less than the entire sample when considering males at 79.25% accuracy. Females were correctly predicted at 83.53%.

When comparing the sexes within populations, both white South African females and black South African females presented with greater dimensions when compared to white South African males and black South African males, respectively. Measurements that were statistically larger included the WTI diameter and the subpubic angle. Sex discrimination improved when considering populations separately, with 89.16% accuracy within the black South African population and 96.36% accuracy within the white South African population.

5.2.2 Analysis of linear dimensions on the crania

The mean values, the standard deviations and range of each linear cranial dimension are reported in Table 28. Comparisons between sex-population groups were performed and significant p-values ($p \leq 0.05$) are indicated by the superscripts a–d.

Regarding intra-observer errors for cranial scans, only moderately good repeatability could be achieved on the scans of crania. The cranial length fared the best at 0.7934 and biparietal distance the lowest at 0.4375. Inter-observer ICC tests fared marginally better than intra-observer tests, but showed the same pattern, with cranial length faring the best at 0.9378 and biparietal distance at 0.4970.

Discriminant function analyses were then performed to determine whether the size of the crania was effective in predicting population group, sex group and sex-population group. Firstly, a discriminant analysis was performed between the two population groups and sexes (Figure 59), secondly, between populations within the sex groups (Figure 60) and thirdly, between the sexes within the population groups (Figure 61).

Table 28. Linear measurements taken on crania of the radiological sample

Parameter	BF n =52	WF n =33	BM n=31	WM n =22	Black South African n = 83	South African Whites n = 55	South African females n= 85	South African males n = 53
Cranial height (N – B)	**117.75** [a] *9.22* (102.85 -147.26)	**112.83** [a] *6.78* (95.38 - 125.21)	**119.04** *11.93* (72.98 - 36.081)	**122.28** *10.74* (96.22 - 45.62)	**118.23** *10.26* (72.98 -147.26)	**116.61** *9.69* (95.38 -145.62)	**115.84**[f] *8.66* (95.38 -147.26)	**120.39**[f] *11.45* (72.98 - 145.62)
Greatest cranial length [MaxCL] (G - OP)	**180.74**[a] *5.65* (163.70 - 193.46)	**173.97** [a,c] *9.87* (154.01 -191.29)	**189.20** *7.37* (173.63 -203.97)	**186.21** [c] *11.09* (160.44 -201.94)	**182.99**[e] *9.42* (128.28 -200.16)	**178.87**[e] *11.92* (154.01 - 01.94)	**178.11**[f] *8.22* (154.01 -193.46)	**186.44**[f] *12.53* (123.06 -201.94)
Biparietal diameter [BPD] (EU_L - EU_R)	**122.03**[a] *8.15* (104.44 -138.11)	**130.15**[a] *9.53* (102.63 -143.73)	**122.78** *7.89* (104.58 -138.48)	**126.06** *9.77* (107.58 -42.36)	**122.31**[e] *8.01* (104.44 -138.48)	**128.52**[e] *9.75* (102.63 - 43.73)	**125.18** *9.53* (102.63 - 143.73)	**124.14** *8.78* (104.58 - 142.36)
Ratio [BDP/ MaxCL]	**0.68** [a] *0.04* (0.57 - 0.78)	**0.75** [a c] *0.07* (0.57 - 0.91)	**0.65** *0.05* (0.52 - 0.75)	**0.68** [c] *0.07* (0.56 -0.80)	**0.67**[e] *0.06* (0.52 - 0.94)	**0.72**[e] *0.08* (0.56 - 0.91)	**0.70**[f] *0.07* (0.57 - 0.91)	**0.67**[f] *0.07* (0.52 - 0.98)

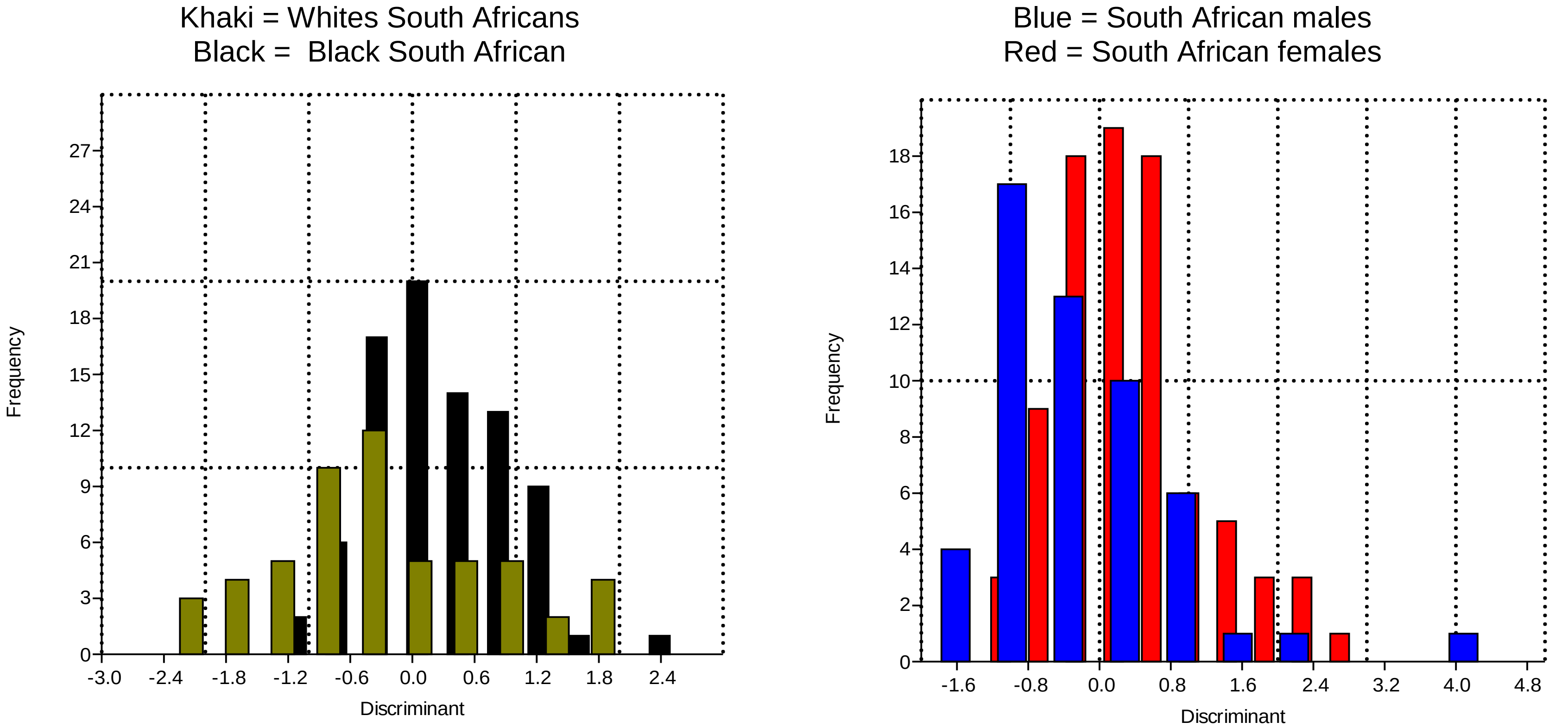
The four sex-population groups are abbreviated as follows: 1= Black South African females; 2= White South African females; 3= Black South African males; and 4= White South African males. The number per group is indicated by N values. The mean (mm) values are indicated in **bold.** The standard deviation is indicated in *italics and* the range is shown within the round (brackets).

a Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African females
b Indicates a significant difference in the mean values ($p \leq 0.05$) between populations within South African males
c Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the white South Africans
d Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes within the black South Africans
e Indicates a significant difference in the mean values ($p \leq 0.05$) between South African populations
f Indicates a significant difference in the mean values ($p \leq 0.05$) between sexes

5.2.2.1 Comparisons between populations and sexes

Black South Africans compared to white South Africans, as well as males compared to females, presented with a statistically significantly greater cranial length. Similarly, the cranial height was greater in black South Africans compared to white South Africans, and males compared to females, but was only significant between the sexes. On the other hand, black South Africans compared to white South Africans, as well as males compared to females, presented with a smaller BPD which was statistically significant between sexes, as well as a statistically significantly smaller ratio [BDP/ MaxCL].

Discriminant function analyses (Figure 59) revealed 65.22% accuracy when predicting population group and 69.57% accuracy when predicting sex.



Discriminant function analysis: 65.22% correctly classified

Discriminant function analysis: 69.57% correctly classified

Figure 59. Discriminant function analyses of the linear cranial dimensions between populations and sexes on the radiological sample

5.2.2.2 Comparisons between populations within sexes

Following the same trends as noted in the comparison between population groups, the comparison between females of different population groups presented with a statistically significantly greater cranial height and length in black South African females as compared to white females. White South African females presented with a statistically significantly greater BPD and BPD/MaxCL ratio as compared to black South African females. At this dimension (MaxCL), white South African females measured a smaller mean distance (173.97 mm) than black South African females (180.74). The different behaviour of these two measurements is reflected in the larger BPD/MaxCL ratio seen in white South African females.

Contrary to what was noted in the comparison between population groups, white South African males and black South African males did not present with any statistically significant difference in the linear measurements. White South African males, however, presented with a greater cranial height, BPD and BDP/MaxCL ratio, while black South African males presented with a greater cranial length. It should be noted that the white South African male group is the smallest sex-population group (n= 22).

Black South African males and females presented with a non-statistically significantly overall longer (anteroposteriorly) and narrower (transversely) shaped cranium when compared to the white South African males and female groups, respectively. Black South African females (not males) presented with a greater cranial height (supero-inferiorly) as compared to white South African females.

A discrimination function analysis was performed (Figure 60) and separated populations within both the male and female groups with 100% accuracy.

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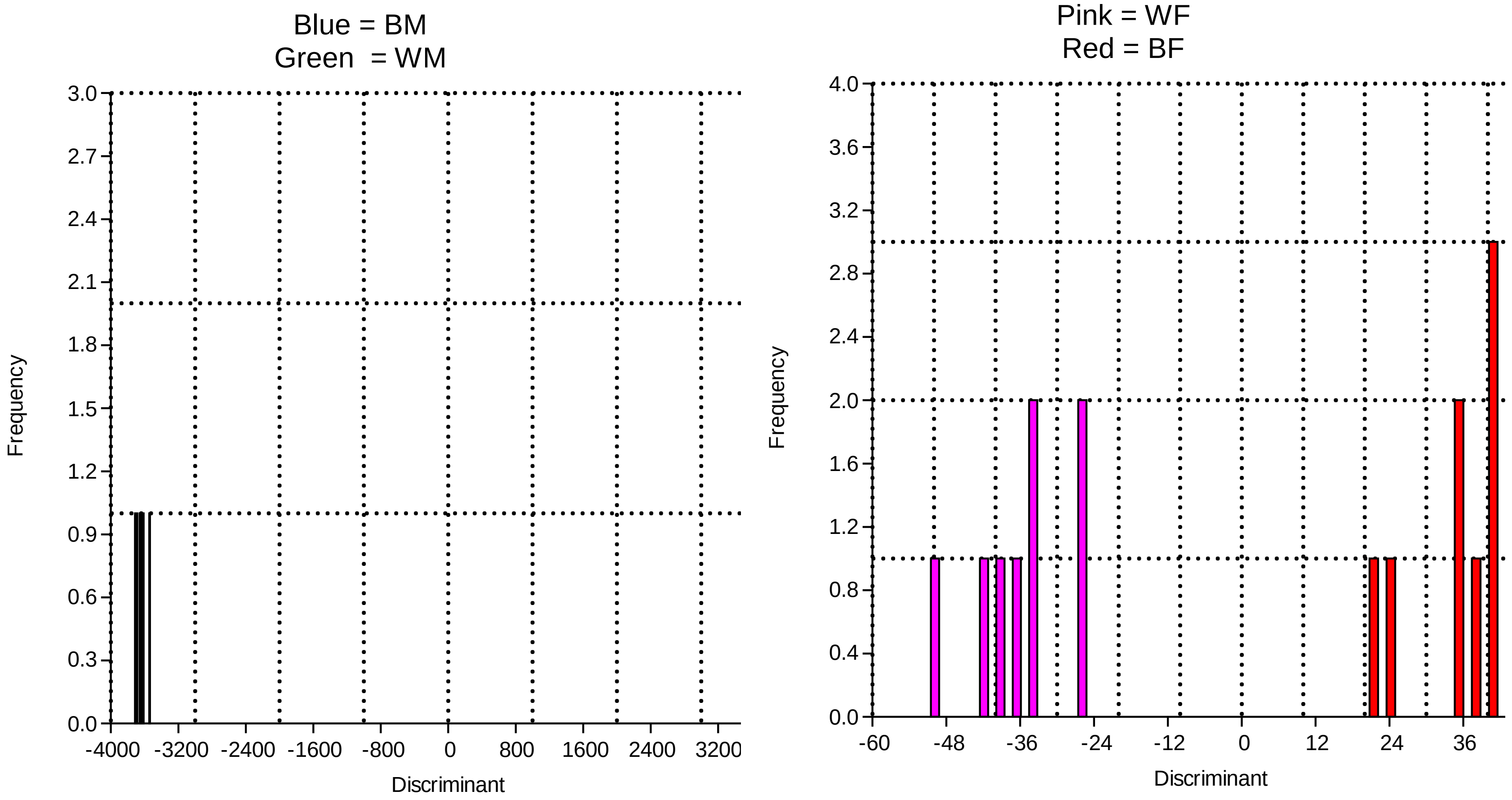


Discriminant function analysis: 100% correctly classified

Discriminant function analysis: 100% correctly classified

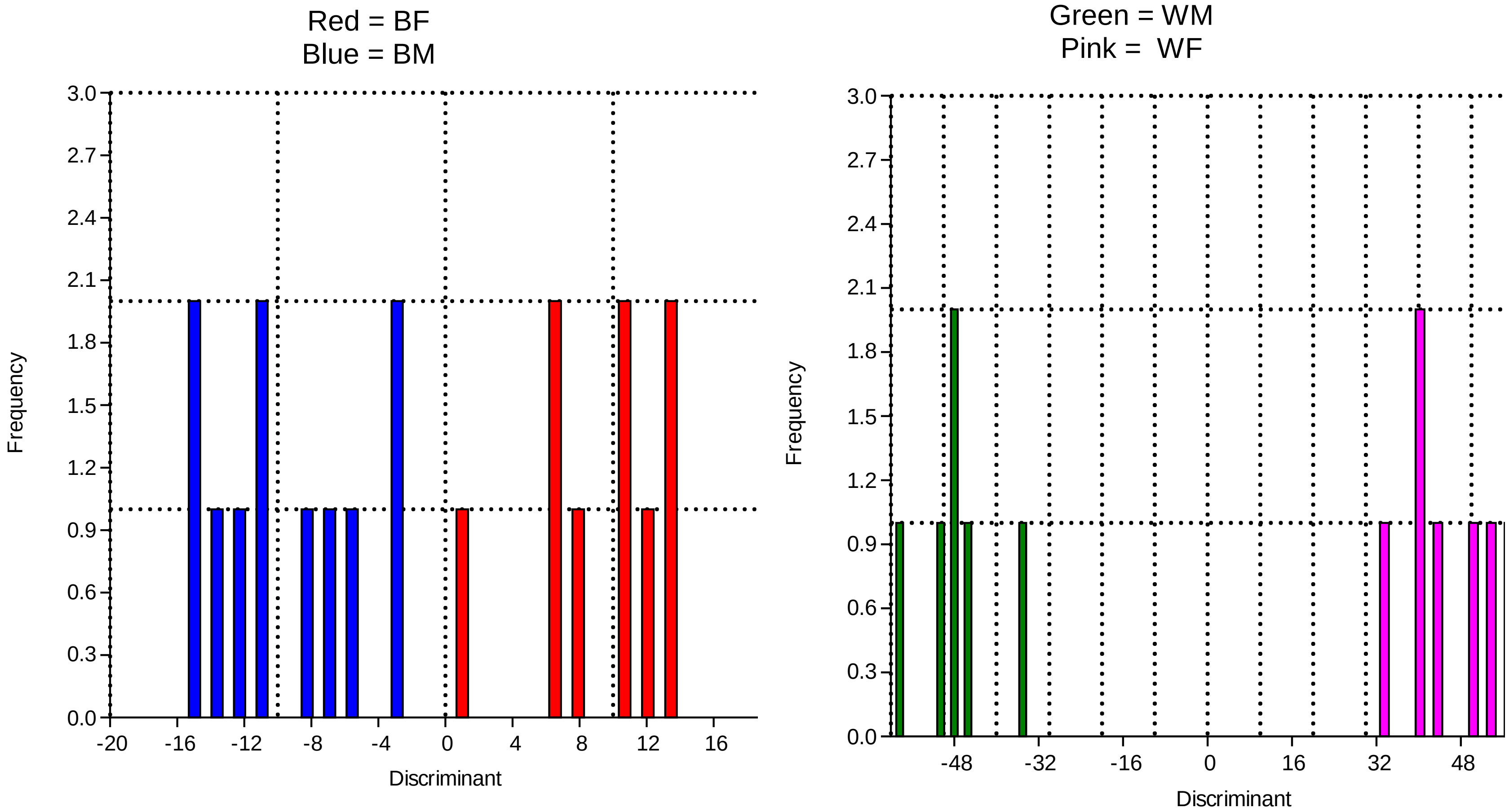
Figure 60. Discriminant function analyses of the linear cranial dimensions between populations within the sexes on the radiological sample

5.2.2.3 Comparisons between sexes within population groups

Black South African males reported overall larger distances than black South African females. These distances were not significantly larger. This is reflected in the similar but slightly larger BPD/Head circumference ratio seen in black South African females compared to black South African males.

White South African males presented with the largest cranial height, while white South African females presented with the greatest biparietal distance (130.15 mm, as opposed to white South African males (126.06 mm). White South African males, however, showed a significantly longer MaxCL when compared to white South African females. A shorter cranial length, paired with a significantly larger BPD in white South African females, suggests a more globular-shaped head. This is evident in the larger BPD/MaxCL ratio seen in white South African females.

A discrimination function analysis was performed (Figure 61) which separated the sexes within both population groups with 100% accuracy.



Discriminant function analysis: 100% correctly classified

Discriminant function analysis: 100% correctly classified

Figure 61. Discriminant function analyses of the linear cranial dimensions between sexes within the populations on the radiological sample

Summary of sex and population group variations in linear radiological cranial dimensions:

Black South Africans compared to white South Africans, as well as males compared to females, presented with a statistically significantly greater cranial length. Similarly, the cranial height was greater in black South Africans compared to white South Africans, and males compared to females, but was only significant between the sexes. On the other hand, black South Africans compared to white South Africans, as well as males compared to females, presented with a smaller BPD, which was statistically significant between sexes and a statistically significantly smaller ratio (BPD/MaxCL).

Statistical significance in the comparisons between populations were not retained throughout when splitting the complete sample into smaller sex-population groups. Nevertheless, the black South African male and female population group presented with an overall longer (anteroposteriorly) and narrower (transversely) shaped cranium when compared to the white South African males and female groups, respectively, resulting in a more globular-shaped cranium, in especially white South African females as reflected in the larger BPD/MaxCL ratio. While black South African females presented with a greater cranial height (supero-inferiorly) as compared to white South African females, black South African males presented with a shorter cranial height than white South African males.

In the complete sample, classification accuracy for cranial dimensions was low when predicting population (65.22 %) and sex (69.57 %). However, within a population, sexes separated with 100% accuracy and within sex groups, populations separated with a 100% accuracy.

5.2.3 Shape analysis for intact pelves

Shape variation of the overall pelvic shape, pelvic inlet, midpelvis and pelvic outlet are presented here as principal component analysis (PCA) scatter plots, where principal component 1 (represented on the X-axis) contributed to the greatest shape difference and principal component 2 (represented on the Y-axis) contributed to the second greatest variation. Statistically significant variations in shape between sexes, population groups and sex-population groups were determined by two group permutation multivariate statistical analysis in a PAST v4.03 software programme on the principal component scores and a p-value derived. In addition, discriminant function analysis were performed and a classification accuracy of each comparison given.

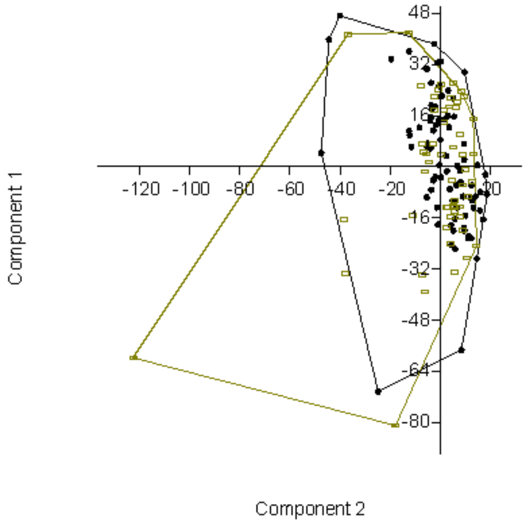
5.2.3.1 Overall shape

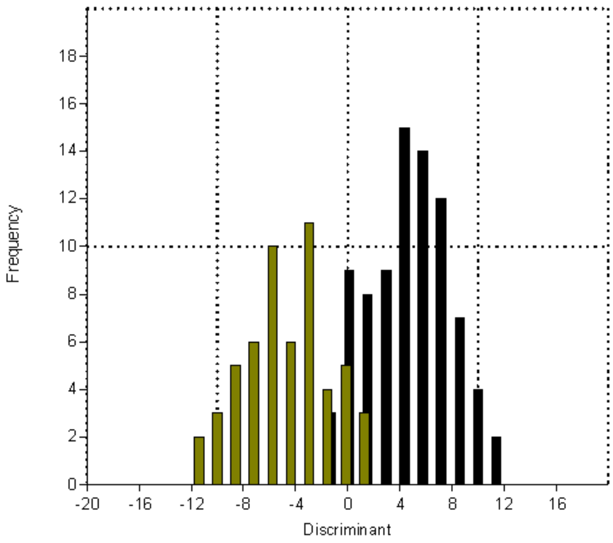
5.2.3.1.1 Comparison between population groups and sexes

Figure 62 displays the graphs of the principal component analysis (PCA) with p-value, as well as the discriminant analysis with classification accuracy of each comparison within the entire sample, as indicated. There is a distinct separation of the population groups on the PCA graphs, while the sexes did not visually clearly separate. The variations of the overall pelvic shape between the populations and sexes were highly statistically significant with a discriminant analysis separation of 95.65% accuracy between populations and 98.55% between sexes.

Comparison of the overall pelvic shape between populations within the entire sample:

Khaki = White South Africans
Black = Black South Africans



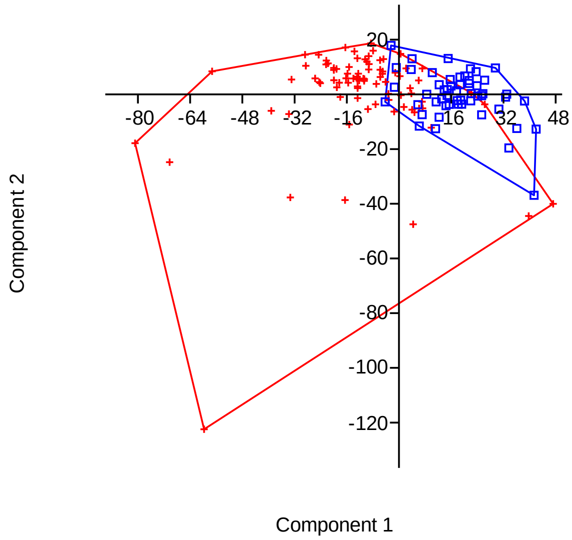


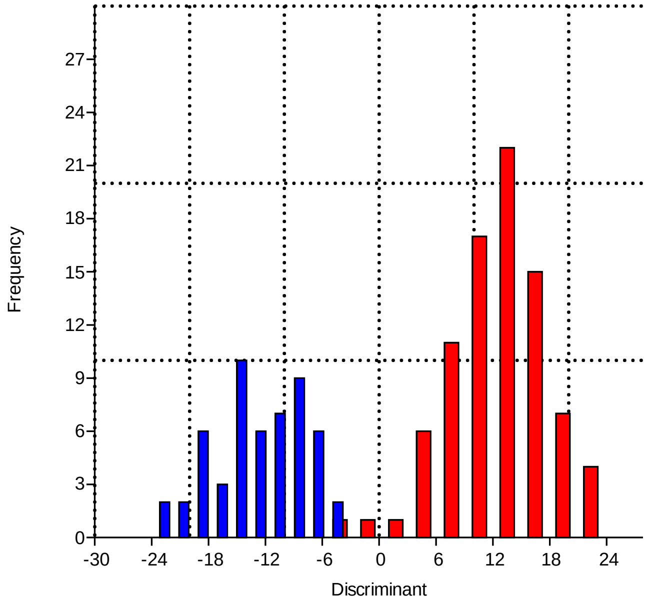
PCA: p = 0.0001

Discriminant function analysis: 95.65% correctly classified

Comparison of the overall pelvic shape between sex groups within the entire sample:

Blue = South African males
Red = South african females





PCA: p = 0.0005

Discriminant function analysis: 98.55%correctly classified:

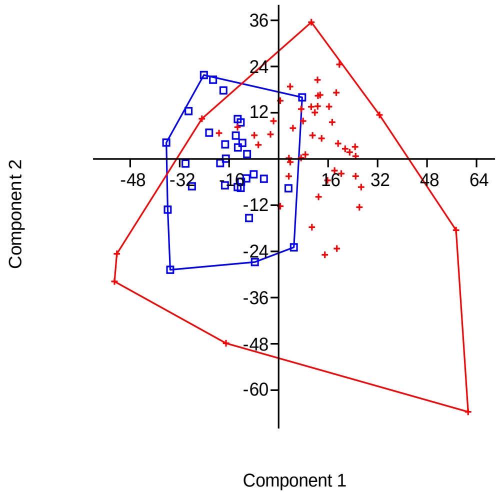
Figure 62. Comparison of overall pelvic shape dimensions between populations and between sexes on the radiological sample

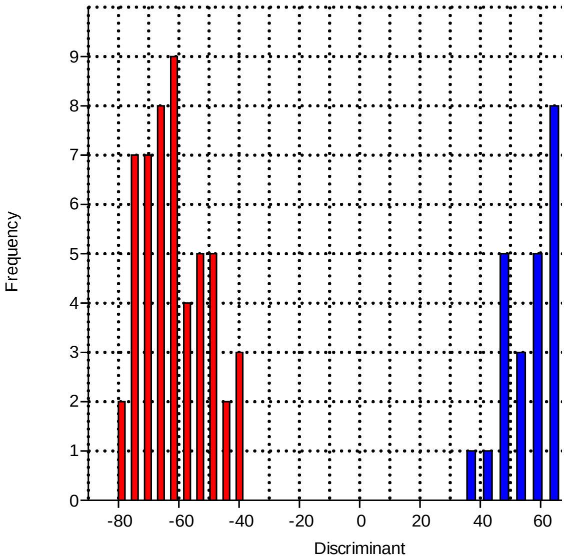
5.2.3.1.2 Comparison between sexes within population groups

Figure 63 displays the graphs of the principal component analysis (PCA) with p-value, as well as the discriminant analysis with classification accuracy of each comparison between sexes within each population group, as indicated. The groups showed some separation on the PCA graphs and were highly significant between the sexes for the overall pelvic shape in each population group. In addition, a discrimination of 100% was noted between the sexes within each population group.

Comparison of the overall pelvic canal shape between black South African males and females:

Red = BF
Blue = BM



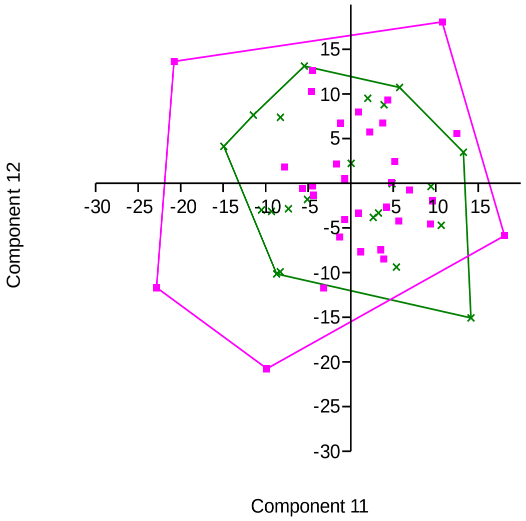


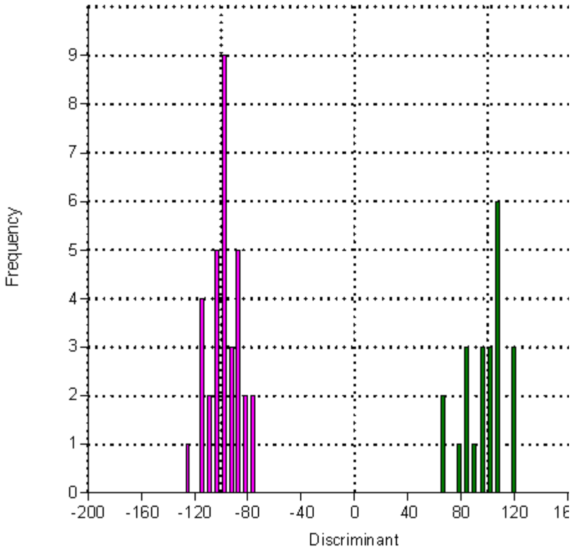
PCA: p = 0.0005

Discriminant function analysis: 100% correctly classified

Comparison of the overall pelvic canal shape between white males and females:

Green = WM
Pink = WF





PCA: p = 0.0005

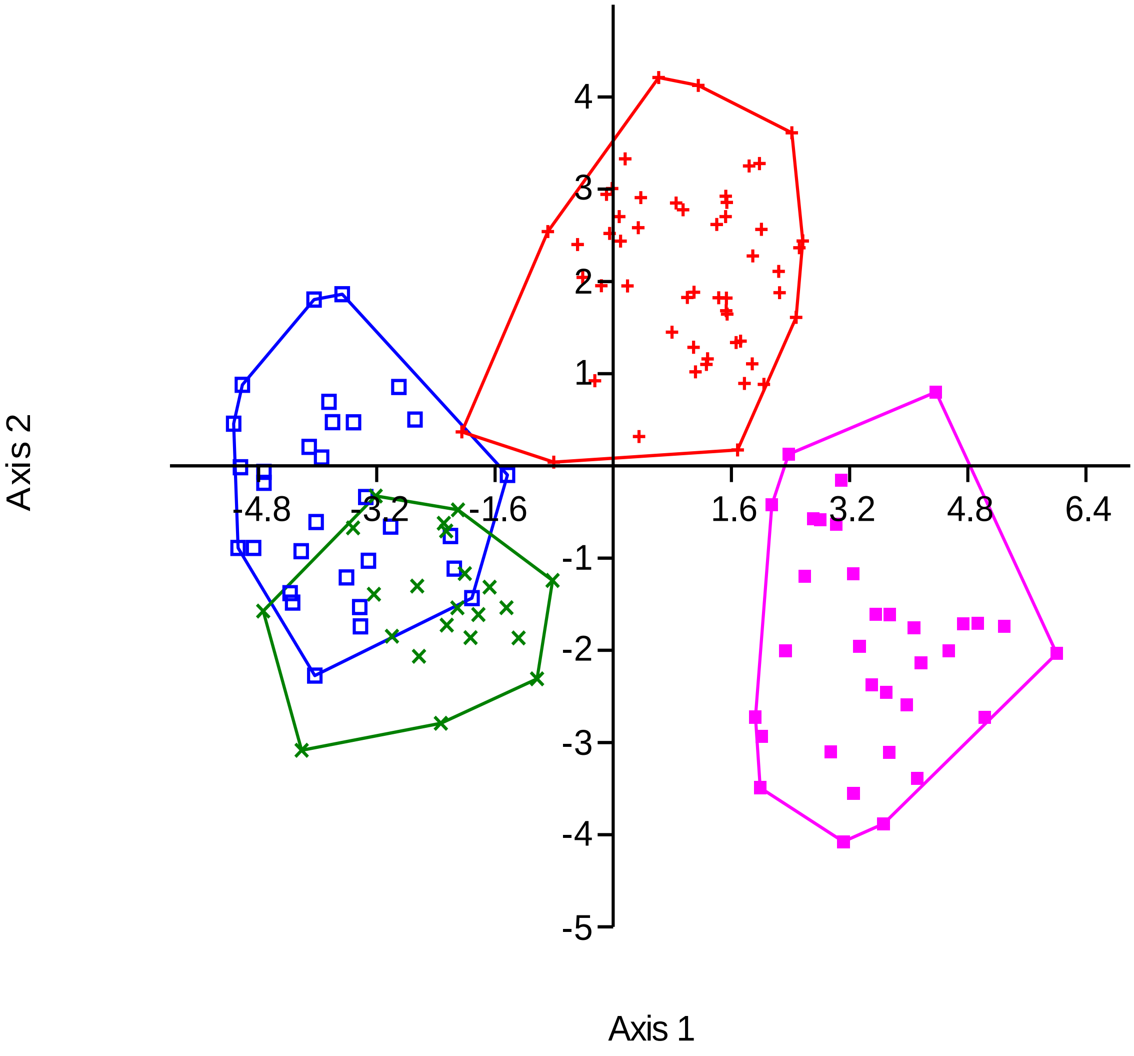
Discriminant function analysis: 100% correctly classified

Figure 63 Comparison in overall pelvic canal shape between sexes within populations

5.2.3.1.3 Comparison in overall pelvic shape between sex-population groups

Figure 64 displays the graphs of the canonical variate analysis (CVA) with a highly significant p-value between sex-population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p= 0.000

Figure 64 Comparison of the overall pelvic canal shape between sex-population groups

The groups showed complete separation between the female groups, between the females and the males and some separation between the male groups on the CVA graphs. There were no significant differences for the overall pelvic shape in any sex-population group comparisons with pairwise comparisons (Table 29). In addition, the Mahalanobis distance failed when performing the two group permutation tests involving some comparisons with white South African males and white South African females, because of the number of individuals compared to the high number of landmarks.

