Metric Pair-Matching of Calcanei in Commingled Human Remains Cases:

A Case Study from South Africa

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A Thesis Submitted to
Saint Mary's University, Halifax, Nova Scotia
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Applied Science

August 2019 Halifax, Nova Scotia

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Date: 8 August 2019

ABSTRACT

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The current research uses the calcaneus to establish an accurate method of osteometric pair-matching in White, Black, and Coloured South Africans. Paired calcanei of 419 individuals (210 males, 209 females), 20 to 103 years old, were utilized. Six measurements were collected from each calcaneus. The MAXL and MIDB exhibited the least amount of directional and absolute asymmetry. Articular facets (DAFL, DAFB, MAFL, and MAFB) exhibited greater degrees of directional and absolute asymmetry. There were no statistically significant differences in directional and absolute asymmetry between sexes for most variables. There were statistically significant differences in absolute asymmetry between the three South African populations for some variables. Therefore, population-specific osteometric pair-matching methods are necessary. The statistic *M* was utilized to create reference tables for osteometric pair-matching. The values of *M* for MAXL for pair-matching comparisons resulted in the greatest reduction in the number of possible pairs with acceptable false rejection rates. The osteometric pair-matching tables of the current study can be combined with visual pair-matching techniques to assist in resolution of commingled remains cases.

Date: 8 August 2019

ACKNOWLEDGEMENTS

This thesis could not have reached completion without the numerous people and institutions that provided support to this project. First and foremost, I would like to express gratitude to my thesis committee supervisor, Dr. Tanya Peckmann for her outstanding devotion and patience throughout this time, especially the many hours spent reading and revising thesis chapters. Furthermore, your undergrad courses opened my eyes to forensic anthropology and steered me into this field I am so passionate about. You have also provided many invaluable educational and work opportunities over the years that will undoubtedly shape future career prospects, for which I cannot begin to express my gratitude. I also would like to thank the other committee members for their support and guidance. Thank you Dr. Susan Meek, not only for your statistical expertise and direction with this thesis and other research endeavours, but also for your guidance and friendship during this time. Dr. Claudia Garrido-Varas, thank you for your expertise and feedback, providing insights from your studies and forensic advising casework involving bilateral asymmetry and resolution of commingled remains.

This project would also not be possible without outside institutions and individuals. I would like to thank Professor Mandi Alblas and Professor Greyling for granting me access to the Kirsten Collection, and the hospitality of you and your students (thanks Daniella!). I would also like to thank Professor Ericka L'Abbe, not only for access to the Pretoria Bone Collection, but also for welcoming a random girl from Canada into your home (Marius, you were a wonderful host and cook!). I would also like to thank Gabi Kruger and Christian Marais for your assistance with data collection. Thank you to those I met in the bone labs (especially Marie, Clarisa, and Sam) for keeping me company

for tea/coffee breaks and helping me experience South African culture outside of the lab, and have since provided much assistance with the writing process of this thesis.

I would like to acknowledge those who have provided financial support for this research. I would like to thank the Nova Scotia Medical Examiner Service for the invaluable experiences I gained completing my Co-operative Education term with you. I would like to thank the selection committee of the Vice-President Academic & Research International Mobility Award whose award assisted in funding this research. Also, gratitude is extended to the Saint Mary's University Faculty of Graduate Studies and Research, Saint Mary's University SMUworks Program, and SMUSA for their financial assistance.

Lastly, but certainly not least, I would like to thank my family and friends. I would have never made it through this degree without your support. I cannot begin to express the gratitude I have for my parents, whom not only gave me constant encouragement, but who also supported me in many other ways to ensure the completion of this thesis. A special thank you goes out to Ciara who, while going through the same process and had other responsibilities of their own, would always offer to help, whether that was by lending an ear, being a sounding board, or editing my writing. I would also like to thank Natasha for her constant support and for giving me perspective. Thank you to each of my friends and family members for providing all varieties of support, founded within their differing strengths and perspectives. I can now answer those who ask "are you done yet?" with "yes, it is *finally* done!"

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CHAPTER I: INTRODUCTION

1.1 Commingled Human Remains

Commingled remains refers to a single assemblage where multiple sets of remains are present and cannot be distinguished as single individuals due to mixing of their skeletal elements (Byrd and Adams 2003; Osterholtz, Baustian, and Martin 2014; Ubelaker 2002). Anthropologists and forensic experts are tasked with the resolution of human skeletal remains that are found commingled in mass graves, and in accidental and natural contexts. In *Resolving Commingled Human Remains*, the Scientific Working Group for Forensic Anthropology (SWGANTH) outlined the best practices for forensic anthropologists to follow when excavating, sorting, and analyzing commingled human remains (SWGANTH 2013). Proper excavation and sorting techniques for skeletal remains are important, as the biological profile (i.e. estimation of ancestry, sex, age at death, stature, pathologies, and trauma) is most accurate when the skeleton is complete or nearly complete (Byrd and Adams 2003).

1.2 The Development of the Biological Profile

The identification of decomposed or skeletal human remains of unknown individuals requires the expertise of a forensic anthropologist. Forensic anthropologists assist in the identification of unknown human skeletal remains by creating a biological profile that includes estimation of ancestry, biological sex, living stature, age at death, pathologies, and trauma. The skeleton provides discriminating features, such as shape and size, assessed using non-metric and metric methods. Non-metric methods apply morphological (shape of bones and presence or absence of particular morphological

features) and morphoscopic (morphological features graded into categories) analyses (Komar and Buikstra 2008). Metric methods refer to the use of bone measurements and statistical analyses for an objective validation of results (Berg and Ta'ala 2014). Non-metric methods are more subjective and are dependent on observer experience in comparison to metric methods (Hefner 2009; Maier et al. 2015). The combination of non-metric and metric analyses of the skeleton allows the anthropologist to develop a biological profile.

1.2.1 Ancestry

The estimation of ancestry of unknown human remains is an important first step in the development of the biological profile (Berg and Ta'ala 2014). Estimates of sex, age, and stature can be evaluated once the ancestry is known, as research demonstrates that population-specificity affects the accuracy of these analyses (Garvin, Sholts, and Mosca 2014; İşcan 2005; Spradley and Jantz 2011).

Forensic anthropologists most often use the skull to assess ancestry. Morphological methods are often utilized for estimating ancestry based on the skull, e.g. marking such traits as orbital shape, suture complexity, and dental morphology (Komar and Buikstra 2008). However, these non-metric approaches rely less on the understanding of trait distribution among humans and more on observer experience, and thus are subject to potential errors (Hefner, Ousley, and Dirkmaat 2012).

Few morphological methodologies for estimating ancestry use the post-cranial skeletal elements (Berg and Ta'ala 2014). The femur is an exception as femoral geometry has been examined for the estimation of ancestry (Baker, Gill, and Kieffer 1995; Gilbert

and Gill 1990; Stewart 1962; Stewart and Kerley 1979). For example, femoral neck torsion, anterior curvature of the femoral shaft, and cross-sectional shape of the femur exhibit discernable differences between 'Native Americans', 'American Blacks', and 'American Whites' (Stewart 1962). However, these methodologies can only be utilized with populations from which the methods were developed and therefore are limited in their usage.

Metric methods for the assessment of ancestry were developed to avoid subjectivity and to create statistically strong analyses. Research by Wescott (2005, 2006) and Okrutny (2012) have utilized measurements of post-cranial elements for estimating ancestry. The subtrochanteric shape of 'American Indian' femora differ from 'American Black' and 'American White' populations (Wescott 2005, 2006). The subtrochanteric shape is evaluated using measurements of the femur. The measurements are applied to a linear equation, known as the Platymeric Index (PI), for estimating ancestral group affiliation (Birkby, Fenton, and Anderson 2008; Wescott 2005). However, evaluating subtrochanteric shape on other populations has shown low accuracy rates (Berg and Ta'ala 2014; Spradley 2014; Tallman and Winburn 2011). Okrutny (2012) found differences in post-cranial measurements between Koreans and U.S. service personnel with an approximate accuracy rate of 80% for their sample.

Additionally, forensic anthropologists use the interactive discriminant functions computer software program FORDISC: *Personal Computer Forensic Discriminant Functions* (Jantz and Ousley 2005) for metric assessments of ancestry. FORDISC has been shown to be a statistically robust approach to the development of the biological profile if the ancestry of your unknown individual is included in the population database utilized by FORDISC (Berg and Ta'ala 2014). The FORDISC computer program contains

compiled data from various human population groups, which it then uses to evaluate input measurements and compute the probable ancestral affiliation of the unknown individual. FORDISC measures an individual's "phenotypic affinity" (i.e. ancestral affinity) based on craniometrics and/or postcranial measurements entered into the database (Gowland and Thompson 2013, pp. 122). However, the database consists mainly of males and females of White European and Black African descent, and a lesser representation of Native Americans, Hispanics, and East Asians (Komar and Buikstra 2008). The limited population groups included in the FORDISC program is problematic. If an unknown individual does not belong to one of the ancestral groups included in FORDISC then this will affect the accuracy of the ancestry assessment and subsequent estimations (i.e. biological sex, age at death, and living stature) for the biological profile. While data submission to FORDISC continues to expand, more data are needed to provide more robust methods of ancestry estimation (Spradley 2014).

1.2.2 Sex

The second step in the development of the biological profile is estimation of biological sex. Estimating the sex of unknown human remains narrows the possibility by 50% when determining individual identity (i.e. who was the individual). The individual's sex influences other estimates of the biological profile, i.e. estimates of age at death and living stature (Scheuer and Black 2004; Feldesman and Fountain 1996).

Morphoscopic methods for sex estimation evaluate the degree of expression of 'masculine' and 'feminine' skeletal features. The pelvis is the most sexually dimorphic structure in humans as the female pelvis has unique functionality for childbirth as

compared to the male pelvis (Komar and Buikstra 2008). When assessing the sex of an adult skeleton, the pelvis has the highest accuracy rate at 96% (Buikstra and Ubelaker 1994; Gowland and Thompson 2013). Forensic anthropologists also evaluate the morphology of the skull for estimating sex. Features of the skull, such as the morphology of brow ridges and the nuchal crest, are useful for the estimation of sex. However, activity patterns also influence the morphology of these features. For example, in a female who participates in boat rowing, use of the trapezius muscles would develop a larger nuchal crest that is 'male-like'. Therefore, analyses could falsely estimate the individual as male when, in fact, they are a female (Case and Ross 2007).

Metric methods for the estimation of sex have been published for a variety of bones of the human skeleton (Berrizbeitia 1989; Case and Ross 2007; Peckmann et al. 2015a, 2015b; Steyn and İşcan 1997, 1998, 1999; Steyn and Patriquin 2009). The male skeleton is typically more robust, with greater overall bone size and larger muscle attachment sites, as compared to the female skeleton. However, sexual dimorphism in the subadult skeleton is less pronounced and difficult to assess as males may retain a more gracile structure until skeletal maturity, around 20 years of age (Buikstra and Ubelaker 1994). Metric methods for sex estimation consider sexual dimorphism in bone length, breadth, circumference, and articular facet dimensions. Analysis of the pelvis is considered the most accurate method for estimating sex (Spradley and Jantz 2011). When the pelvis is absent, analysis of the skull and post-cranial elements can be used for estimating sex. Spradley and Jantz (2011) found that multivariate models using the cranium for estimating sex were 90% accurate, and multivariate analyses of some post-cranial elements (clavicle, scapula, humerus, radius, ulna, femur, and tibia) are 88% to 94% accurate.