Table 29. MANOVA pairwise comparisons between sex-population groups for the overall pelvic shape

0	**BM**	**BF**	**WM**	**WF**
BM	0	0.5230	Fail	Fail
BF	0.5230	0	1.00	0.6032
WM	Fail	1.00	0	Fail
WF	Fail	0.61	Fail	0

Significant differences (< 0.05) between groups are indicated in **bold**

However, as can be noted in the confusion matrix (Table 30), sex-population groups were very seldom misclassified (BF: 3/31; WF: 0/50; BM: 4/24; WM: 0/33).

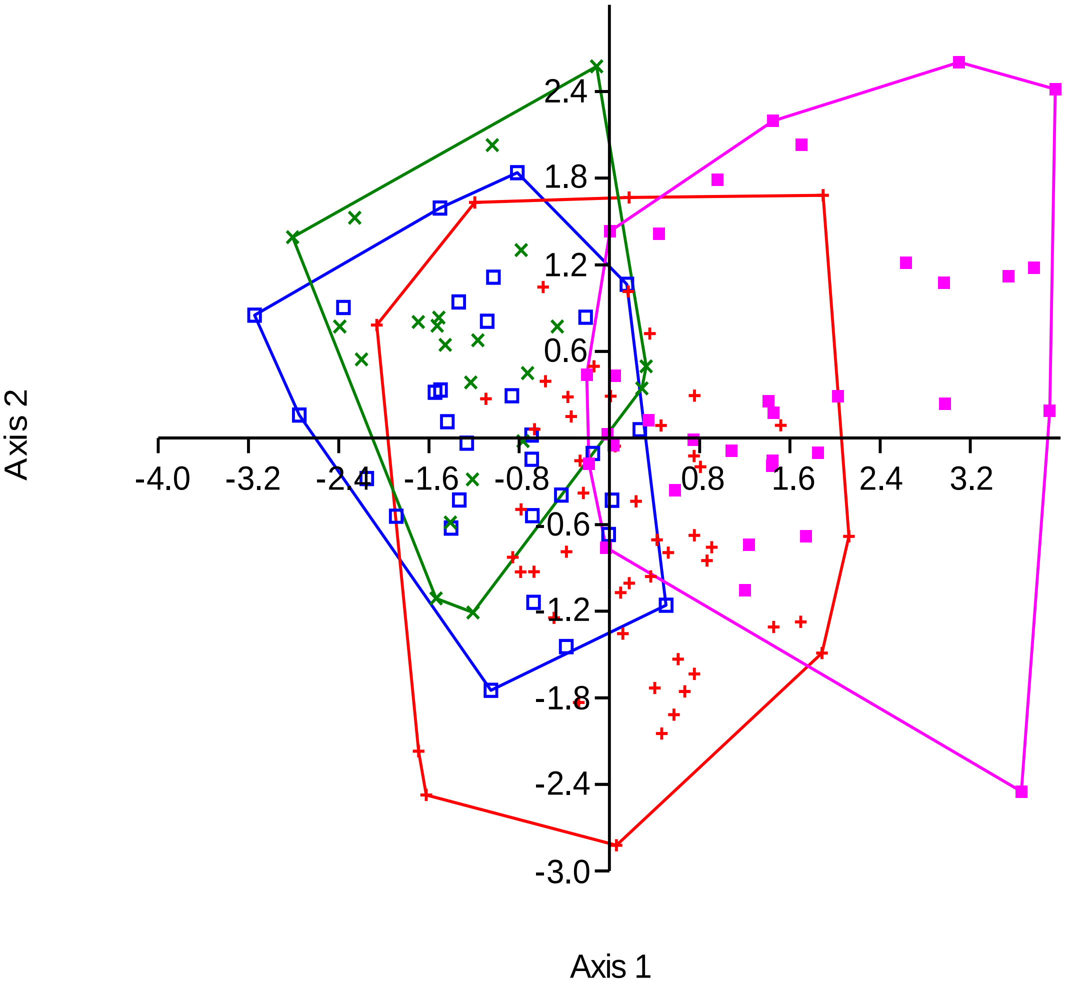
Table 30. Confusion matrix for overall pelvic shape between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	28	0	3	0	31
WF	1	50	1	0	52
BM	2	0	20	0	22
WM	0	0	0	33	33
Total	**31**	**50**	**24**	**33**	**138**

5.2.3.2 Pelvic inlet

Figure 65 displays the graphs of the canonical variate analysis (CVA) with a highly statistically significant p-value between sex-population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p= 0.000

Figure 65. Comparison of the overall pelvic inlet shape between sex-population groups

The groups showed very little separation on the CVA graphs but showed a significant difference for the pelvic inlet shape when comparing black South African males and white South African females, black South African females and white South African males, as well as white South African females with pairwise comparisons (Table 20), but not between black South African males and black South African females, or black South African males and white South African males. White South African females showed a significant difference in the shape of the pelvic inlet when compared to all other groups. White South African males showed a significant difference when compared to black South African females.

Table 31. MANOVA pairwise comparisons between sex-population groups for the pelvic inlet

0	**BM**	**BF**	**WM**	**WF**
BM	0	0.1140	0.9176	**0.0006**
BF	0.1140	0	**0.0310**	**0.0013**
WM	0.9176	**0.0310**	0	**0.0035**
WF	**0.0006**	**0.0014**	**0.0035**	0

Significant differences (< 0.05) between groups are indicated in **bold**

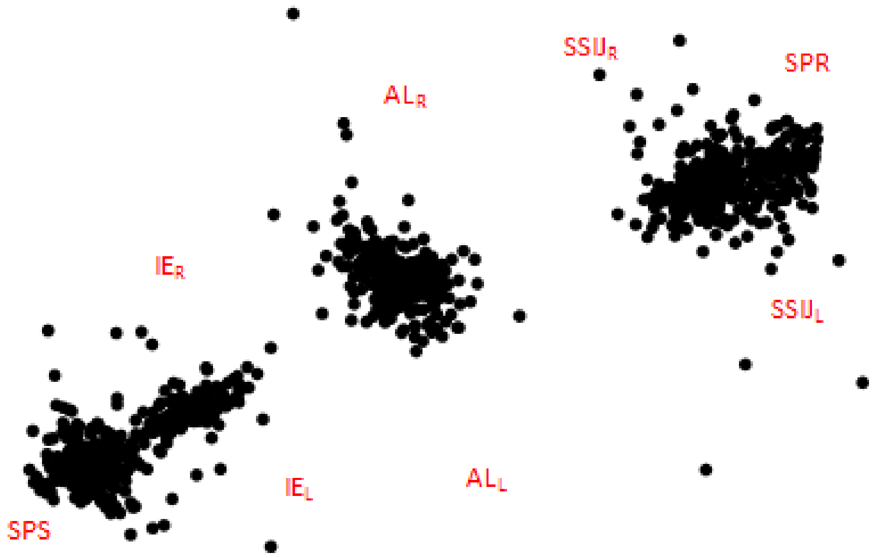
However, as can be noted in the confusion matrix (Table 32), sex-population groups were often misclassified (BF: 8/31; WF: 17/52; BM: 7/22; WM: 9/33).

Table 32. Confusion matrix for pelvic inlet shape between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	23	3	5	0	31
WF	6	35	5	6	52
BM	3	2	15	2	22
WM	3	5	1	24	33
Total	**35**	**45**	**26**	**32**	**138**

The clustering of the landmarks representing the shape of the pelvic inlet in all individuals is illustrated in Figure 66. Both the lateral and anterior views are shown. The points which outline the pelvic inlet taken are listed in Table 4. Clustering of the pelvic inlet shape 3D points for each sex-population group is represented in Figure 67.

Lateral view



Anterior view

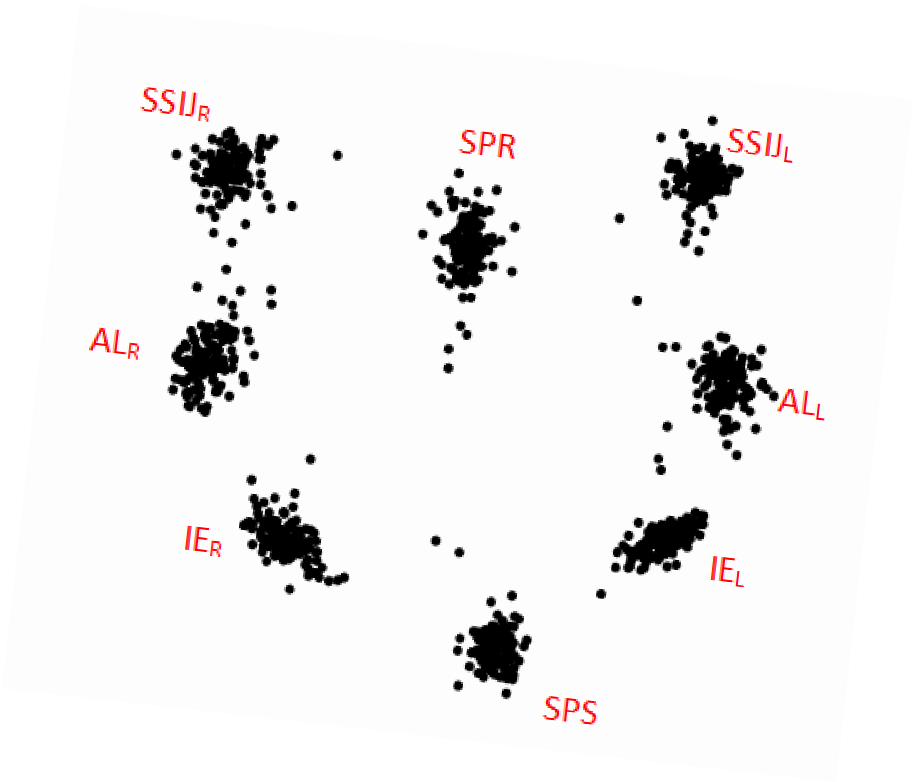


Figure 66.Visual representation of the clustering of the shape of the pelvic inlet in all individuals (Table 4)

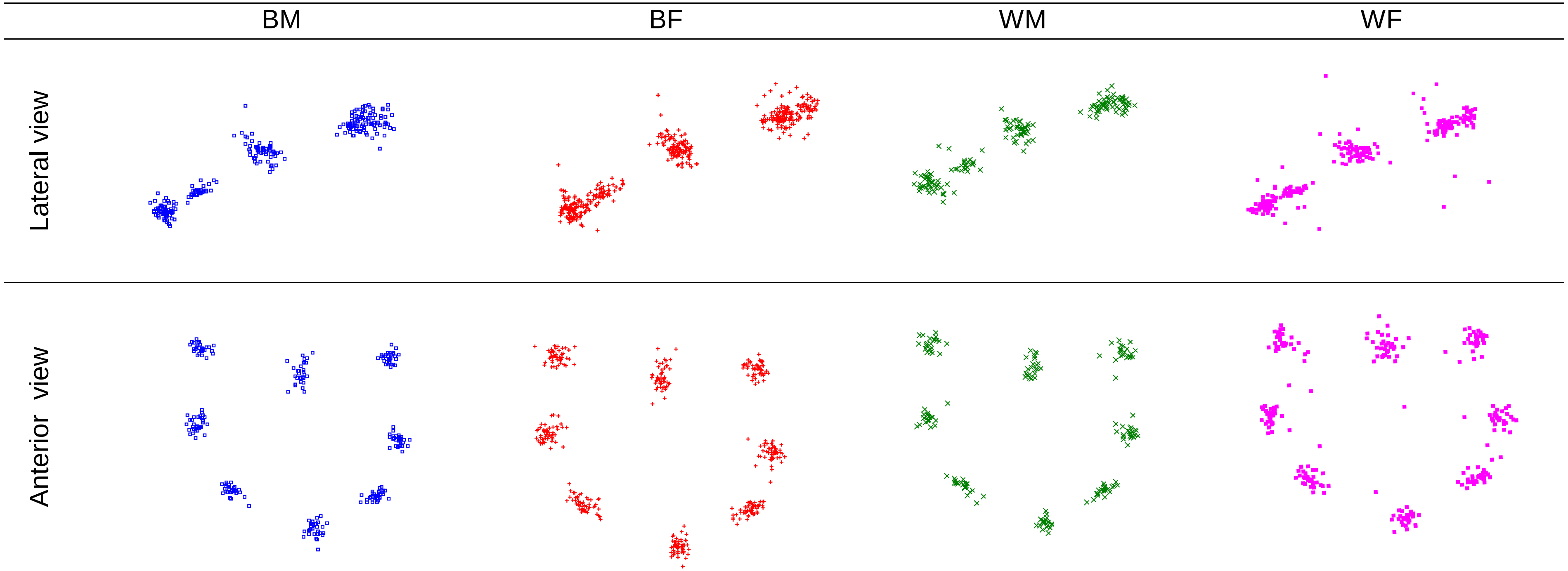


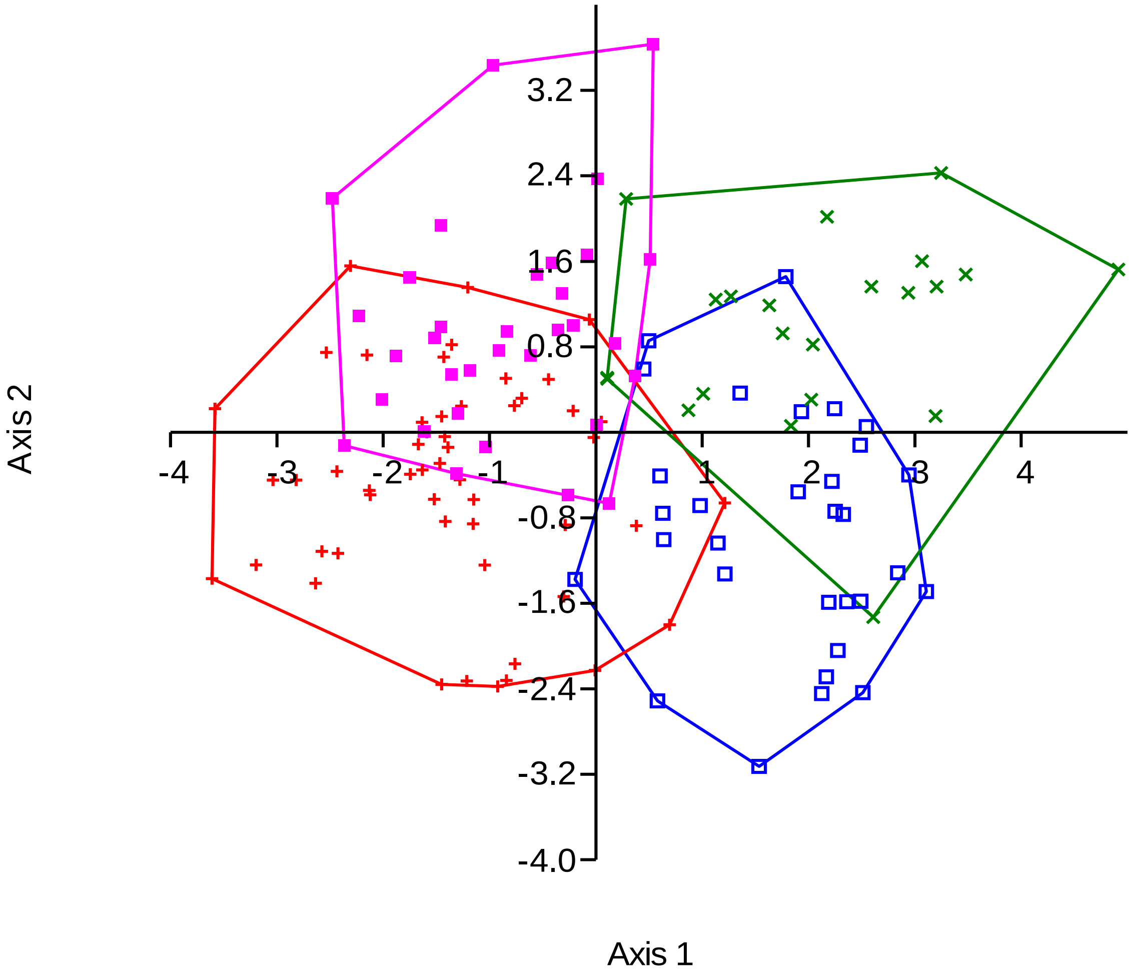
Figure 67. Clustering of pelvic inlet shapes landmarks in the sex-populations groups

From the clustering of pelvic inlet 3D points, differences are evident in the female groups. Females presented with a large diameter across the pelvic brim. Males presented with more anteriorly projecting midpoints on the sacral promontory than females, especially white South African females.

5.2.3.3 Midpelvis

Figure 68 displays the graphs of the canonical variate analysis (CVA) with p-value between sex-population groups as indicated

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.000

Figure 68. Comparison of the midpelvic shape between sex-population groups

The groups showed very little separation on the CVA graphs with a significant difference for the midpelvic shape in each sex-population group with pairwise comparisons (Table 33). Both black South African females and white South African females showed a significant difference in the shape of the midpelvis when compared to black South African males and white South African males. The comparison between white South African and black South African males, as well as between white South African and black South African females, were not significant.

Table 33. MANOVA pairwise comparisons between sex-population groups for the midpelvis

0	**BM**	**BF**	**WM**	**WF**
BM	0	**< 0.0001**	0.0516	**0.0003**
BF	< 0.0001	0	**< 0.0001**	0.0879
WM	0.0516	< 0.0001	0	**0.0178**
WF	0.0003	0.0879	0.0178	0

Significant differences (< 0.05) between groups are indicated in **bold**

These differences can also be noted in the confusion matrix (Table 34). Black South Africans were less often misclassified than white South Africans (BF: 2/31; WF: 7/52; BM: 4/22; WM: 8/33).

Table 34. Confusion matrix for midpelvic shape between sex-population groups

Given groups→ **Predicted groups↓**	**BF**	**WF**	**BM**	**WM**	**Total**
BF	29	0	2	0	31
WF	0	45	1	6	52
BM	2	0	18	2	22
WM	1	7	0	25	33
Total	**32**	**52**	**21**	**33**	**138**

The average shape of the midpelvis is visually represented by 3D points taken as illustrated in Figure 69. The superior view is shown. The points which outline the midpelvis taken are listed in Table 5. Clustering of the midpelvic shape for each sex-population group is represented in Figure 70.

Superior view

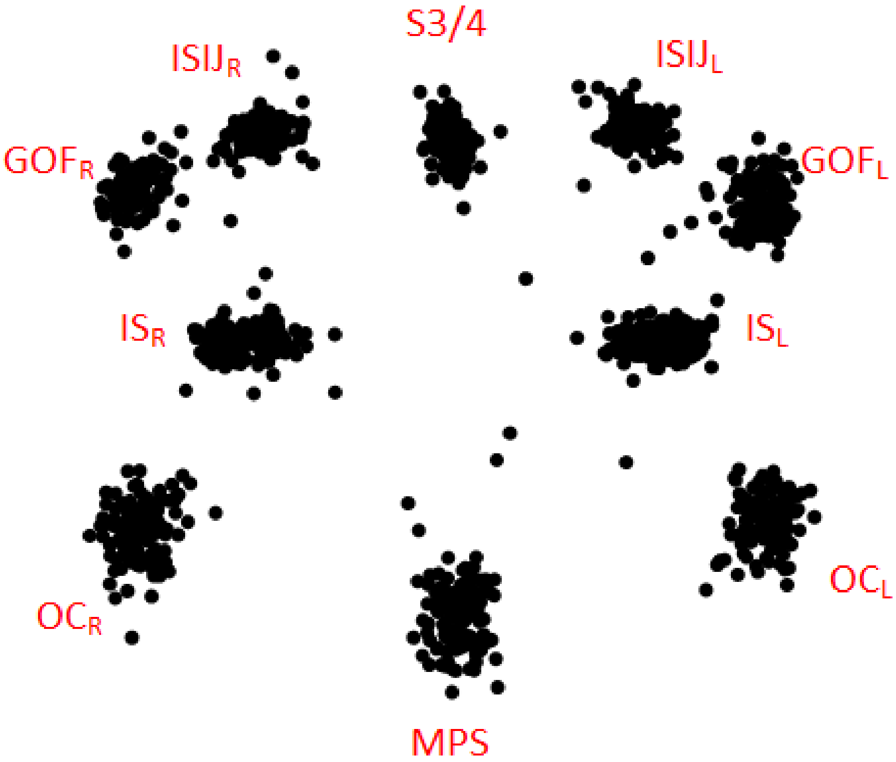


Figure 69. Visual representation of the clustering of the shape of the midpelvis in all individuals (Table 5)

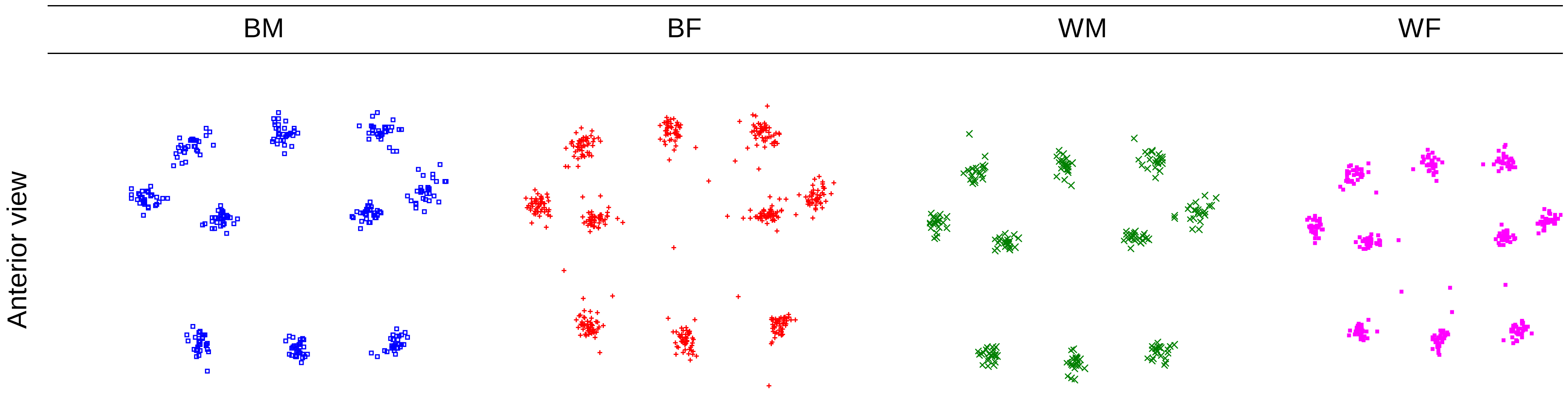


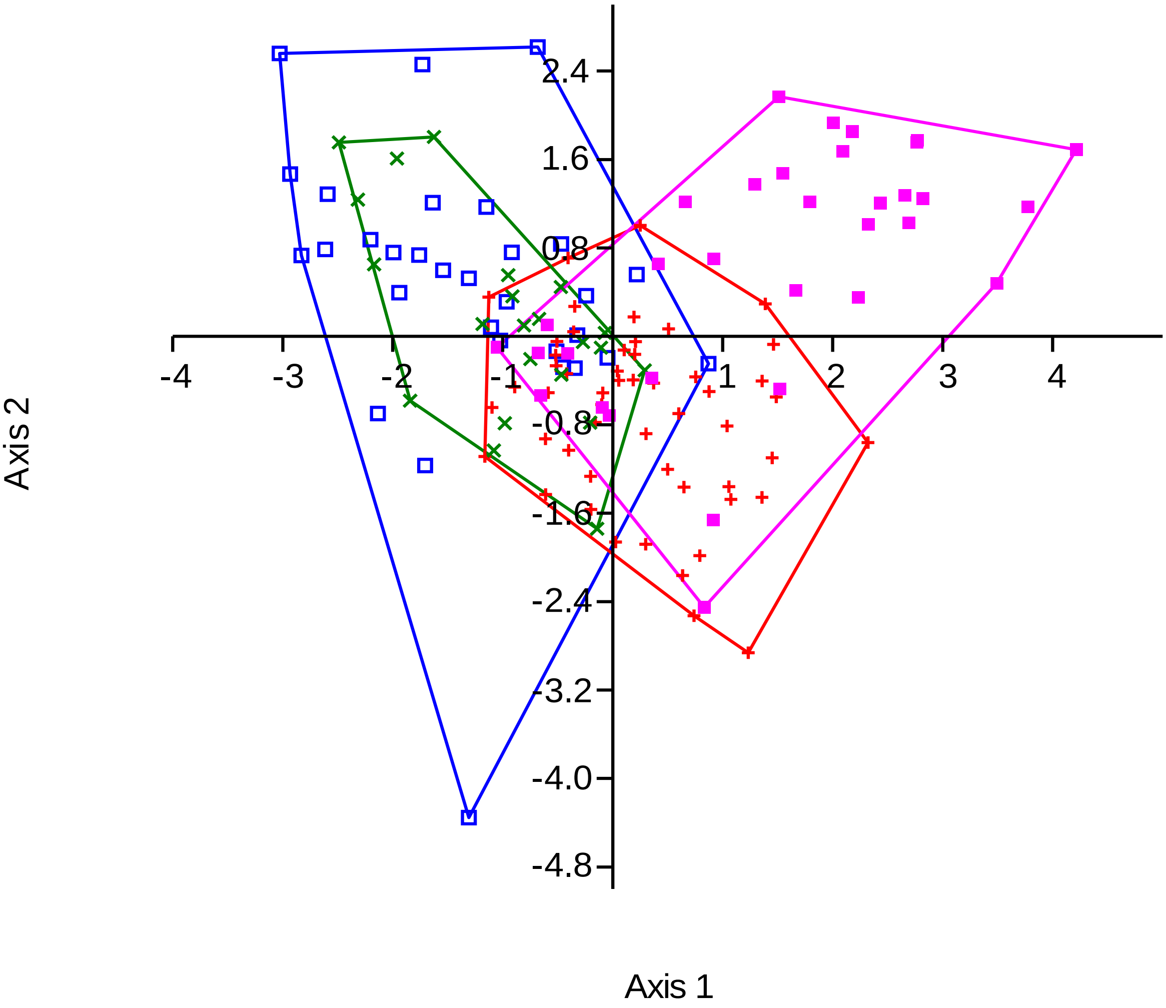
Figure 70. Clustering of midpelvic landmarks in the sex-populations groups

The variations observed in the midpelvis in the radiological sample were similar to those in the cadaver collection. Noticeably, there is great variation in the posterior aspect of the midpelvic shape. Females presented with a relatively wider shape than males. White females in particular, presented with wider midpelvic shapes when compared to black South African females.

5.2.3.4 Pelvic outlet

Figure 71 displays the graphs of the canonical variate analysis (CVA) with p-value between sex-population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.000

Figure 71. Comparison of the pelvic outlet shape between sex-population groups

Although the groups showed almost no separation on the CVA graphs, it was highly statistically significantly different. This is also the case for the pelvic outlet shape between each sex-population group with pairwise comparisons (Table 35). The shape of the pelvic outlet showed the greatest amount of difference when compared to all the other components of the pelvis.

Table 35. MANOVA pairwise comparisons between sex-population groups for the pelvic outlet

0	**BM**	**BF**	**WM**	**WF**
BM0	0	**< 0.0001**	**< 0.0001**	**< 0.0001**
BF	< 0.0001	0	**< 0.0001**	**< 0.0001**
WM	< 0.0001	< 0.0001	0	**< 0.0001**
WF	< 0.0001	< 0.0001	< 0.0001	0

Significant differences (< 0.05) between groups are indicated in **bold**

As noted in the confusion matrix (Table 36) black South African males and females were seldom misclassified (BF: 1/31; BM: 1/22), while white South African males and females were often misclassified (WF: 7/52; WM: 8/33).

Table 36. Confusion matrix for pelvic outlet shape between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	30	0	0	1	31
WF	1	45	6	0	52
BM	0	1	21	0	22
WM	1	2	5	25	33
Total	**32**	**48**	**32**	**26**	**138**

The shape of the pelvic outlet is visually represented by 3D points taken and is illustrated in Figure 72. Both lateral and superior views are shown. The points which outline the pelvic outlet taken are listed in Table 6. Clustering of the pelvic outlet shapes for each sex-population group is represented in Figure 73.

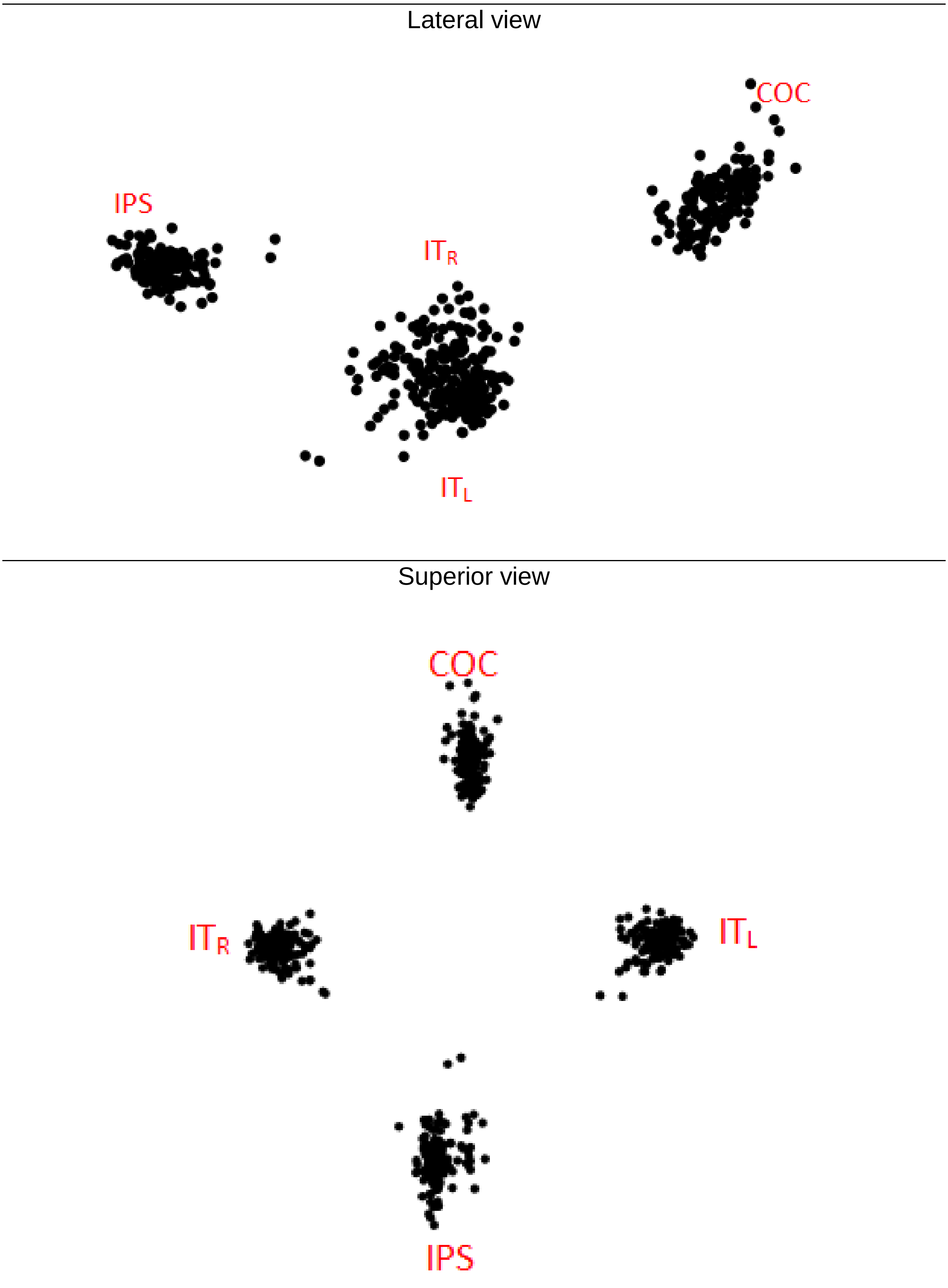


Figure 72. Visual representation of the clustering of the shape of the pelvic outlet in all individuals (Table 6)

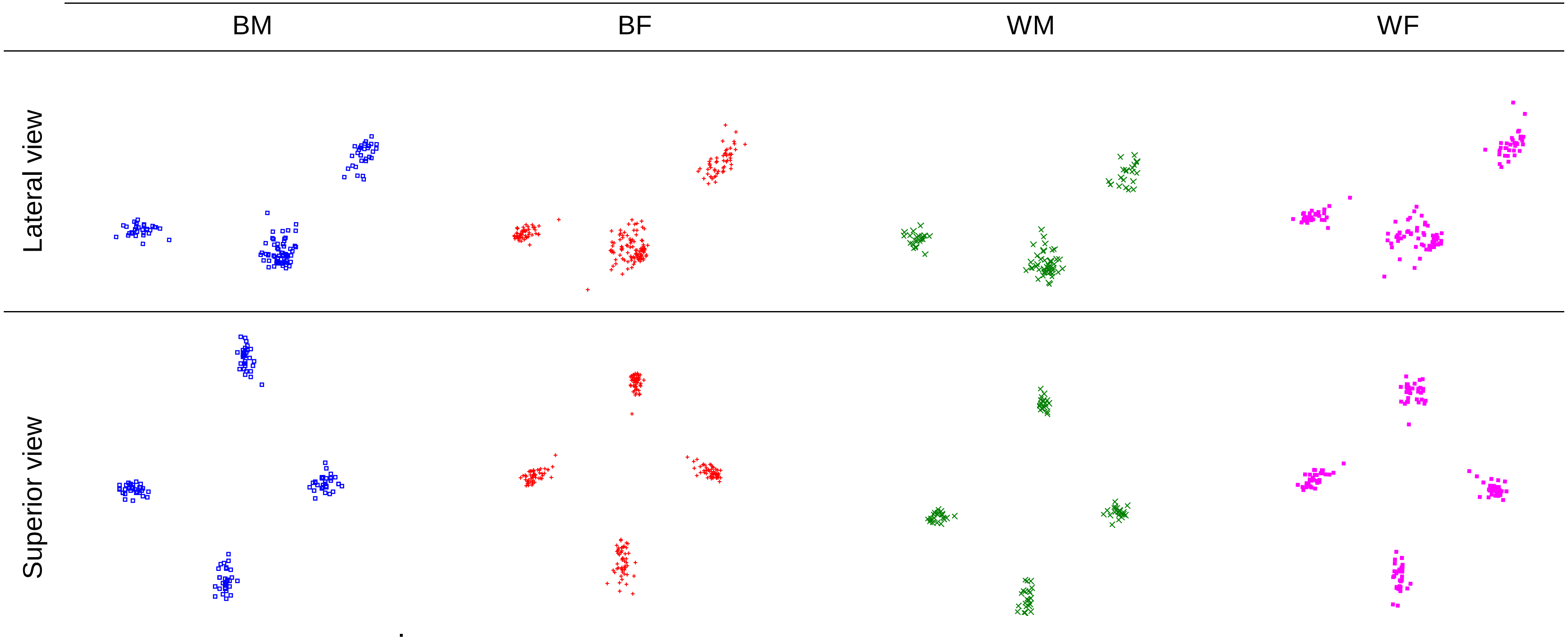


Figure 73. Clustering of pelvic outlet landmarks in the sex-populations groups

From an anterior view, the relative size of the urogenital triangle is larger in females. The relative transverse diameter to the anteroposterior diameter is also larger in females, thereby creating a broader outlet shape when compared to males. In white males, the urogenital triangle occupies a relatively smaller and flattened part of the entire pelvic outlet.