1.2.3 Age

Sequential chronological changes of skeletal morphology and dentition are the basis for estimating the age at death for unknown human remains. The relationship between chronological age and biological age is not a linear relationship. *Chronological age* refers to the actual time an individual has been alive, i.e. how many years, months, days, hours, minutes, and seconds. *Biological age* is a statistical concept based on the calculation of the degree of maturation of the body (e.g. sexual maturation), the skeletal system, or dentition. Developmental and degenerative changes evaluated for estimating age include eruption and exfoliation of deciduous teeth, eruption and wear of adult dentition, the appearance of ossification centers, formation and fusion of epiphyses, cartilage ossification, bone involution, and progression of bone porosity (Komar and Buikstra 2008; Scheuer and Black 2004). Skeletal and dental changes are complex as they occur along a developmental continuum, where individuals of the same chronological age may vary in degree of development (biological age) (Garvin et al. 2012; Iscan 1989; Scheuer and Black 2004). Therefore, forensic anthropology can only assess the biological age of an individual (Scheuer and Black 2004).

Methods for the estimation of age at death of subadult remains evaluate dental and bone development. Age estimations based on dentition evaluate the sequential emergence, maturation, and mineralization of the teeth. Buikstra and Ubelaker's (1994) *Standards for Data Collection from Human Skeletal Remains* includes dental charts developed by Moorrees, Fanning, and Hunt (1963a; 1963b) and Ubelaker (1989b) that illustrate the progression of dental development. The dentition of an unknown subadult is then compared to these charts when estimating age at death. Demirjian (1978) and Smith (1991) have also developed dental charts for estimating age at death. Evaluating subadult

skeletal remains for estimating age at death relies on the sequential appearance and fusion of ossification centers, morphology and size of the bones (Scheuer and Black 2004). Scheuer and Black (2000; 2004) present measurements of subadult bones throughout development and maturation; diaphyseal measurements of long bones are compared to documented measurements or applied to regression equations for estimating the age at death for the pre-natal and post-natal skeleton up to 18 years of age. Additionally, Stull and colleagues (2014) developed univariate and multivariate models using diaphyseal measurements that could estimate subadult age at death of individuals in their sample with 95% prediction intervals. However, models were less successful for individuals older than 10 years of age, as estimates were less precise and did not adhere to the 95% prediction interval (Stull, L'Abbé, and Ousley 2014).

Biologically, an adult is described as having fused long-bone epiphyses, spheno-occipital synchondrosis, and erupted third molars (Scheuer and Black 2004). Typically, by the time an individual reaches their late 20's or early 30's, the medial epiphyses of the clavicles have fused (Langley-Shirley and Jantz 2010). When epiphyses have fused and dental emergence and bone growth have ceased, osteological degenerative changes are evaluated for estimating age. Methods for estimating age in the adult skeleton include: cranial suture closure (Meindl and Lovejoy 1985), morphologies of the pubic symphyseal surface (Brooks and Suchey 1990), auricular surface of the ilium (Buckberry and Chamberlain 2002; Lovejoy et al. 1985), sternal rib ends (Işcan, Loth, and Wright 1984), maxillary suture closure (Mann, Symes, and Bass 1987), tooth-root translucency (Zerilli et al. 1992), osteoarthritis (Snodgrass 2004), dental-cementum annulations (Wittwer-Backofen, Gampe, and Vaupel 2004) and bone histology. "As an individual's chronological age increases, so does the accumulation of these extrinsic factors resulting

in greater variation in biological age" (Garvin et al. 2012, 203). Therefore, estimating age at death based on the development of the adult skeleton and dentition is less accurate and produces broader estimated age ranges in comparison to the subadult skeleton and dentition.

1.2.4 Stature

Biological anthropologists estimate living stature from skeletal remains by the application of osteological measurements to regression formulae. When assessing a complete skeleton, the most accurate method for estimating stature is the revised Fully technique (Raxter, Auerbach, and Ruff 2006). The Fully technique uses a combination of measurements from bones of the axial skeleton to create a linear equation; the Revised Fully technique includes the addition of correction factors, to account for soft tissue during life, producing a more accurate estimate of living stature (Raxter, Auerbach, and Ruff 2006). Raxter and colleagues (2006) found that by using the Revised Fully technique estimates of living stature were within 4.5 cm of the actual documented stature for 95% of the individuals in their sample. When the skeleton is incomplete, long bones, particularly those of the lower limb (femur, tibia, and fibula), provide the most accurate rates for estimation of stature because of the strong correlation between stature and limb bone length (Jantz 1992; Trotter 1970). Regression equations created by Ousley (1995), and derived from data from the Forensic Data Bank (FDB), resulted in prediction intervals within 3 inches (7.6 cm) to 4.5 inches (11.4 cm) of the actual living stature. When only fragments of the long limb bones are present, other complete skeletal elements can be used to estimate living stature: e.g. metacarpals (Meadows and Jantz 1992), metatarsals

(Byers, Akoshima, and Curran 1989), tarsals (Holland 1995), skull, clavicles, scapulae, and os coxae (Peng and Zhu 1983).

Most methodologies for estimating stature state they are either population-specific, sex-specific, or both, and if the ancestry or sex are unknown then less accurate estimates of stature are obtained by using 'generic' equations (Feldesman and Fountain 1996). However, Albanese and colleagues (2016a) tested stature estimations on White and Black Americans of both sexes using the FORDISC 3.1 computer program and found that sex-specific and population-specific equations were comparable in accuracy to equations that were not sex-specific nor population-specific. Albanese and colleagues (2016b) used the Terry Collection (White and Black Americans) to develop regression formulae. They tested these formulae on the FDB and the Lisbon Collection (White Europeans), which have known stature demographics. They found that without considering known population affinity or sex, their method could accurately estimate stature; the actual stature of the individual was within the estimated stature range for over 95% of their samples (Albanese et al. 2016b). While Albanese and colleagues state that stature estimates can be made independent of ancestry, sex, and age at death, further research must evaluate this methodology with other populations.

1.3 The calcaneus in biological anthropology

1.3.1 Ancestry

The calcaneus has been shown to be of limited use when used for the estimation of ancestry. Metric (Bidmos 2006b; Pickering 1986 and non-metric (Bidmos 2006b; Orr and Meek 2016) studies have suggested that there are population differences in the size

and shape of the calcaneus. The continued examination of this bone for ancestry studies is important as it is often found in forensic cases; the calcaneus is often well preserved during excavations due to its increased strength and density of the bone's trabeculae and because it is often encased in socks and/or shoes (Pickering 1986).

Due to the preservation and abundance of calcanei in Thailand, post-Vietnam War, Pickering (1986) developed a metric method for estimating ancestry from the calcaneus, to distinguish between American ('Caucasoid' and 'Negroid') and 'Mongoloid' populations (Southeast Asians, Japanese, and Amerindians). The author used six calcaneal measurements and two indices to develop discriminant function equations for classifying ancestry. This methodology was shown to have an accuracy rate of 83% to 94% for the estimation of ancestry for their specific population samples.

Bidmos (2006b) used metric and non-metric analyses of the calcaneus to examine differences between White and Black South African populations. The author collected nine measurements from the calcaneus of the White and Black South African groups to develop discriminant function equations for assessing ancestry. The accuracy of the equations was between 70% and 90%. In the same study, Bidmos collected non-metric data from the calcanei, specifically the number of talar articular facets. Chi-square tests showed statistical significance in the number of talar articular facets of the calcaneus between the two groups. The White South African group had a higher propensity for three talar articular facets (64%), whereas the Black South African group were more likely to display two talar articular facets (79%). Bidmos (2006b) concluded that when assessing ancestry, overall, the metric assessment of ancestry showed higher accuracy rates than the non-metric analysis. He suggested that when examining calcanei in forensic cases, the

non-metric method should be combined with other methods that show higher accuracy rates for ancestry estimation.

Orr and Meek (2016) studied the number of talar articular facets of the calcaneus from White, Black and Coloured South Africans for the estimation of ancestry. The number of talar articular facets were documented from dry calcanei located in the Pretoria Bone Collection (White and Black South Africans) and Kirsten Collection (Coloured South Africans). The Black and Coloured South African populations showed greater incidence of two talar articular facets (67.5% and 72.6%, respectively) than three talar articular facets (20.4% and 16.4%, respectively). The White South African calcanei showed a nearly equal frequency of two talar articular facets (41%) and three talar articular facets (46%). This is in contrast to Bidmos (2006b) who reported a higher incidence of three talar articular facets (64%) in White South Africans. Orr and Meek concluded that while there were variances in the number of talar articular facets between the White, Black, and Coloured South African populations, these differences were not statistically significant. Therefore, this methodology is not useful as the sole identifier for the estimation of ancestry for forensic cases that involve White, Black, and Coloured South Africa individuals. This methodology must be used in combination with other, more accurate, methods.

1.3.2 Sex

Sex estimation using the calcaneus has only been studied using metric analyses. Studies have shown that the calcaneus is sexually dimorphic, and methods have relatively high accuracy rates for sex estimation. However, sexual dimorphism is variable between

populations. When using discriminant functions developed for a particular population group, applying data from another population group most often results in low accuracy rates (Bidmos and Asala 2004, 2003; DiMichele and Spradley 2012; Peckmann et al. 2015). Thus, when estimating sex based on measurements of the calcaneus, population specific methods are necessary for accurate results. Methods for estimating sex using measurements of the calcaneus have been developed for the following populations: Black South Africans (Bidmos and Asala 2004), White South Africans (Bidmos and Asala 2003), White Americans (DiMichele and Spradley 2012; Steele 1976), Black Americans (DiMichele and Spradley 2012; Steele 1976), Central Europeans (Riepert et al. 1996), Southern Italians (Introna et al. 1997), Northern Italians (Gualdi-Russo 2007), prehistoric New Zealand Polynesians (Murphy 2005, 2002), Greeks (Peckmann et al. 2015b), Koreans (Kim et al. 2013), Thai (Scott et al. *accepted*; Wanpradab, Prasitwatthanasaree and Mahakkanukrauh 2011), and Egyptians (Zakaria et al. 2010). The accuracy rates for estimating sex in these studies, ranged between 63.8% and 90.2% using demarking points, 64% and 90.2% using univariate discriminant functions, and 79% and 93.5% using multivariate discriminant functions. All of these studies measured dry calcanei from skeletal collections, except Riepert et al. (1996) and Zakaria et al. (2010) who utilized calcaneal radiographs.

These population studies collected between one and 10 measurements from the calcaneus. These sex estimation studies have utilized measurements from dry calcanei from skeletal collections, except Riepert et al. (1996) and Zakaria et al. (2010) who utilized calcaneal radiographs. Radiographs, however, can exhibit size discrepancies (i.e. the image may be larger than the bone is in reality) and the angle of the radiograph may impede the ability to collect accurate measurements (Riepert et al. 1996).

Breadth measurements of the calcaneus were the most sexually dimorphic variables in the White South African (Bidmos and Asala 2003), Korean (Kim et al. 2013), Black American and White American (DiMichele and Spradley 2014; Steele 1976) populations. Conversely, length measurements were the most sexually dimorphic variables in Black South African (Bidmos and Asala 2004), Central European (Riepert et al. 1996), Greek (Peckmann et al. 2015), Egyptian (Zakaria et al. 2010), prehistoric New Zealand Polynesian (Murphy 2002), and Southern Italian (Introna et al. 1997) populations.

1.3.3 Age

Estimation of age using the calcaneus has been studied with varying success rates. Walker and Lovejoy (1985) attempted to document age-related changes in bone mineral density for utilization in age estimates. The authors assessed radiographs of adult calcanei, as well as femora, humeri, and clavicles, from the Hamann-Todd Collection. Radiographs of the calcaneus were visually seriated to observe trabecular involution for age estimates. The authors found that, while the other bones exhibited marked age-related changes, there was no correlation between calcaneal mineral density and age. Therefore, estimating age using the calcaneus was not possible for adult skeletons.