Males, as compared to females, and black South Africans, as compared to white South Africans, present with a further distance from the pubic symphysis to the ischial tuberosity, directed more posteriorly. Females in general, and white South African females specifically, present with a relatively wider shape and the more anteriorly placed widest diameter shows much variability in the placement of the ischial tuberosities as compared to other groups.

<u>Summary of sex and population variations in the shape analysis of radiological pelvic dimensions:</u>

The variations of the overall pelvic shape between the populations and sexes were highly statistically significant with a discriminant analysis separation of 95.65% accuracy between populations and 98.55% between sexes. The accuracy increased to 100% when population groups were considered separately. Pairwise comparisons could not demonstrate any statistically significantly differences between sex-population groups and the Mahalanobis distance failed. However, groups were very seldom misclassified.

There was a significant difference for the pelvic inlet shape in each sex-population group with pairwise comparisons, apart from black South African males compared to black South African females, as well as black South African males compared to white South African males. Sex-population groups were, however, often misclassified. Females presented with a large diameter across the pelvic brim. Males presented with more anteriorly projecting midpoints on the sacral promontory than females, especially white South African females.

The shape of the midpelvis showed a significant difference between sex groups within population groups, but not between population groups within each sex. Females presented with a relatively wider shape than males. White South African females in particular presented with wider midpelvic shapes when compared to black South African females. Black South Africans were less often misclassified than white South Africans.

The pelvic outlet shape exhibited the greatest extent of statistically significant comparisons between each sex-population group. Black South African males and females were seldom misclassified, while white South African males and females were more often misclassified. Males, as compared to females, and black South Africans, as compared to white South Africans, presented with a further distance from the pubic symphysis to ischial tuberosity which was directed more posteriorly. Females in general, and white South African females specifically, presented with a relatively wider shape and the more anteriorly placed widest diameter shows much variability in the placement of the ischial tuberosity, compared to other groups.

5.2.4 Shape analysis for crania

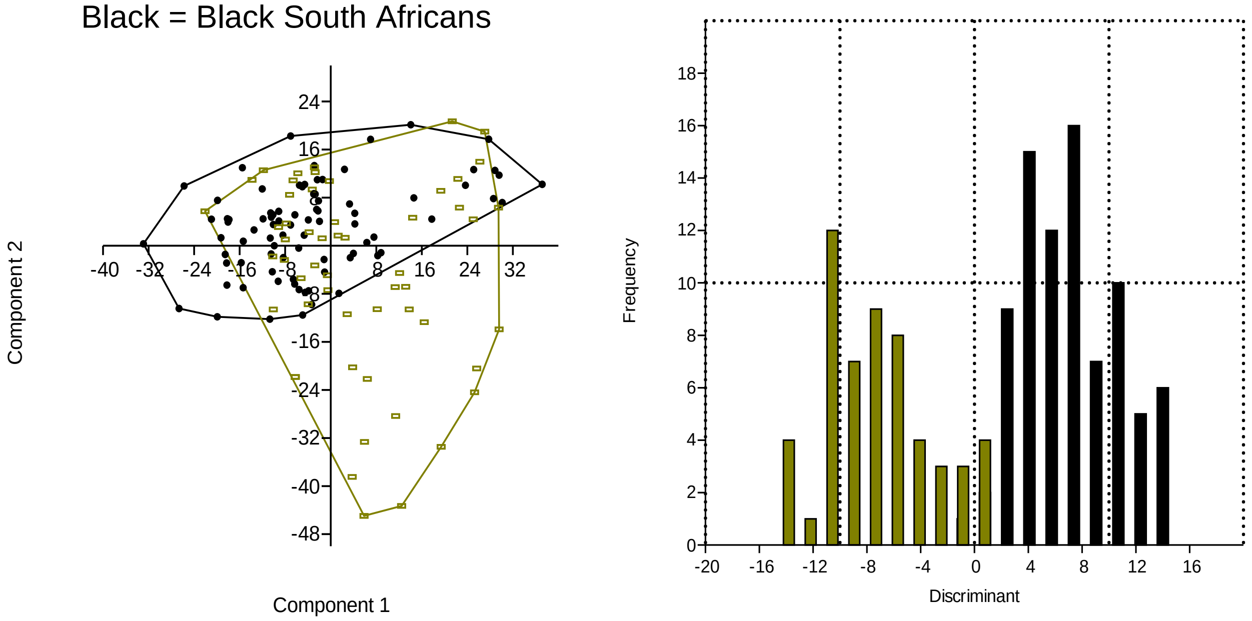
The overall shape of the cranium was analysed by standard geometric morphometric methods and discriminant function analysis to visualise the pattern of intra- and inter-group variations, and to test for statistical significance.

5.2.4.1 Comparison between populations and sexes

Figure 74 displays the graphs of the principal component analysis (PCA) with p-value, as well as the discriminant analysis with classification accuracy of each comparison within the entire sample, as indicated. There is a distinct separation of the population groups on the PCA graphs, while the sexes did not visually clearly separate. The variations of the overall cranial shape between the populations were highly statistically significant with a discriminant analysis separation of 96.38% accuracy. The variations between the sexes were also significant, with discriminant analysis separating the sexes with 74.65% accuracy.

Comparison of the cranial shape between populations within the entire sample:

Khaki = White South Africans
Black = Black South Africans

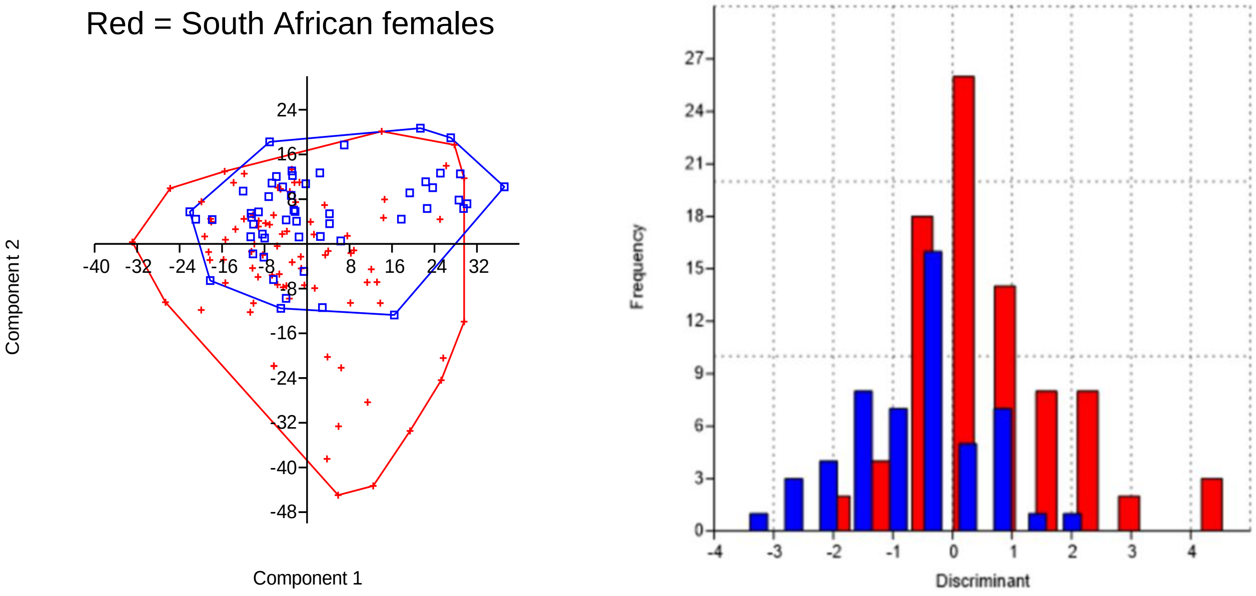


PCA: p = 0.0005

Discriminant function analysis: 96.38% correctly classified

Comparison of the cranial shape between sex groups within the entire sample:

Blue = South African males
Red = South African females



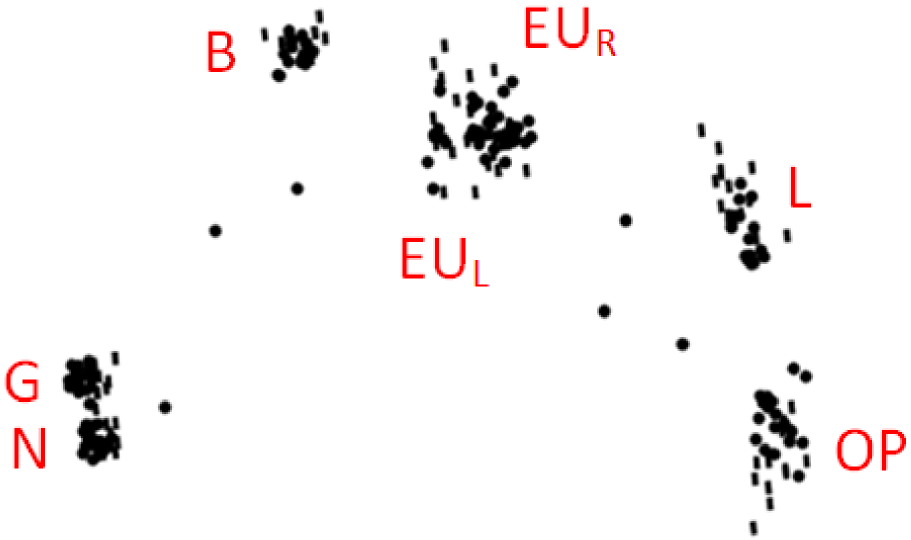
PCA: p = 0. 0.0005

Discriminant function analysis: 74.65% correctly classified

Figure 74. Comparison of the cranial shape dimensions between population groups and between sexes

Visual representation of the clustering of the landmarks representing the cranial shape in all individuals is illustrated in Figure 75 and in Figure 76, landmarks are colour-coded to indicate the comparison between populations and sexes, respectively. Both lateral and superior views are shown. The points used to outline the cranial shape, are listed in Table 7.

Lateral view



Superior view

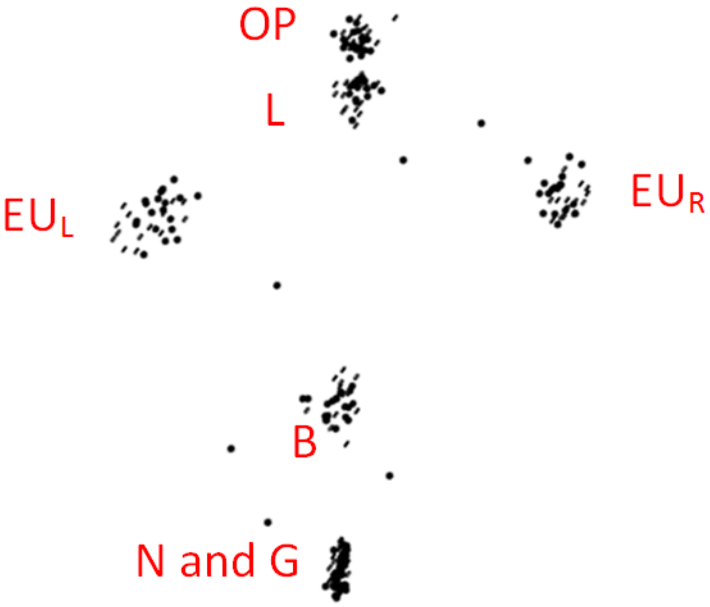


Figure 75. Visual representation of the clustering of the shape of the cranial in all individuals

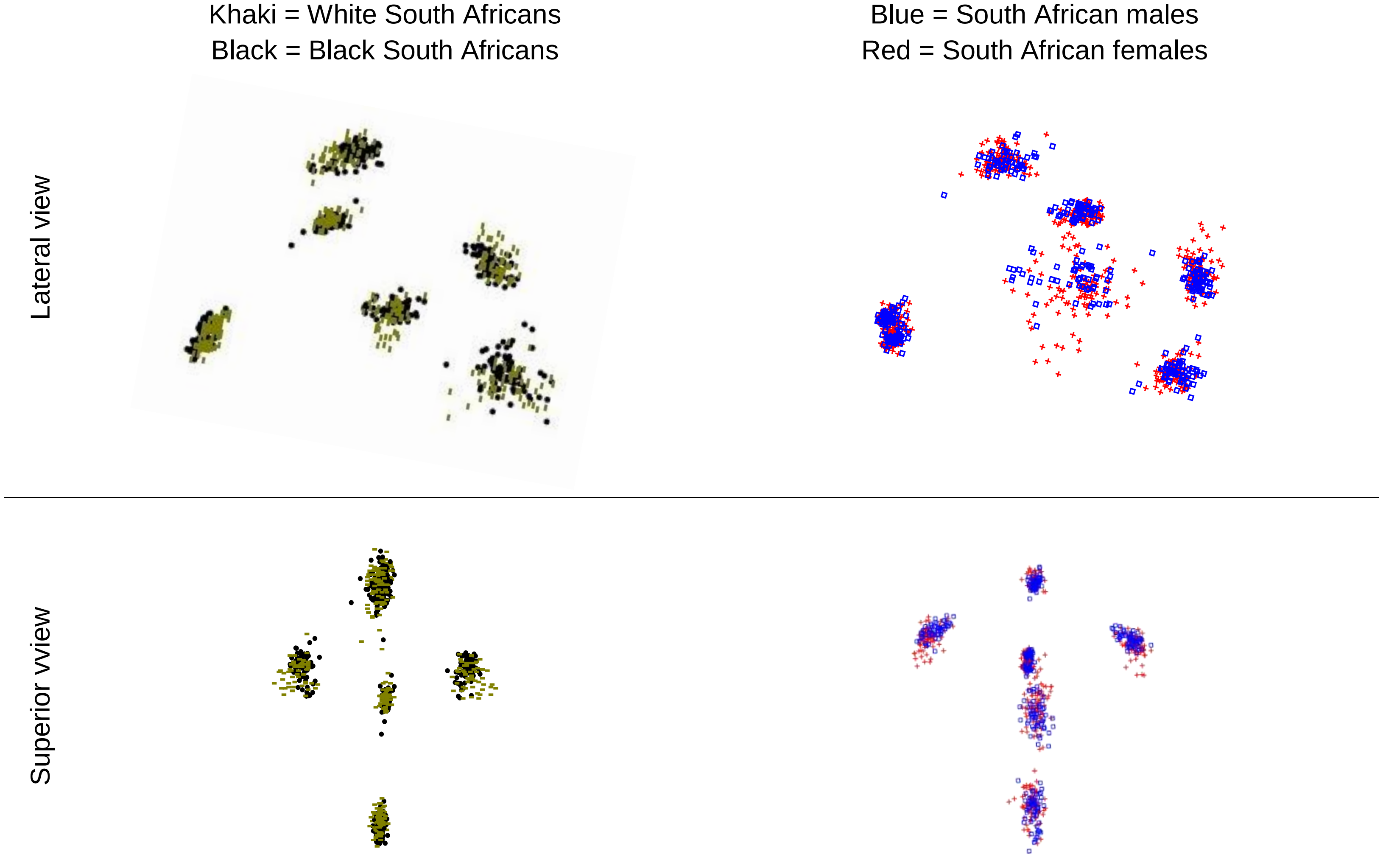


Figure 76. Comparison of the overall cranial shape between populations and sexes within the entire sample

It is shown that black South Africans have a relatively narrower cranium as compared to its width, than white South Africans. White South African also presented with a longer cranial length. The BPD from a superior view showed a wider dimension in the white South African population when compared to the black South African group.

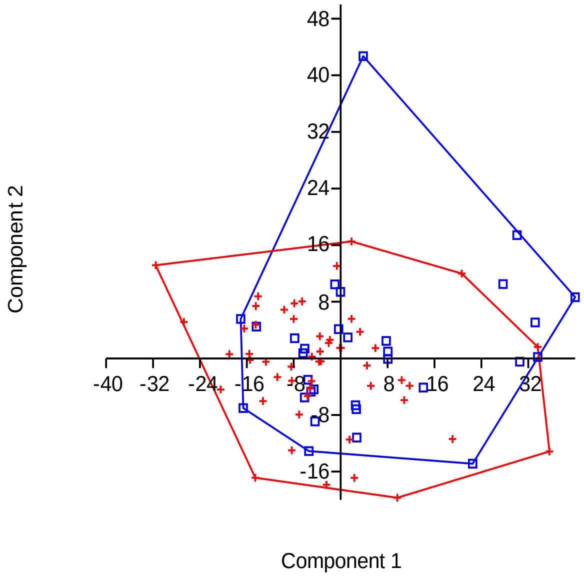
While the widest distance across the cranium was placed more posteriorly in black South Africans than in white South Africans, white South African females presented with a more globular cranial shape. From a lateral view, males presented with a longer cranial height when compared to females. .

5.2.4.2 Comparison between sexes within population groups

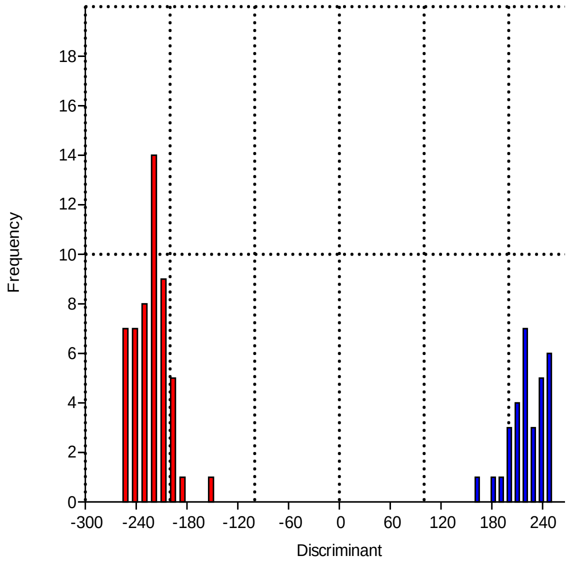
Figure 77 displays the graphs of the principal component analysis (PCA) with p-value, as well as the discriminant analysis with classification accuracy of each comparison between sexes within each population group, as indicated. The groups showed some separation on the PCA graphs and were highly significant between the sexes for the overall cranial shape in each population group. In addition, a discrimination of 100% was noted between the sexes within each population group.

Comparison of the cranial shape between black South African males and females:

Red = BF
Blue = BM



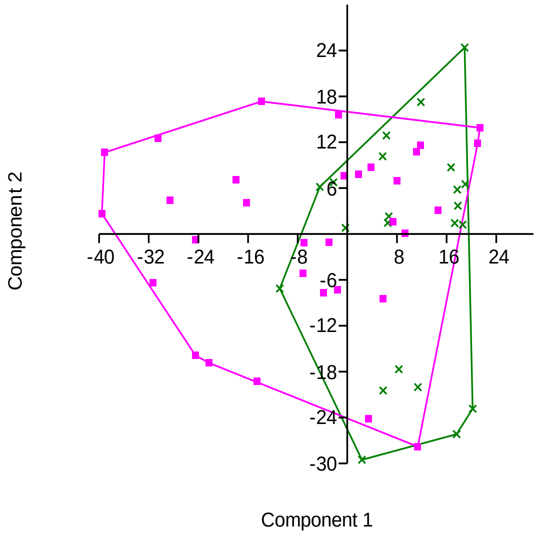
PCA: p = 0.0115



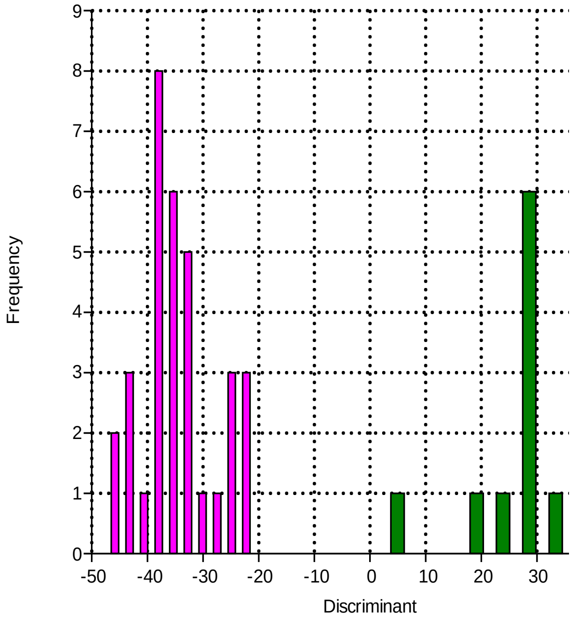
Discriminant function analysis: 100% correctly classified

Comparison of the cranial shape between white South African males and females:

Green = WM
Pink = WF



PCA: p = 0.0005



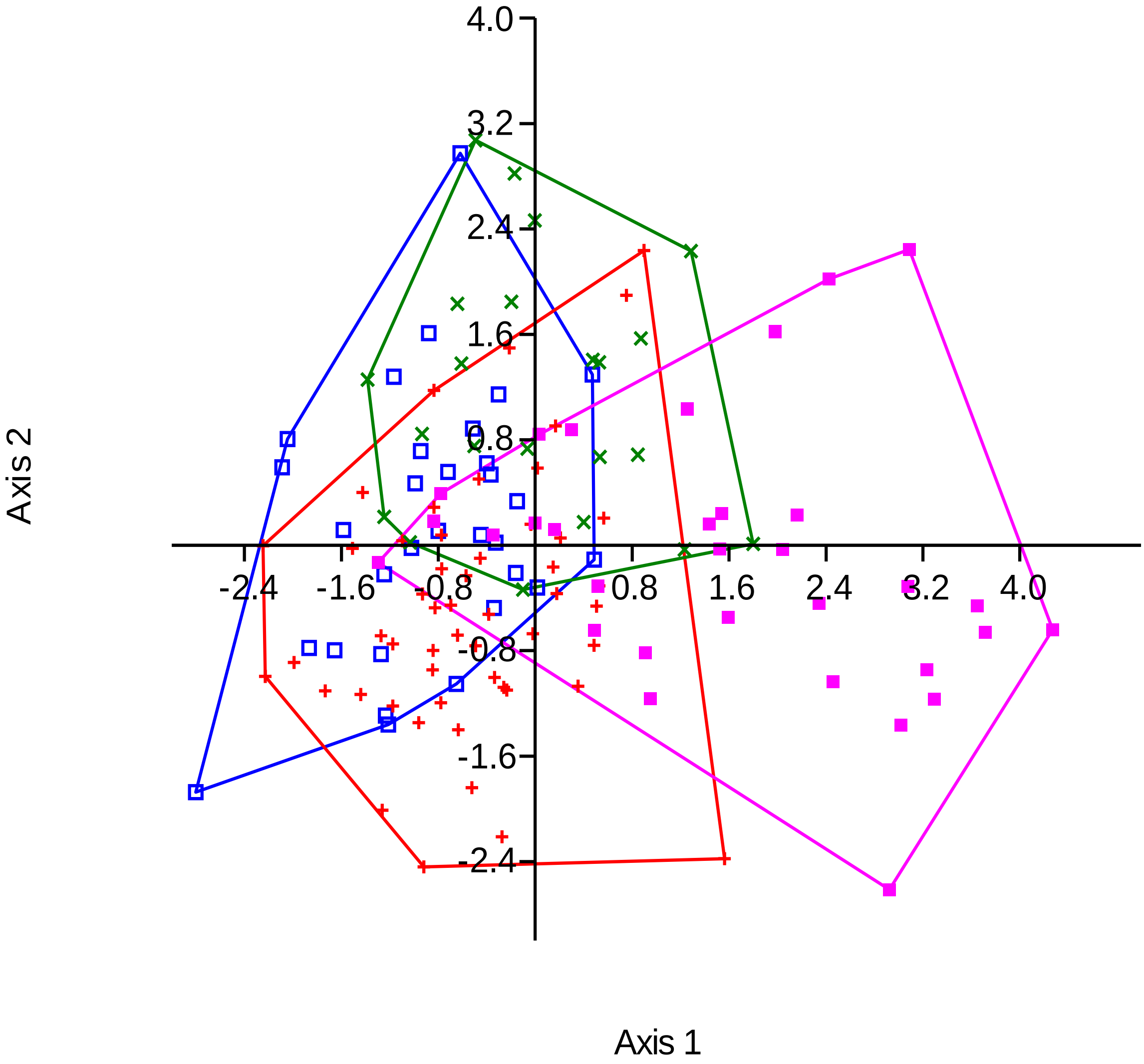
Discriminant function analysis: 100% correctly classified

Figure 77. Comparison of cranial shape dimensions between sexes within populations

5.2.4.3 Comparison between sex-population groups

Figure 78 displays the graphs of the canonical variate analysis (CVA) with p-value between sex-population groups as indicated.

Pink= WF
Green= WM
Blue= BM
Red= BF



CVA: p = 0.0000

Figure 78. Comparison of the cranial shape between sex-population groups

The groups showed an incomplete separation on the CVA. The overall cranial shape of white South African females differed significantly from the black South African population groups with pairwise comparisons (Table 37).

Table 37. MANOVA pairwise comparisons between sex-population groups for the cranial shape

0	**BM**	**BF**	**WM**	**WF**
BM0	0	1	1	**0.0008**
BF	1	0	0.1464	**< 0.0001**
WM	1	0.1464	0	0.1926
WF	0.0008	< 0.0001	0.1926	0

Significant differences (< 0.05) between groups are indicated in **bold**

However, as can be noted in the confusion matrix (Table 38), sex-population groups were often misclassified (BF: 13/33; WF: 13/46; BM: 16/32; WM: 4/27).

Table 38 . Confusion matrix for overall cranial shape between sex-population groups

Given groups→ Predicted groups↓	**BF**	**WF**	**BM**	**WM**	**Total**
BF	20	7	4	0	31
WF	9	33	8	2	52
BM	1	3	16	2	22
WM	3	3	4	23	33
Total	**33**	**46**	**32**	**27**	**138**

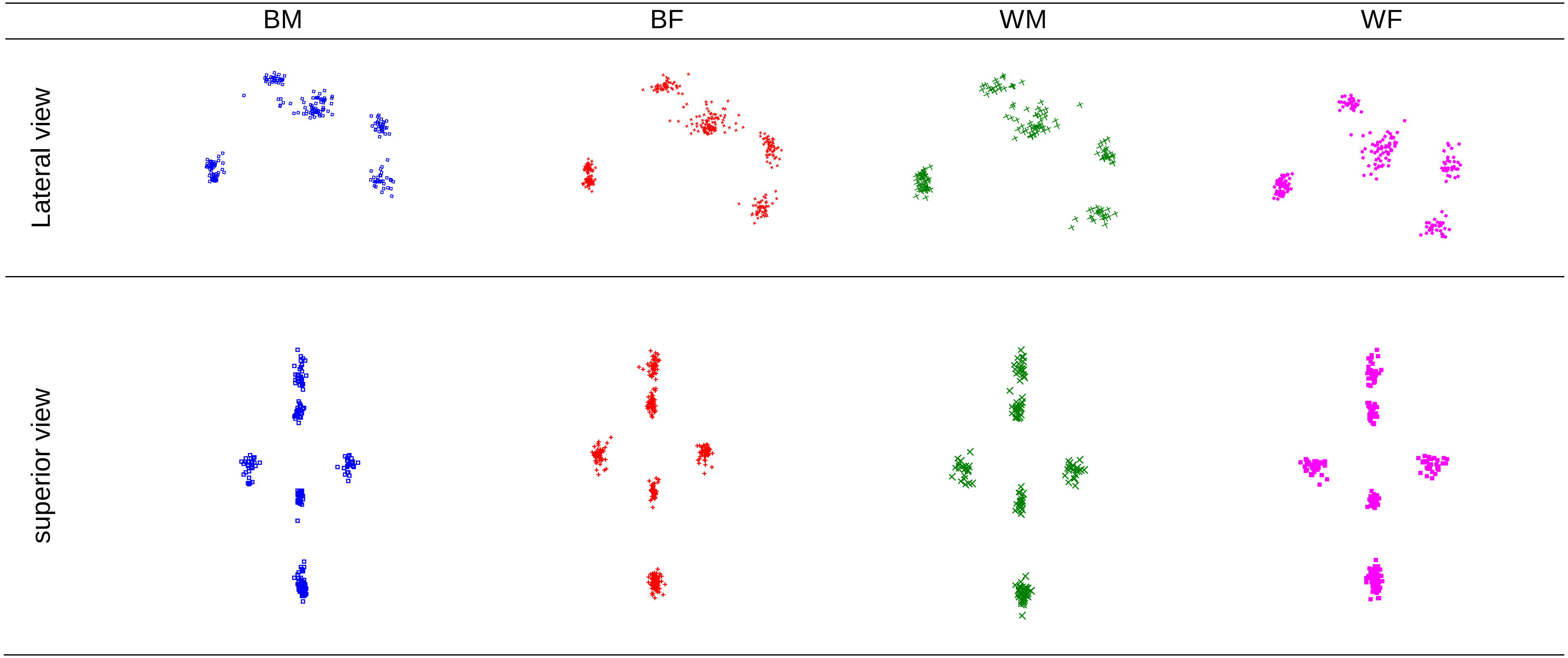


Figure 79 . Clustering of cranial landmarks in the sex-populations groups

Summary of sex and population group variations in the shape analysis of radiological cranial dimensions:

The variations of the overall cranial shape between the populations and sexes were statistically significant with a discriminant analysis separation of 96.38% accuracy between populations and a 74.65% accuracy between sexes. The white population has a relatively wider shaped cranium, with the widest distance more anteriorly placed when compared to the black South African group, while females compared to males, presented with a wider and shorter cranium. From a lateral view, males presented with a longer cranial height when compared to females. In each population group comparisons between sexes were highly significant with a 100% discrimination. The cranial shape showed statistically significant differences within the female group and between white South African females and black South African males. From the confusion matrix, black South African males were often misclassified as white South African females and white South African females sometimes misclassified as black South African females.

5.2.5 Integration of cadaver and radiological linear and shape variations noted in the pelvis

Apart from the subpubic angle which was marginally wider in the cadaver group, cadaver linear measurements were, in general, smaller than the radiological measurements.

All cadaver and radiological pelvic linear dimensions were greater in females than in males, and in white South Africans compared to black South Africans. All relationships were statistically significant when considering the sexes, apart from the DC of the pelvic inlet which was greater in males, and the OC which was greater, but not statistically significant so, in females. All comparisons between populations were statistically significant, apart from the subpubic angle. Shape analyses on the cadaver and radiological collection revealed highly significant relationship between sexes and population groups in the overall pelvic shape.

All cadaver and radiological pelvic linear dimensions were greater in white South African females than those in black South African females, and in white South African males as compared to black South African males. When comparing the sexes within population group, both white South African females and black South African females presented with greater dimensions when compared to white South African males and black South African males, respectively, apart from the DC. The DC was smaller in white South African females than in white South African males and greater in black South African females compared to black South African males for the cadaver measurements, while for the radiological dimensions, the DC was smaller in black South African females than in black South African males, and greater in white South African females compared to white South African males. Statistically significant comparisons varied between the radiological and the cadaver sample, possibly because of the different numbers in each sex-population group.

The number of statistically significant comparisons between the sex-population group shape variations increased while progressing through the birth canal. Significant differences for the pelvic inlet shape were noted between black South African females and white South African males, representing the extremes between population and sex group for the cadaver data. In the radiological sample, all sex-population group comparisons, apart from black South African males and black South African females, as well as black South African males and white South African males, were statistically significant. Females, especially white South African females, presented with more posteriorly located midpoints on the sacral promontory, with the WTI diameter situated relatively more anteriorly than in males (round vs heart-shaped inlets). The heart-shaped pelvic inlet in males presented with transversely narrower pelvic inlets with the greatest transverse diameter at a more posterior position, possibly denoting a relatively smaller anterior pelvis in males, especially in black South African males.

Shape variation of the midpelvis was statistically significantly different between all sex-population group comparisons, except between black South African and white South African females. Females presented with a relatively wider shape than males. White South African females in particular, presented with wider midpelvic shapes when compared to black South African females. A more prominent sacral hollow and a relatively more spacious posterior aspect between the sacral notch and the sacro-iliac joint, wider placed ischial spines and a wider angle between the symphysis pubis and the obturator canal were noted in females, as compared to males, especially black South African males.

For the pelvic outlet all sex-population comparisons were highly statistically significant. Although from an inferior view, females, in general, and white South African females, especially, had a relatively shorter distance from the pubic symphysis to the ischial tuberosity and was directed more vertically. White South African females presented with a generally wider shape and a relatively more anteriorly placed IT diameter. From the lateral view the coccyx was directed more posteriorly and downwards in black South African females than other groups. White South African males presented with an almost symmetrical diamond shape on inferior view as reflected in the size of the urogenital triangle approximating the anal triangle. Black South African males presented with a relatively more inferiorly placed ischial tuberosity, as noted on lateral view.

Considering pelvic linear dimensions for the entire cadaver sample, prediction of population group was more accurate (85.33%) than sex (78.00%). With a greater representation of black South African females in the radiological collection, prediction of sex was more accurate (87.68%) than population group (80.43%). These accuracies improved to 97.87% (cadaver sample), 95.65% (radiological sample) for population groups and 94.67% (cadaver sample) and 98.55% (radiological sample) for sexes, using shape variations.

When considering linear measurements for sex group separately, accuracies for population groups was 86.49% (males in the cadaver sample) and 79.25% (males in the radiological sample), while 85.53% (females in the cadaver sample) and 83.5% (females in the radiological sample). When considering shape variations, accuracy improved to 100% between sexes and populations when considering, respectively, populations and sexes separately.

Sex discrimination of the linear measurements, when considering populations separately was 85.07% (Black South Africans cadaver sample), 89.16% (Black South Africans radiological sample), 82.93% (White South Africans cadaver sample) and 96.36% (White South Africans radiological sample). A 100% accuracy was achieved when evaluating shape variations between sexes and populations, respectively, when considering populations and sexes separately on the cadaver and radiological sample.

When considering shape variations for each sex-population individually in the cadaver and the radiological sample for the overall pelvic shape, groups separated on the CVA graphs and were seldom misclassified. Variations in the shape of the pelvis involved more correct sex-population group classifications when progressing through the pelvic canal: from pelvic inlet to pelvic outlet in females (cadaver and radiological sample) and males (radiological sample). In the cadaver sample, males had the highest correct classification for the shape of the midpelvis.

5.2.6 Integration of cadaver and radiological linear and shape variations noted in the cranium

The radiological sample presented with larger measurements as compared to the cadaver sample with statistically significant comparisons by non-parametric testing for cranial height and BPD, but not for cranial length. However, the cadaver sample was small (n=33) and not well represented for all groups (e.g. 6 white South African male samples).

In both cadaver and radiological samples, black South Africans generally presented with smaller cranial dimensions (of which BPD and head circumference were statistically significantly smaller, as well as BPD/MaxCL), apart from the cranial length, which was statistically significantly greater in the radiological sample when compared to the white South African population. Cranial length was also statistically significantly greater in males compared to females and cranial height was statistically significantly greater in males than in the radiological sample. On the other hand, males presented with a smaller BPD compared to females, which was statistically significant between sexes in the radiological sample with a statistically significantly smaller BPD/MaxCL ratio.

White South African males presented with larger distances in all cranial dimensions when compared to black South African males, although the BPD/Head circumference ratio was the same. Similarly, white South African females presented with greater distances in all cranial dimensions and ratios when compared to black South African females, apart from the greatest cranial length as reflected in the larger BPD/Head circumference ratio seen in white South African females. White South African males presented with the largest cranial dimensions, except at the BPD and the BPD/Head circumference ratio, which was greater in white South African females. Black South African males reported overall non-significantly larger distances than black South African females. This is reflected in the similar BPD/Head circumference ratio seen between the two groups.

In summary, the black South African male and female population groups presented with an overall longer (anteroposteriorly) and narrower (transversely) shaped cranium when compared to the white South African male and female groups, respectively, resulting in a more globular-shaped cranium in especially white South African females as reflected in the larger BPD/MaxCL ratio. Cranial height (supero-inferiorly) was smaller in black South African females as compared to white South African females in the cadaver sample, but vice versa for the radiological sample. In both sample groups black South African males presented with a shorter cranial height than white South African males. From the shape analysis it was clear that the BPD in black South Africans were placed more posteriorly than in white South Africans.

The variations in the overall cranial shape between the populations were highly statistically significant in both cadaver and radiological samples, but between sexes, only significant in the radiological sample. The variations of the overall cranial shape between the populations and sexes were statistically significant. The cranial shape in the cadaver sample did not differ significantly between each sex-population group with pairwise comparisons, but in the radiological sample the cranial shape showed strong statistically significant differences within the female group, as well as between white South African females and black South African males.

Prediction of population group was more accurate (94.12%) in the cadaver sample than in the radiological sample (65.22%), while the prediction of sex was 88.24% in the cadaver group and 69.57% in the radiological sample. However, discrimination function analysis completely (100%) separated sexes within population groups and population groups within sex groups in both the cadaver and radiological samples.

The variations of the overall cranial shape between the populations were highly statistically significant in the cadaver and in the radiological samples with discriminant analysis separations of 94.12% (cadaver sample) and 96.38% (radiological sample). The variations between the sexes were not significant in the complete cadaver sample, but were in the complete radiological sample. The discriminant accuracy was, however, 100% for sex in the cadaver sample and 74.65% in the radiological sample.

In each population group, comparisons between sexes in both cadaver and radiological samples were highly significant with a 100% discrimination. The cranial shape showed strong statistical differences within the female group and between white South African females and black South African males.

5.2.7 Correlation between cranial and pelvic data

5.2.7.1 Linear cranial dimensions vs linear pelvic dimensions

Least square regressions were presented for each sex population group's pelvic and cranial shape dimension to demonstrate a relationship. Only r-values that showed a moderate to strong positive or negative correlation ($r > 0.5$) and significant p values ($p < 0.05$) were reported in Table 39.

Table 39. Correlations between linear cranial dimensions and linear pelvic dimensions

	Pelvic inlet			Midpelvis		Pelvic outlet		
Linear pelvic dimensions→ Linear cranial dimensions↓	**TC**	**Widest transverse distance**	**Diagonal conjugate**	**Obstetric conjugate**	**Interspinous diameter**	**Anteroposterior distance**	**Intertuberous distance**	**Subpubic angle**
Cranial height	**0.45*** **0.35***							
MaxCL								***0.31****
Biparietal diameter						**-0.45*** **0.07***		
BPD/ MaxCL					**0.05***			

BF, WF, BM, WM, Black South Africans, White South Africans, South African males, South African females

r values are indicated in **bold**

p < 0.05 is indicated with *

In Table 39, only a few correlations between linear cranial dimensions and linear pelvic dimensions were significant, notably cranial height in the South African male group as a whole and white South African males separately when correlated to the TC, while biparietal distance presented with a moderately negative relationship for the anteroposterior pelvic outlet distance in males. The maximum cranial length correlated mildly, but significantly, with the subpubic angle in black South African females, while the BPD/MaxCL correlated mildly significantly with the IS in females.

5.2.7.2 Linear cranial dimensions vs pelvic shapes

All cranial and pelvic dimensions between each sex-population group, population and sexes, were correlated by means of ordinary least squares regressions. Only r-values that showed a moderate to strong positive or negative correlation (r≥0.5) and significant p values (p<0.05) were reported in Table 40.

Table 40. Correlations between pelvic shape and cranial linear dimensions

Linear cranial dimensions→ Pelvic shape↓	**Cranial height**	**MaxCL**	**biparietal diameter**	**BPD/ MaxCl**
Overall pelvic shape				**0.50** *(0.02)* **0.37** *(0.01)*
Pelvic inlet			**0.37** *(0.03)*	
Midpelvis	**0.29** ***(**0.04)* **0.23** *(0.03)* **0.21 (**0.06)		**0.38** *(0.01)*	**0.37** *(0.01)*
Pelvic outlet	**0.32** *(0.02)* **0.65** *(0.00)*		**0.41** *(0.01)* **0.33** *(0.00)*	**-0.64** *(0.00)* **0.31** *(0.00)*

BF, WF, BM, WM, Black South Africans, South African Whites, South African males, South African females

r values > 0.50 are indicated in **bold**

p < 0.05 is indicated in *(italics)*

When understanding the r- and p-values as presented in Table 29, certain trends were noted in each sex, population or sex-population group. In females as a group, weak positive significant relationships were noted between cranial height and the midpelvis, and the BPD and the BPD/MaxCL and the pelvic outlet. Males, as a group, as well as black South African males, did not illustrate any strong or significant relationships between the pelvic shapes and the cranial linear dimensions.

Black South Africans as a group showed a weak positive, albeit not significant, relationship between the cranial shape and the midpelvis, while white South African South Africans showed a weak postive statistically significant relationship beween the BPD/MaxCL and the overall pelvic shape.

In the black South African female group, the cranial height, BPD and BPD/MaxCL each showed a weak positive and statistically significant correlation to the shape of the midpelvis. Additionally, the BPD showed a mild postive significant relationship to the pelvic outlet, white South African females showed a statistically significant weak to moderately positive relationship between the BPD and the pelvic inlet and outlet shapes, respectively.

The BPD/MaxCL in white South African males displayed a moderately positive significant relationship to the overall pelvic shape, and a moderately negative significant correlation to the pelvic outlet. The pelvic outlet also showed a moderately positive significant relationship to the cranial height.

5.2.7.3 Shape of crania vs shape of pelvis

Lastly the shape of the crania versus the shape of the pelvis was correlated by two block partial least squares analysis and the squared covariance percentage recorded (Table 41).

Table 41. Summary of two block partial least squares analysis between cranial shape and overall pelvic shape recording squared covariance percentage

Pelvic shape dimensions→ Cranial shape ↓	**Overall pelvic shape**	**Pelvic inlet**	**Midpelvis**	**Pelvic outlet**
BF	**3.53** *3.38*	**2.85** 3.09	**3.71** *3.80* [g]	**4.76** *4.09* [p]
WF	**4.18** *5.30*	**3.36** [d] 4.53	**4.99** *6.99* [h]	**3.71** [q] *7.33*
BM	**4.05** *4.02*	**4.13** 4.22	**3.71** *3.80* [i]	**6.13** *6.51*
WM	**4.99** *5.30*	**4.58** 5.44	**4.79** [j] *5.51* [k]	**6.19** *5.93*
Black South Africans	**2.44** *2.75*	**2.60** 2.91	**2.50** *3.14* [l]	**4.20** 4.80
White South Africans	**3.21** *4.13* [a]	**3.23** 4.15 [e]	**3.59** [m] *5.32* [n]	**3.26** 5.60
South African Males	**2.81** *2.81* [b]	**2.91** 3.03	**2.61** *3.18*	**4.82** *4.70*
South African Females	**3.25** *3.63* [c]	**2.70** 3.26 [f]	**3.48** *4.10* [o]	**4.11** *4.92*

The variance- covariance matrix (VC) is indicated in **bold**
The correlation matrix (C) is indicated in *italics*

The statistical significant covariances noted:
a: axis 2 accounting for 31.51% of the co-variation, p value = 0.01
b: axis 6 accounting for 4.90% of the co-variation, p value = 0.04
c: axis 2 accounting for 31.85% of the co-variation. p value = 0.03
d: axis 2 accounting for 28.50% of the co-variation. p value = 0.05
e: axis 2 accounting for 30.15% of the co=variation, p value = 0.02
f: axis 2 accounting for 30.68% of the co-variation, p value = 0.03
g: axis 2 accounting for 31.46% of the co-variation. p value = 0.03
h: axis 2 accounting for 63.95% of the co-variation. p value = 0.04
i: axis 2 accounting for 31.46% of the co-variation, p value = 0.01
j: axis 4 accounting for 7.19% of the co-variation, p value = 0.05
k: axis 3 accounting for 19.04% of the co=variation, p value = 0.03
l: axis 2 accounting for 34.33% of the co-variation, p value = 0.01
m: axis 2 accounting for 32.90% of the co=variation, p value = 0.04
n: axis 2 accounting for 32.32% of the co-variation. p value = 0.02
o: axis 2 accounting for 35.12% of the co=variation, p value = 0.01
p: axis 2 accounting for 36.61% of the co-variation. p value = 0.01
q: axis 4 accounting for 8.41% of the co-variation, p value = 0.01

Many significant covariations were noted when comparing the cranial shape with the pelvic shape in the radiological sample. The most important co-variances, i.e. those contributing to the highest percentage of covariance and in the correlation matrix, seemed to be in white South Africans and in females. The midpelvic shape demonstrated the greatest incidences of covariation with the cranial shape, apart from males.

5.2.8 Integration of cadaver and radiological correlation between cranial and pelvic data

When considering the linear measurements of the crania in females, the head circumference and the BPD showed correlations with many linear measurements of the pelvis. In males, however, the head circumference was important, while BPD had a negative correlation.

For the cadaver sample, females, as a group, presented with moderate and statistically significantly positive relationships between the BPD and head circumference on the one hand, and the TC, DC, OC and the intertuberous distance on the other hand. In white and black South African females respectively, head circumference had a strong statistically significant relationship with the TC and the OC. In the radiological sample, the maximum cranial length correlated mildly but significantly with the subpubic angle in black South African females, while the BPD/MaxCL correlated mildly significantly with the IS in females.

In the male cadaver sample, head circumference was moderately and statistically significantly correlated to all pelvic dimensions, except for the interspinous distance. In the radiological sample, cranial height in males and white South African males were statistically significantly correlated to the TC, while biparietal distance presented with a moderately negative relationship for the anteroposterior pelvic outlet distance in white South African males.

In white South Africans, as a group, the cranial height was moderately and statistically significantly related to the anteroposterior distance of the pelvic outlet. There were no statistically significant correlations between linear cranial and pelvic dimensions in black South Africans as a group.

In the radiological sample, the white South African group, and more specifically white South African males, displayed a statistically significant relationship beween the BPD/MaxCL and the overall pelvic shape. Black South Africans in the cadaver sample showed statistically significant correlations between the BPD and the midpelvis, while cranial length and head circumference correlated to the pelvic outlet shape.

In the radiological sample in females, as a group, correlations were found between cranial height and the midpelvis, as well as the BPD and the BPD/MaxCL to the pelvic outlet, while white South African females showed a statistically significant relationship between the BPD and the pelvic inlet and outlet shapes, respectively. In the black South African female cadaver group, the head circumference showed a significant relationship to the pelvic outlet shape, while the cranial length showed a strong positive statistically significant relationship to the shape of the pelvic inlet. In the radiological black South African female group, the cranial height, BPD and BPD/MaxCL each showed a significant correlation to the shape of the midpelvis. Additionally, the BPD also showed a mild postive significant relationship to the pelvic outlet.

In males, as a group, mild positive statistically significant correlations existed between the head circumference and the pelvic inlet shape, and the cranial height and the midpelvic shape. The shape of the midpelvis displayed a strong positive significant correlation to the cranial height in black South African males. The BPD/MaxCL in white South African males displayed a moderately postive significant relationship to the overall pelvic shape, and a moderately negative significant correlation to the pelvic outlet. The pelvic outlet also showed a moderately positive significant relationship to the cranial height

In the cadaver sample, the statistical significant covariances noted between the shape of the crania and the pelvis were confined to female groups: for the pelvic inlet and midpelvis, as well as the pelvic outlet in the black South African female group. Many significant covariations were noted when comparing the cranial shape with the pelvic shape in the radiological sample. Significant covariances for overall pelvic shape were noted in white South Africans as a group, and in males and females in isolation. The pelvic inlet had significant covariances for white South Africans, white South African females and females as a group. The midpelvic shape demonstrated the greatest incidences of covariation with the cranial shape, apart from in the male group. The pelvic outlet had a significant covariance in black South African females only.

5.3 Patient sample

5.3.1 Analysis of maternal and foetal linear dimensions

In Table 42, it can be noted that of the 89 mothers studied, 29 mothers delivered by caesarean section, while 60 delivered vaginally. Of those that delivered by caesarean section, 20 were white South African women and nine were black South African women, whereas for the vaginal deliveries, 40 of the 60 women were black South Africans and 20 of the 60 were white South Africans.

The mean values in Table 42 indicate that the black South African mothers who had a vaginal delivery had the greatest BPD, maternal BPD/Head circumference ratio, foetal adjusted ratio and the longest duration of active labour, as compared to the other three groups. Black South African mothers who delivered vaginally were also non-significantly taller than black South African mothers who had a caesarian section. Of the black South African women who delivered vaginally of which the duration of labour was known (thirteen in total), the average duration of active labour was 764 minutes. Of the white South African women who delivered vaginally of which the duration of labour was known (ten in total), the average duration of active labour was 728 minutes. Differences in vaginal delivery were not statistically significant.

The white South African vaginal delivery group presented with the smallest maternal BPD and head circumference, while having the greatest stature, newborn head circumference and length. On the other hand, the white South African caesarean group presented with the greatest maternal head circumference, while the newborn head circumference and length was the smallest.

Table 42. Observations on the patient sample

	Parameters	**BF (C/S)**	**WF (C/S)**	**All C/S**	**BF (V/D)**	**WF (V/D)**	**All V/D**	**BF**	**WF**
Maternal parameters	BPD [BPD] (mm)	9 **139.78** *9.63* (129.00 - 154.00)	20 **141.20** ^{bdf} *5.58* (130.00 – 150.00)	29 **140.76** ^{efi} *6.93* (129.00 – 154.00)	26 **148.23** *7.91* (135.00 – 160.00)	11 **137.91** ^{cdh} *7.41* (130.00-150.00)	37 **145.16** ^{fghi} *9.03* (130.00 – 160.00)	35 **146.06** ^{ace} *9.05* (129.00 - 160.00)	31 **140.03** ^{abg} *6.37* (130.00 – 150.00)
	Head circumference (mm)	9 **578.89** *22.46* (548.00 – 620.00)	21 **579.33** *20.40* (540.00 – 620.00)	30 **579.20** *20.65* (540.00 – 620.00)	40 **570.25** *23.49* (525.00 – 630.00)	20 **563.75** *22.88* (530.00-610.00)	60 **568.08** *23.30* (525.00 – 630.00)	49 **571.83** *23.32* (525.00 -630.00)	41 **571.73** *22.78* (530.00 – 620.00)
	Maternal ratio (BPD/ head circumference)	9 **0.24** *0.02* (0.22 - 0.27)	20 **0.24** ^{b} *0.01* (0.22 - 0.28)	29 **0.24** ^{d} *0.02* (0.22 - 0.28)	26 **0.26** ^{abcd} *0.01* (0.24 - 0.29)	11 **0.24** ^{c} *0.01* (0.22-0.26)	37 **0.25** *0.02* (0.22 - 0.29)	35 **0.26** *0.02* (0.22 -0.29)	31 **0.24** ^{a} *0.01* (0.22 - 0.28)
	Stature (cm)	9 **160.00** *6.82* (144.00 - 168.00)	21 **164.83** *5.88* (156.00 – 175.00)	30 **163.38** *6.46* (144.00 – 175.00)	37 **162.34** *7.20* (145.00 – 178.00)	20 **168.53** ^{b} *7.05* (156-180)	57 **164.51** *7.69* (145.00 – 180.00)	46 **161.88** ^{ab} *7.12* (144.00 – 178.00)	41 **166.63** ^{a} *6.66* (156.00 – 180.00)
Foetal parameters	Foetal adjusted ratio: BPD / head circumference	1 **1.02** *0* (1.02 -1.02)	20 **1.05** ^{bcg} *0.04* (0.93 - 1.10)	21 **1.05** ^{deh} *0.04* (0.93 - 1.10)	10 **1.10** ^{acef} *0.04* (1.06 -1.17)	8 **1.07** *0.03* (1.02-1.13)	18 **1.09** ^{gh} *0.04* (1.02 - 1.17)	11 **1.10** ^{bd} *0.05* (1.02 - 1.17)	28 **1.06** ^{af} *0.04* (0.93 - 1.13)
	Newborn head circumference (mm)	9 **346.67** ^{b} *16.58* (320.00 - 370.00)	19 **326.53** ^{abcef} *16.46* (291.00 -355.00)	28 **333.00** *18.81* (291.00 – 370.00)	39 **340.64** ^{cd} *14.24* (300.00 – 370.00)	20 **349.06** ^{f} *17.64* (321.20-390.00)	59 **343.49** ^{de} *15.84* (300.00 – 390.00)	48 **341.77** ^{a} *14.71* (300.00 – 370.00)	39 **338.08** *20.35* (291.00 – 390.00)
	Newborn length (cm)	9 **50.56** *2.13* (47.00 - 54.00)	21 **50.14** *2.52* (47.00 -58.00)	30 **50.27** *2.38* (47.00 – 58.00)	39 **50.46** *3.24* (42.00 – 57.00)	20 **50.98** *2.27* (48.00-58.00)	59 **50.63** *2.93* (42.00 – 58.00)	48 **50.48** *3.04* (42.00 – 57.00)	41 **50.55** *2.41* (47.00 – 58.00)
	Duration of active labour (mins)				13 **764.15** *443.01* (270-1845)	10 **727.90** *410.90* (225-1610)			

C/S indicates patients who have undergone a Caesarean section. V/D indicated patients who have undergone a vaginal delivery

The top number in each cell indicates the number of samples per group. The mean (mm) values are indicated in **bold.** The standard deviation is indicated in *italics and* the range is shown within the round (brackets).

Alphabet letters in the superscript indicate statistical significant differences (p value < 0.05) per row

The black South African caesarean group had the shortest stature. No inferences could be drawn from the one case where the foetal adjusted ratio was known.

The BPD of white South African mothers who delivered vaginally, was statistically significantly smaller than white South African mothers delivering by caesarean section. Although an opposite relationship was noted for black South African mothers who had a vaginal delivery and those who had a caesarean section, it was not statistically significant. White South Africans had a statistically smaller BPD as compared to black South Africans.

No statistically significant differences were noted in the maternal head circumference between the groups considered. Nevertheless, the maternal head circumference in the caesarean section group, and also per population group, was greater than in the vaginal delivery group. The greatest BPD/Head circumference ratio was noted in the black South African vaginal delivery group and the black South African group in total. It follows then that all statistically significant relationships were confined to the comparisons with the black South African vaginal delivery group, excluding the black South African C/S, all V/D and total black South African groups. The white South African vaginal delivery group was the tallest of all groups and statistically significantly taller than the total black South African group. White South Africans in general, were statistically significantly taller than black South Africans.

The foetal adjusted ratio: BPD/Head circumference was the greatest in the black South African vaginal delivery group and in black South Africans. The caesarean section group presented with the smallest ratios and was statistically significantly smaller than black South Africans, the black South African vaginal delivery group, as well as the total vaginal delivery group. On the other hand, head circumference was the greatest in the white South African vaginal delivery group and the smallest in the white South African caesarean section group, and this relationship was statistically significant. Conversely, the black South African C/S group had a greater head circumference than the black South African vaginal delivery group. The newborn head circumference in the white South African caesarean group was statistically significantly smaller than in the black South African caesarean section group, black South African vaginal delivery group and the total black South African group, as well as white South African vaginal delivery group and the total vaginal delivery group.

Newborn length was weakly statistically significant correlated with newborn head circumference in black South Africans, white South Africans and the black South African V/D group.

Table 43. Correlations between observations

	Parameters	BPD [BPD] (mm)	Head circumference (mm)	Maternal ratio (BPD/ head circumference)	Stature (cm)	Foetal adjusted ratio: BPD / head circumference	Newborn head circumference (mm)	Newborn length (cm)	Duration of active labour (mins)
Maternal parameters	**BPD [BPD] (mm)**							**0.59**	
	Head circumference (mm)				**0.47***		**-0.41***	**0.63***	
	Maternal ratio (BPD/ head circumference)								
	Stature (cm)						**0.30***		**-0.52**
Foetal parameters	**Foetal adjusted ratio: BPD / head circumference**						**0.33*** **0.41**	***0.63****	
	Newborn head circumference (mm)							**0.29*** **0.40*** **0.38***	
	Newborn length (cm)								
	Duration of active labour (mins)								

Entire group, White South Africans V/D, White South Africans C/S, White South Africans, Black South African V/D, Black South African C/S, Black South Africans

r^2 values are indicated in **bold**

$p < 0.05$ is indicated by *

In the white South African caesarean section group, maternal head circumference and height were moderately statistically significantly correlated, while in the total white South African group, there was a non-significant but moderately inverse relationship between maternal head circumference and newborn head circumference. Stature was weakly but statistically significantly correlated to the newborn head circumference in black South Africans, and so was the foetal adjusted ratio in the entire group and the white South African vaginal delivery group. Foetal adjusted ratio was also moderately and significantly correlated to the newborn length in the black South African vaginal delivery group.

Newborn length was weakly statistically significant with newborn head circumference in black South Africans, white South Africans and the black South African vaginal delivery group.

6. SEX AND/OR POPULATION VARIATIONS WITHIN MODALITY AS COMPARED TO THE LITERATURE

Sex and population differences have been reported for the skull and the pelvis. The pelvis has been described as the most sexually dimorphic bone in the human body (Işcan and Steyn 2013). Sexual pelvic differences are expected and permit a wider birth canal for childbirth in females (Greulich et al. 1939; Tague and Lovejoy 1986; Rosenberg 1992; İşcan 2005; Wittman and Wall 2007; Louis and Warren 2009; Weaver and Hublin 2009). However, significant population differences in pelvis morphology have also been reported (Patriquin et al. 2002; Hoyte et al. 2005; Handa et al. 2008). These differences may be due to adaptive responses to various factors, for example, the thermoregulatory adaptations to different climates are known to have shaped the pelvis of extinct hominins and modern humans (Sharma et al. 2016). The biogeographic patterns of variations in body size and proportions between geographically widely spread human populations, are referred to as Allen's and Bergmann's rules (Sharma et al. 2016). Populations living in colder climates have relatively wider pelves in order to reduce heat loss, while narrower pelves in tropical climates would help to reduce the heat stress (Weaver and Hublin 2009; Sharma et al. 2016).

As with body build in general, head form is subject to the same physical principles which underlie the rules of Allen and Bergmann. The most efficient radiators of heat are those with high surface area/mass ratios, while the least efficient are those with the converse. The geometric form with the lowest possible ratio is the sphere. Theoretically, therefore, it should be expected that under conditions of cold stress, the most advantageous head shape would be rounded, as this most closely approximates the spherical ideal. Under opposing conditions, long-headedness would be more suitable (Beals 1972).

The general distribution of the cephalic index (maximum breadth of the skull to its maximum length) is explainable in terms of climatic adaptation. Populations living in cold climates are more likely to have rounder heads, also termed brachycephaly, which is characterised by a relatively larger cephalic index (Fee 1979) than those dwelling in hot climates. The magnitudes of the indices are statistically different between zones of predominantly dry heat, wet heat, wet cold and dry cold. There is an inverse relationship between the mean cephalic index and temperature. It is argued that the occupation of cold climates is one of the circumstances increasing the frequency of brachycephaly through time (Beals 1972; Beal et al. 1983).

Sex differences in the shape of the head have also been reported (Fee 1979; Urban et al. 2016), but the exact reasons are still being debated. The female skull is regarded by some as being more juvenile than the male, possibly because of an earlier puberty and growth cessation, and is reflected by a higher cranial index (De Villiers 1968; Del Bove et al. 2020; Sassi et al 2020).

Sex and/or population variations within modality, as compared to the literature, are summarised in Table 44.

Table 44. Comparison of results from this study and other studies related to the pelvis and the cranium

Modalities→ Dimension (mm)↓	This study: Cadaver	This study: CT	Cadaver	Dry bones	X rays	CT scans	3D CT models	Intra-operative
Pelvic dimensions								
Pelvic inlet								
True Conjugate	BF: 112.77 WF: 127.06 BM: 105.20 WM: 120.17	BF: 116.28 WF:129.55 BM:112.44 WM:121.02	Japanese Males: 110.00 Females: 115.00 (Kambe et al. 2003) American Males: 122.50 (Sonoda et al. 2011)		Males: 100.00 Females: 112.00 (Young and Ince 1940; Gutman et al. 2005; Killeen et al. 2010; Maharaj 2010; Moore et al. 2013; Standring) Females: 109.00 (Ehigiegba et al. 2005)	French 103.50 (Seizeur et al. 2005) Chinese Female: 121.38 (Ye et al. 2020) Americans Males: 119.60 Females: 126.76 (Decker et al. 2011)	WF: 142.79 Females: 135.28 WM: 129.13 Males: 128.49 (Ye et al. 2020; Zhang et al. 2020; Shah et al. 2018)	Females: 108.00 (Ehigiegba et al. 2005)
Widest Transverse Dimension of the Pelvic Inlet	BF: 119.15 WF: 135.28 BM: 114.97 WM: 128.49	BF:127.55 WF:142.79 BM:120.91 WM:129.13	Japanese Females: 120.00 Males:108.00 (Kambe et al. 2003) North American BF: 120.60 WF: 133.90 BM: 112.00 WM: 114.97 (Işcan, 1983)		Females 131.00 Males 125.00 (Handa et al. 2008; Louis and Warren 2009; Maharaj 2010; Standring 2015)			
Diagonal Conjugate	BF: 126.86 WF: 133.85 BM: 122.31 WM: 134.99	BF:130.94 WF:142.15 BM:133.43 WM:141.07	American Females: 137.00 (Lazarou et al. 2008) (American) Black and white: 116.17 (Ehigiegba et al. 2005)					Females: 110.00 (Maharaj 2010)

Modalities→ Dimension (mm)↓	**This study: Cadaver**	**This study: CT**	**Cadaver**	**Dry bones**	**X rays**	**CT scans**	**3D CT models**	**Intra-operative**
Pelvic dimensions								
Midpelvis								
Obstetric conjugate	BF: 110.38 WF: 128.26 BM: 105.87 WM: 120.85	BF:114.62 WF:128.28 BM:113.53 WM:122.25			Males and females: 100.00 (Michel et al. 2002; Louis and Warren 2009; Maharaj 2010; Moore et al. 2013)			Ghana Females:_129.00 (Adadevoh et al. 1989)
Interspinous diameter	BF: 94.26 WF: 106.34 BM: 83.40 WM: 89.97	BF: 104.31 WF:107.85 BM: 86.24 WM: 89.12	American 113.17 (Ehigiegba et al. 2005)		Females: 95.00 (Young and Ince 1940; Gutman et al. 2005; Killeen et al. 2010; Maharaj 2010; Moore et al. 2013) Females: 100.00 (Maharaj 2010)	Chinese 107.90 (Zhang et al. 2020) Japanese 109.80 (Torimitsu et al. 2015)’ French 101.20 (Seizeur et al. 2005) Indian 97.80 (Shah et al. 2018)		

Modalities→ Dimension (mm)↓	This study: Cadaver	This study: CT	Cadaver	Dry bones	X rays	CT scans	3D CT models	Intra-operative
Pelvic dimensions								
Pelvic outlet								
Anteroposterior dimension of the pelvic outlet	BF: 89.43 WF: 96.25 BM: 84.41 WM: 91.96	BF:120.11 WF:126.42 BM: 112.98 WM: 117.50	American Male:118.00 (Sonoda et al. 2011)		Males: 80.00 Females: 125.00 (Handa et al. 2008; Louis and Warren 2009; Maharaj 2010; Standring 2015)			
Intertuberous diameter	BF:108.49 WF:125.94 BM: 97.04 WM: 107.87	BF: 129.13 WF:137.29 BM:112.39 WM:122.64	Australian Females: 145.00 Males: 122.50 (Sussman et al. 2013)		Males: 85.00 Females: 118.00 (Maharaj 2010)			
Subpubic angle (degrees)	BF: 87.63 WF: 91.52 BM: 76.71 WM: 79.46	BF:86.62 WF:87.45 BM:75.12 WM:78.13		South African BF: 4.18 BM: 63.98 WM: 70.78 WF:93.98 (Brits et al. 2012)		Japanese Males: 74.80 Females: 112.71 (Torimitsu et al. 2015)		

Modalities→ Dimension (mm)↓	**This study: Cadaver**	**This study: CT**	**Cadaver**	**Dry bones**	**X rays**	**CT scans**	**3D CT models**	**Intra-operative**
Cranial dimensions								
Cranial height	BF:110.76 WF: 112.28 BM: 114.43 WM: 117.28	BF: 117.75 WF: 112.83 BM: 119.04 WM: 122.28						
Maximum cranial length	BF: 181.27 WF: 178.39 BM: 188.97 WM: 190.81	BF: 180.74 WF: 173.97 BM: 189.20 WM: 186.21				Tunisian Females: 179.66 Males: 188.27 (Zaafrane et al. 2018) Western Australian Females: 179.5 mm and Males: 189.67 (Franklin et al. 2013) Anambra Nigerian 185.5 (Adejoh and Nzotta 2016) Thai Females: 165.15 Males: 173.09 (Rooppakhun et al. 2011) Ghanaian Females: 175.60 Males: 182.00 (Paulinus et al. 2019) Calbar Nigerian Females: 178.53 Males :182.90 (Botwe et al. 2021)		

Modalities→ Dimension (mm)↓	This study: Cadaver	This study: CT	Cadaver	Dry bones	X rays	CT scans	3D CT models	Intra-operative
Cranial dimensions								
Biparietal diameter	BF: 105.52 WF: 119.80 BM: 108.71 WM: 111.63	BF: 122.03 WF: 130.15 BM: 122.78 WM: 126.0				Thai Females: 140.83 Males: 144.13 (Rooppakhun et al. 2011) Ghanaian Females: 138.00 Males: 140.50 (Paulinus et al. 2019) Calabar Nigerian Females: 137.21 Males: 138.59 (Botwe et al. 2021) Ananmbra Nigerian 137.40 (Adejoh and Nzotta 2016)		

6.1. Pelvis

Standards for pelvic measurements were established in the previous century and used in the planning of childbirth options (Rosenberg 1992; Rosenberg and Trevathan 2002; Walrath et al. 2003; Louis and Warren 2009). These pelvic measurements were performed on normal X-rays and were referred to as pelvimetry. Some of these dimensions have been verified intra-operatively (Coleman 1969; Katanozaka et al. 1999; Sonal et al. 2006; Louis and Warren 2009; Augustine et al. 2018) during caesarian section as a possible means to determine pelvic size incompatible with normal vaginal delivery.