Development of the juvenile calcaneus bone has been documented in the literature and morphoscopic evaluation of the calcaneus may be used to assist in the estimation of juvenile skeletal age. The development of the calcaneus proceeds as follows: i) the ossification centre of the calcaneus appears in the prenatal skeleton between five and six months, ii) after birth the epiphysis for the calcaneus appears at 5 to 6 years for females

and 7 to 8 years for males, iii) the epiphysis commences fusion at 10 to 12 years for females and 11 to 14 years for males, iv) fusion completes between 15 and 16 years for females and between 18 and 20 years for males (Scheuer and Black 2004). However, this developmental sequence had not been utilized to create a methodology for estimating age using statistical testing and known accuracies, until the research investigation by Ekizoglu and colleagues (2015).

Ekizoglu and colleagues (2015) assessed epiphyseal fusion of the calcaneus using Magnetic Resonance Images (MRIs) of 97 males and 70 females between 8 and 25 years of age. A three-stage scoring system was utilized for the metaphysis and epiphysis: exhibited no fusion (Stage 1); exhibited partial fusion (Stage 2); exhibited complete fusion (Stage 3). The authors found that Stage 2 fusion appeared earliest in females, at 10 years of age, and in males as early as 14 years of age. Stage 3 appeared as early as 12 years of age in females, and 16 years of age in males. However, Stage 1, Stage 2, and Stage 3 appeared as late as 12 years, 14 years, and 25 years of age in females, respectively, and as late as 14 years, 20 years, and 25 years of age in males, respectively. Age estimates using this methodology were within a range of ±1.3 to ±3.6 years and the stages had a large overlap in age ranges. Therefore, Ekizoglu et al. (2015) found that their analysis provided limited information for estimating age using the calcaneus, and thus would not be suitable for forensic contexts.

Whitaker et al. (2002), Coqueugniot and Weaver (2007), Hackman et al. (2013), and Davies et al. (2013) have investigated the development of juvenile foot and ankle bones for the estimation of age, although the calcaneus was not examined independently of other bones. Therefore, these studies will not be discussed further as a method of utilizing the calcaneus specifically for estimating age was not proposed. Research has

demonstrated that when other bones are present, the calcaneus should not be used as the sole osetological element when estimating age at death for unknown human remains (Davies, Hackman, and Black 2014; Ekizoglu et al. 2015).

1.3.4 Stature

In biological anthropology, stature is estimated by using measurements of the skeleton (sometimes individual bones and sometimes a combination of bones) for linear and multiple regression analyses. Regression equations calculate stature within standard errors of estimates (SEE); i.e. when the SEE is 4 cm for a regression equation, the stature estimate would be e.g. 178 cm ± 4 cm, or a range of 174 cm to 182 cm. Research investigating the estimation of stature from calcaneal measurements was conducted by Holland (1995), Bidmos and Asala (2005), and Bidmos (2006a). These authors concluded that the regression equations were population-specific and displayed low accuracy rates when applied to skeletal remains from other populations.

Holland (1995) collected two measurements from the calcanei of 30 Black American males, 30 Black American females, 30 White American males, and 30 White American females from the Hamann-Todd Collection. The author used the maximum length and the posterior length of the calcaneus to create the linear regression equations for stature estimation of these population groups, separated by population and sex, and for pooled populations and sex. The equations had standard errors between 4.09 cm and 6.11 cm, with the largest standard errors for pooled population and pooled sex. The accuracy of these regression equations were between 40% and 100%. The equation using the variable PCAL and the equation using variables PCAL and MCAL for White females

were the least accurate (40%), while the equations using the variable MCAL for White females and White or Black females were the most accurate (100%) within 1SE.

Bidmos and Asala (2005) collected nine calcaneal measurements to develop stature regression equations for Black South Africans. The univariate regression equations have a SEE of 4.69 cm to 5.88 cm, and the multivariate regression equations have a SEE of 4.01 cm to 5.11 cm. The variables MIDB, MAXL, MAXH, BH, and DAFL showed the strongest correlation with stature of Black South African males, where the univariate regression equations utilizing each of these variables, separately, had accuracy rates of 87.5% within 1 SEE. The variable MINB had the strongest correlation with stature of Black South African females, where the univariate regression equation using this variable had an accuracy rate of 66.7%. The multivariate regression equations were more accurate for Black South African males, with accuracies between 62.5% and 100% within 1 SEE. However, the Black South African female multivariate regression equations showed low accuracy rates for estimation of stature, between 16.7% and 33%. Due to these lower accuracies, the authors suggested using a range of 2 SEE for more accurate estimations of stature for both males and females (between 83.3% and 100%); however, these estimates provide too broad of a range to be of use in forensic contexts.

Bidmos (2006a) also collected nine calcaneal measurements to develop stature regression equations for White South Africans. The univariate regression equations showed a SEE of 4.56 cm to 5.95 cm, and the multivariate regression equations displayed a SEE of 4.22 cm to 4.55 cm. The variable MAXL had the strongest correlation with stature in the White South African male ($R = 0.72$; SEE = 4.56 cm) and female ($R = 0.75$; SEE = 4.59 cm) groups. The multivariate regression equations, which used a combination of length, breadth, and height variables, were most strongly correlated with stature for the

White South African male (R = 0.78; SEE = 4.27 cm to 4.30 cm) and female (R = 0.81; SEE = 4.22) groups.

1.4 Terminology

1.4.1 Sex and gender

The terms *sex* and *gender* are not interchangeable, in biological anthropology, as they have different meanings. *Sex*, or *biological sex*, is a dichotomous term that encompasses genetic/chromosomal and physical/anatomical attributes of individuals, such as sex chromosomes, genitalia, gonads, and hormones (Walker and Cook 1998). Size and shape differences between females and males of a given species are referred to as *sexual dimorphism* (Berg 2013). Although differences between sexes in soft tissues are easily visible, sexual dimorphism is also evident in the human skeleton. Sexual hormone production during puberty causes sexual dimorphism in the human skeleton (Berg 2013). Sexual dimorphism in the human skeleton allows forensic anthropologists to estimate biological sex based on the size and shape of the bones. The foundation for these methods is biological. For this reason, forensic anthropologists use the term *biological sex* or *sex* in the assessment of the biological profile. The term *sex* will be used in this thesis when referring to biological dimorphism in unknown human remains.

Gender is a socially constructed identifier with multiple classifications; there is no biological basis to a person's gender (Berg 2013; Holobinko 2012). Gender is "a matter of culture: it refers to the social classification into 'masculine' and 'feminine'" (Oakley 1985, 16). The idea of sex roles, i.e. division of labour and the hierarchy between men and women, founded the idea of gender (Delphy 1993). The division of gender is often a

function of such factors as occupation, clothing, and personality, and not simply a reflection of the genitalia (i.e. biology) present (Oakley 2015). Since the term *gender* has no biological basis, it will not be used in this thesis when referring to biological dimorphism in unknown human remains.

1.4.2 'Race' and ancestry

The term '*race*' is defined as the division of a species into distinct population groups, where shared observable characteristics define members of one group from the others (Relethford 2009; Sauer 1992). Carolus Linneaus (1707-1778) initiated the concept of human 'races' by creating a classification system for plants and animals (Hefner, Ousley, and Dirkmaat 2012). The belief in Divine creation influenced Linneaus' categorization of humans into fixed types (Kelso 1967). Linneaus gave his four primary human categories Latin names: *Homo sapiens americanus, asiaticus, europaeus,* and *afer* (Ta'ala 2014). Shared anatomical characteristics were the foundation of the categorizations, though perceived social and behavioural characteristics were also attached to these categories (Hefner, Ousley, and Dirkmaat 2012). Linneaus assigned the most favourable behavioural characteristics to *Homo sapiens europaeus,* whom were described as White, cheerful, muscular; *afer* were described as Black, phlegmatic/relaxed, and lazy; *asiaticus* were described as pale Yellow, melancholy, and stiff; and, *americanus* were described as Red, choleric/prone to anger, and upright (Gould 1994, 67; Sauer 1993, 79; Quintyn 2010, 17).

Johann Blumenbach (1752-1840) disagreed with Linneaus' discrete categories (Brace 2005; Hefner, Ousley, and Dirkmaat 2012; Ta'ala 2014). Blumenbach attributed

the differences between humans to environmental influences and population migration, and classified humans as one of five types or 'races': 'Caucasoid', 'Negroid', 'Mongoloid', 'Malayan', and 'American Indian' (Harrison 2010; Kelso 1967). Blumenbach's categorization system created a marked shift in the scientific community for the categorization of human populations (Harrison 2010).

The method of categorization exercised by Blumenbach was grounded in the theory of *monogenesis*. Monogenesis is the theory that humans were descended from a single common ancestor, as conveyed in the Bible (Ta'ala 2014). By the late 19th Century, scientists began to question the biblical account of creation as the extent of human variation became more evident. Within the scientific community, the theory of *polygenesis* became more accepted (Harris 1968; Gould 1996; Hefner, Ousley, and Dirkmaat 2012). The theory of polygenism stated that different 'races' originated from distinct and separate ancestors (Ta'ala 2014).

Polygenists Samuel Morton (1799-1851) and Earnest Hooton (1887-1954) greatly influenced American anthropology with their research on metric and non-metric traits of the human skeleton (Hefner, Ousley, and Dirkmaat 2012; Ta'ala 2014). Morton studied craniometrics and cranial capacity, correlating those skeletal features to intellect. Morton believed that human 'races' were created unequal (Hefner, Ousley, and Dirkmaat 2012). Similar to Morton's research, Hooton compared anthropological data with behaviour and correlated 'race' to the likelihood of criminal acts (Hefner, Ousley, and Dirkmaat 2012). Research by Morton and Hooton influenced biological determinist and racist research (Rushton 1995, for example) that aimed to justify slavery and genocide (Brace 2005; Hefner, Ousley, and Dirkmaat 2012).

The Second World War brought attention to the negative effects of 'racial' categorization (Ta'ala 2014, 6). Ashley Montagu's (1942) publication *Man's Most Dangerous Myth: The Fallacy of Race* was the first significant challenge to the concept of 'race' in American physical anthropology (Harrison 2010; Littlefield et al. 1982). Montagu argued that humans are "characterized by an educability, a capacity for wisdom and intelligence" and therefore basing a 'race' on phenotypic characteristics diminishes the definition of what it is to be human (Harrison 2010, 38; Montagu 1942, 48). This marked a shift towards the study of human variation, rather than the discrete categorization into human 'races' (Marks 1995; Montagu 1963).

Most physical anthropologists believe 'race' is not an "empirically valid model for categorizing human biological diversity" (Sauer 1992; Ta'ala 2014, 11). However, in the medicolegal context, 'racial' classification is an important aspect of the identification process (Berg and Ta'ala 2014; Kennedy 1995; Sauer 1992; Ta'ala 2014). Though 'scientific racism' was criticised, 'racial typology' continued throughout the mid-20th Century, not as an acknowledgement of the existence of 'races' but rather as a translation of biological traits to the socio-cultural system of labelling (Littlefield et al. 1982; Sauer 1992; Ta'ala 2014). Kennedy (1995) notes that human evolution and biological diversity (scientific) paradoxically co-exist with the belief in human 'races' (non-scientific) in forensic anthropological investigations. However, Sauer (1992) suggests the abandonment of the term 'race', which holds negative connotations, and proposes the use of *ancestry*.

Ancestry refers to the heredity and/or geographic region of a specific population (SWGANTH 2013). Stanley Garn observed that those who live in the same geographical area resemble each other and noted the geographic influence of gene flow (Hefner,

Ousley, and Dirkmaat 2012). The morphology of the human skeleton is highly heritable and influenced by genetic and environmental factors. Social forces, geographical distance, and assortative mating create barriers to gene flow, establishing recognizable morphological differences in humans (Ousley, Jantz, and Freid 2009; Relethford 2009; Risch et al. 2002; Stull, Kenyhercz, and L'Abbé 2014). The physical characteristics of the skeleton express this biological diversity, allowing forensic anthropologists to qualify and quantify the differences in morphology among ancestral groups (Ember and Ember 1988; Stull, Kenyhercz, and L'Abbé 2014). This thesis will therefore use the term *ancestry* to distinguish between population groups.

1.5 Ancestral Groups in South Africa

South Africa is comprised of multiple ancestries with a variety of parent groups that have contributed genetically to the current population groups (L'Abbé et al. 2011; Tishkoff et al. 2009). In addition to the genetic structure, South Africa is diverse culturally and linguistically, being home to 11 official languages – nine Black African languages, English, and Afrikaans (McDowell 2012; Sutherland 2015). According to Statistics South Africa (2009; 2013), Black, Coloured, and White are the largest identifiable ancestral populations in South Africa.

As mentioned previously, forensic anthropologists analyze the morphological differences that exist between ancestral groups (Ember and Ember 1988; Stull, Kenyhercz, and L'Abbé 2014). These morphological differences are influenced by social forces, geographical distance, and assortative mating (Ousley, Jantz, and Freid 2009; Relethford 2009; Risch et al. 2002; Stull, Kenyhercz, and L'Abbé 2014). The complex

history of migration, colonization, and segregation in southern Africa has influenced the biology of modern South African populations. It is also important to consider how South African history has influenced the relationship between the social identity and biological ancestry of South Africans. Forensic anthropologists must account for these factors when evaluating the variation of skeletal morphology of the Black, Coloured, and White South African populations as this influences identification of unknown individuals within South Africa.

The indigenous Khoe-San, Bantu-speakers, and White European settlers greatly contributed culturally and genetically to the modern South African populations. The Khoe-San are descendants of the pastoralist Khoikhoi ('Hottentots') and foraging San ('Bushmen') groups who occupied southern Africa around 2000 years ago (Patterson et al. 2010; Sutherland 2015). The Khoe and San formed small familial bands, though the bands were open and had fluid congregations allowing for some admixture (Sutherland 2015). Therefore, the Khoe and San groups are referred to collectively as Khoe-San. Bantu-speaking groups from the Nigerian and Cameroon regions began migrating through eastern and western Africa between 5000 and 3000 years ago (Beck 2000; May et al. 2013; Tishkoff and Williams 2002; Tishkoff et al. 2009), converging in southern Africa around 300 AD (1700 years ago) (Sutherland 2015; Thompson 2014). From this divergent migration, two variants of Bantu-speakers arose: Nguni and Sotho-Tswana (Ross 2008; Thompson 2014). Interactions between the Khoe-San and Bantu-speakers is evident due to the presence of clicking sounds, from Khoe-San language, in the Bantu-language, isiXhosa. There is also evidence of maternal (mtDNA) and paternal (Y-chromosome) Khoe-San genetic contributions in Bantu-speaking groups (Petersen et al. 2013). However, there are other genetic and morphological differences between the

Khoe-San and Bantu-speaking groups and they are considered distinct population groups (Barbieri et al. 2013; Herbert 1990; Liebenberg et al. 2015; Petersen et al. 2013; Stynder 2009).

Merchant trade routes past the Cape of Good Hope and colonization of Cape Town in the 17th Century introduced White Europeans to southern Africa (Patterson et al. 2010; Petersen et al. 2013; Stull, Kenyhercz, and L'Abbé 2014; Sutherland 2015). White Europeans, particularly the Dutch, British, German, and French settlers, established the White population in South Africa (Steyn, Pretorius, and Hutten 2004). White South Africans and their European counterparts (i.e. original parent groups) have distinct differences in their osteology, attributed to the founder effect and admixture (Steyn, Pretorius, and Hutten 2004). The founder effect is the loss of genetic variation that occurs when a new population is established by a very small number of individuals from a larger population; modern White Europeans are products of the founder effect as White Europeans who immigrated to South Africa married and procreated with other White Europeans who had immigrated to and were living in South Africa. 'Mixed-race' unions between White European males and female slaves established a new ancestral group in South Africa, the Coloured population.

Black South Africans are the largest ancestral population group (79.8%) in modern South Africa (Lehohla 2013). The modern Black South Africans are mainly descendant from the indigenous Bantu-speaking Nguni and Sotho-Tswana groups. During apartheid, the Bantu-speaking chiefdoms were considered as 10 distinct nations (Thompson 2014), which relates to the variations of language of the Nguni and Soth-Tswana groups. The Nguni languages include Ndebele, Swati, Xhosa, and Zulu, and the Sotho-Tswana languages include Northern Sotho, Southern Sotho, Tswana, Tsong, and

Venda (Sutherland 2015). Within the modern Black South African community, language continues to play a large role in their self-identity (Norris et al. 2008). While most Black South Africans speak one or more Bantu-languages, these individuals also speak English and Afrikaans (Sutherland 2015).

The Coloured South African group comprises approximately 9% of the South African population. They originated approximately 350 years ago as an indirect result of colonization (L'Abbé and Steyn 2012; Lehohla 2013; Quintana-Murci et al. 2010). Dutch colonization in the 17th Century brought slaves from East Africa, India, Indonesia, and Madagascar to Cape Town, and many indigenous Khoe-San were enslaved (Patterson et al. 2010; Ross 2008; Stull, Kenyhercz, and L'Abbé 2014; Thompson 2014). During the 17th and 18th Centuries, 'mixed-race' unions between White European males and female slaves were common (Sherman and Steyn 2009; Stull, Kenyhercz, and L'Abbé 2014). The slaves and their offspring remained a part of the slave community and formed their own identity (Nurse et al. 1985; Sutherland 2015). The term 'Coloured' was introduced as a label of this uniquely admixed population, separate from the Black and White populations (Patterson et al. 2010; Stull, Kenyhercz, and L'Abbé 2014; Van Der Ross 2005).

Within the South African community, the term 'Coloured' is the "most widely recognized population-specific identifier" (Adhikari 2005; Christopher 2002; Patterson et al. 2010; Stull 2014, 38). Cultural markers, such as language, and some genetic markers are strongly correlated with a Coloured identity (Mateos 2007). Most Coloured people speak Afrikaans and English. The Afrikaans language, an amalgamation of Dutch, Khoe-San, German, French, Malay, Portuguese, and other languages (Giliomee 2003), is

connected to the ancestral background and genetic composition of Coloured South Africans.

Coloured South Africans are descendent from populations from Africa, Europe, and Indonesia, with the greatest genetic contributions from indigenous Khoe-San and Bantu-speakers, White Europeans and Indians (Henneberg, Brush, and Harrison 2001; Patterson et al. 2010; Petersen et al. 2013; Quintana-Murci et al. 2010; Stull 2014; Stull, Kenyhercz, and L'Abbé 2014; Tishkoff and Williams 2002). The mitochondrial DNA of Coloured South Africans demonstrates a strong Khoe-San female component, greater than that from White Europeans, while Y-chromosome DNA indicates a stronger genetic contribution of Eurasian origin in comparison to Khoe-San (Quintana-Murci et al. 2010). However, genetic contributions of different ancestral groups to Coloured South Africans vary between individuals, i.e. in different geographical locations, within South Africa (Quintana-Murci et al. 2010; Stull, Kenyhercz, and L'Abbé 2014).

South Africa's modern White population (8.7%) is the direct result of colonization and immigration from Europe (L'Abbé and Steyn 2012; Lehohla 2013). Most White South Africans speak English or Afrikaans, and many speak Dutch, German, French, or other European languages (Sutherland 2015). White South Africans descended, with approximately equal genetic contributions, from Dutch, British, German, and French settlers (Greeff 2007; L'Abbé et al. 2011; Steyn and İşcan 1998). However, unions between White Europeans and slaves (i.e. genetic admixture) are evident within the genetic makeup of modern White South Africans. After the abolishment of slavery in the early 1800s, some White European males, who immigrated to South Africa, married freed females (Jacobson, Amoateng, and Heaton 2004; Patterson et al. 2010; Stull, Kenyhercz, and L'Abbé 2014). Therefore, a low frequency of alleles typical to Khoe-San and Bantu-

speaking peoples are present within the White South African genome (Greeff 2007; Krüger 2014; Patterson et al. 2010; Sherman and Steyn 2009).

The identities of modern South Africans are deeply entrenched in past segregation and social behaviour, particularly those imposed during apartheid (McDowell 2012). Apartheid (1948-1994) was the legal segregation of South Africans based on 'racial' categorization (Adhikari 2005; Beck 2013; Christopher 2002; Sutherland 2015; Thompson 2014). The Population Registration Act (1950) required classification and registration of each South African inhabitant with regards to their 'racial' characteristics. The Population Registration Board determined 'race' categories, predominantly defined by the person's appearance (e.g., hair colour and texture, skin colour and facial structure) and the geographic origin of the person's ancestors (Adhikari 2005; Christopher 2002; Sutherland 2015; Thompson 2014).

The Group Areas Act, Immorality Act, and the Separate Amenities Act were other keystones of segregation during the apartheid era (Morris 2012). Under the Group Areas Act (1950), these 'race groups' were designated to particular residential areas within the country (Morris 2012). As part of the Immorality Act, the Prohibition of Mixed Marriages Act was introduced in 1949, outlawing 'mixed-race' marriages (i.e. marriage between White and 'non-White') (Jacobson, Amoateng, and Heaton 2004; Stull, Kenyhercz, and L'Abbé 2014). In 1953, the Separate Amenities Act legalized the 'racial' segregation and dictated, for examples, the job or school a particular 'race' could occupy (Morris 2012).

The social and geographical laws imposed by apartheid restricted gene flow within each ancestral ('race') group (Morris 2012; Ross 2008; Sutherland 2015; Thompson 2014). These barriers for gene flow allowed for the preservation of distinct morphological differences that exists among population ('race') groups (McDowell

2012). The hierarchical system of apartheid not only legally segregated people based on physical characteristics, but also enhanced the social system of class that existed before apartheid (Liebenberg 2015). The genetic and cultural uniqueness of each of the rigidly classified 'racial' groups through apartheid has instilled in their identity (Sutherland 2015). While apartheid was abolished in 1994, South Africans continue to classify themselves into one of these social 'race' groups (Lehohla 2013; Patterson et al. 2010). Therefore, while law no longer regulates gene flow between population groups, gene flow continues to be limited by social behaviour (Liebenberg 2015).

The variation in skeletal morphology of the South African population groups is of particular interest to anthropologists due to the complex history in southern Africa (Krüger 2014). Barriers to gene flow throughout South Africa's history have allowed the distinct skeletal differences between the South African populations to persist (L'abbé et al. 2013). The South African White, Black, and Coloured population samples therefore offer a unique opportunity to evaluate the use of osteometric analyses for pair-match calcanei, as the performance of these methods can be assessed while accounting for sexual dimorphism and ancestral variation.

1.5.1 Osteological collections examined in this study

This study utilized two skeletal collections, described in detail below: the Pretoria Bone Collection for the examination of White and Black South African individuals and the Kirsten Collection for examination of Coloured South African individuals.

The current study examined the Pretoria Bone Collection, a contemporary cadaveric skeletal collection consisting mostly of White and Black South Africans. The

human skeletal remains are housed in the Department of Anatomy at the University of Pretoria, Pretoria, South Africa. This collection consists of mostly complete cranial and post-cranial skeletons with documented demographic information (i.e. age, sex, ancestry, and cause of death) (L'Abbé, Loots, and Meiring 2005).