Anthropologists have been using re-assembled dry bones (Ridgeway et al. 2008; Bonneau et al. 2012; Brits et al. 2012) for taking measurements across the midline. Measurements have also been taken on computer tomography (CT) (Young and Ince 1940; Buli 1949; Stewart et al. 1979; Ehigiegba et al. 2005), magnetic resonance images (Michel et al. 2002; Keller et al. 2003; Killeen et al. 2010; Ayad et al. 2012), as well as 3D reconstructed CT models made possible by sophisticated software (Pretorius et al. 2006; Betti et al. 2013; Betti et al. 2014; Colman et al. 2019). Measurements taken on 3D reconstructed CT models may be useful for detecting CPD as verified by the clinical impression and sonographic findings (Salk et al. 2016). However, in this study, a greater repeatability of measurements were found when using intact cadaver pelves than using 3D measurements on 3D reconstructed CT images.

As dimensions may vary according to modality used, care should be taken when comparisons are made. Intact cadaver pelvic measurements were not directly comparable to other studies, but for the purposes of this discussion, reference values established on normal X-ray pelvimetry, intra-operative measurements, as well as re-assembled dried bones, were used.

Pelvic linear measurements:

As expected, most cadaveric and radiological pelvic linear dimensions were statistically significantly greater in females than in males, as well as in white South

Africans compared to black South Africans (Patriquin et al. 2002; Patriquin et al. 2003; Işcan and Steyn 2013).

6.1.1 Pelvic inlet

True Conjugate

The TC is the first anteroposterior limit of the birth canal, but does not represent the shortest anteroposterior distance for the foetus to pass through during the birth process (Young and Ince 1940; Michel et al. 2002; Maharaj 2010). In the previous century, the TC was assessed by X-rays as part of routine prenatal pelvimetry to assess the shape of the pelvic inlet (Buli 1949; Maharaj 2010). The TC, measured between the most anterosuperior point on the sacral promontory to the superior midline point on the dorsal aspect of the pubic symphysis, is considered to be on average, 100.00 mm in males and 112.00 mm in females, in standard textbooks (Young and Ince 1940; Gutman et al. 2005; Killeen et al. 2010; Maharaj 2010; Moore et al. 2013; Standring 2015). Smaller measurements could be predictive of CPD (Buli 1949), for instance, the mean TC diameter taken on patients who have had a caesarean, measured 108.00 mm and 109.00 mm using both pelvic calipers (intra-operatively) and X-ray methods, respectively (Ehigiegba et al. 2005). Patients with cephalopelvic disproportion had statistically smaller TC than others when assessed by both methods (Ehigiegba et al. 2005).

These standard dimensions derived from X-rays cannot directly be compared to cadaveric dimensions which seems to be somewhat larger according to Kambe et al. (2003). On a Japanese sample, the average TC was 110.00 mm (range 100–125 mm) in males and 115.00 mm (range 95– 134 mm) in females (Kambe et al. 2003). In this study, the TC measurements in the black South African population were, to some extent, similar to previous reports and measured 105.20 mm in males and 112.77 mm in females. The TC measurements in the white South African population were larger than expected from the literature (males: 120.17 mm and females: 127.06 mm) and more in line with an American study by Sonoda et al. (2011) done on male cadavers, who found that the TC measured 122.5 mm (Maharaj 2010; Sonoda et al. 2011).
Computer tomographic studies performed on eight cadavers (five male, three female) in France, found a mean value for the TC of 103.50 mm (Seizeur et al. 20,05) which

was much smaller than the mean values of any of the sex-populations in this study. The mean TC reported by Ye et al (2020) on a Chinese CT female sample, was 121.38 mm (Ye et al. 2020), which fell between the mean values determined in this study for black South African and white South African female CT scans. The values reported by Decker et al (2011) on an American sample, approached that of the white South African sample in this study and were 119.60 in males and 126.76 in females (Decker et al. 2011). The mean values of the white South African CT sample in this study was greater than in the literature researched, with a mean value of 129.55 mm in white South African females and 121.02 mm in white South African males.

From the results of this study and supported by the literature reviewed, it is evident that the size of the TC is dependent on the modality and population used, and is always greater in females than males. Computer tomographic measurements were greater than the cadaveric measurements, and measurements on white South African groups greater than those on black South African groups. In the sample of South African cadavers, black South Africans presented with values similar to the standard derived from X-ray pelvimetry. The mean value in black South African female cadavers of 112.77 mm and 116.28 mm on CT scans was also greater than the 108/109 mm reported to require caesarian section. White South Africans, and especially white South African females, presented with greater measurements for the TC than could be found in other reports.

Widest transverse dimension of the pelvic inlet

The WTI dimension on the pelvic inlet is considered the greatest transverse width measured across the pelvic inlet. Standring et al. 2015, as well as other authors (Handa et al. 2008; Louis and Warren 2009; Maharaj 2010; Standring 2015), reported a standard measurement that was greater in females (131.00 mm) than in males (125.00 mm). This measurement may vary among populations, as reported by İşcan (1983). A Japanese cadaver sample, for instance, measured much smaller values of 120.00 mm in females and 108.00 mm in males compared to the standard measurements (Kambe et al. 2003). Findings and population trends on the cadaver sample in this study were more in line with the study by İşcan (1983) on a North American skeletal collection. Smaller measurements were noted in the black South African female group (119.15 mm) when compared to white South African females

(135.28 mm). Although the mean WTI diameter of the black South African female group approached that of the black North American female group of 119.15 mm and 120.60 mm, respectively, the measurements of the WTI dimension was greater in the other South African cadaver sex-populations as compared to the North American counterparts: white South African females 135.28 mm versus 133.90 mm; white South African males 128.49 mm versus 123.60 mm and black South African males: 114.97 mm versus 112.00 mm, respectively. These differences could be accounted for by the different modalities used, or could be true population differences.

Despite the trend noted in this study of greater measurements when using 3D reconstructed CT models as compared to the cadaver sample, studies performed on Chinese groups reported smaller WTI than the expected standards (Ye et al. 2020; Zhang et al. 2020), as well as an Indian sample measured (Shah et al. 2018). These researchers reported values somewhat similar to the South African black South African 3D reconstructed CT model, which were smaller than the expected standards. South Africans presented with greater dimensions on 3D reconstructed CT models and the cadaver sample than reported in the literature and were 142.79 mm and 135.28 mm, respectively, in white South African females, and 129.13 mm and 128.49 mm, respectively, in white South African males.

Diagonal Conjugate

Values for the DC (the distance between the most anterosuperior point on the sacral promontory and the most inferior point on the pubic symphysis) varied between studies. The DC measured 137.00 mm in an American sample of female cadavers (no mention of ancestry) (Lazarou et al. 2008), while another American study, comprising 27 white and three black female cadavers, measured 116.17 mm on average (Albright et al. 2005). In this study, the mean DC values fell between these two measurements, with black South African females having a value of 126.86 mm, and white South African females, a value of 133.85 mm.

6.1.2 Midpelvis

Obstetric Conjugate

The OC (shortest distance from the sacral promontory to the most prominent point on the posterior aspect of the pubic symphysis) is considered to be 100.00 mm or more in both males and females (Michel et al. 2002; Louis and Warren 2009; Maharaj 2010; Moore et al. 2013). However, an OC of less than 117.00 mm has been associated with breech presentation of the foetus, resulting in a caesarean section (Joyce et al. 1975). These studies have been based on X-ray pelvimetry findings and might not be comparable to the cadaver findings.

A Ghanaian intra-operative sample measured distances of 129.00 mm ± 8.80 mm (Adadevoh et al. 1989; Sonal et al. 2006), which was more in line with the white South African females in this study with a mean value of 128.26 mm, while a study on an Indian population found that the OC measured 109.40 mm (Shah et al. 2018), which were more similar to the black South African female sample of 110.38 mm.

Interspinous diameter

The IS is described as the distance between the ischial spines. This distance is important to clinicians, as it represents the narrowest part of the pelvic canal through which the infant's head must pass and, therefore, might be a limiting factor during parturition (Gabbe et al. 2016). The IS should be at least 95.00 mm in adult females (Moore et al. 2013; Standring 2015; Gabbe et al. 2016), with Maharaj (2010) suggesting 100.00 mm. In this study, the mean interspinous distance in the black South African female sample approximated this minimum value, having a mean value of 94.26 mm, while the mean white South African female cadaver measurement was 106.34 mm. Reconstructed 3D CT models samples had mean interspinous distances marginally greater than this minimum (104.31 mm in black South African females and 107.85 mm in white South African females). The difference between cadaver and 3D CT models measurements could have once again be explained by contraction following desiccation of pelvic specimens which could have had an influence on this measurement crossing the midline.

The size of the interspinous dimension in this study for white South African females was similar to a Chinese CT sample of 107.90 mm (Zhang et al. 2020), and a Japanese CT sample of 109.80 mm (Torimitsu et al. 2015). The black South African female sample were more in line with a French sample measuring 101.20 mm (Seizeur et al. 2005), but greater than an Indian sample with the mean IS of 97.80 mm (Shah et al. 2018).

The size of the interspinous dimension in this study was, however, smaller than in the American cadaveric sample which measured 113.17 mm (Albright et al. 2005). It is not clear why this study presented with greater values than previously reported. Perhaps the difference in the technique could account for this greater measurement, as dissections were performed that were designed to spare and measure soft tissues.

Males presented with smaller measurements as compared to females, which is also reflected in the literature. However, the mean interspinous dimension was smaller in males in this study than in the other studies (Torimitsu et al. 2015; Zhang et al. 2020).

6.1.3 Pelvic outlet

Anteroposterior dimension of the pelvic outlet

The PO (between the tip of the coccyx and the most inferior point on the dorsomedial aspect of the most inferior point on pubic symphysis) is, on average, 80.00 mm in males and 125.00 mm in females (Standring 2015). However, in a study by Sonoda et al (2011) on an American male cadaver sample, a mean measurement of 118.00 mm is reported (Sonoda et al. 2011). In this study, both male cadaver groups presented with smaller measurements (WM: 91.96 mm and BM: 84.41 mm). The female cadaver sample also presented with smaller dimensions than the standard (WF: 96.25 mm and BF: 89.43 mm). Contraction due to desiccation, as well as anteroposterior compression of the skeleton while being stored, could have had an influence on this measurement.

Mean values for females approximated the values given by Standring (WF: 126.42 mm and BF: 120.11 mm), while exceeding those values in males (WM: 117.50 mm and BM: 112.98 mm) (Standring 2015). However, mean measurements achieved on

3D reconstructed CT models in all four sex-populations in this study were larger than other reports in the literature (Seizeur et al. 2005; Decker et al. 2011; Shah et al. 2018), especially in females and more so, white South African females.

Intertuberous distance

The mean IT's in this sample were in general greater (BM: 97.04 mm; WM: 107.87 mm; BF: 108.49 mm and WF: 125.94 mm) than those reported by some (Maharaj 2010; Standring 2015), but smaller than in an Australian cadaver sample (females: 145.00 mm and males: 122.50 mm) (Sussman et al. 2013). Once again, different degrees of desiccation could have been a factor contributing to varying results.

In this study, the diameters measured were greater in the 3D CT models (BM: 112.39 mm; WM: 122.64 mm; BF: 129.13 mm and WF: 137.29 mm) than in the cadaver sample, but also greater than in other studies reporting on CT findings on Japanese groups (Torimitsu et al. 2015) and Chinese groups (Zhang et al. 2020).

Subpubic angle (degrees)

The subpubic angle is sharper (more acute) and narrower in males and more rounded and obtuse in females (Warwick and Williams 1973; Oladipo et al. 2010). It should, however, be taken into consideration that the subpubic angle is unfortunately not a true reflection of the subpubic space, as the subpubic concavity forming the pubic arch is not taken into account (Phenice 2005).

According to Frudinger (2002) and Maharaj (2010), it is believed that this angle should be 90° or more if problems during delivery are to be avoided (Frudinger et al. 2002; Maharaj 2010). Moore and Dalley maintain that, if the ischial tuberosities are far enough to permit three fingers to enter the vagina side by side, the subpubic angle is considered sufficiently wide to permit the passage of an average head at full term (Moore and Dalley 1999).

Despite the importance of the subpubic angle, only a few studies exist (Inuwa 1992; Nwoha 1992; Igbigbi and Nanono-Igbigbi 2003; Brits et al. 2012) that quantify the subpubic angle in South African males and females of both African (black South African) and European (white South African) descent, and to determine whether any statistically significant differences exist between the sexes and the populations. In these studies, dried pelvic bones were used which are not directly comparable to cadaver pelves. In the study by Brits et al. (2012), all pelves were articulated with elastic bands, placed into a custom-built stand and the subpubic angles were photographed. The subpubic angle in the cadaveric sample in this study approximated the advocated angle of at least 90° for successful delivery (BF: 87.63° and WF: 91.52°) and were greater than the findings of Brits et al. (Date?) but smaller than other studies researched (Heyns 1947; Ridgeway et al. 2008; Brits et al. 2012).

Brits et al. (Date?) found that black South African males and females have mean subpubic angles of 63.98° and 84.18°, respectively, as opposed to 76.71° and 87.63° in this study, while white South African males and females proved to have larger mean subpubic angles of 70.78° and 93.98°, respectively, as opposed to 79.46° and 91.52° in this study, when photographs were used. The thickness of the symphyseal fibrocartilage and asymmetry was not taken into consideration (Brits et al. 2012).

The subpubic angle measured on the 3D reconstructed CT models in this study was not much different to the cadaver sample, possibly because anteroposterior compression overcame desiccation, resulting in contraction across the midline. The subpubic angle on the CT scans was smaller than in a Chinese study (Zhan et al. 2020), but greater than in an American study (Decker et al. 2011) and showed less variation between sex groups than in a study on a Japanese sample which reported 74.80° in males and 112.71° in females (Torimitsu et al. 2015).

In summary, while differences between modalities had to be considered, variations between populations were evident. In general the mean values in the populations studied were compatible with normal vaginal delivery, with white South African females presenting with greater measurements than previously reported, apart from the IS (Albright et al. 2005), IT (Sussman et al. 2013) and subpubic angle (Heyns 1947; Ridgeway et al. 2008; Zhan et al. 2020), where some studies reported greater values. This finding is not surprising, as previous studies reported that white South Africans are generally taller with presumably larger pelves than their counterparts in America (Steyn et al. 2004).

Pelvic shape

In general, the expected shape variations between the sexes were observed in the study sample, including a more rounded or oval-shaped pelvic inlet in females, as opposed to males. Males further had more prominent ischial spines and narrower subpubic regions (Warwick and Williams 1973). These shape variations were more pronounced in white South African females than in black South African females, as previously reported (Todd and Lindala 1928; Patriquin et al. 2003).

Apart from the pelvis being narrower and smaller in the African group (Todd and Lindala 1928; Patriquin et al. 2003), the relative anteroposterior outlet dimension has increased, as observed by Betti (2021), in order to preserve a minimum size for the passage (Betti 2021). It was thought that the narrower body favoured in hot climates, could limit the transversal width of the birth canal,

6.2. Cranium

6.2.1 Absolute measurements: Maximum cranial length and breadth

Regarding the absolute measurements derived from 3D reconstructed CT models, black South African and male groups presented with greater maximum cranial length measurements (BF: 180.74 mm; WF: 173.97 mm; BM: 189.20 mm and WM: 186.21 mm). The mean maximum cranial length measurements of the black South African population in the 3D reconstructed CT models of this study were similar to a Tunisian sample (females: 179.66 mm and males: 188.27 mm) (Zaafrane et al. 2018), a Western Australian sample (females: 179.5 mm and males: 189.67 mm) (Franklin et al. 2013) and an Anambra, Nigerian sample (both sexes: 185.5 mm) (Adejoh and Nzotta 2016).

The maximum cranial length in the white South African population in this study was smaller than in the studies mentioned above, but greater than reported in a Thai population (females: 165.15 mm and males: 173.09 mm) (Rooppakhun et al. 2011). Interestingly, a Ghanaian sample and a Calabar, Nigerian sample recorded values which approached that of the white South African population in this study, but with a smaller variance between sexes (females: 175.60 mm; males:182.00 mm and females: 178.53 mm; males :182.9 mm, respectively) (Paulinus et al. 2019; Botwe et al. 2021; Paulinus et al., 2019). However in the Thai, Ghanaian, Calabar, Nigerian and Anambra, Nigerian samples, the maximum cranial breadths (females: 140.83 mm; 138.00 mm; 137.21 mm and males: 144.13 mm; 140.50 mm; 138.59 mm and both sexes: 137.4 mm, respectively) (Rooppakhun et al. 2011; Adejoh and Nzotta 2016; Paulinus et al. 2019; Botwe et al. 2021) were greater than in any of the sex-populations in this study. Differences in methodologies, namely medical CT scans versus 3D reconstructed CT models, could have accounted for these perceived variations, but true population variations cannot be excluded (Colman et al. 2019).

No other studies could be found in the literature reporting BPD dimensions to be greater in females than males, as noted in white South African females, for both the cadaver sample and the 3D reconstructed CT models of 130.15 mm, which was greater than any of the other three sex-populations.

6.2.2. Skull shape and cephalic index

The expected geographical related patterns of skull shape variation associated with, for instance, temperature (Harvati and Weaver 2006; Hubbe et al. 2009), was supported by the findings of this study. The shape variation of the head between black South African and white South African individuals fits in with the rules of Allen and Bergmann in that individuals of European ancestry under cold stress, presented with more rounded (brachycephalic) heads, while those of African ancestry were more long-headed (dolichocephalic) (Beals 1972; Beals et al. 1983). As expected, apart from the cranial length in females, all dimensions were greater in white South Africans compared to black South Africans. The cranial height (nasion to glabella) dimension was, however, not greater in black South Africans compared to white South Africans, as could have been expected from the findings of other researchers comparing white South Africans (Sardi and Rozzi 2012).

For a given population, some distinct but not absolute differences observed in the cranial features of the male and female crania exist (Jeremiah et al. 2013), for instance, and as expected, skulls of white South African women in this study were brachycephalic (Fee 1979) with the greatest BPD measurements of all sex-populations, while no difference in the cephalic index (or BPD/MaxCL ratio) was noted between sexes in the black South African sample. The Kenyan and Ghanaian sample did display the trend of greater brachycephaly in the female sample. The mean cranial index was 71.04 and 77.30 for the male sample and 72.37 and 79.00 for the female sample (p = 0.095), respectively (Jeremiah et al. 2013; Botwe et al. 2021).

In summary, the black South African sample in this study displayed a more dolichocephalic skull compared to the white South African sample with a longer, but narrower skull. Maximum cranial lengths in both groups fell within the ranges reported before, while the maximum cranial breadths were narrower than communicated elsewhere. This resulted in a narrower cranial index for both groups than expected. Different methodologies used could be accountable for the variations, but true population variations cannot be excluded. A general trend of brachycephaly in females compared to males is described in the literature as reflected in white South African females in this study, but no references could be found that reported a greater BPD in females, as noted in the white South African females compared to white South African males in this study.

6.3. Patient findings

Patient findings in this study compared to the literature are summarised in Table 45.

Table 45. Comparison of results from this study and other studies related to the patient aspects

This study:	Other studies
Maternal parameters	

BPD (mm)	BF (C/S): 139.78 WF (C/S): 141.20 BF (V/D): 148.23 WF (V/D): 137.91	Nigerian 141.50 (Oria et al. 2018)
Head circumference (mm)	BF (C/S): 578.89 WF (C/S): 579.33 BF (V/D): 570.25 WF (V/D): 563.75	American Females:554 (Hshieh et al. 2016) British Black (C/S): 548.97 White (C/S): 553.16 (Bushby et al. 1992)
Stature (cm)	BF (C/S): 160.00 WF (C/S): 164.83 BF (V/D): 162.34 WF (V/D): 168.53	South African 158 cm (Worlddata 2019)
Foetal parameters		
Newborn head circumference (mm)	BF (C/S): 346.67 WF (C/S): 326.53 BF (V/D): 340.64 WF (V/D): 349.06	White Americans 346.10 (Hadlock et al. 1984)
Newborn length (cm)	BF (C/S): 50.56 WF (C/S): 50.14 BF (V/D): 50.46 WF (V/D): 50.98	American 51 cm HealthwiseStaff 2020

6.3.1 Absolute measurements of maternal head: Head circumferences, Maximum cranial length and breadth

Differently to the 3D reconstructed CT models, the patient data presented with statistically significantly greater mean BPD in black South Africans compared to white South Africans (146.06 vs140.03), which was also greater than reported in the literature (Oria et al. 2018). While the head circumference was similar between the groups in this study, an American study on a sample of patients ≥70 years old reported a mean head circumference value of 554 mm in females (Hshieh et al. 2016), which was smaller than found in our groups: black South Africans: 571.83 mm, white South Africans: 571.73 mm.

Head circumference has been related to height in a British study, and the line describing the mean of the distribution is 41.02 + 0.08673 x height (cm) (Bushby et al. 1992). When applying this formula to the mean values of the groups in this study, smaller calculated head circumferences were obtained than when measured in real life (black South African (C/S): 548.97 mm vs 578.89 mm, white South African (C/S): 553.16 mm vs 579.33 mm, All C/S: 551.90 mm vs 579.2 mm, black South African (V/D): 551.00 mm vs 570.25 mm, white South African (V/D): 556.37 mm vs 563.75 mm, All V/D: 552.88 mm vs 568.08 mm, black South Africans: 550.60 mm vs 571.83 mm, white South Africans: 554.72 mm vs 571.73 mm). Also, on the 50th centile, the head circumference is 542 mm for 16 year old girls, which was much smaller than the measurements recorded for groups in this study (Bushby et al. 1992). In this study, the only subgroup that demonstrated a correlation between maternal head circumference and height, was the white South African caesarean section group, and this correlation was moderately statistically significant.

Greater head circumference in black South Africans compared to white South Africans could be partly explained by variant hairstyles and textures, or scalp thickness (Nooranipour and Farahani 2008; Perret-Ellena et al. 2015; Hshieh et al. 2016). Thermoregulatory factors might be responsible for geographical variations in hair texture and scalp thickness (Acharya et al. 2015; Lasisi et al. 2016). Interestingly, skin thickness has been found to be statistically significantly thicker in the temporal area compared to other areas and might have contributed to the wider BPD measurements than expected (Babiloni et al. 1997). However, sample size, selection and observer errors could also have had an effect leading to sampling errors.

6.3.2 Maternal stature

Maternal height was significantly greater in the white South African sample compared to the black South African sample (mean height: 161.88 cm vs. 166.63 cm, respectively). This height is taller than the expected 158 cm for South Africans (average measurements were based on women between the ages of 18 and 25) (Worlddata 2019). This deviation from the expected could have been an effect of sample selection and size.

In summary, from the limited literature on BPD and head circumference in adults, it could be noted that both populations in this study presented with greater BPD, stature and head circumferences than expected. Head circumferences were largely unrelated to height, except in the white South African caesarean section group. Difference in hair texture, scalp thickness and technique could be involved, but actual differences between populations should not be excluded.

6.3.3 Newborn head circumference (mm), foetal adjusted ratio of BPD/Head circumference and length (cm)

The mean newborn head circumference in the white South African caesarean group (326.53 mm) was statistically significantly smaller than in the black South African caesarean section group (346.67 mm), the black South African vaginal delivery group (340.64 mm) and the total black South African group (341.77 mm), as well as the white South African vaginal delivery group (349.06 mm) and the total vaginal delivery group (343.49 mm). The smaller mean newborn head circumference noted in the white South African caesarean group does not support cephalopelvic disproportion factors, but could fit in with elective caesareans, which are performed at earlier gestational ages (Bettegowda et al. 2008; Nassar et al. 2013) or other obstetric emergencies. On the other hand, the white South African vaginal delivery group presented with the greatest mean foetal head circumference (349.06 mm) of all other groups considered, which was also greater than the expected 346.1 mm, according to the ultrasonographic reference ranges compiled by Hadlock et al (1984) on white Americans, for 40 gestational weeks (Hadlock et al. 1984). The black South African caesarean section group (346.67 mm) and black South African vaginal delivery group (340.64 mm) approximated the expected foetal head circumference reference for 40 gestational weeks.

The foetal adjusted ratio of BPD/Head circumference represented the actual BPD/Head circumference divided by the expected BPD/Head circumference. A value greater than 1 would be an indication of a greater BPD/Head circumference or rounder head shape than expected. In our groups, all ratios were greater than 1. Greater BPD/Head circumference, implicating a more rounded head shape, could be a reflection of maturity of the baby, but it could also reflect actual population differences. It is therefore not surprising that the vaginal delivery group, as opposed to the caesarean section group, associated with a younger gestational age, presented with statistically significantly greater values. It is also of note that black South African newborns presented with greater ratios (rounder heads) than white South African newborns. This trend was also noted in the maternal BPD and BPD/Head circumference ratios, which were greater in black South Africans than white South Africans and more specifically, black South African women who delivered vaginally.

The length of the newborns, although the shortest in the white South African caesarean section group and the tallest in the white South African vaginal delivery group, was surprisingly similar with no significant differences and were within 1 cm of the expected standard (HealthwiseStaff 2020).

6.3.4 Duration of labour

In the small sample where the duration of labour was available, a longer duration of labour was noted in the black South African population (764.15 minutes) as compared to the white South African population (727.90 minutes). This duration of labour in both groups seems to be longer than generally reported (Duignan et al. 1975; Albers 1999; Stephansson et al. 2016). The difference might be due to different definitions for the start of labour and the impossibility to precisely define the onset of labour (Duignan et al. 1975). Duignan et al (1975) used the time of admission to the labour ward as the starting time of labour. The longer duration of labour noted in the black South African sample is in line with the findings of Duignan et al (1975) on North Americans. However, care should also be taken in the interpretation of the duration of labour recorded in this study because of the small sample size for this specific parameter.

6.4 Summary

- As expected, most pelvic canal linear dimensions were greater in white South Africans than in black South Africans, and in females compared to males. Dimensions in black South Africans were, in general, in line with those reported elsewhere, while white South Africans presented with greater measurements.
- The pelvic canal shape in black South Africans compared to white South Africans were narrower and smaller, while the relative anteroposterior outlet dimension was increased.
- Sexual dimorphism of the pelvic canal shape was more pronounced in white South Africans as compared to black South Africans, and included a more rounded or oval-shaped pelvic inlet in females, while more prominent ischial spines and narrower subpubic regions were found in males.
- The BPD, cranial index and head circumference were statistically significantly greater in white South Africans, while the cranial length was statistically significant greater in black South Africans.
- All linear dimensions of the skull were greater in males, apart from the BPD which was non-significantly greater in females, as well as the cranial index, which was significantly greater in females.
- White South African women, as compared to black South African women, presented with a statistically significantly greater BPD and also with the greatest BPD compared to the other sex-population groups.
- A relative trend of brachycephaly, as opposed to dolichocephaly, was displayed in females compared to males, and in white South Africans compared to black South Africans.
- In contrast to the findings on the cadaver and scan samples, maternal dimensions of black South Africans compared to white South Africans presented with a statistically significantly greater mean BPD and similar head circumferences, despite a statistically significantly shorter stature.
- The BPD, head circumferences and stature for both groups were greater than reported in the literature.

- The white South African vaginal delivery group presented with the greatest mean newborn head circumference of all other groups considered which was also greater than the expected, according to the literature researched.
- The length of newborns was surprisingly similar and according to the expected standards.

7. DISCUSSION

For a better understanding of geographical trends between population groups and variance in sexual dimorphism, a full account of the findings of this study, compared with the published literature, are given in Appendix B. In this chapter, the focus will be on the implications of the findings. Anthropometric factors that could predict cephalopelvic disproportion were investigated, the functional pressures related to bipedalism and childbirth were considered, possible consequences for forensic anthropological assessments are made, as well as inferences for perineal and pelvic procedures. The limitations and advantages of each modality used are weighed and possible future studies considered.

7.1 Implications for obstetrics

The relationship between the shape and size of the female pelvis and reproductive performance is of fundamental importance in obstetrics. As an alternative to vaginal delivery, elective caesarean sections became increasingly more acceptable for pregnancies associated with cephalopelvic disproportion during the twentieth century (Holland et al. 1982; Todman 2007). In an attempt to predict cephalopelvic disproportion in other ways, many studies aimed at determining factors such as stature, for instance, which might influence pelvic anatomy (Baird 1949). This observation has led to many studies aimed at determining factors such as stature, nutrition and body hormones, which might influence pelvic anatomy and therefore possible favourable outcome or not, (Baird 1949). Later, standardised radiological pelvimetry (Allen 1947) was developed particularly for predicting difficult labour (Chassar Moir 1946), but this technique lost favour however, due to reports implicating lower abdominal and other types of X-rays of mothers early in pregnancy with the subsequent development of leukaemia and cancers in their children.

Cephalopelvic disproportion (CPD) is considered common among Africans, leading to prolonged labour, as well as maternal and perinatal mortality (Tobias 1974; Merchant et al. 2001). Two aspects need to be considered when CPD is expected: 1) the size and shape of the pelvic canal and 2) the size of the foetus, more specifically the foetal cranium (Todd and Lindala 1928; Patriquin et al. 2002; Patriquin et al. 2003; Patriquin et al. 2005; Leong 2006; Oladipo et al. 2010). Many previous studies suggest that the shape of the pelvic inlet and outlet may reflect the shape of the crania passing through the birth canal (Patriquin et al. 2002; Patriquin et al. 2003; Correia et al. 2005; Oladipo et al. 2010). As cephalopelvic disproportion is considered more common among Africans than in European groups (Tobias 1974; Merchant et al. 2001; Patriquin et al. 2003), it was not surprising to find that all mean cadaver and radiological pelvic linear dimensions, as well as the subpubic angle, were smaller in black South Africans compared to white South Africans.