The second skeletal collection used for this study is the Kirsten Collection housed at Stellenbosch University, Tygerberg Medical Campus in Cape Town, South Africa. The Kirsten Collection, a mostly cadaver-derived collection, consists of historic and contemporary human skeletal remains of White, Black, and Coloured South Africans with documented demographic information (i.e. age, sex, ancestry, and cause of death) (Van Rooyen 2010). The contemporary Coloured South Africans were used in the current study. This collection consists of individuals with documented demographic information (i.e. age, sex, ancestry, and cause of death).

1.6 Admissibility of forensic anthropology evidence in court

The *Mohan* ruling in Canada and the *Daubert* ruling in the United States regulate expert testimony on forensic human identification in the courtroom. Regulation of expert testimony is a crucial process in the court system to ensure that the evidence submitted is based on scientific techniques that are relevant and reliable (Christensen 2004; Christensen and Crowder 2009; Holobinko 2012; Lesciotto 2015).

The Canada Evidence Act (R.S., 1985, c.C-5) regulates expert testimony in Canada. Under this Act, the testimony given by an expert regarding the evidence must be beyond the comprehension of the average person who, without the assistance of an expert, would not be able to explain the judgements correctly (Holobinko 2012). The

Mohan admissibility criteria arose from the *Regina v. Mohan* (2 S.C.R. 9 File No. 23063) case (Holobinko 2012). Four governing factors of evidence admissibility characterize the *Mohan* decision: the evidence must be necessary, relevant, absent of the exclusionary rule (i.e. inappropriately or illegally obtained), and the expert witness must have the proper qualifications (Glancy and Bradford 2007; Rogers and Allard 2004).

The *Daubert v. Merrell Dow Pharmaceuticals, Inc.* (No. 92-102 509 US 579, 1993) court case significantly impacted the admissibility of scientific evidence in the United States, providing a new standard for the assessment of the admissibility of scientific testimony (Gold et al. 1993; Holobinko 2012). The *Daubert* rulings were introduced in 1994. These rulings ensure that the methodologies presented by expert witnesses are accepted in their field of practise, and require that the scientific evidence meets reliability and relevance standards within these forensic fields. In other words, *Daubert* ensures there are no pseudoscientific principles and methods presented as evidence, while acknowledging that new techniques that are developed and implemented in the field must also meet these strict standards (Christensen 2004; Christensen and Crowder 2009; Gold et al. 1993; Grivas and Komar 2008; Holobinko 2012; Lesciotto 2015). As per the *Daubert* standard, court testimony must be testable and have been tested through the scientific method, have been subject to peer review, have established standards, have a known or potential error rate, and have widespread acceptance by the relevant scientific community (Grivas and Komar 2008).

Also in the United States, the *Kumho* decision, which arose from *Kumho Tire v. Carmichael* (1999) case, is used as a complement to the *Daubert* decision. The *Kumho* decision acknowledges the complexity of science and the need to evaluate the techniques with more than a single set of standards (Grivas and Komar 2008). Guidelines from

Kumho state that expert witnesses can develop theories based on their observations and experience and then apply those theories to the case before the court. Further, they state that all forms of expert witness testimony should be evaluated with the same level of rigor but also that the *Daubert* standards are flexible guidelines that may not be applicable in every instance of expert witness testimony (Grivas and Komar 2008, 772). The *Kumho* ruling allows some "latitude" for forensic anthropologists, such that if the anthropologist's analysis is deemed by the court to be scientific and rigorous then the techniques meet the *Kumho* standard for admissibility (Christensen and Crowder 2009, 1213; Grivas and Komar 2008)

Following the *Daubert* decision in the United States, experts in the field of forensic anthropology anticipated difficulties in the courtroom in regards to the admissibility of their testimonies (Christensen 2004; Christensen and Crowder 2009; Dirkmaat et al. 2008; Lesciotto 2015). Since forensic anthropology employs a combination of "traditional scientific methods and less rigorous observational methodologies", it makes certain methods difficult to evaluate using the *Daubert* standards (Christensen and Crowder 2009, 1213). Since implementation of the *Daubert* standards, there has been a large influx of publications on forensic anthropological methods citing the need to adhere to the *Daubert* standards (Christensen and Crowder 2009; Lesciotto 2015). Therefore, the forensic anthropology community is now producing more objective and quantifiable techniques to assist in the identification of unknown human remains (Christensen and Crowder 2009; Lesciotto 2015). Since the *Daubert* and *Kumho* rulings, experts have noted an increase in the acceptance of forensic anthropological methods in the courtroom (Christensen and Crowder 2009, 1213; Grivas and Komar 2008).

While the recent literature has addressed many issues in the field of forensic anthropology, Christensen and Crowder (2009) have cited other issues of quality assurance, validation, and professional standards that must also receive attention. They state that, "quality assurance will help ensure the high quality of anthropological research, assist with establishing method transparency, and provide a secure foundation for forensic anthropologists in the courtroom" (Christensen and Crowder 2009, 1214). Validation studies are important as they demonstrate the reliability of the method by evaluating the level of precision and accuracy (Christensen and Crowder 2009). *Precision* refers to repeatability of results, whereas *accuracy* assesses whether and to what degree the results are a true representation of what is studied (Komar and Buikstra 2008). While the precision of a measurement may be high (i.e. highly repeatable), the method of measurement may not be accurate (i.e. poor representation of reality) for assessing characters (Komar and Buikstra 2008). While the *Daubert* standard is concerned with the errors associated with the scientific methodology, the court has not determined the degree of error that is acceptable (Christensen and Crowder 2009). Therefore, forensic anthropologists must recognize the legal concerns regarding the clarity, reliability, and validity of their methods (Christensen, Passalacqua, and Bartelink 2013). Forensic anthropologists must also communicate the limitations and sources of error in their anthropological analyses (Christensen, Passalacqua, and Bartelink 2013). The court will then decide on the admissibility of forensic evidence on a case-by-case basis (Christensen, Passalacqua, and Bartelink 2013).

1.7 Objectives

Forensic anthropologists analyze skeletal human remains to assist in the identification of unknown individuals. Forensic anthropologists employ a combination of skeletal analyses to create a biological profile, including estimates of ancestry, biological sex, living stature, age at death, and assessment of pathologies and trauma. However, damaged, missing, and/or mixed (commingled) skeletal remains impede the completion of a biological profile.

Developing reliable and accurate methodologies for sorting and pair-matching skeletal elements is important to resolve cases of commingled human remains. Morphological assessment of skeletal remains relies heavily on the experience of the observer whereas metric assessment provides objective analyses (Introna et al. 1997; Peckmann et al. 2015; Spradley and Jantz 2011). The Gap Analysis Committee of the Scientific Working Group for Forensic Anthropology (SWGANTH) has expressed the need for the development and validation of metric methods for the reassociation of commingled human remains (SWGANTH 2013).

The current published research demonstrates that osteometric pair-matching of skeletal remains is possible for a number of long bones, such as the femur and humerus, and some smaller bones, such as metacarpals (Adams and Byrd 2006, 2008; Byrd 2008; Byrd and Adams 2003; Chew 2014; Garrido-Varas et al. 2014; LeGarde 2012; Rodríguez et al. 2015; Thomas, Ubelaker, and Byrd 2013). However, research involving the pair-matching of tarsal bones is scarce; the study by Thomas and colleagues (2013) is the only research to date that has investigated pair-matching tarsal bones (i.e. calcaneus and talus).

Calcanei are resistant to taphonomic change and they are often protected within shoes and/or socks in forensic cases (Bidmos and Asala 2003; Pickering 1986; Peckmann

et al. 2015). These factors increase the likelihood of recovering the calcanei from forensic contexts. The current project tests the accuracy and reliability of metric analyses of the calcaneus for pair-matching left and right skeletal elements. Until now, few studies on metric pair-matching have accounted for the influence of bilateral asymmetry, ancestry, and sex (Byrd 2008; Vickers et al. 2014). The current study will account for these variables in cases of osteometric sorting and pair-matching.

The objectives of this thesis are to:

1) Investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled,
2) Investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled,
3) Investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations separated, and
4) Use the *M* statistic to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations.

CHAPTER II: BACKGROUND

2.1 Commingled Skeletal Remains

The term *commingled remains* refers to a single assemblage where multiple sets of remains are present and cannot be distinguished as single individuals due to mixing of their skeletal elements (Byrd and Adams 2003; Osterholtz, Baustian, and Martin 2014; Ubelaker 2002). Commingling of human remains is encountered in bioarchaeological contexts, such as ossuaries, and forensic contexts, such as mass graves or mass disasters. Bioarchaeological analysis is focused on demographic information, population lifeways (Owsley et al. 1977; Ubelaker 1974; Willey 1990), and reconstructing mortuary practices (Curtin 2008; Ubelaker and Rife 2008). Forensic analysis, however, focuses on the identification of the individual (Adams and Byrd 2014, 2008, 2006; Byrd and Adams, 2009, 2003).

When human remains are found, the role of the forensic anthropologist is to create a biological profile. Creating a biological profile is most effective when the skeleton is complete as forensic anthropologists rely on a combination of non-metric and metric analyses to estimate ancestry, biological sex, age at death, stature, and evaluate pathologies and trauma (Byrd and Adams 2003). Identification of the individual, cause and manner of death cannot be fully evaluated without individualization of the skeletons (Byrd and LeGarde 2014). Therefore, an effort must be made in commingling scenarios to sort and individualize human remains for completing the biological profile. Current research that investigates methodologies for the resolution of commingling focuses on the reassociation of individuals and identification of victims (Adams and Byrd 2014, 2008).

2.1.1 Causes of Commingling

Commingling of human remains can occur through natural processes or by purposeful human action (Komar and Buikstra 2008). Burial practices, for example, are important to consider when dealing with a commingling scenario. The first site of deposition is referred to as the *primary burial site* and includes traditional burials, war graves, plague pits, or abandoned catastrophic sites (Garrido Varas 2013). *Secondary burials* are burials rearranged by intentional human action. These secondary burials result in mixing and/or loss of human remains and hinder the resolution of commingling. Commingling also occurs unintentionally when environmental activity or animal scavenging causes admixture of human remains. It is more difficult to resolve cases of commingling when outside forces disturb the gravesites (Garrido Varas 2013).

Mass graves are defined as graves containing two or more individuals resulting from extra-judicial, summary, or arbitrary executions (Bassiouni and Manikas 1996). Countries suffering from human rights violations often have large scale commingling in the mass graves where perpetrators dispose of human remains (Haglund and Sorg 2001). The aftermath of dictatorships and genocides in e.g. Chile, Spain, Bosnia-Herzegovina, and Argentina resulted in a number of mass graves. These graves are arduous for forensic anthropologists as a large number of individuals have been buried together and often are moved to secondary, or even tertiary, sites to conceal human rights violations. Anthropologists and forensic scientists continue to try to resolve commingling in these mass graves and identify victims to return them to their next of kin.

Mass fatality incidents, such as natural disasters or terrorist attacks, are also significant causes of commingled human remains. The Indian Ocean tsunami (2004), the earthquakes in Haiti (2010) and Nepal (2015), the Air India bombing (1985), and

Swissair Flight 111 (1998) are examples of mass death incidents. In these circumstances, human remains may be buried under soil or debris from the disaster, or scattered on the surface, and the degree of fragmentation and commingling will vary between scenarios.

2.1.2 Recovery of human remains in mass graves

While many aspects of forensic anthropology receive attention in the literature, there is little focus on the issues of commingling (Ubelaker 2002). To resolve commingling, anthropologists apply great attention and organization to the search and recovery of human remains, analyses and identification, and the final deposition (Haglund and Sorg 2001). Anthropologists should use systematic, methodological recovery, and analytical techniques to resolve commingling. This helps in establishing the number of individuals involved, the accurate reassociation of skeletal elements, and positive identification of the individuals.

2.1.2.1 Locating mass graves

Perpetrators of human rights violations often attempt to conceal their crimes by burying their victims in mass graves (Tuller 2012). Observations of vegetation changes, presence of depressions in the soil, surface cracks, and other surface clues are indicative of the presence of a mass grave (Dirkmaat 2012; Tuller 2012). However, these observations can only be made when there is some general idea of where the mass grave is located. The use of remote sensing and topographic pattern analysis has been used for locating mass graves by comparing satellite images of an area over time; aerial photos of geographical regions over time have shown landscape changes, presence of construction

machinery, and even bodies (Tuller 2012). This method for detection of mass graves was successful in Bosnia and Herzegovina, the Balkans, and Iraq. Using technology such as ground-pentrating radar (GPR), resistivity and magnetometry, and the assistance of cadaver dogs have been used for locating mass graves. However, these resources are not always readily available for human rights investigations due to costs and the dependency on external organizations (Tuller 2012). Therefore, locating mass graves relies heavily on witness accounts (Komar and Buikstra 2008). Witnesses are considered to be the best sources of information when searching for clandestine graves. Simple methods to confirm or deny the presence of a mass grave, such as surface scraping and probing, are quickest and most reliable (Tuller 2012).

The reconnaissance process of human rights violations is extensive. Egaña and colleagues (2014), members of the Equipo Argentino de Antropología Forense (EAAF), outlined their research methodology for locating mass graves, recovery and analysis of remains. Their techniques for locating the clandestine burials, and information regarding the victims themselves, included "thorough historical research; interviewing relatives, witnesses, and survivors; reviewing military, police, and other official archives" (Egaña et al. 2012, 72). Once the information is gathered, hypotheses can be made to locate the mass grave and investigate.

2.1.2.2 Recovery process

In the past, the recovery of human remains has been the focus of human rights excavations. Recently, more emphasis has been placed on evidence collection and understanding the grave formation process (Skinner et al. 2003). Methods of recovery

vary from case to case and depend on the aim of the investigation, i.e. whether is it a humanitarian or medicolegal investigation (Komar and Buikstra 2008).

Humanitarian efforts focus on victim identification and repatriation of human remains. While victim identification is important in human rights investigations, recovery and analysis of forensic evidence is vital (Steadman and Haglund 2005). The reconstruction of past events is not possible without geophysical, environmental, and archaeological evidence; evidence admissibility for court could be jeopardized without this evidence (Tuller 2012). At a mass grave, proper excavation techniques and detailed documentation are important for interpreting the events (Komar and Buikstra 2008). Therefore, the assistance of those trained in forensic archaeology is invaluable. Since 2002, the International Commission on Missing Persons (ICMP) has excavated mass graves with the assistance of forensic archaeologists (Tuller 2012). Applying forensic archaeological techniques to mass death scenarios allows for a better reconstruction of events and more thorough recovery of human remains and evidence (Cabo et al. 2012; Dirkmaat 2012; Tuller 2012; 2008; 2005).

Extensive notes and scene maps document the position of remains and associated material evidence. An inventory of the remains and clothing found within the grave should also be documented. In the past, and in current excavations, these notes and maps were created using pen and paper, using string grids and measuring tapes, and a compass, for recording positioning. However, more sophisticated surveying equipment such as a geographic information system (GIS), also known as a *total station* (TST or total station theodolite), has also been implemented in some excavations (Dirkmaat 2012; Komar and Buikstra 2008; Tuller 2012). The use of electronic surveying equipment allows for faster and more accurate recording of the site and measuring points of evidence without

impeding activities at the site (Tuller 2012). The total station can map the site in three dimensions as it is being excavated, preserving data throughout the excavation process while features are removed. This allows for spatial relationships to be made between evidence along multiple planes and between the levels of the excavation.

Common methods of excavation in mass grave contexts are the *stratigraphic* method and the *pedestal* method (Tuller and Đurić 2005). The stratigraphic method focuses on the grave features and all grave contents (including the bodies) are excavated. Conversely, the body masses are the only focus of the pedestal method; the grave walls may be compromised to pedestal the body. Tuller and Đurić (2005) tested both excavation methods on two separate mass graves, which were created using the same techniques and in close proximity to one another. It was found that the stratigraphic method and pedestal method had strong significant differences between recovery rates. The stratigraphic method performed better for recovery of unassociated whole bones. Smaller bones in the grave using the stratigraphic method were found at a rate significantly higher than those in the grave using the pedestal method. The stratigraphic method also maintained body part articulation better than the pedestal method. Therefore, the authors concluded that the stratigraphic method is more appropriate for the complex mass grave sites found in human rights cases (Tuller and Đurić 2005).

The forensic archaeological approach to excavating mass graves is imperative for ease and accuracy when attempting to individuate and identify victims. For example, disarticulated limbs are likely to be in close proximity to one another (Tuller 2012). When skeletal remains are thoroughly documented in the grave, success rates for matching bones to the 'nearest-neighbour' are close to 100% (Tuller et al. 2005; 2008). However, if the remains have been moved to a secondary burial site, this may not hold true.

Disturbing the burial causes more commingling of the remains and when primary burial sites are uncovered, and remains are relocated, skeletal elements (especially smaller bones such as carpals and tarsals) and material evidence are often lost (Osterholtz, Baustian and Martin 2014). Sometimes one burial site is used multiple times, with layers of deposits from other primary burials. In these cases, the stratigraphic excavation method is useful for separating deposits and searching within them for re-articulation and identification. Investigation of these burials can also indicate the time of placement, which can provide useful information regarding the potential identities and number of individuals present (Tuller 2012).

2.1.2.3 Establishing the number of individuals

Establishing the number of individuals present plays an integral role in the success of resolving commingling. Once the anthropologist establishes an estimate of the number of individuals, reassociation of skeletal elements for each individual can be attempted. The literature outlines various methodologies for establishing the number of individuals in commingled remains (Adams and Konigsberg 2004; Konigsberg and Adams 2014; L'Abbé 2005; Nikita and Lahr 2011).

The method of quantification used most often by forensic anthropologists is the *Minimum Number of Individuals (MNI)* (Byrd and LeGarde 2014). The anthropologist estimates the minimum number of individuals present in the scene using the skeletal element that is most repeated. The number of missing elements influences the estimation of the number of individuals present and can underestimate the number by a large margin.

Zoologists use the *Lincoln Index (LI),* for population studies of living animals; zooarchaeologists adapted this method for use in their assemblages. The original zoological formula does not change when used by zooarchaeologists, rather, the variable E_1 (species 1) and E_2 (species 2) are now cited as *L* (number of left elements) and *R* (number of right elements), respectively.

Archaeologists and anthropologists also use the LI method for commingled human remains (Byrd and LeGarde 2014). The LI method uses capture-recapture techniques for living population studies, but in skeletal assemblages the LI is based on pair-matching. The original death assemblage estimate is calculated as:

$$LI=\frac{LR}{P}$$

where L is the number of left elements, R is the number of right elements, and P is the number of elements that can be matched to form pairs.

A variation of the LI method is the *Most Likely Number of Individuals (MLNI)*:

$$MLNI=\frac{(L+1)(R+1)}{P+1}-1$$

The MNLI results in improved accuracy of the estimation of the number of individuals present and considers underestimates of left and right elements and their pairs. The MNLI method also removes bias from the estimate (Konigsberg and Adams 2014).

Adams and Konigsberg (2004, 2014) examined the MNI, LI, and MLNI techniques to assess their applicability to commingled remains cases. Since the MNI makes a direct relationship between the number of skeletal elements and the number of individuals necessary to provide those elements, the authors found the MNI to be misleading when recovery is not near one hundred percent. The LI and MLNI provided the most accurate methods for quantification; the MLNI compensates for potential

underestimates of the MNI and potential bias from the LI in small sampling (Adams and Konigsberg 2004). The authors noted that the selection of skeletal elements for pairing plays a role in the quantification accuracy when using the MLNI method, as misidentified pairs affect the estimate (Konigsberg and Adams 2014). Skeletal elements such as tibiae should be utilized for the MLNI formula as they are more easily paired compared to radii, for example. This is because, in the human population, left and right tibiae are more symmetrical than their left and right radii.

2.1.2.3.1 Asymmetry

Specific skeletal elements are affected differently by environmental and genetic factors, creating differences in size and/or shape between the left and right sides of the body (Auerbach and Raxter 2008; Auerbach and Ruff 2006; Burwell et al. 2006; Garrido Varas 2013; Garrido Varas and Thompson 2011; Garroway 2013; Glassman and Dana 1992; Kanchan et al. 2008; Krishan, Kanchan, and DiMaggio 2010; Kujanová et al. 2008; Lazenby et al. 2008; Naugler and Ludman 1996; Palmer and Strobeck 1992; Roy, Ruff, and Plato 1994; Ruff and Jones 1981; Sakaue 1998; Sládek et al. 2007; Steele and Mays 1995; Stirland 1993; Trinkaus, Churchill, and Ruff 1994; Weiss 2009). This is known as *asymmetry*. Anthropologists must consider asymmetries in the human skeleton when sorting commingled remains; they must work with the understanding that there is variation in paired elements (Lyman 2006). An inexperienced observer may consider two bony elements to be too dissimilar in shape or size to be a pair. This misunderstanding of asymmetry leads to false rejection of pairs or incorrect reassociation of elements of an individual.

Directional asymmetry is a consistent difference in a pair of morphological structures with a marked bias to one side. *Antisymmetry* is an inconsistent asymmetry that occurs in all organisms. *Fluctuating asymmetry* is random variation with normal distribution due to a complex interaction between genetic and environmental factors (Garroway 2013). Humans are a unique species due to *crossed symmetry* between contralateral limbs, i.e. one region of the body exhibits directional asymmetry to one side while another region exhibits directional asymmetry to the opposite side (Auerbach and Ruff 2006:203; Latimer and Lowrance 1965; McGrew and Marchant 1997, 201-232; Plochocki 2004, 328-333; Ruff and Jones 1981, 69-86; Schaeffer 1928, 293-398). Humans have a large magnitude of directional asymmetry in the size of the upper limb, towards the right side, and a smaller directional asymmetry towards the left side in the lower limb (Latimer and Lowrance 1965; McGrew and Marchant 1997; Plochocki 2004; Ruff and Jones 1981; Schaeffer 1928).

Studies of palaeoanthropological, faunal, and modern human skeletal remains have discovered a similar pattern of asymmetry; bone lengths and articular surface sizes are asymmetrical, though diaphyseal breadths exhibit asymmetry to a greater degree (Auerbach and Ruff 2006; Churchill and Formicola 1997; Garroway 2013; Ruff et al. 1994; Ruff and Jones 1981; Sakaue 1998; Trinkaus, Churchill, and Ruff 1994). Research has shown that diaphyseal dimensions are more plastic than lengths of long bones and articular surface dimensions (Auerbach and Ruff 2006; Ruff et al. 1994; Trinkaus, Churchill, and Ruff 1994). For example, Trinkaus and colleagues (1994) found that while this pattern of asymmetry was present in a modern skeletal collection (with no account of habitual activity), asymmetry in diaphyseal dimensions were greater in (living) athletes who engaged in unilateral activities. A similar pattern, i.e. differences between

asymmetry in diaphyseal measurements and bone length and articular surface dimensions, was found in Neandertal remains (Trinkaus, Churchill, and Ruff 1994).