While mean linear measurements in black South African females were often smaller than the quoted desired minimum viz., widest inlet transverse diameter, OC, PO and the subpubic angle, the mean linear measurements were adequate for white South African females according to the literature researched (Patriquin et al. 2002; Patriquin et al. 2003; Brits et al. 2012; Işcan and Steyn 2013). Although the mean subpubic angle in the radiological sample was approximately three degrees smaller than the quoted desired for obstetric success (Frudinger et al. 2002; Maharaj 2010), when using a comparable methodology, the mean subpubic angle was greater in both populations of this study (white and black South African females) (Decker et al. 2011). It is, however, also important to take note of the minimum values recorded for each of these dimensions and to consider the possible impact of CPD for those women. The relatively smaller dimensions in black South African females as opposed to white South African females in this study group, should also be interpreted in the context of the literature on other populations reporting similar dimensions (Patriquin et al. 2002; Patriquin et al. 2003; Brits et al. 2012; Işcan and Steyn 2013). Thus, although black South African females presented with smaller dimensions than white South African females, many other studies reported similar measurements than those found in the black South African females of this study.

Dimensions of the pelvic inlet in females are important to consider during the engagement phase of parturition. During this phase, the BPD of the foetal head enters the ‘true’ pelvis. The OC, as a dimension, is palpable by obstetricians and clinicians during labour to assess the adequacy of the birth canal and is significantly larger in white South African females (128.26 mm) than in black South African females (110.38 mm). This difference observed in the OC, could contribute to the delay or inability of engagement of the head during parturition.

The IS represents the narrowest part of the pelvic canal through which the baby's head must pass through during birth and should be greater than 10 cm according to Moore (Moore et al. 2013). This, however, is not a fixed distance. Increased levels of sex hormones and relaxin causes the pelvic ligaments to relax during the latter half of pregnancy, allowing increased movement of the pelvic joints. Relaxation of the sacroiliac joints and the pubic symphysis permits increases of as much as 10-15% in the transverse diameter and IS. This facilitates the passage of the foetus through the pelvic canal.

Although the pelvic outlet dimensions, important for the exit of the baby, were larger in white South African females it was not statistically significant and therefore might indicate that once the head has engaged, passing through the outlet should not be different in black South African women.

As described previously (Todd and Lindala 1928; Patriquin et al. 2003; Betti 2021), the individual horizontal pelvic rings also demonstrated wider shapes in white South Africans as compared to black South Africans. These variations in shape were statistically significant for both the pelvic inlet and outlet. White South African females presented with a more spacious posterior inlet and a less encroaching sacral promontory and, therefore, a rounder pelvic inlet shape. The sacrum articulated more posteriorly with the ilium and the sacral promontory was placed more posteriorly in white South African females. White South African females presented with a generally wider shape and a relatively more posteriorly placed widest diameter of the pelvic outlet as compared to black South African females.

This study offered the unique opportunity to not only compare the cranial dimensions with that of the pelvic dimensions in the same cadaver, but also on 3D CT models in the same person. As cranial size and shape have been proposed predictors of pelvic size and shape (Işcan 1983; Patriquin et al. 2003), the correlations noted were not entirely unexpected. The possibility that cranial size and shape can predict pelvic canal size and shape is supposedly a valuable means to predict CPD and was noted in the correlations between cranial and pelvic data. Cadaveric and scan cranial dimensions of the black South African females had at least a moderate to significant correlation with one or more pelvic measurements, as well as with the shape of the pelvic rings.

Head circumference was the only dimension of the cadaver cranial in white South African females which correlated statistically significantly with pelvic dimensions. As the head circumference was statistically significantly correlated with certain pelvic dimensions in both groups, it would appear a simple way to predict pelvic canal adequacy.

To explore what the implications of these relationships between cranial and pelvic data would be for childbirth, a patient sample was included. Supposedly, the values of cranial dimensions could ideally predict childbirth outcomes. Comparable head measurements were taken in the patient sample and although pelvic measurements were not available in the retrospective records, successful vaginal delivery was considered to equate to an adequately sized pelvic canal as previously described (Philpott and Castle 1972; McGuinness and Trivedi 1999; Wittman and Wall 2007; Louis and Warren 2009; Stephansson et al. 2016). In addition, foetal and newborn measurements were assessed, as CPD not only depends on pelvic shape and size, but also on the size of the baby being born.

With reference to the variations noted between population groups in the cadaveric and radiological cranial findings, it was surprising to find that the variations in the dimensions of the patient sample differed. Head dimensions in white South African females were smaller (in the case of the BPD or BPD/ head circumference) or similar (head circumference) than in Black South African females. The stature in white South African females, though, was statistically significantly greater.

From the cadaveric and radiological pelvic measurements, the newborn measurements were expected to be smaller in black South African individuals to enable vaginal delivery (Patriquin et al. 2002; Patriquin et al. 2003; Correia et al. 2005; Oladipo et al. 2010). Although the newborn head circumference (in mm) was greater in black South Africans, this trend could have been influenced by the earlier gestational age of the white South African caesarean section subsample. On the other hand, newborn head circumference in the white South African vaginal delivery group was the greatest, followed by the black South African caesarean section group, black South African vaginal delivery group and the smallest, the white South African caesarean section group, which was statistically significantly smaller than that of the other groups.

From these observations, it seems that the black South African caesarean section group, which presented with greater foetal head circumference, could have experienced CPD. As the white South African C/S group delivered newborns with statistically significantly smaller head circumferences, it seems unlikely that caesarean section were performed because of CPD. It is interesting to note that both white South African and black South African caesarean groups presented with non-statistically significantly greater maternal head circumferences than the vaginal delivery groups respectively. This observation supposedly contradicts the impressions from the cadaveric and radiological samples, that cranial size predicts pelvic size. Perhaps maternal head size and shape is also a predictor of newborn head size and shape.

The foetal adjusted BPD/head circumference, for instance, presented with greater ratios in black South Africans compared to white South Africans in the vaginal delivery subgroups, similar to the maternal BPD/head circumference ratio. This notion is confirmed by Osborne et al. (1980) who found that maternal head circumference (and not paternal head circumference) had a significant effect on that of the newborn infant (Osborne et al. 1980).

Although genetic factors may could be responsible, Winder et al. (2011) found an association between maternal head circumference (and not maternal height) and increased placental efficiency, and newborn size. In their study of Winder and colleagues, maternal head circumference was regarded an indicator of the mother's foetal and infant growth. (Winder et al. 2011).

Adolescent physical growth is characteristically variable in timing, intensity and duration among individuals. Consequently, growth data during adolescence are aligned on a biological parameter, rather than chronological age. During adolescence, girls show greater growth of the internal acetabular and pubic regions relative to the amount of total growth achieved in other anatomical pelvic regions (Coleman 1969; Sharma et al. 2016). A special relationship between growth in pelvis size and reproductive maturation occurs. Studies have shown that if menarche occurred late in adolescence in a particular population, the pubis bone growth would be completed at a mensurately later age (Sharma et al. 2016).

The adolescent growth spurt occurs before menarche, but it does not influence the size of the pelvis in the same way as the rest of the skeleton (Sharma et al. 2016). The female pelvic growth is slower and the pelvis continues to grow for several years after adult stature is achieved (Ellison and de Wet 2001). Pelvis remodeling and the enlargement of the female birth canal are reportedly among the last events in skeletal growth. Girls with late menarche are consistently larger in pelvic size than girls with early menarche and skeletal measurements are being used as predictors of menarche (Ellison and de Wet 2001).

Many other factors apart from head size and shape could have an influence on the childbirth choice. Stature, for instance, is often used as a predictor of pelvic shape and CPD (Baird 1949; Bernard 1952; Adadevoh et al. 1989; Dujardin et al. 1996). From the results of this study, it appeared that stature had some influence on the decision to perform a caesarean section, as the stature was shorter in the overall caesarean group and per population group, but not statistically significantly so. A greater stature also seemed to promote labour and to protect against CPD, as in the black South African vaginal delivery group, stature was moderately inversely, but not statistically significantly correlated to the duration of labour. Merchant et al. (2001) commented that a woman with a height of 146 cm as compared to one of 160 cm, has a 2.5 times higher risk of intra-partum caesarean delivery (Merchant et al. 2001). On the other hand, a greater maternal stature was weakly but statistically significantly correlated to the newborn head circumference in black South Africans. Merchant and co-workers (2001) suggest that smaller women tend to have smaller babies, some of whom will show signs of intra-uterine growth restriction. This raises the possibility that this biological relationship may protect shorter women from suffering an excess of delivery complications (Merchant et al. 2001).

The relationship between stature and pelvic dimensions were confirmed by a study conducted by Adadevoh et al. (1989), who also related the size of the TC with the height of the individual and found that the TC measured a mean distance of 106.10 ± 8.10 mm in 114 Ghanaian subjects without CPD (cephalopelvic disproportion), while the mean heights of the individuals were 157.2 ±5.69 cm. Those with CPD were found to have a significantly shorter conjugate of 95.40 mm ± 6.30 and a height of 152.68cm ± 5.46. Adadevoh et al. (1989) commented on a study done by Stewart et al. (1979), which radiologically determined the true OC in Shona and Zulu women (Stewart et al. 1979; Adadevoh et al. 1989). The Shona women who had major CPD in labour requiring caesarean-section, had a mean maternal height of 151.32 cm and a mean TC diameter of 99.00 mm. The Zulu women with major CPD had a mean TC diameter of 96.00 mm. Their heights were not stated. Thus, all patients who had CPD in the three populations reviewed had a mean TC diameter of less than 100.00 mm and a mean maternal height less than 155.00 cm. Although the mean TC's in both populations and modalities in this study were greater than 100.00 mm, it should be noted that some minimum values were less than 100.00 mm in both populations and could have resulted in CPD in life.

Bernard (1952) performed a study on a group of Scottish women. In his study, the TC was determined radiologically and they found that women with a height of 152.00 cm had a TC of 108.00 mm. Those with a height of 167.00 cm had a TC of 127.00 mm and showed that the degree of mechanical difficulty in labour was inversely proportional to the patient's height (Bernard 1952). On the other, hand Ellison and De Wet (2001), found that stature was not a useful parameter when deciding to perform a caesarean section in a black South African sample (Ellison and de Wet 2001), as also demonstrated in this study. The shortest black South African in this sample who delivered vaginally was 145 cm tall and in the caesarean section group, 144 cm. A stature below 155 cm was neither recorded in this study for white South African women who delivered normally, nor for those that delivered by caesarean section. In the caesarean section group there were mothers with heights of up to 168 cm in the black South African sample, while the tallest white South African who delivered by caesarean section, was 175 cm.

Although maternal head circumference, stature, pelvic shape and size, as well as newborn head shape and size, and labour success appear to have some relationship in this study, as also described in the literature (Bernard 1952; Stewart et al. 1979; Adadevoh et al. 1989; Bushby et al. 1992), it seems to not always be related in such a way to avoid CPD. In this study, the white South African vaginal delivery group (VD) presented with the smallest maternal BPD and head circumference, while having the greatest stature, newborn head circumference and length, and the shortest duration of labour. The black South African C/S group, on the other hand, presented with the smallest BPD and shortest stature of all groups, with smaller maternal BPD/head circumference ratio, smaller foetal adjusted ratio: BPD/head circumference, but greater maternal head circumference, as well as newborn head circumference and length than the black South African VD group. As these trends were not statistically significant, larger samples could perhaps confirm or dismiss the notion that in the presence of a shorter stature, greater maternal head circumference is associated with greater newborn head size that could predict CPD. As not all caesarean sections were performed for CPD reasons, the progress of labour, as reflected in the duration of labour, could rather be employed when these correlations in larger samples are explored (Philpott and Castle 1972; Stephansson et al. 2016).

7.2 Possible evolutionary aspects in the variation in pelvic canal and cranial dimensions in South Africans

Investigations of the human pelvis have been of immense interest to biological anthropologists because of atypical evolutionary responses of a human pelvis to accommodate erect posture (Sharma et al. 2016). This favoured a narrow pelvis that increases locomotor efficiency (Rosenberg 1992; Gruss and Schmitt 2015) while simultaneously meeting the competing demand of obstetrical requirements. Biological anthropologists claim that in order to maintain adequate space for a safe delivery of a large sized foetal head the mother requires a wide sacrum that is tilted backward (Washburn 1949), a wider bi-acetabular diameter (Lovejoy 2005) and more elongated pubic rami (Patriquin et al. 2003) that reduce the risk of obstructed labour.

The action of these two antagonistic evolutionary selection pressures resulted in having a difficult childbirth process in humans due to a large-brained neonate, despite having a birth-canal space constrained by bipedality. Krogman (1951) referred to this phenomenon as a “scar of evolution” while Washburn (1960) described it as an “obstetric dilemma” (Washburn 1949; Krogman 1951), making midwifery obligatory to facilitate childbirth.

Gruss and Schmitt (2015) have estimated that the narrow, anatomically modern pelvis and a circular birth canal and the further encephalised neonate, requiring foetal rotation during birth, with a narrow body shape to enhance locomotion and for meeting thermoregulatory demands, evolved approximately 200,000 years ago in Africa and the Middle East (Gruss and Schmitt 2015). The different functional requirements in males and females in relation to the intensity of obstetrical selection pressures have been often emphasised for the observed sexual dimorphism in the pelvis (Patriquin et al. 2003; Salerno et al. 2007) as noted in this study. This sexual dimorphism resulted in decreased height and increased lateral breadth of the pelvis in females (Patriquin et al. 2005).

Warrener et al. (2015) concluded that pelvic width has no role in predicting hip abductor mechanics or locomotor costs in either men or women, and both are equally efficient at both walking and running, even if women have wider pelves (Warrener et al. 2015). This argument of Warrener et al. (2015) could also be extended to the variance in pelvic dimensions noted in this study. These authors attribute birth complications, caused by a neonate too large to fit through the birth canal, to other factors affecting pelvic and foetal size.

Betti et al. (2013), note that the variation in the shape of the pelvis as well as for the cranium reflects genetic diversity based on ancient demographic events as explained by neutral phenotypic evolution. The variations in the dimensions of the pelvis and cranium as noted in this study are, therefore, useful in population history (Johnson et al. 1989; Patriquin et al. 2002; Stull et al. 2014; Betti 2017) and in forensic anthropological estimations of sex and population. However, because of obstetrical constraints, dimensions of the true pelvis show less variation (Betti et al. 2013; Betti 2017).

This finding of Betti et al. (2013) was also reflected in the findings of this study where the pelvic dimensions limited to the pelvic/birth canal did not reach the same level of accuracies for population group differentiation described by others, who included dimensions beyond the pelvic cavity. However, population differentiation for females within the pelvic canal were greater than for males (Betti, et al. 2013).

Although stature is considered an important risk factor for cephalopelvic disproportion, shorter women present with relatively larger pelvic dimensions including dimensions within and outside the pelvic canal. However, dimensions outside the pelvic canal are more plastic and dependent on stature (Ricklan et al. 2021). As compared to those of the pelvic inlet dimensions, it is interesting to note that the mid-pelvic and pelvic outlet dimensions reported not to correlate with height in the literature, were also not statistically significantly greater in white South Africans, compared to black South African females in this study. In addition, the midpelvic shape did not demonstrate statistically significant differences between population groups. These differences noted between population groups could relate to differences noted in stature. As in the case with patient sample of this study and also from the literature, stature was greater in White South Africans as compared to black South Africans (Patriquin et al. 2002; Dayal et al. 2008). It seemed, therefore, that the smallest dimensions showed relative freedom of height and in this study, showed no statistically significantly differences between populations. The mid-pelvis and pelvic outlet dimensions show more integration and have relatively low variation because of the shared functional purpose of childbirth (Ricklan et al. 2021).

Variations in pelvic and cranial dimensions also reflect climatic variation, where a narrower pelvis and crania are found in lower-latitude populations, while the converse is true for higher-latitude populations (Howells 1957; Adadevoh et al. 1989; Keller et al. 2003; Harvati and Weaver 2006; Hubbe et al. 2009; Gruss and Schmitt 2015; Sharma et al. 2016). Populations who originated in colder climates, as noted in the white South African population group in this study, have relatively wider pelves and rounder heads in order to reduce heat loss. Narrower pelves and heads found in tropical climates, as noted in black South Africans, would help reduce heat stress (Beals 1972; Fee 1979; Beals et al. 1983; Weaver and Hublin 2009; Sharma et al. 2016). In the present study, all cadaveric and radiological pelvic linear dimensions were greater in white South African females than those of black South African females, as well as in white South African males as compared to black South African males. Although it has been suggested that the effects of climatic selection on the pelvis may be more prominent in size (via Bergmann's rule) than shape (Beals et al. 1983; Patriquin et al. 2002; Hubbe et al. 2009; Betti 2017), statistically significant differences between population groups within sex groups in this study were noted in the pelvic inlet and outlet shapes, but not in the mid-pelvic shape.

Recent publications consider nutritional status to have a more important impact on the obstetric dilemma than pelvic morphology. Improved nutritional status accompanying progress in agriculture may worsen the obstetric dilemma by increasing the size of the neonate without increasing the stature and pelvic canal accordingly. Palaeo-demographic comparisons showed lower rates of perinatal mortality in foragers when compared to agriculturalists (Udosen et al. 2006; Wells et al. 2012; Ricklan et al. 2021). These impressions were also reflected in this study, where, in both population groups, the caesarean section group demonstrated a non-significant shorter stature and greater maternal head circumference. The black South African caesarean section group, with presumable CPD, further also demonstrated a non-significantly greater newborn head circumference. An expanded patient sample may support or refute these relationships in future studies.

7.3 Implications for forensic anthropological assessments

The ultimate objective of a forensic anthropological assessment is to identify unknown individuals (İşcan 2005; Işcan and Steyn 2013). As part of this identification or estimation process, a biological profile is created (Turner et al. 2005; Braun et al. 2022). Two important components of the biological profile are estimations of population affinity and sex. Although much debate regarding the existence of distinct populations exists, it is essential to first identify the population, as it is an important determiner of the sexual variation of that specific group (Johnson et al. 1989; Patriquin et al. 2003; Hoyte et al. 2005; Patriquin 2005; Işcan and Steyn 2013; Sharma et al. 2016). It is, therefore, fundemental to establish population-specific standards (Zaafrane et al. 2018).

In the assessment of population variation, the skull is the most useful determiner and reaches an accuracy of 90% in specific reported groups (Krogman 1951; İşcan 2001). The estimation of sex relies on shape and size-based continuous traits (i.e. overlap, not discrete. The pelvis is the most sexual dimorphic complex in the skeleton, with up to 95% accuracy for the pelvis alone, up to 95% for the skull alone and up to 98% for the pelvis plus skull (Djorojevic et al. 2014; Franklin et al. 2014; Işcan and Steyn 2013). Morphoscopic, metric and geomorphometric methods are used for population or sex estimations from skeletal remains. Geometric morphometrics allow the visualisation and quantification of shape variations. However, as the differences between groups are often mainly only size-based, metric parameters are used as part of a discriminant function analysis (Işcan and Steyn 2013) as they are more rapid and straightforward to undertake from the bones directly, compared to performing GM analysis of size from digital landmarks on bones.

7.3.1 Pelvis

Variation in the pelvis between sexes and populations are often limited to descriptions of the pelvic inlet alone (Turner 1885; Greulich et al. 1939; Gutman et al. 2005; Killeen et al. 2010; Maharaj 2010; Betti 2017). Sex and population group differences that involve the entire pelvis have been described (Patriquin et al. 2002; Fischer and Mitteroecker 2015). Despite the fact that the pelvic dimensions used in this study were limited to the pelvic/birth canal and arranged in an overall shape, pelvic inlet, mid-pelvis and pelvic outlet, it delivered similar or improved sex estimation percentages compared to other studies including other parts of the pelvis as well (Stewart 1948; Işcan and Steyn 2013). This finding is not unexpected, as the main differences between the sexes relate to the shape of the ilium and of the pubis (Betti 2021), which are the anterior components of the pelvic cavity.

The pelvic dimensions limited to the pelvic/birth canal in this study did not reach the same level of accuracies for population group differentiation described by Patriquin et al. (2002), who included dimensions beyond the pelvic cavity. When considering linear measurements within sex groups separately, accuracies for population group was 79.25% (males in the radiological sample) and 83.53% (females in the radiological sample) as opposed to 88% for males and 85% for females in the study of Patriquin et al. (2002). This discrepancy in findings between sex groups could indicate that population differentiation for males is also situated outside the pelvic canal, while more within the pelvic canal for females.

Illustrating the importance of the prior identification of population group before the estimation of sex is attempted, sex discrimination for both populations, on the radiological and the cadaver sample for linear and overall pelvic shape analyses, improved as follows: linear dimensions on the entire cadaver sample: 78.00% versus

85.07% black South Africans and 82.93% white South Africans; shape dimensions on the entire cadaver sample: 94.67% versus 100% in white South Africans and black South Africans; linear dimensions on the entire radiological sample: 87.68% versus 89.16% black South Africans and 96.36% white South Africans; overall pelvic shape dimensions on the entire radiological sample: 98.55% versus 100% in white South Africans and black South Africans. The improved performance of sex estimation when populations are separated, contradicts the notion that the shape of the ilium and of the pubis, which form part of the pelvic canal, are stable across human populations (Betti et al. 2003). The reason why shape variations performed better than linear dimensions in differentiating sexes and groups in general, was that only those meaningful and well described linear dimensions (distances between two landmarks) were included in the discriminant analyses, as opposed to all permutations between two possible landmarks.

Should it not be possible to identify the population group prior to sexing, the overall pelvic canal shape could still be useful in the identification of the unknown remains. When considering shape variations for each sex population individually in the cadaver and the radiological sample, the groups were seldom misclassified: for the cadaver sample and radiological sample, respectively: black South African females: 3/34; 3/31; white South African females: 0/42; 2/52; black South African males: 2/34; 2/22 and white South African males: 2/40; 0/33.

When considering only the pelvic inlet shape, as has been relied upon by many other researchers in the past (Turner 1885; Greulich et al. 1939; Katanozaka et al. 1999; Louis and Warren 2009; Betti 2017), only white South African females showed a significant difference in the shape of the pelvic inlet when compared to all other groups. In addition, white South African males showed a significant difference when compared to black South African females. Despite these significant differences, sex-population groups were often misclassified, as can be noted in the confusion matrices. The pelvic inlet in isolation, therefore, does not seem to be the best way to describe the variation between the sexes or population groups.

The mid-pelvis seemed a better way to classify sex within a population group, as statistical significant differences were present between the sexes. Misclassifications were still evident. The shape of the pelvic outlet displayed the greatest variability between sex-population groups, as all comparisons for the radiological sample were highly statistically significant. However, misclassifications were still noted for the white South Africans.

From the results of this study, it is evident that the variations between sex and populations group are not limited to the pelvic inlet, but rather include the entire pelvic canal becoming more pronounced as progress is made through the canal. These findings could fit in with a study by Franklin et al. (2013) on the Western Australian population in which they concluded that the transverse pelvic outlet and subpubic angle contributed most significantly to sex discrimination, with accuracy rates between 81.2% and 100% (Franklin et al. 2013).

The subpubic angle, on the other hand, was significantly greater in females of both populations. Significant differences existed between black South African males and white South African males, with this angle in white South African males being larger. In general, the subpubic angle was smaller than reported and this should be taken into consideration when identifying unknown South African remains (Inuwa 1992; Hoyte et al. 2005; Ridgeway et al. 2008; Bonneau et al. 2012).

In several primate species the pelvic skeleton exhibits marked sexual dimorphism (Fischer and Mitteroecker 2017; Işcan and Steyn 2013; Wood and Chamberlain 1986). While pelvis size was similar in both sexes, the average differences in pelvis shape reflected the well-documented pattern of sexual dimorphism. There is almost no overlap between females and males in shape space (Işcan and Steyn 2013; Fischer and Mitteroecker 2017).

Sexual dimorphism in the human pelvis has evolved in response to the role of the pelvis in locomotion and childbirth. Because human males are, on average, taller than females, some aspects of sexual dimorphism in pelvis shape might result from allometry, the association between stature and pelvis shape across individuals (Fischer and Mitteroecker 2017).

Using geometric morphometric analysis of a dense set of 3D landmarks, measured on 99 female and male adult individuals, Fischer and Mitteroecker (2017) showed that that pelvis size and shape were similarly associated with stature in both sexes. It was found that dimorphism in the height-to-width ratio of the pelvis and in the orientation of the iliac blades was largely allometric, whereas dimorphism in the subpubic angle and the relative size and distance of the acetabula was largely non-allometric. It was concluded that, in contrast to the overall pelvic proportions, sexual dimorphism in the birth-relevant pelvic dimensions was mainly of non-allometric origin and was presumably mediated via steroid hormone secretion during puberty (Fischer and Mitteroecker 2017.

7.3.2 Cranium

It seems it was even of greater importance to identify population prior to estimating sex when using linear dimensions of the cranial vault compared to the pelvic canal (Johnson et al. 1989). Discrimination function analysis completely (100%) separated sexes within population groups, and population groups within sex groups in the cadaver and radiological samples for linear measurements. Prediction of population in the complete cadaver sample was 94.12% and the radiological sample, 65.22%, while the prediction of sex in the complete cadaver group was 88.24% and in the radiological sample, 69.57% for linear measurements.

As for the pelvic canal shape, the variations of the overall cranial shape delivered greater discrimination between groups, compared to linear dimensions, as also noted by (Stull et al. 2014). Discriminant analysis for the population group was 94.12% (entire cadaver sample) and 96.38% (entire radiological sample). The discrimination between population groups was higher than previously reported for South Africans in the study performed by Stull et al. of 89% on 18 stepwise selected shape free variables on the cranium for three population groups (Stull et al. 2014). In each population group, comparisons between sexes in both cadaver and radiological samples were highly significant with a 100% discrimination.

From only seven landmarks identified on the cranial vault, it was possible to accurately (100% accuracy) identify the sexes within a population group, and population groups within sexes. These findings reinforce the statement made by Johnson et al. (1988) that a large number of craniometric measurements does not necessarily give the best possible discrimination for a population group. However, from the results of this study, prior identification of population group from the crania, using linear dimensions, were disappointing and shape analysis would be better with accuracies greater than 90%.

7.4 Implications for pelvic and perineal procedures and incontinence

In this section the variations in the pelvic canal measurements will be reflected upon in pelvic procedures, while pelvic outlet dimensions will be considered in perineal procedure examples. Pelvic shape and size will be reflected upon for incontinence.

Pelvic procedures

The larger and wider pelvic canal dimensions reported in white South Africans and in females may be beneficial for the planning and performance of pelvic procedures whereas a small pelvic canal may impede vision, access and space for surgical excision. Hong et al. (2007), as well as Salerno et al. (2007), support the possibility that performing surgical procedures for rectal cancer may be easier in a wider and shallower pelvis as opposed to patients presenting with a narrower and deeper pelvis. (Hong et al. 2007; Salerno et al. 2007; von Bodman et al. 2010). Our results support that, because an anatomically narrower pelvis as found in black South Africans, and in males in general, may lead to a technically more challenging operation. With shape analysis, it was found that the ischial tuberosities were directed medially in black South African males.

Killen et al. (2010) suggest that a prominent sacral promontory, an acute curved sacrum or a pelvis narrow in the transverse plane (as noted in our black South African sample) could considerably represent anatomical bottlenecks, thereby impeding vision, access and space in which instruments can be manipulated (Killeen et al. 2010). Black South African males further had a more anteriorly directed coccyx as demonstrated by geometric morphometric shape analysis

Perineal procedures

The perineal procedures considered involved procedures designed to alleviate urinary and rectal incontinence or vaginal prolapse in the case of sacrospinous colpopexy. Perineal incontinence procedures require the dissection of the perineum, insertion of needles and the blind passage thereof. A wider pelvic outlet, as noted in white South Africans and females, could facilitate these procedures.

The tension free vaginal tape (TVT) procedure requires the blind passage of needles through the retropubic space via two small incisions in the abdomen just above the pubic bone for placement of a mesh. The smaller dimensions, including pubic symphysis length and inter-obturator distance, as seen in some black South Africans, need consideration during these procedures.

The use of instrumentation with a fixed dimension, may not take into account the variability in the relevant pelvic dimensions observed in the different populations and sexes considered. A 2-3 cm approximation for placement of the anchors from the urethra (or from the midline) as described by White (2004), may be too far apart in certain black South African females) (White and Walters 2004). The 2 cm margin described by Madjar et al. (2000) may be more suitable in these individuals to avoid misplacement of the anchors into non-osseous tissue. (Madjar et al. 2000).

The subpubic angle will give a reflection of the available space for the mesh (Ridgeway et al. 2008). As the ease of placing these meshes, as well as performance of rectal prolapse procedures in both males and females, may be enhanced by a wider dissection plane, white males may have an advantage. This plane is smaller in black South African males as a result of a significantly smaller subpubic angle and IT. The length of the pubic symphysis was also found to be significantly larger in white males. Increased care should be taken when placing this sling in black South African males, due to this smaller dissection plane, to ensure that the trajectory of the passer encroaching onto the perineal nerves (Grise 2009). A dissection performed at a shallower level may be necessary to avoid this problem.

The procedure in individuals who have a smaller subpubic angle and shorter distance between the ischial tuberosities and interobturator foramina distance, as in the case of black South African males, may result in the mesh tape having a slightly decreased route to exit at the expected point. If not anticipated, this might lead to mesh folding and mesh exposure in black South African males.

Another procedure for repair of vaginal prolapse, called a sacrospinous colpopexy, uses fingers or centimeter guides, which might be problematic if the anatomy varies (Giberti 2001; Guner et al. 2001; Maher et al. 2001; Sagsoz et al. 2002; Stanford 2004; El Tohamy 2006; Goldberg 2007; Sonoda et al. 2011). Verdeja et al. (1995) noted that the larger the OC, the longer the sacrospinous ligament and the distance from the ischial spine to the sciatic nerve (Verdeja et al. 1995).

Incontinence:

Stav et al. (2007) found that metric pelvic inlet and outlet dimensions were significantly larger in incontinent women. In our study, the pelvic inlet size was significantly larger in white South African females; this could predispose this group to incontinence. The pelvic outlet size, however, seems to be more important in incontinence, and was not significantly different between population groups. Further clinical data may be researched to support this hypothesis (Stav et al. 2007).

On the other hand, studies have also shown that a wider transverse inlet and a shorter obstetrical conjugate, as seen in the black South African female group common to a platypelloid shape, were significantly associated with pelvic floor disorders in females. They also found that the pelvic type at lowest risk may be the heart-shaped anthropoid pelvis. These pelves have a narrow transverse inlet and wide obstetrical conjugate. The anthropoid pelvis is more prevalent in black South African women (Handa et al. 2008).

7.5 Advantages and limitations of the methodologies and modalities used

7.5.1 Methodology

Traditionally, there are two methodological approaches for sexing skeletal remains, namely morphological and metric. Most of the older studies on sex differences in the skeleton focusing on the cranium and pelvis mainly, concentrate on morphological traits in a descriptive manner. These descriptions focus on shape, emphasising the bony configurations that are macroscopically visible. There are many advantages to this approach, such as recognising a particular characteristic or form despite variation in size, or the experience of the observer. However, the accuracy of the outcome is dependent on some subjectivity. Many of these assumptions of morphological differences are now challenged, and their existence and accuracy in separating between sexes are reassessed with modern morphometric techniques such as geometric morphometrics as described by, among others Patriquin et al. (2003), Steyn et al. (2004). Işcan and Steyn (2013), Del Bove et al. (2020) and Baca et al. (2022).

Three-dimensional geometric morphometrics is a relatively recent analytic tool in the field of biological anthropology, used to quantify and visualise bone morphology (for instance Pretorius et al. 2004; Işcan and Steyn 2013; Del Bove et al. 2020; Baca et al. 2022). Using this method, shape differences can be observed and quantified in three dimensions and it is possible to observe with more detail (one more dimension) exactly in what areas of a skeletal structure the variations in shape occur, and how large those differences are by statistical analyses..

In this study, a combination of metric and morphometric analysis were performed on the pelvis and cranium. The results were integrated for a better understanding of the variation in shape and size between groups and their correlations with each other, for instance, the commonly described tendency for females to present with gynaecoid pelves was only evident when shape analysis was performed. It was noted that the transverse diameter seemed to shift more anteriorly, further away from the sacral promontory in females, describing a more oval/round shape as compared to the heart shaped inlets of males (Turner 1885).

7.5.2 Cadaver sample

Direct measurements on intact cadaver pelves were made to eliminate error associated with re-articulation of the dried bones. The real life stature was unknown and correlations with height were not made. 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 (Ridgeway et al. 2008; Driscoll 2010; Bonneau et al. 2012; Brits et al. 2012). 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 (Bonneau et al. 2012). Furthermore, the present study found that asymmetrical subpubic arches were the rule, rather than the exception. The wedge-shaped appearance of the pubic symphysis seen in many cases at least partly contributed to the width of these subpubic arches (Brits et al. 2012). Studies on disarticulated pelves by other researchers (Heyns 1947; Brits et al. 2012) could possibly have overseen this contribution of the shape of the pubic symphysis to the width of the subpubic area.