Understanding asymmetry in the human skeleton is vital for forensic anthropological analyses (Garroway 2013). Pair-matching bones relies on the ability to understand the degree of variation that is expected in certain regions of the body and individual bone dimensions. When attempting to sort skeletal remains it is therefore best to use variables (i.e. measurements of the elements' length and articular surface dimensions) that exhibit less asymmetry. This selection of variables influences the accuracy and reliability of pair-matching elements, facilitating reassociation of commingled remains.

2.2 Sorting techniques for commingled human remains

Snow (1948) combined anthropological techniques, dental analyses, and personal effects to create the first procedures for sorting commingled human remains. Anthropologically, sorting elements is based on duplicates of skeletal elements, incongruences in sexual dimorphism, articulating facets, developmental stages, overall size and shape differences, and pathologies (Byrd 2008; Garrido Varas 2013; Gordon and Buikstra 1980; Snow 1948; Ubelaker 2002). The experience of the observer plays an important role in the accuracy of individuation and assessment of the individuals in a commingled case. While forensic anthropologists use various methodologies for sorting commingled remains, they have not agreed upon a standard way to manage commingling scenarios, but instead offer suggestions for *best practices* (Osterholtz, Baustian, and Martin 2014).

2.2.1 Non-metric techniques

The techniques used for sorting commingled human remains are primarily morphology-based (Ubelaker 2002). *Visual pair-matching* is the comparison of element antimeres, i.e. left and right elements, in order to reassociate proper pairs (SWGANTH 2013b). Estimated age and biological sex of the human remains are first used to organize the skeletal elements, sorting by element type, side, and size (i.e. seriating). The observer examines general symmetry between elements, noting robusticity, muscle markings, epiphyseal shape, and bilateral expression of periosteal reactions for pair-matching (Byrd and Adams 2003; Rösing and Pischtschan 1995).

Adams and Königsberg (2004) report accurate reassociation of skeletal elements by visual pair-matching. The authors found that the humeri, femora, and tibiae could be accurately pair-matched using visual methods when they took a random sample from 15 individuals. However, obtaining a random sample from 30 individuals resulted in lower accuracies and more false rejections of true pairs. They noted that in larger samples the differences between individuals becomes less obvious to the observer therefore decreasing the accuracy of visual pair-matching.

Taphonomic similarities may also be considered for sorting commingled remains. *Taphonomy* is "the study of post-mortem processes which affect the 1) preservation, observation, or recovery of dead organisms, 2) reconstruction of their biology or ecology, or, 3) reconstruction of the circumstances of their death" (Haglund and Sorg 1997, 13). Kerley (1972) cautions the use of taphonomy to assist with individuating skeletal elements as many variables, such as soil composition and clothing dyes, can affect taphonomy and lead to false pairing or overlooking true pairs.

In addition to visual pair-matching and taphonomy, anthropologists use articulation and the process of elimination. *Articulation* of elements is useful for individuating commingled remains as it indicates that two or more bones form a congruent joint (SWGANTH 2013b). This is most accurate when articulating surfaces closely fit together, such as two vertebrae (Gordon and Buikstra 1980; Reichs 1989; Ubelaker 2002). The *process of elimination* refers to the process of associating unmatched, duplicated elements to a specific individual based on incongruences with other remains. In cases of small-scale commingling, the process of elimination is useful but becomes more problematic as the number of individuals increases.

L'Abbé (2005) applied visual pair-matching, taphonomy, articulation, and the process of elimination techniques to a commingled human remains case in South Africa. The police recovered a grain bag in a forest containing a number of skeletonized individuals. The author determined an MNI of 10, although she estimated that 80% of the skeletal remains were missing. The author documented taphonomy – the preservation, staining, colours, presence of tissues, mould, and odour – to assist with other techniques. She observed that the taphonomy differed between the individuals, suggesting that the individuals decomposed at a different site from where they were found, under different environmental conditions, and had not died at the same time. L'Abbé used a combination of non-metric techniques in their attempt to resolve commingling and identify the individuals. However, the author found that 58.9% of the skeletal elements could not be directly assigned to any one individual, i.e. they could not be individuated.

Until recently, much of the published literature about commingled human remains examined how the variability of the human skeleton is predictable and can be used to associate skeletal elements. For example, someone with a long, robust left femur should

have a matching right femur that is a “mirror” image. The observer might assume that the same individual would also have long, robust humeri. However, Byrd and Adams (2003) cite that it is unknown what degree of variability is accurately recognizable, and the level of confidence acceptable, for visual methods. The authors question whether to emphasize the size or the shape of the bones for reassociation. Some athletes, for example, could contradict the previous assumption of symmetry due to unilateral limb use. Therefore, anthropologists need a method that incorporates objective measurements with known accuracies (Byrd and Adams 2003).

2.2.2 Metric techniques

The technique of *osteometric sorting* uses statistical models to compare shape and size of skeletal elements objectively (SWGANTH 2013b). This technique is useful when anthropologists cannot segregate skeletal remains using other methods and/or when remains are fragmentary. The Scientific Working Group for Forensic Anthropology (2013b) (SWGANTH) notes that the real strength of this method is the recognition of incongruences between elements, allowing sorting by exclusion.

Buikstra et al. (1984, 1980), and London and colleagues (1998, 1986) studied osteometric methods. The authors based their studies on congruencies in measurements of articular surfaces to reassociate adjacent skeletal elements; osteometric sorting relies on formally characterizing normal size and shape relationships among skeletal elements (Byrd 2008; Chew 2014). The method estimates population parameters to formulate a null hypothesis of a “typical” size and/or shape relationship and is subjected to significance testing as described by Fisher (1948).

In a 1980 study, Buikstra and Gordon developed a model for assessing size congruencies between adjacent vertebrae and applied their findings retroactively to a forensic case to evaluate the number of individuals present. Investigators originally had assumed that the three cervical vertebrae recovered were from one individual. However, Buikstra and Gordon found minimal congruence between two of the vertebrae, which indicated the elements were from at least two individuals.

Rösing and Pischtschan (1995) provided opposing conclusions to the applicability of osteometric sorting in real life scenarios. The authors tested osteometric sorting in an archaeological site where no commingling was present. The authors compared 16 measurements from the ulna and radius of 32 individuals and used a 98% confidence bivariate model. The authors found that mismatched (rather than correctly matched) specimens tended to be closer to the regression model line. They concluded that anthropologists should make subjective judgements as they do not rely solely on measurement data but on "broad personal experience" of the observer, which is "sufficiently successful" for smaller-scale commingling cases (Rösing and Pischtschan 1995, 40).

Byrd and Adams (2003) comment on the methods of Rösing and Pischtschan (1995), addressing issues of small sample size and the use of their statistical procedures. Byrd and Adams (2003) contend that the regression model ignores human variation (i.e. asymmetries) as most true matches would not lie perfectly on the regression line but be within a less strict confidence interval.

Research completed by Byrd and Adams (2003) aimed to validate osteometric sorting and provide examples of its utility in actual forensic cases. The authors suggest a statistical approach to osteometric sorting using bivariate statistical models calculated

from reference data. The measurements for each element are summed and converted to a natural logarithm. A regression model is calculated from the reference data and the second element is regressed on the first. Therefore, measurements of one bone, e.g. the left tibia, is used to predict the dimensions of another bone, e.g. the right femur, of the same individual. Test applications of the regression model resulted in low (2% to 5%) Type I error (i.e. elements from the same individual were rejected by the null hypothesis) and a 90% Power Index:

$$PI = \frac{A}{(A+B)}$$

where A is the number of successful rejections of the null hypothesis and B is the number of comparisons involving bones from different individuals where the null hypothesis must be accepted.

There are both disadvantages and advantages to the regression method for osteometric sorting proposed by Byrd and Adams (2003). The authors found that the method is more accurate and reliable for individuals of different sizes (e.g. differ in stature); problems arise when applied to individuals of the same general size. Also, when measurements cannot be taken, due to pathologies or traumas, or because of poor preservation, then the method is considered ineffective (Byrd and Adams 2003, 6). The authors noted that the effects of handedness, secular trends, 'race', and sex were not explored in their research. However, they state that osteometric sorting is an inexpensive method and reduces the amount of time required for the reassociation of skeletal elements. The method has a high power to reassociate individuals of varying size, the error rates are low, and the statistics are simple and well-grounded in anthropology (Byrd and Adams 2003).

Byrd (2008) presents a model for pair-matching skeletal remains. The formula reads:

$$D = \sum (a_i - b_i)$$

where *a* is the right-side bone measurement of variable *i*, and *b* is the left-side bone measurement of variable *i* for each of the measurements in the comparison. Testing the null hypothesis (i.e. no difference) is completed by comparing the value of D to "0" and the standard deviation of D from the reference data. The deviation from "0" is divided by the standard deviation of the reference data. This value is then evaluated against the *t*-distribution to obtain a *p*-value. A low *p*-value is strong evidence against the null hypothesis (i.e. if the elements are a true pair, it would be atypical to differentiate that much in size). The author suggests using a 0.10 significance level for most applications of this model. Byrd and LeGarde (2014) found that at the 0.10 significance level, this method showed low error rates in their test applications pairing femora, humeri, and radii where the average error rates were 6.3%, 9.2%, and 11.25%, respectively. Byrd (2008) states that osteometric comparisons of paired bones and adjoining bones is advantageous when sorting large assemblages where it would be impractical to make visual comparisons of every possible match; osteometric sorting has great potential and should be included with other techniques practiced in commingled remains cases.

Vickers and colleagues (2015) tested the method proposed by Byrd (2008) for predicting pair-matches in cases of commingled human remains. Vickers and colleagues stated that Byrd violated the normality assumption for use of a *t*-score approach and had a high rate of false rejections (up to 22%). Vickers and colleagues suggested that the rate of false rejections undermined the ability to show true incompatibilities for potential

matches. They also noted that Byrd does not address bilateral asymmetry. While Vickers and colleagues did not recommend the use of this method, they did report that there was an 86% reduction in the number of potential pairs requiring visual matching by using bilateral asymmetry.

To simplify the process of osteometric sorting, Thomas and colleagues (2013) developed a statistic (*M*) that calculates the amount of size variation between element pairs, where L is the size of the left element and R is the size of the right element, using the following equation:

$$M = \frac{|\,L + R\,|}{((L+R)/2)}$$

The authors combined databases to create a large sample consisting of men of White, Black, Asian, Hispanic/Mexican, and 'other' descent. They measured clavicles, scapulae, humeri, radii, ulnae, os coxae, femora, tibiae, fibulae, and calcanei. The authors calculated the 90th and 95th percentiles of *M* with statistical software that uses an algorithm to conduct linear interpolation between data points. The value of *M* is calculated for suspected matches and compared to 90th and 95th percentiles and the maximum value of *M*. If the value of *M* is greater than that for the percentile, then the two elements likely did not originate from the same individual; if the value of *M* is less than that for the percentile, then it is possible that the elements did originate from the same individual. The authors noted that the rejection of the null hypothesis does not allow the observer to conclude the elements are from the same individual, but the use of additional analyses could assist with this conclusion. Thomas and colleagues determined that the use of the statistic *M* in addition to visual pair-matching would be very effective for resolving commingling of human remains.

2.2.2.1 Applications of osteometric sorting

Chew (2014) used osteometric sorting techniques to resolve large scale commingling at the Piggot ossuary site in North Carolina. The author subjected 114 skeletal elements to visual pair-matching followed by osteometric sorting techniques using three models for confirmation. The first model compared left and right sides and emphasized shape, length, and diameter of elements. The second model compared articulating surfaces, and the third model compared bones of different sizes using a linear regression model. Approximately 50%, 30%, and 71% of the bone pairs could be individuated using the first, second, and third models, respectively (Chew 2014). The author concluded that osteometric sorting is a good first approach when trying to reassociate commingled human remains.