Measurements on intact cadaver pelves stripped from its flesh are not directly comparable to live patients intra-operatively and radiographically, and consideration should be taken when interpreting the findings (Adadevoh et al. 1989). Inlet diameters were smaller in our groups as compared to intra-operative findings on other groups (Bernard 1952; Adadevoh et al. 1989; van Dillen et al. 2007), as well as on X-rays performed in earlier studies (Bernard 1952; Adadevoh et al. 1989; van Dillen et al. 2007). The subpubic angle in our population groups were also found to be smaller than in all other studies researched (Heyns 1947; Hoyte et al. 2005; Ridgeway et al. 2008). The closest findings were those of a study by Oladipo and Hart on the Ikwerres and Kalabaris tribes of Nigerian populations (Oladipo et al. 2010). The reasons for the Nigerian group to have the closest values to the present study cannot be ascribed to a population correspondence, as both and black South Africans were affected.

Apart from the subpubic angle, which was marginally and not significantly wider in the intact cadaver pelves in this study, cadaver linear measurements were, in general, smaller than the radiological findings. Except for the TC and OC, these comparisons were statistically significant. A consistently greater WTI, for instance, was noted in the radiological sample among all groups, with the greatest difference observed in the black South African female group where the WTI measured 119.15 mm in the cadaveric sample and 127.55 mm in the radiological sample. As the TC and OC involves only the promontory of the sacrum and not the more distal parts, a feasible explanation could be that the more distal protruding and movable parts of the sacrum and coccyx become suppressed by the weight of the cadaver and other cadavers during storage thereof. Measurements involving the distal sacral parts and the coccyx could then be affected to a greater extent. Anteroposterior compression could widen the sacro-iliac joints and explain the marginally greater subpubic angles, but general desiccation processes could have been involved in the contracted distances crossing the midline and involving joint spaces.

As 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 (van Dillen et al. 2007). The proficiency to conduct a manual pelvic examination is a skill not achieved and accurately performed by all helpers, as these measurements depend on the estimation of the length and width of the examiners fingers. The determination of the conjugates should be considered an estimation. The obstetrical conjugate is calculated by subtracting 1.5 to 2.0 cm from the DC, and it is therefore by definition, not an accurate measurement. These shortcomings may yield inconsistencies in the measurements taken (Adadevoh et al. 1989).

The cadaveric cranial measurements in the current study also presented with smaller measurements as compared to the scan. However, the cadaver sample was small (n = 33) and not well represented for all groups (e.g. six white South African male samples). Even though it seems logical that measurements done on real three-dimensional objects would be closer to the truth and more repeatable (Waitzman et al. 1992) than those done on radiographic films (Brown et al. 2009; Colman et al. 2019), and despite the fact that dried specimens are often used to determine dimensions on the cranium (Lieberman et al. 2000; Harvati and Weaver 2006; Brown et al. 2009; Hubbe et al. 2009; Işcan and Steyn 2013; Menéndez et al. 2014), shrinkage needs to be taken into account (Todd 1923). Comparisons of the cephalic index, as described by Fee (1979), as the ratio of the maximum breadth of the cranium to its maximum length, could not overcome the differences between the modalities used, and mean cadaveric ratios were smaller than radiologically, perhaps because shrinkage might not have been even or predictable (Todd 1923), or were more pronounced transversely (Todd 1923; Fee 1979). Supporting this notion, the maximum length is very similar, or even larger in the cadaveric sample, while BPD in the cadaver sample was markedly narrower than in the scan sample.

7.5.3 Radiological sample

Research has demonstrated that measurements performed on ordinary X- rays may not be entirely accurate. Heyns (Heyns 1947), for instance, suggests that certain dimensions such as the transverse diameter of the pelvic brim cannot be measured accurately on film. He further states that this diameter, in females, will always be less, never greater on the film than it actually is. The dried bone used by Heyns (1947), implies that disarticulation preceded re-articulation of pelves used for measuring dimensions manually and radiographically. This reassembly procedure might lead to errors (Heyns 1947).

In this study, 3D CT models were used to derive linear and shape data. The reason why 3D CT models were preferred to ordinary medical CTs was to improve the identification of the 3D landmarks. Although craniofacial measurements obtained from medical CT scans are considered accurate and reproducible (Waitzman et al. 1992), patients are scanned from different positions and angles, affecting the orientation of the slices. In the creation of a 3D virtual model, though, the orientation can be corrected so that homologous and repeatable planes and 3D landmarks can be defined. When Colman et al. (2019) compared CT scanned os coxae using a standard patient scanning protocol, and then repeated and segmented the scans to create 3D virtual bone models, their findings indicated different degrees of measurement error, attributed to differences in size because of segmentation and difficulties in landmark recognition. They concluded that, as these errors are substantial, medical CT scans should not be used as an alternative source for forensic anthropological reference data (Colman et al. 2019). Measurements from the study of Colman et al. (2019) of os coxae were 0.36–0.45 mm larger than the 3D reconstructed CT models (Colman et al. 2019). From the intra-observer intra-class correlations in this study, it seems that, despite the use of 3D reconstructed CT models, certain landmarks such as the inferior point of the coccyx and the ischial tuberosity, as well as the euryon, and, on either side, the most lateral point on the parietal or temporal bone, were not reliably repeatedly identified.

Another advantage of the radiological sample was that it offered the unique opportunity to correlate the cranial dimensions and pelvic dimensions of the same person, which not only improved the sample number (n =138) compared to the cadaver sample (n = 33), but also rendered the findings more meaningful. However, the real life stature was unknown and correlations with height could not be made.

7.5.4 Patient sample

Validity and reliability could not be adequately addressed as it is not part of the routine practice to repeat anthropometrics either by the main caregiver or another person before or after the delivery. Validity and reliability are therefore shortcomings in this study and findings on this section should be applied with caution in other contexts. There is however, no reason why the anthropometric data will be biased as measurements were taken before the birth outcome was known or in the case of the collection of prospective data, the measurements were taken blindly, i.e. without taking the birth outcome into account.

The maternal head measurements taken on the patient sample did not reflect the variation patterns noted in the cadaveric sample and supported in the radiological sample. Although white South African females had a greater BPD and/or head circumference than black South African females in both the cadaver and radiological samples, the white South Africans patient sample had a statistically smaller BPD as compared to black South Africans. No statistically significant differences were noted in the maternal head circumference between the groups considered and the BPD/head circumference ratio. A possible explanation for the different trends noted when comparing the patient sample with both the cadaveric and radiological sample may involve different hairstyles and textures among the population groups. The research done by Perret-Ellena et al. (2015) and Hshieh et al. (2016) alerts us that hair thickness may be responsible for inaccurate representation of the anthropometric investigations of head shape and size (Nooranipour and Farahani 2008; Perret-Ellena et al. 2015; Hshieh et al. 2016).

From the patient sample in this study, shorter mean stature might be a way to predict caesarean section for CPD, as both the total caesarean group and each population group individually, presented with a non-significantly shorter stature. The importance of stature as a reflection of CPD, or need for a caesarean section, was also found in the literature (Camilleri 1981; Adadevoh et al. 1989; Van Roosmalen and Brand 1992; Van Bogaert 1999; Liselele et al. 2000; Fischer and Mitteroecker 2015; Shachar et al. 2015), although it is not known whether the decision to perform a caesarean section on a shorter individual was based on the perception of a shorter mother not being able to deliver vaginally (Bergman and Bergman 2013; Shachar et al. 2015). Other studies suggest that in modern western society, the childbirth options presented to the mother are made to suit health professionals and hospital routines, rather than the mother herself or the baby's concerns (Bergman and Bergman 2013). It should also be noted that in this study, white South Africans, who more often underwent a caesarean section than black South Africans (20/31 as opposed to 9/35, respectively) were statistically significantly taller than black South Africans.

Population group differences in caesarean section rates among South African women are not explained by differences in demographic risk factors for assisted delivery, nor by differences in access to private health care facilities. Instead, the differences in section rates may reflect the effect of bias in clinical decision-making, and/or differences among women from different 'population groups' in their attitude towards assisted delivery and their capacity to negotiate with clinicians (Matshidze et al. 1998).

Using anthropometric head measurements as a way to predict caesarean section for CPD could have had some relevance for the black South African patient sample and was expected from the cadaveric and radiological findings. Many sex specific correlations existed between the linear cranial measurements and those of the pelvic dimensions, as well as between cranial and pelvic shapes. Black South African mothers who delivered vaginally, presented with the greatest BPD, as did the entire vaginal delivery group (possibly influenced by the greater representation of black South Africans in the sample) when compared to the caesarean section group. The greatest BPD/head circumference ratio was noted in the black South African vaginal delivery group and the black South African group in total.

Unexplainably, white South African mothers who delivered vaginally presented with the smallest head circumferences and BPD, but with the greatest newborn head circumference and length. On the other hand, the white South African caesarean group presented with the smallest newborn head circumference and length. White South African mothers undergoing caesarean section delivering smaller babies, could have been an indication of elective caesarean section. The estimation of exact gestational age is not always accurate, creating errors in judging when to do elective caesarean section (Wagner 2000). The observation of smaller head dimensions in white South African women who delivered vaginally was surprising, as sex specific correlations of linear pelvic measurements and shape dimensions to head circumference and the BPDs existed in females.

Caesarean section or vaginal birth did not bear any relationship with the anthropometric head measurements in white South Africans. The findings in this part of the study were confusing and no real pattern could be discerned on which deductions could be based. It seemed that in white South African women, decisions to perform caesarean section were based on reasons other than the size of the baby. According to a study done by Lauer et al. (2010), not only mother's choices, doctors' preferences or higher income should be considered in the rising caesarean delivery rates, but also health system factors financing surgical obstetric care (Lauer et al. 2010). Greater sample numbers and perhaps more information regarding the duration of active labour as a reflection of CPD (Philpott and Castle 1972), could have shed more light on this matter.

7.6 Future studies

Larger cadaver samples could elucidate whether the biparietal dimension is indeed statistically significantly greater in white South African women than in the other groups. This finding could have implications for forensic estimations. Larger patient samples could perhaps confirm or refute the notion that a greater maternal head circumference is associated with a greater newborn head size, and, in the presence of a shorter stature, could be risk factors for CPD. In studies exploring risk factors for CPD, the duration of labour should rather be correlated with anthropometrics, as caesarean sections are not always performed for CPD reasons. Studies correlating intra-operative outcomes with pelvic dimensions will be beneficial in the planning of intrapelvic and perineal procedures.

8. CONCLUSION

This study is a unique exploration of the variations in the size and shape of the pelvic canal and skull of the same individual, from an intact cadaver sample and from 3D CT models from patient scans, of black and white South Africans. Anthropometric data of mother and baby were additionally used to bring these findings into obstetrical context. The implications of the variations in the pelvic canal and skull dimensions for evolutionary changes in the human lineage, forensic anthropological estimations from skeletal remains and from clinical contexts were also considered.

- The longer duration of labour in black South Africans could possibly be indicative of some degree of CPD in this group. In both populations, the non-significantly shorter maternal stature, but greater maternal head circumference noted in the caesarean section group, as opposed to the vaginal delivery groups, could implicate these trends as CPD risk factors. In addition, the greater new-born head circumference in the black South African caesarean section group, as opposed to the vaginal delivery group, could further escalate the risk of CPD.
- Thermoregulatory factors could have been the drivers for the relative dolichocephalic (narrower) crania and dolichopellic (narrower) pelves in black South Africans.
- Unexpectedly, the pelvic canal shape did show population differentiation, however, the mid-pelvic and pelvic outlet dimensions were less variable, presumably because of the shared functional purpose of childbirth.
- Nutritional status may worsen the obstetric dilemma by increasing the size of the neonate without increasing the stature and pelvic canal accordingly, as noted in the black South African caesarean section group.
- Shape analyses of the pelvis and crania yielded better results in the prediction of population and sex when compared to the linear dimensions, illustrating that shape, and not size, differentiated these groups. Prior identification of a population group improved sex estimations.
- The prediction of population by linear pelvic canal dimensions reached 85.33% accuracy, similar to that of other studies which included pelvic measurements beyond the pelvic canal. Pelvic canal shape yielded accuracies of up to 97.87%.

- Discrimination between the sexes by linear pelvic dimensions reached 87.68%. Prior identification of population improved the sex discrimination for both populations: 89.16% for black South Africans and 96.36% for white South Africans. Sex discrimination based on pelvic canal shape reached 100% accuracy.
- For linear measurements of the crania, population prediction reached 94.12%, while 100% within sex groups. An accuracy of 96.38% was achieved for cranial vault shape.
- For linear measurements of the crania, the prediction of sex reached 88.24%, while sexes were completely (100%) separated within populations. Cranial vault shape had a 100% accuracy for sex estimation in the total sample, as well as within populations. It was unexpected that, from only seven landmarks on the cranial vault, it was possible to 100% accurately identify the sexes within populations and population within sexes.
- Technically challenging operations may be experienced when performing pelvic or perineal surgery in black South Africans and in South African men because of the relative anatomically narrower pelves found in these groups.

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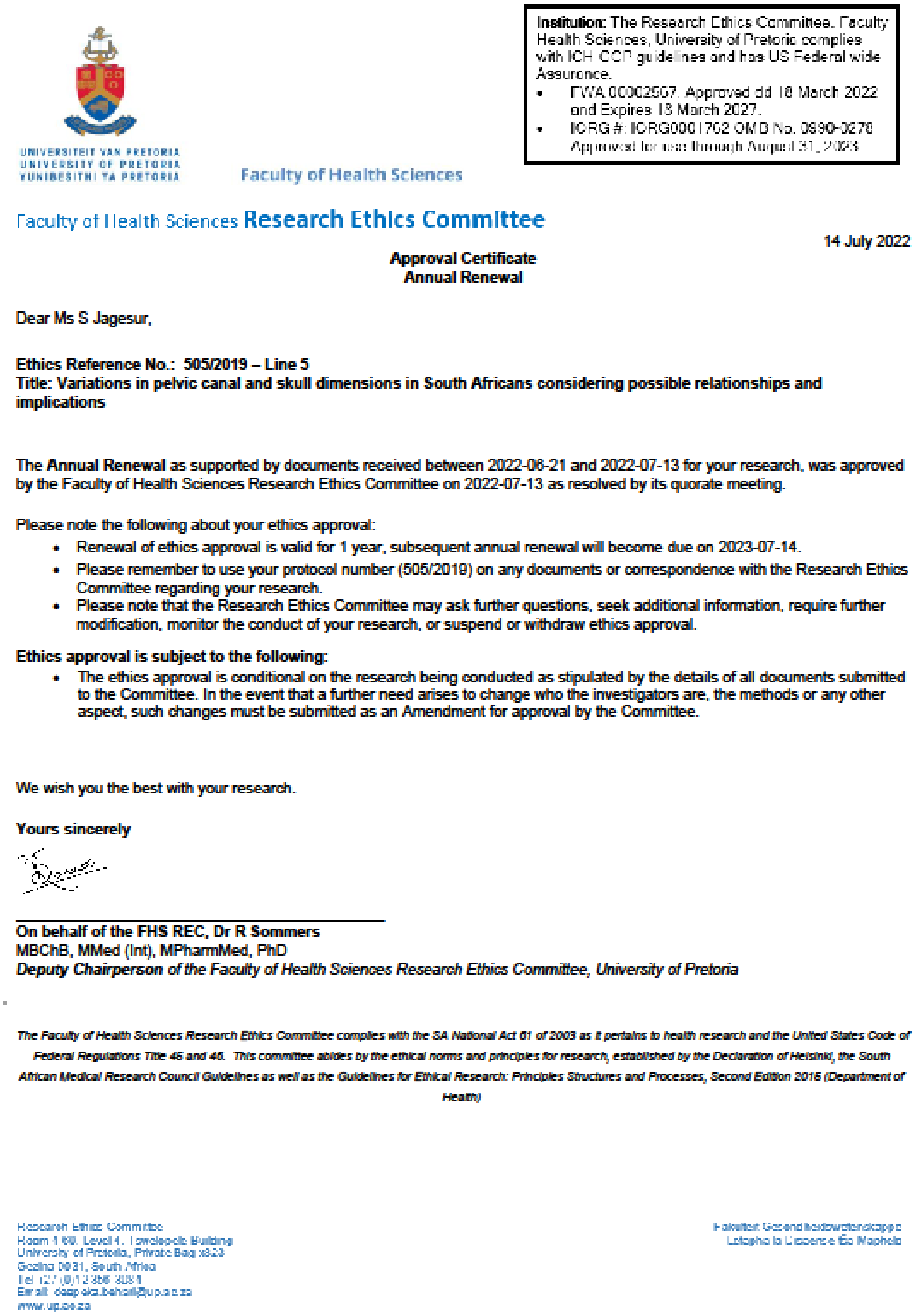
[END]

10. ANNEXURES

Annexure A: Ethical Approval Certificate



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0278 Approved for use through August 31, 2023.

Faculty of Health Sciences **Research Ethics Committee**

14 July 2022

Approval Certificate
Annual Renewal

Dear Ms S Jagesur,

Ethics Reference No.: 505/2019 – Line 5
Title: Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications

The **Annual Renewal** as supported by documents received between 2022-06-21 and 2022-07-13 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2022-07-13 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2023-07-14.
- Please remember to use your protocol number (505/2019) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
***Deputy Chairperson** of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

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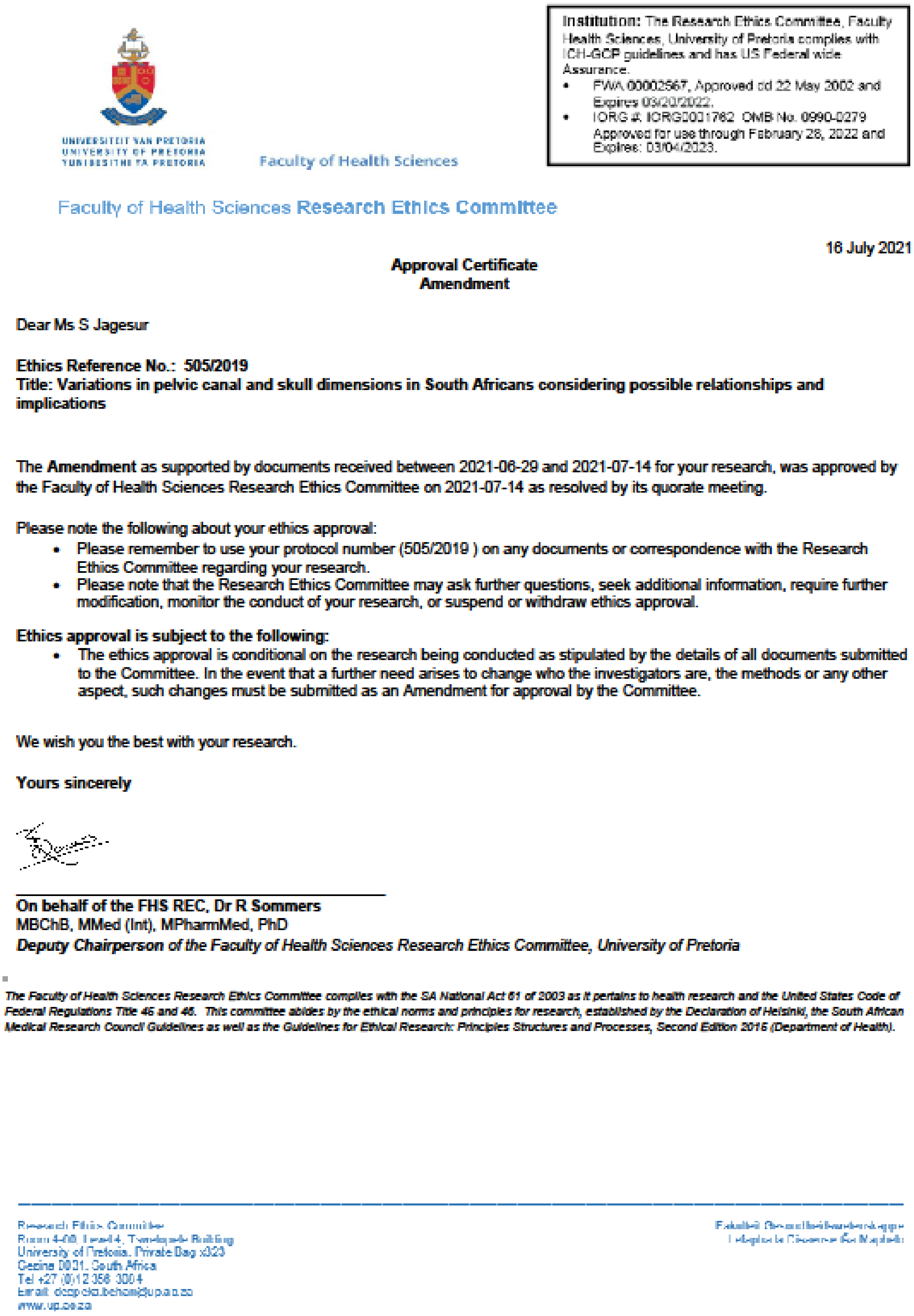
Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure B: Amendments to the ethical clearance certificate



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through February 28, 2022 and Expires: 03/04/2023.

Faculty of Health Sciences **Research Ethics Committee**

16 July 2021

Approval Certificate
Amendment

Dear Ms S Jagesur

Ethics Reference No.: 505/2019
Title: Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications

The **Amendment** as supported by documents received between 2021-06-29 and 2021-07-14 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2021-07-14 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Please remember to use your protocol number (505/2019) on any documents or correspondence with the Research Ethics Committee regarding your research.
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We wish you the best with your research.

Yours sincerely

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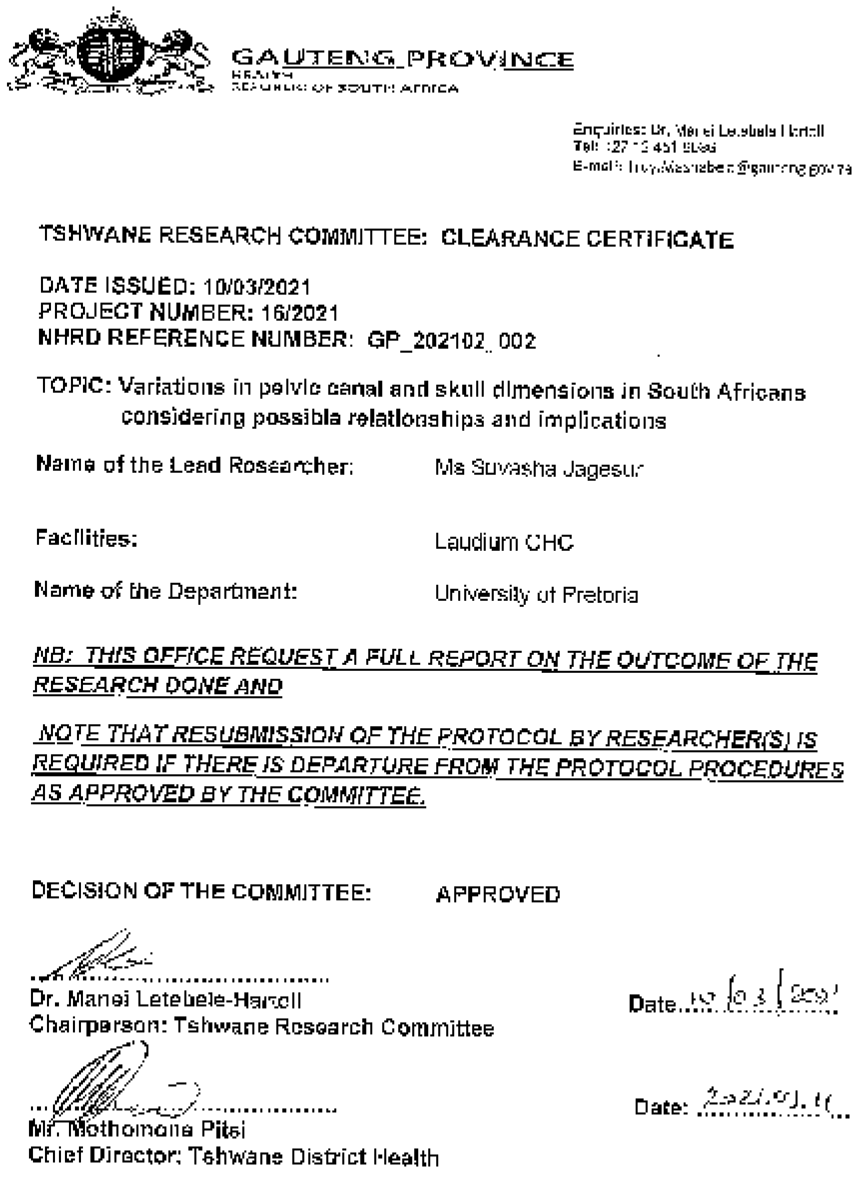
Lefapha la Disaense tša Maphelo

Annexure C. Tshwane Research Committee: Clearance Certificate



GAUTENG PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

Enquiries: Dr. Manei Letebele Hartell
Tel: +27 12 451 [illegible]
E-mail: [illegible]@gauteng.gov.za

TSHWANE RESEARCH COMMITTEE: **CLEARANCE CERTIFICATE**

DATE ISSUED: 10/03/2021
PROJECT NUMBER: 16/2021
NHRD REFERENCE NUMBER: GP_202102_002

TOPIC: Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications

Name of the Lead Researcher:	Ms Suvasha Jagesur
Facilities:	Laudium CHC
Name of the Department:	University of Pretoria

NB: THIS OFFICE REQUEST A FULL REPORT ON THE OUTCOME OF THE RESEARCH DONE AND

NOTE THAT RESUBMISSION OF THE PROTOCOL BY RESEARCHER(S) IS REQUIRED IF THERE IS DEPARTURE FROM THE PROTOCOL PROCEDURES AS APPROVED BY THE COMMITTEE.

DECISION OF THE COMMITTEE: APPROVED

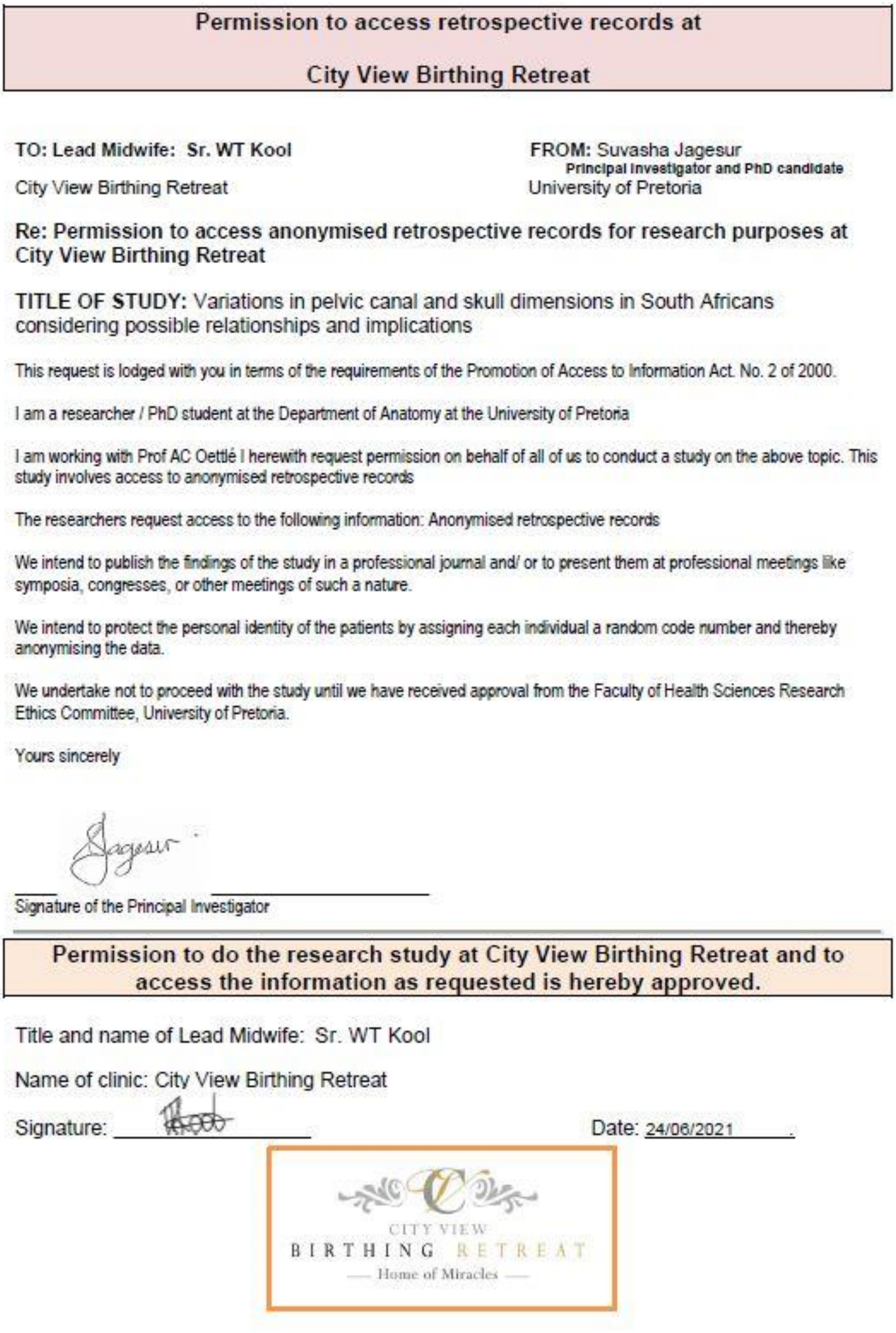
....
Dr. Manei Letebele-Hartell
Chairperson: Tshwane Research Committee

Date 10/03/2021

....
Mr. Mothomone Pitsi
Chief Director: Tshwane District Health

Date: 2021.03.11

Annexure D. Permission to access retrospective records at City View Birthing Retreat



Permission to access retrospective records at

City View Birthing Retreat

TO: Lead Midwife: Sr. WT Kool
City View Birthing Retreat

FROM: Suvasha Jagesur
Principal Investigator and PhD candidate
University of Pretoria

Re: Permission to access anonymised retrospective records for research purposes at City View Birthing Retreat

TITLE OF STUDY: Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications

This request is lodged with you in terms of the requirements of the Promotion of Access to Information Act. No. 2 of 2000.

I am a researcher / PhD student at the Department of Anatomy at the University of Pretoria

I am working with Prof AC Oettlé I herewith request permission on behalf of all of us to conduct a study on the above topic. This study involves access to anonymised retrospective records

The researchers request access to the following information: Anonymised retrospective records

We intend to publish the findings of the study in a professional journal and/ or to present them at professional meetings like symposia, congresses, or other meetings of such a nature.

We intend to protect the personal identity of the patients by assigning each individual a random code number and thereby anonymising the data.

We undertake not to proceed with the study until we have received approval from the Faculty of Health Sciences Research Ethics Committee, University of Pretoria.

Yours sincerely

Jagesur

Signature of the Principal Investigator

Permission to do the research study at City View Birthing Retreat and to access the information as requested is hereby approved.

Title and name of Lead Midwife: Sr. WT Kool

Name of clinic: City View Birthing Retreat

Signature: ______________ Date: 24/06/2021

CITY VIEW
BIRTHING RETREAT
Home of Miracles

Annexure E. Patient consent forms

PARTICIPANT'S INFORMATION & INFORMED CONSENT DOCUMENT

STUDY TITLE: Variations in pelvic canal and skull dimensions in South Africans considering possible relationships and implications
Principal Investigators: S Jagesur
Institution University of Pretoria
Contact number: 073 698 8071

DATE AND TIME OF FIRST INFORMED CONSENT DISCUSSION:

				:
Date	**month**	**year**		**Time**

Dear Prospective Participant
Dear Ms. / Mrs. ....

1) INTRODUCTION
You are invited to volunteer for a research study. I am doing research for a degree purpose (PhD Anatomy) at the University of Pretoria. This information in this document is to help you to decide if you would like to participate. Before you agree to take part in this study you should fully understand what is involved. If you have any questions, which are not fully explained in this document, do not hesitate to ask the researcher. You should not agree to take part unless you are completely happy about all the procedures involved.

2) THE NATURE AND PURPOSE OF THIS STUDY
The aim of this study is to see how the measurements of the pelvis and head correlates, so that we can better understand how variations might affect normal vaginal birth leading to caesarian section. By doing so we wish to learn more about the head circumference and height of both mother and baby as well as information regarding the birth outcome (i.e. vaginal vs caesarian section).

3) EXPLANATION OF PROCEDURES AND WHAT WILL BE EXPEXTED FROM PARTICIPANTS.
This study involves answering some questions regarding your age, height, population group and birth outcome i.e. vaginal vs caesarian section. If you agree, we will also specifically measure the height and head circumference of both mother and baby using a measuring tape for research purposes. Sonar measurements recorded before birth and after birth will also be taken into consideration.

4) POSSIBLE RISKS AND DISCOMFORTS INVOLVED
There are no medical risks associated with the study.

5) POSSIBLE BENEFITS OF THIS STUDY
Although you may not benefit directly, the study results may help us to gain a better insight into the possible predictors of birth outcomes in South Africa.

6) COMPENSATION
You will not be paid to take part in the study. There are no costs involved for you to be part of the study.

7) YOUR RIGHTS AS A RESEARCH PARTICIPANT
Your participation in this trial is entirely voluntary and you can refuse to participate or stop at any time without stating any reason. Your withdrawal will not affect your access to other medical care.

8) ETHICS APPROVAL
This Protocol was submitted to the Faculty of Health Sciences Research Ethics Committee, University of Pretoria, telephone numbers 012 356 3084 / 012 356 3085 and written approval has been granted by that committee. The study has been structured in accordance with the Declaration of Helsinki (last update: October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

9) INFORMATION
If I have any questions concerning this study, I should contact:
Miss S Jagesur on 073 698 8701
Prof AC Oettle on 083 870 2379

10) CONFIDENTIALITY

All information obtained during the course of this study will be regarded as confidential. Each participant that is taking part will be provided with an alphanumeric coded number e.g. A001. This will ensure confidentiality of information so collected. Only the researcher will be able to identify you as participant. Results will be published or presented in such a fashion that patients remain unidentifiable. The hard copies of all your records will be kept in a locked facility at your individual health care provider's facilities. An electronic copy of the data derived (measurements taken) will be kept in a locked facility in the Department of Anatomy, University of Pretoria.

11) CONSENT TO PARTICIPATE IN THIS STUDY

- I confirm that the person requesting my consent for myself and my child to take part in this study, has told me about the nature and process, any risks or discomforts, and the benefits of the study.
- I have also received, read and understood the above written information about the study.
- I have had adequate time to ask questions and I have no objections to participate in this study.
- I am aware that the information obtained in the study, including personal details, will be anonymously processed and presented in the reporting of results.
- I understand that I will not be penalised in any way should I wish to discontinue with the study and that withdrawal will not affect my further treatments.
- I am participating willingly.
- I have received a signed copy of this informed consent agreement.

______________________	______________________	______________________
Participant's name (Please print)	Participant's signature	Date

______________________	______________________	______________________
Researcher's name (Please print)	Researcher's signature	Date

AFFIRMATION OF INFORMED CONSENT BY AN ILLITERATE PARTICIPANT
(if suitable)
I, the undersigned, ……………………………………..…, have read and have explained fully to the participant, named ………………………… , the informed consent document, which describes the nature and purpose of the study in which I have asked the him/her to participate. The explanation I have given has mentioned both the possible risks and benefits of the study. The participant indicated that he/she understands that he/she will be free to withdraw from the study at any time for any reason and without jeopardizing the his/hers standard care.
I hereby certify that the patient has agreed to participate in this study.

______________________	______________________	______________________
Participant's name (Please print)	Participant's signature	Date

______________________	______________________	______________________
Researcher's name (Please print)	Researcher's signature	Date

______________________	______________________	______________________
Name of witness (Please print)	Signature of witness	Date

[END]

11. APPENDIX

Published article:

Jagesur, S., Wiid, A., Pretorius, S., Bosman, M.C. and Oettlé, A.C., 2017.

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Assessment of the variability in the dimensions of the intact pelvic canal in South Africans: A pilot study

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ABSTRACT

Cephalopelvic disproportion is common among Africans and is a major cause of maternal and perinatal mortality and morbidity. As the dimensions of the pelvis may vary between populations and according to stature and age, they need to be considered during childbirth and also in the planning and performance of pelvic and perineal procedures. The aim of this study was to assess the possible variations in the dimensions of the intact pelvic canal in South Africans and their implications. Eighty intact cadaver pelves, belonging to 40 white South Africans (20 males and 20 females) and 40 black South Africans (20 males and 20 females) were used for both metric and geometric morphometric analyses. Pelvic inlet shapes did not differ significantly between groups but pelvic inlet and midpelvic dimensions were the greatest in white South Africans and females. The pubic symphyseal length was the greatest in white males and the smallest in black females, resulting in a smaller pelvic cavity anteriorly than for white females. Pelvic outlet shapes varied significantly between sexes in white South Africans and between white and black males. Females presented with the greatest dimensions. Black South African females presented with an elongated anteroposterior outlet diameter. Certain transverse pelvic diameters correlated positively with age in white males and with height in females. In planning childbirth options, the smaller pelvic inlet of black females and stature-dependent diameters should be considered. Pelvic and perineal surgery may be technically more challenging because of smaller pelvic dimensions in black South Africans, especially in males.

Introduction

Measurable differences in the size and shape of the skeletal components of the pelvis between groups, including black and white South Africans, have been documented in the literature (Patriquin et al., 2002, 2003, 2005). Apart from the variations noted between population groups, other factors such as stature and ageing may also have an influence on pelvic skeletal dimensions (İşcan, 2005; İşcan and Steyn, 2013). These variations in pelvic dimensions among South Africa's population groups and with stature and ageing become important when decisions regarding method of parturition are made or pelvic procedures are planned. Stature, for instance, is often used as an early warning for possible cephalopelvic disproportion: the disproportion of the foetal head size as compared to the size of the maternal pelvis during delivery. Cephalopelvic

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disproportion is not an uncommon finding in Africans and could be a major cause of maternal and perinatal mortality and morbidity as indicated by Leong (2006). Constrictive pelvic dimensions could not only have far-reaching implications in obstetrics practice, but could also play a role in surgical procedures involving male and female pelvic structures.

The classic dimensions that are considered of importance are the diameters of the pelvic inlet (anteroposterior and transverse), midpelvis (interspinous distance) and pelvic outlet (anteroposterior and transverse). Several authors have related the size of the anteroposterior inlet diameter to the height of the woman and the obstetric outcome (Adadevoh et al., 1989; Bernard, 1952; Merchant et al., 2001; Stewart et al., 1979). The interspinous distance is also important to consider in parturition, as it is normally the narrowest part of the pelvic canal through which the foetal head must pass during birth. A narrow pelvic outlet may further predispose a woman to a difficult vaginal delivery. A rapid assessment of the outlet adequacy may be made by estimating the angle of the subpubic arch (Frudinger et al., 2002). The smaller the angle, the closer together the ischial tuberosities are and, therefore, the narrower the pelvic outlet.

Specific dimensions of the bony pelvis – relating to pelvic procedures in both males and females and during childbirth – have not been investigated in South Africans. It is therefore of value to study the possible variations in the dimensions of the pelvis among population groups, as well as their correlation with stature and ageing. These diameters and their relationships will be helpful in assessing the possibility of a favourable outcome in vaginal deliveries. They will also be useful when surgical procedures in both sexes are planned, as a small pelvic canal, for example, may impede visibility, access and space for surgical excision (Hong et al., 2007; Killeen et al., 2010; Salerno et al., 2007).

The purpose of this study was to assess certain clinically relevant dimensions on defleshed, but intact South African cadaver pelves and to take note of variations between populations and sexes and the effects of short stature and ageing. The possible implications of the variations between groups are considered in the discussion section.

Materials and methods

A total of 80 intact cadaver pelves from the anatomy departments of both the University of Pretoria and the former Medunsa Campus, University of Limpopo now called Sefako Makgatho Health Sciences University (SMU) were sampled. Cadavers used in this study were obtained between 2005 and 2009 as unclaimed or donated bodies from the surrounding hospitals. The sample was evenly distributed between the sexes and between black and white South Africans. The population group and sex of all individuals were known. Seventy-two of the 80 individuals had known age at death. Pelves that exhibited pathological features were excluded.

Stature was derived by regression analysis using physiological left femur length measurements. Lundy and Feldesman (1987) developed regression formulae incorporating femur lengths for the estimation of antemortem stature in male and female black South Africans, whilst Dayal et al. (2008) similarly developed formulae for male and female white South Africans. The living stature was then determined by adding Raxter's value for soft tissue (Bidmos and Manger, 2012).

The physiological femur length was measured on an osteometric board using the standard technique described in most anthropometry textbooks. The physiological femoral length was defined as the distance from the most superior point on the head of the femur to the most inferior point on the distal condyles. The posterior surface of the femur was placed parallel to the long axis of the osteometric board. The medial and lateral condyles were pressed against the vertical end board while applying the movable upright to the femoral head until the length was obtained (Moore-Jansen et al., 1994).

The pelves were defleshed and stripped to the bone without disarticulation to facilitate the identification of bony landmarks and the measurement of the distances between them. Diameters were measured from bone to bone but did incorporate joint components such as cartilage and ligaments, which would reflect the natural situation and would be more accurate when comparisons with clincial studies were made. Care was taken to keep the specimens moist with embalmimg fluid and covered by linen and waterproofed sheets to prevent dessication of the ligaments and cartilage joints.

The following ten points were marked with pins and then digitised by using a 3DXL MicroScribe® digitiser on intact pelves (Figs. 1 and 2): A: midpoint of the sacral promontory; B: most superior point in the midline of the pubic symphysis; C_L and C_R: left and right widest points on the pelvic inlet; D: most inferior point in the midline of the pubic symphysis; E_L: most inferior point on the ischial tuberosity (left); E_R: most inferior point on the ischial tuberosity (right); F_L: ischial spine (left); F_R: ischial spine (right); G: lowest limit of coccyx.

Distances and angles were calculated using standard mathematical techniques, based on the points measured on a three dimensional Cartesian coordinate system. The following distances were calculated between the various landmarks: AB: pelvic inlet anteroposterior (AP) diameter; C_LC_R: pelvic inlet transverse diameter; BD: length of pubic symphysis; DE_L: distance from the most inferior point in the midline of the pubic symphysis to the most inferior point on the left ischial tuberosity (length of the ischiopubic ramus); E_LE_R: intertuberous (transverse outlet) diameter; F_LF_R: interspinous (midpelvis) diameter; DG: pelvic outlet AP diameter and the subpubic angle between points E_L, E_R and D.

Basic descriptive statistics of all the data were calculated; i.e. the mean and standard deviation. Statistical comparisons of characteristics were made between the various sex-population groups, as well as linear correlations to stature and age using ANOVA. Inter-observer errors were tested on a later occasion by another observer familiar with the method. Thirty randomly selected intact pelves were re-measured and the reliability coefficients calculated.

The digitised landmarks were further considered for shape analyses. The landmarks were grouped into those describing the pelvic inlet landmarks (Fig. 3), pelvic outlet landmarks including ischial spines (Fig. 4) and pelvic canal landmarks (which included those of the pelvic inlet, midpelvis and outlet) (Figs. 5 and 6). Shape analyses were performed on all the intact

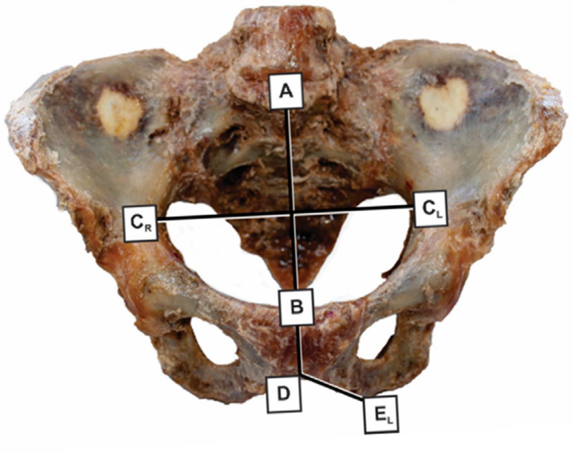


Fig. 1. Anteroinferior view of landmarks on wet intact pelves.

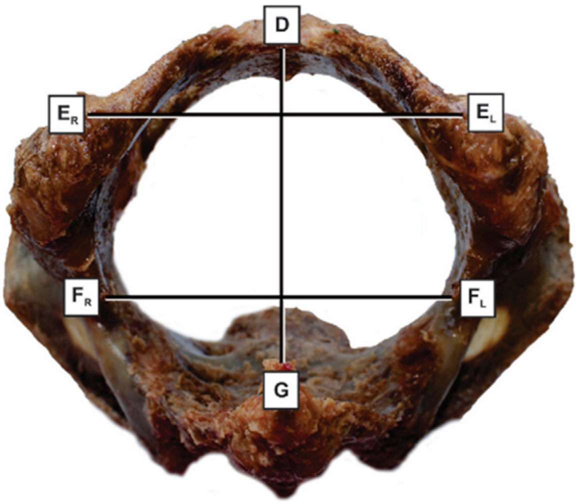


Fig. 2. Inferior view of landmarks on wet intact pelves.

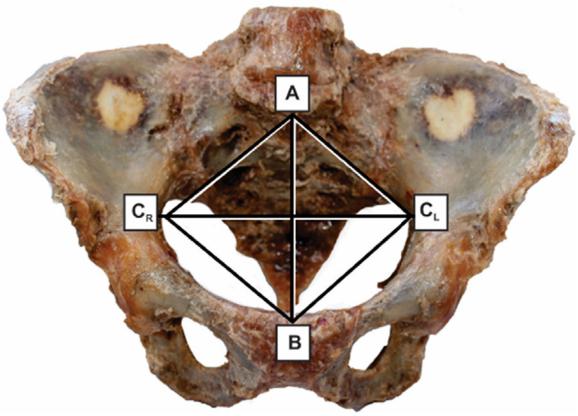


Fig. 3. Landmarks used in shape analysis for the pelvic inlet.

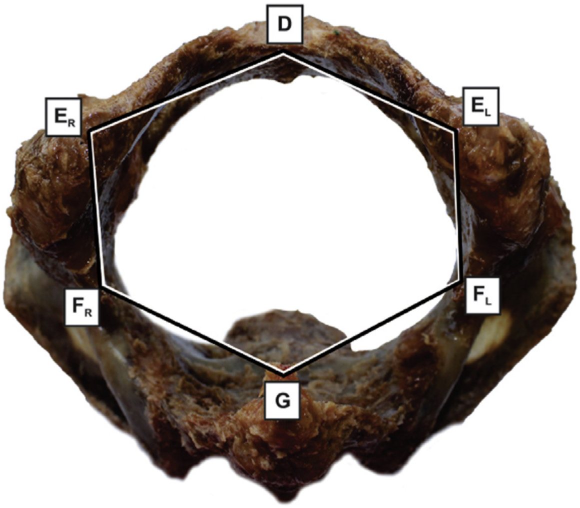


Fig. 4. Landmarks used in shape analysis for the pelvic outlet and ischial spines.

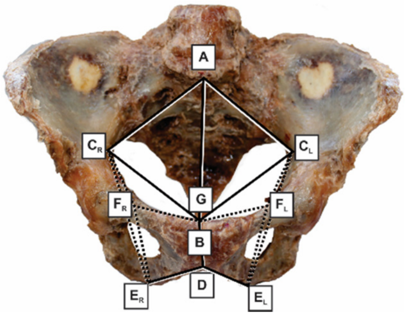


Fig. 5. Landmarks used in shape analysis for the pelvic canal (seen anteroinferiorly).

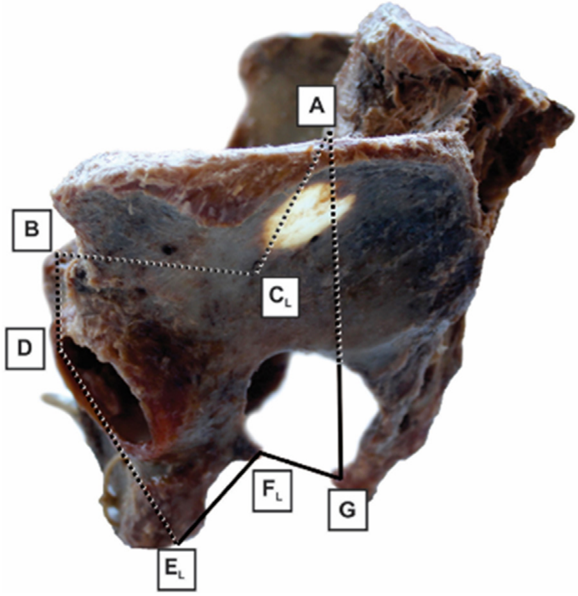


Fig. 6. Landmarks used in shape analysis for the pelvic canal (seen in lateral view).

Table 1
Variables of intact cadaver pelves within sex-population group. Group means, standard deviations (SD), and significant p-values comparing South African black males ($N = 20$), white males ($N = 20$), white females ($N = 20$) and black females ($N = 20$) for the variables used in this study. Measurements are in mm, subpubic angle in degrees and age in years.

Variable	Black SA male		White SA male		Black SA female		White SA female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AB: Pelvic inlet: anteroposterior	113.57^{SP^*}	10.30	123.44^{P^*a}	11.32	119.56^{SP}	7.10	128.62^{P}	11.94
C_LC_R: Pelvic inlet: transverse	112.04^{SP^*}	10.22	126.54^{P^*b}	8.69	118.88^{SP^*a}	7.74	130.76^{P^*}	7.65
BD: Length of pubic symphysis	44.23^{SP^*}	5.40	48.63^{P^*}	4.98	40.04^{SP}	6.13	45.31^{Pa}	5.54
F_LF_R: Midpelvis: interspinous	$78.84^{S^*P^*}$	9.23	$90.03^{S^*P^*}$	6.81	98.93^{S^*}	7.82	102.66^{S^*}	10.90
DE_L: Ischiopubic ramus	74.82^{SP}	5.36	79.30^{Pb}	6.17	80.42^{Sa}	9.82	80.06^{a}	6.54
E_LE_R: Pelvic outlet: intertuberous	$83.45^{S^*P^*}$	8.31	$98.34^{S^*P^*}$	10.00	110.19^{S^*}	9.06	109.96^{S^*a}	12.32
DG: Pelvic outlet: anteroposterior	92.03^{S}	8.63	95.00	8.78	99.60^{S}	11.15	94.87	12.92
Subpubic angle	69.09^{S^*P}	7.90	74.07^{S^*P}	7.31	85.49^{S^*}	7.50	86.85^{S^*}	7.97
Stature	1696.30	81.50	1753.60	84.70	1582.70^{S}	71.80	1643.10	60.40
Age	47.94	15.88	68.45	15.99	40.31^{S}	18.57	69.45	17.67

SA, South Africans.

[a] Statistically significant correlation with stature.

[b] Statistically significant correlation with age.

$^{S/P}$: Statistically significant difference between sex/population group: $0.01 < p < 0.05$.

$^{S^*/P^*}$: Statistically significant difference between sex/population group: $p \leq 0.01$.

pelves by introducing the data into Morphologika2 v2.5. A generalised full Procrustes analysis was performed to correct for orientation and size differences. The distribution of variance was plotted for principal components 1 and 2 representing the main shape differences to visually evaluate the scattering patterns amongst the groups. Two-group multivariate permutation test of PAST, PAleontologicalSTatistics v1.92 was used to test for statistically significant differences between groups (Hammer, 2001).

Ethical considerations

The skeletal material used in this study was obtained between 2005 and 2009 as unclaimed or donated bodies from the surrounding hospitals under the National Health Act No. 61 of 2003. Ethical clearance was granted by the Faculty of Health Sciences Research Ethics Committee, University of Pretoria, under the Protocol Number S42/2011.

Results

The basic descriptive statistics of the measured distances are given in Table 1 and principal component plots in Figs. 7 and 8. The pelvic inlet shape, defined by the position of the four landmarks as described before, did not differ statistically between groups (sexes: Fig. 7a, and population groups: Fig. 7b). In contrast, pelvic inlet dimensions were statistically significantly greater in females compared to males when considering the total sample and black South Africans, but not significantly in white South Africans (Table 1). When comparing population groups within sexes, statistically significantly greater dimensions were found in white South Africans than in black South Africans. When comparing females, the pelvic inlet transverse diameter (C_LC_R) differed at a lower level of significance than the antero-posterior diameter (AB), which could be indicative of some variation in the inlet shape between the population groups (Table 1). In other words, the greater pelvic inlet dimensions noted in South African whites vs. South African blacks, especially in females, seemed to have been associated with relatively wider pelvic inlet shapes.

When comparing pelvic outlet shape between sexes defined by the position of the six landmarks as described before, statistically significant variations were noted in the total sample ($p = 0.0005$) (Fig. 8a) and when considering white South Africans in isolation ($p = 0.0145$) (Fig. 8b). Sex variations in the pelvic outlet shape were only statistically significant at a level of 10% when considering black South Africans ($p = 0.0985$). In females the urogenital triangle, as defined by the distance on either side between the pubic symphysis to the ischial tuberosity and the distance between the ischial tuberosities, was relatively larger and therefore directed further and more posteriorly as compared to males. The coccyx was directed more posteriorly. These shape differences were also reflected in the metric dimensions.

The midpelvic (F_LF_R) dimension/interspinous distance was statistically significantly greater in females compared to males in each population group in isolation: black South Africans ($p = 0.0000$) and white South Africans ($p = 0.0005$). Pelvic outlet dimensions (intertuberous distance (E_LE_R)), anteroposterior outlet distance (DG), subpubic angle and ischiopubic ramus length (DE_L) were the greatest in black South African females and differed significantly from black South African males who presented with the smallest dimensions. The intertuberous distance and along with that the subpubic angle differed the most significantly between the sexes in black South Africans. The intertuberous distance and the subpubic angle also differed statistically significantly between the sexes in white South Africans.

The limitation of the statistically significant intersex differences to the anterior pelvic dimensions in white South Africans could be in keeping with the lower level of statistically significant sex differences in the pelvic outlet shapes in white

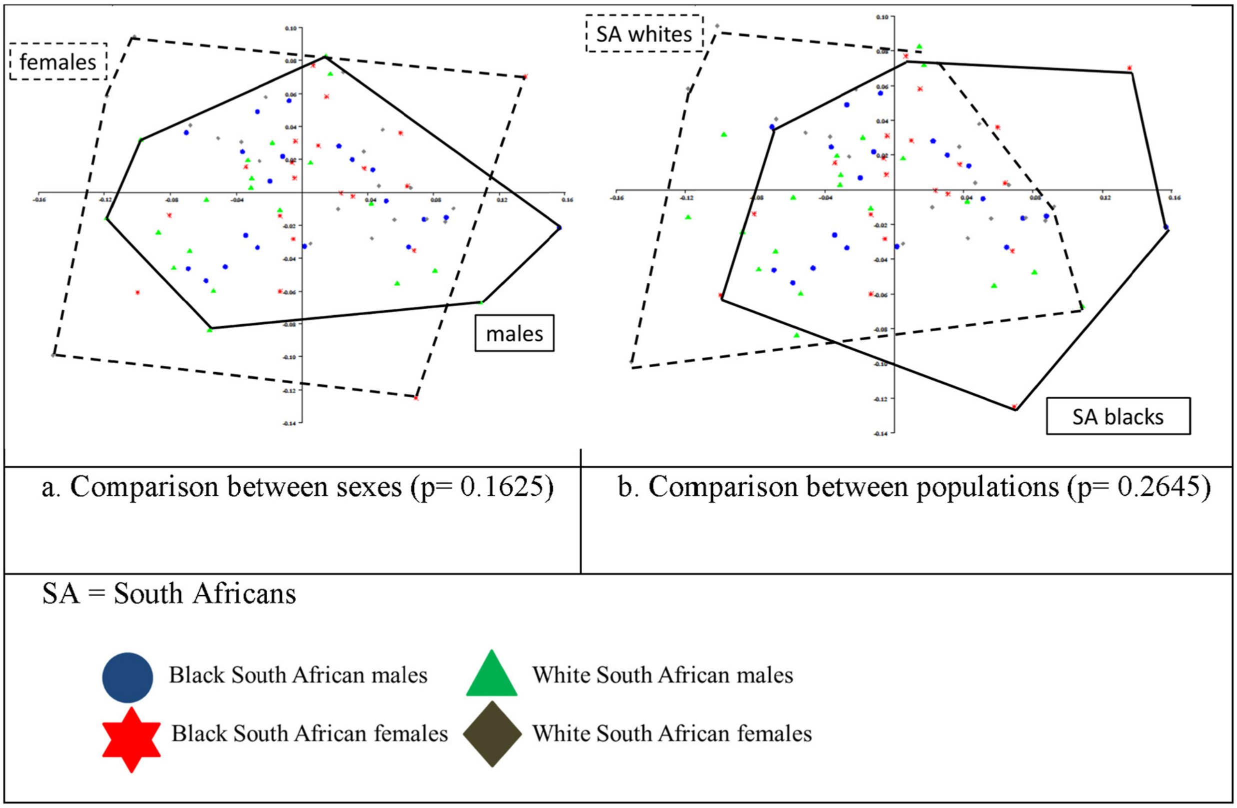


Fig. 7. Principal component 1 vs. 2: Pelvic inlet shape comparisons.

South Africans as compared to black South Africans. In black South African females the pelvic outlet dimensions were more uniformly increased as compared to males. White South African females presented with wider midpelvic and pelvic outlet shapes as compared to white South African males, while all the pelvic outlet dimensions were greater in black South African females as compared to black South African males.

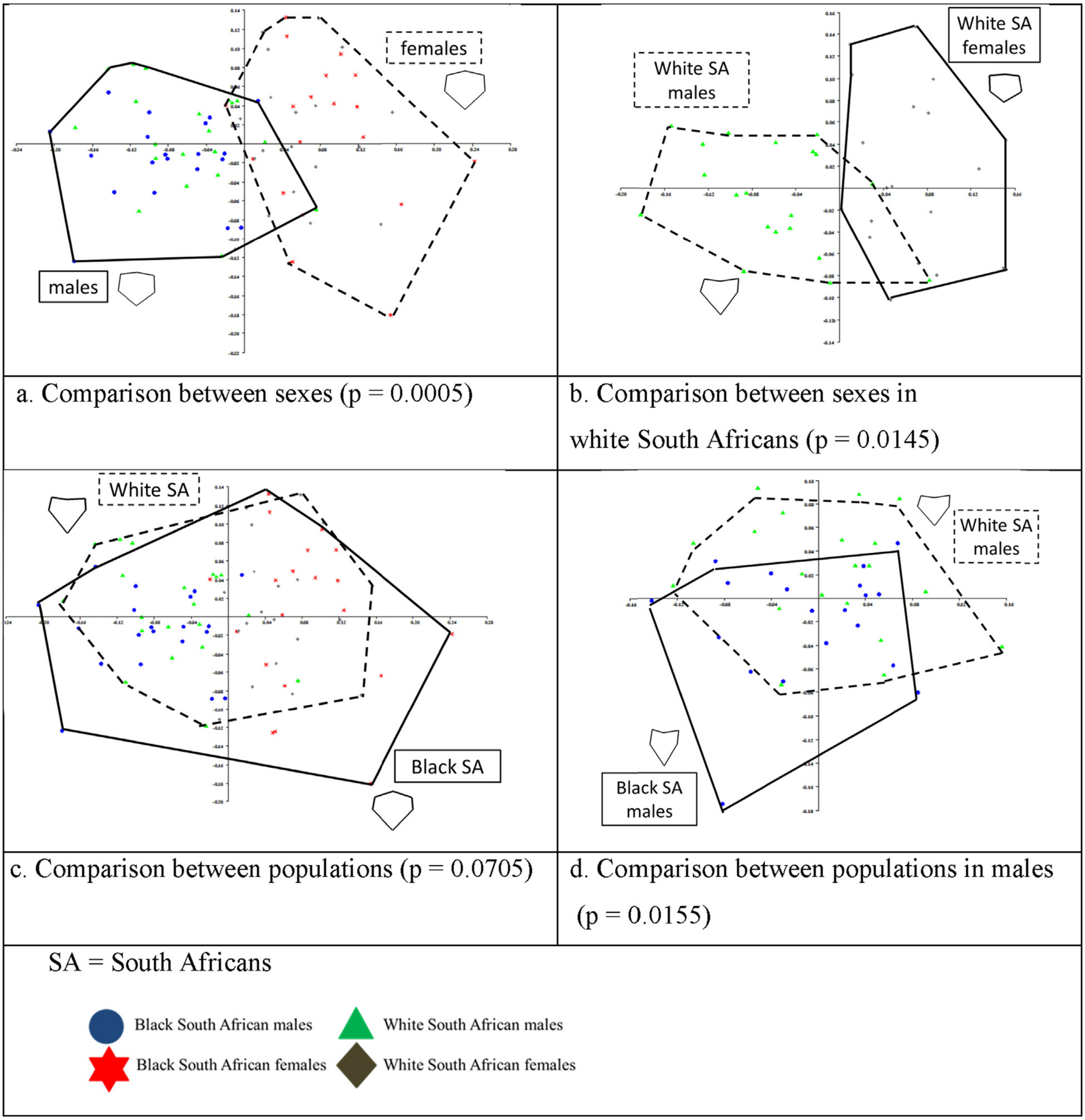
Pelvic outlet shape comparisons between population groups were statistically significant at a level of 10% ($p = 0.0705$) in the complete sample (Fig. 8c) but statistically significant at a level of 5% when comparing males: $p = 0.0155$ (Fig. 8d). These pelvic outlet shape variations were reflected in the statistically significant greater midpelvic and transverse pelvic outlet dimensions [intertuberous (E_LE_R), subpubic angle and ischiopubic ramus length (DE_L)] in white South African males as compared to black South African males but not in the anteroposterior outlet (DG) distance. Differences between females were not statistically significant.

All sex and population group comparisons involving the pelvic canal shape, defined before as the combined pelvic inlet, midpelvis and outlet shapes, were statistically significant: males compared to females: $p = 0.0005$; black males compared to black females: $p = 0.0005$; black females compared to white females: $p = 0.071$; black males compared to white males: $p = 0.008$; white males compared to white females: $p = 0.0005$; black South Africans vs. white South Africans: $p = 0.0415$.

The distance between the pelvic inlet and outlet is reflected in the length of the pubic symphysis (BD). The pubic symphyseal length was the greatest in white South Africans and in males. The pubic symphysis length was the smallest in black females, resulting in a smaller pelvic cavity anteriorly than in white females. Statistically significant variations existed between populations and between sexes in black South Africans but not in white South Africans.

Ageing had an effect especially on the pelvic transverse diameters of males and even more so in white South African males presenting with older average ages than black South African males. White South African males showed a statistically significant correlation when comparing age and pelvic inlet transverse diameter (C_LC_R) ($p = 0.0031$) and length of the ischiopubic ramus (DE_L) ($p = 0.0433$).

Transverse pelvic dimensions in females seemed to have been more sensitive to stature variation than in males. Black South African females showed a 5% statistical significance when comparing height to the pelvic inlet transverse diameter (C_LC_R) ($p = 0.0463$) and to the intertuberous diameter (E_LE_R) ($p = 0.0172$). White South African females showed a 5% statistical significance when comparing height to the length of the pubic symphysis (BD) ($p = 0.0330$), ischiopubic ramus length (DE_L) ($p = 0.0066$) and to the pelvic outlet intertuberous diameter (E_LE_R) ($p = 0.0191$). White South African males showed 5% significance when comparing height and the pelvic inlet anteroposterior diameter (AB) ($p = 0.0453$).



a. Comparison between sexes (p = 0.0005)

b. Comparison between sexes in white South Africans (p = 0.0145)

c. Comparison between populations (p = 0.0705)

d. Comparison between populations in males (p = 0.0155)

Fig. 8. Principal component 1 vs. 2: Pelvic outlet comparisons.

Discussion

The smaller pelvic inlet diameters in black South African females, could be associated with an inability of the foetal head to engage or the overriding of the vertex during parturition (Standring, 2008). The length of the pubic symphysis in black South African females was also the shortest of all groups considered, rendering the pelvic cavity shallower and smaller anteriorly. Sexual dimorphism in the pelvic inlet may be due to the later maturation of the pubis in females, prolonging the period of growth (Leong, 2006). During the accelerated growth period in adolescence, some individuals are vulnerable to poor socio-economic conditions and food deprivation so that growth in for instance the pubic symphysis is limited. These socio-economic factors could be contributing factors for stunted growth in the pubic symphysis in black South Africans females (Bernard, 1952). In cases where the height of the individual is also affected, the pelvic inlet transverse diameter (C_LC_R) may be diminished as well. It might therefore be of value to take the height in black females into account before contemplating normal vaginal delivery.

As the interspinous distance is normally the narrowest part of the pelvic canal through which the foetal head must pass during birth, diameters less than 100 mm could be a risk for midpelvic arrest (Keller et al., 2003; Moore et al., 2013). As the interspinous distance was sometimes smaller than 100 mm in black females and stature dependent on a 10% level of significance ($p = 0.0525$), it might also be of value in this regard to take the height of the mother concerned into account when planning assistance during childbirth.

On the other hand, Kurki (2013) relates population specific variations in the pelvic canal to genetic reasons. Kurki's (2013) findings on an archaeological collection are in line with those we report here. South African females display small pelvic inlets relative to a larger lower canal in anteroposterior diameters. Cephalopelvic disproportion might be negated if population specific variations in foetal head size and shape are contemplated to be accommodated by the population specific pelvic canal size and shape. Further research in this regard is necessary to improve understanding regarding the relationship between the shape and size of the foetal head and pelvis.

The greater pelvic transverse inlet diameters noted in white South African males vs. black South African males may have been influenced by ageing (Berger et al., 2011). Pelvic surgery may be technically more challenging in black South Africans, especially in males, because of restricted pelvic access. In addition the smaller subpubic angle in black South African males might contribute to difficult perineal access. Females in general presented with shorter pubic symphyseal lengths and greater pelvic diameters compared to their male counterparts, which might also facilitate intrapelvic and perineal procedures.

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