Rodríguez and colleagues (2015) evaluated the methodologies of Byrd and Adams (2003) and Byrd (2008) for osteometric sorting (i.e. matching paired elements, articulating bone portions, and comparing other bone portions) on a Colombian population. Rodríguez and colleagues (2015) used a reference sample of 100 individuals (53 males, 47 females) for their osteometric sorting models. They created artificial, small-scale commingling with an independent sample of three males and five females. Variables used for this study included standard measurements of the scapulae, humeri, radii, ulnae, os coxae, femora, tibiae, fibulae, and tali. While the authors noted that the sample sizes for this study were small, the pilot study showed promising results and supported previous research promoting osteometric sorting techniques to aid in scenarios of commingled human remains.

A multimethod approach was employed by Finlayson and colleagues (2017) to resolve a case of small-scale commingling in northern California. Two individuals were murdered and buried in shallow graves in a marijuana field. Scavenging caused fragmentation and commingling of remains. The authors collected the human remains and laid them out in anatomical position, then individuated the remains by reconstructing the fragmented bones and articulating adjacent skeletal elements. They used visual pair-matching, osteometric pair-matching, taphonomic analysis, DNA analysis, and x-ray fluorescence spectrometry methods for reassociation. Osteometric pair-matching was completed using methods presented by Thomas, Ubelaker, and Byrd (2013), i.e. calculating the *M* statistic. Measurements of the femora, tibiae, and fibulae pairs were compared using the 95th percentile of the *M* statistic. The femora were reassociated using osteometric pair-matching, taphonomy, and DNA. The tibiae were reassociated using osteometric and visual pair-matching, DNA, and taphonomy. The fibulae were reassociated using osteometric and visual pair-matching, and taphonomy. The authors concluded that the multimethod approach greatly facilitated the resolution of the small-scale commingling. The combination of sorting techniques successfully reassociated remains, and resulted in the identification and repatriation of the individuals. This case resulted in the suspect being convicted and sentenced for murder for both deceased individuals.

2.2.3 Geometric morphometrics

Garrido-Varas and colleagues (2013, 2014) have investigated a new pair-matching method for sorting commingled remains. The studies combined both non-metric and metric techniques in an attempt to develop a more objective morphological analysis.

Garrido-Varas (2013) applied anthropometry and geometric morphometrics to pair-match elements of the appendicular skeleton. The author found a significant difference between homologous elements in both sexes, with strong directional asymmetry. The author created a new method to pair-match the humerus, radius, femur, and tibia. The method combines metric ranges of asymmetry and principal component analysis of shape variables, resulting in 95% accuracy (Garrido-Varas 2013). Garrido-Varas noted that this methodology provided an objective and repeatable mathematical component, an important contribution for forensic casework.

The 2014 study by Garrido-Varas and colleagues investigated shape similarities for pair-matching metacarpals, also using geometric morphometric shape analyses. Asymmetry of the metacarpals were calculated and shape characteristics were analyzed using generalized Procrustes analysis and multivariate statistics. The method showed an accuracy of 100% using their combined methodology. The authors concluded that incorporating geometric morphometrics is useful for anthropological assessments when comparing element shapes between individuals (Garrido-Varas et al. 2014).

McCormick (2017) aimed to evaluate the use of geometric morphometrics for osteometric reassociation of commingled human remains. The author collected geometric morphometric landmark data from femora of 208 individuals and linear measurements from femora of 435 individuals. McCormick randomly selected 10 individuals to create a test group, imitating a small-scale commingling scenario, for pair-matching comparisons. The author found that geometric morphometrics accurately reassociated 78.2% of the sample. However, linear measurements reassociated 93.2% of the sample. Therefore, McCormick concluded that, because linear measurement data are informative and easy to

execute, using linear measurements are best for osteometric sorting in commingling scenarios.

2.2.4 DNA in commingled human remains cases

In cases of mass fatality incidents, there is often a reliance on DNA analysis for identification (Mundorff and Davoren 2014). The use of nuclear DNA versus mitochondrial DNA (mtDNA) is dependent on the scenario (Komar and Buikstra 2008). The Swissair Flight 111 crash, which occurred off the shore of Nova Scotia, killed all on board and dismembered the 229 passengers and crew into approximately 15,000 body parts; due to the high level of fragmentation, scientists processed 1,370 victim samples for identification and reassociation using nuclear DNA analysis (Robb 1999). In cases such as the Swissair plane crash, where families were travelling together, nuclear DNA was necessary to discern between individuals for reassociating human remains and identification. "While nuclear DNA provides a more specific finding, it also requires a more specific basis for comparison" (Komar and Buikstra 2008, 249), i.e. because nuclear DNA is different for every individual, comparisons require a victim sample or parental samples for positive identification. Victim and parental samples are rare in these circumstances, therefore, nuclear DNA comparisons are not often a viable option in commingling cases (Komar and Buikstra 2008).

Mitochondrial DNA analysis has been used as a primary method for identification in such contexts as mass graves in Kosovo and Bosnia (Byrd et al. 2003; Komar and Buikstra 2008). In a mass grave context, mtDNA can be utilized for identifying family groups. In these cases, mtDNA can be compared with any individual in the family who

share the maternal mtDNA with the missing individuals. However, mtDNA cannot be used for identification of the individual since mtDNA is shared throughout the maternal lineage (Komar and Buikstra 2008).

Anthropological expertise assists with identifying the number individuals found within a commingled scenario, which can ultimately decrease the number of elements tested for DNA analyses. Following the World Trade Centre attacks, the triage phase of the identification process included anatomical matching: where experts reassociated elements, e.g. feet with their corresponding limbs. There was a reduction in the number of DNA tests needed due to the success of anatomical matching, without which DNA testing of all fragments would have been required as per Disaster Victim Identification (DVI) protocol (Davies, Hackman, and Black 2014; Mundorff 2012).

The International Committee of the Red Cross (2009) published current recommendations for DNA analyses from skeletal remains. It suggests sampling from the femoral shaft or molar teeth. However, there is evidence that tarsal elements may provide a higher yield of genetic material (Mundorff and Davoren 2014). A study by Mundorff and Davoren (2014) found that the samples obtained from long bones of the upper and lower limbs yield less genetic material than the tarsals. Among the tarsal bones, much of the genetic material lies within the talus, calcaneus, and cuneiforms. These cancellous bones not only have a higher level of DNA, than other bones, but are also easier to work with because smaller skeletal elements can be sampled with scalpels (rather than bone sawing) and using intact bones eliminates the risk of contamination (Mundorff, Bartelink, and Mar-Cash 2009). The use of tarsal elements for DNA analysis would be a useful tool in the reassociation of human remains (Davies, Hackman, and Black 2014); if tarsal elements are properly pair-matched and reassociated with articulating bones, a tarsal

element can then be utilized for DNA testing rather than segments of, for example, the tibial or femoral shaft.

2.3 Context of the current study

The SWGANTH recognized priority areas of research within the field of forensic anthropology and outlined them in a public document. When examining commingled remains cases, research should focus on: 1) validation studies of pair (antimere) matching and, 2) development and validation of metric methods of reassociation (SWGANTH 2013a).

The published research illustrates that pair-matching of skeletal remains using metric methods is useful for some long bones, e.g. the femur and humerus, and some smaller bones, e.g. metacarpals (Chew 2014; Garrido-Varas et al. 2014; Garroway 2013; Thomas, Ubelaker, and Byrd 2013). However, research involving pair-matching of tarsal bones is scarce. Thomas and colleagues (2013) studied pair-matching for the calcaneus using metric methods. The maximum length and middle breadth of the calcaneus were the only two variables used in their study. As reported in previous studies, articulating surfaces exhibit less asymmetry (Churchill and Formicola 1997; Garroway 2013; Ruff and Jones 1981; Sakaue 1998; Trinkaus, Churchill, and Ruff 1994) and, because tarsal elements are close-fitting, the ability to reassociate and individuate elements is more likely (Gordon and Buikstra 1980; Reichs 1989; Ubelaker 2002). Therefore, it would be worthwhile investigating other variables of the calcaneus for purposes of osteometric pair-matching. The goals of this project are to: 1) investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled, 2) investigate sex

differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled, 3) investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations separated, and 4) use the *M* statistic to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations.. This study will account for the concerns in previous studies regarding bilateral asymmetry, ancestry, and sex in cases of osteometric sorting (Byrd and Adams 2003; Rodríguez et al. 2015b; Vickers et al. 2014).

There are a number of benefits for the development of new methods for pair-matching. A new method could decrease the number of skeletal elements that would require visual assessment, which will lessen the time and costs required for analyses in the field (Byrd and Adams 2003). Developing a new analytical method for commingled human remains cases gives stronger statistical power to individuating human remains, ensures that the reassociated individuals are more complete, and reduces the probability of mismatched elements. The successful pair-matching of skeletal elements helps decrease the amount of elements needed for DNA testing in commingled remains cases, which lessens the time needed to complete, and costs associated with, the analyses (Davies, Hackman, and Black 2014; Mundorff and Davoren 2014). Ultimately, improving upon the current methodology for reassociating individuals in commingled human remains cases would aid efforts of victim identification and provide closure for loved ones.

CHAPTER III: MATERIALS AND METHODS

3.1 Research Objectives

The current study focuses on six measurements (maximum length, dorsal articular facet length, dorsal articular facet breadth, middle breadth, middle articular facet length, middle articular facet breadth) of the calcaneus to establish an accurate and reliable osteometric sorting method to pair-match calcanei for White, Black, and Coloured South African populations. The objectives of this research are to:

(1) Investigate the degree of asymmetry between left and right calcanei within each individual when sexes and populations are pooled,

(2) Investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled,

(3) Investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations separated, and

(4) Use the *M* statistic to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations.

3.2 Skeletal Materials Utilized

This study examined 419 paired calcanei (419 left calcanei and 419 right calcanei; $N_{calcanei}$=838) from 419 skeletal cadaveric individuals (210 males, 209 females) of White, Black, and Coloured South Africans housed within two South African reference collections, the Pretoria Bone Collection and the Kirsten Collection. Individuals were selected at random. The sample consists of adult individuals between the age of 20 years

and 103 years of age. Juveniles (<20 years of age) were excluded from this study because they are not skeletally mature. Individuals were excluded from the sample if there were any trauma, taphonomic damage, or pathologies present to one or both calcanei that would affect the accuracy of calcaneal measurements.

3.3 Methods

Both the left and right calcanei of 140 individuals ($N_{calcanei}$=280) were examined from the Kirsten Collection, including 70 males and 70 females of Coloured South African ancestry. Both the left and right calcanei of 279 individuals ($N_{calcanei}$=558) were examined from the Pretoria Bone Collection, including 70 males and 69 females ($N_{calcanei}$=278) of White South African ancestry and 70 males and 70 females ($N_{calcanei}$=280) of Black South African ancestry. Thirty left and 30 right calcanei were re-measured for intra-observer error analysis. These skeletal elements were randomly selected from each of the White, Black, and Coloured South African populations: 10 left and 10 right calcanei (5 males, 5 females) from the White South African population, 10 left and 10 right calcanei (5 males, 5 females) from the Black South African population, and 10 left and 10 right calcanei (5 males, 5 females) from the Coloured South African population. A second sample of 30 left and 30 right calcanei, independent of the intra-observer sample, were randomly selected from each of the three sampled populations and measured by a research assistant for inter-observer error analysis: 10 left and 10 right calcanei (5 males, 5 females) from the White South African population, 10 left and 10 right calcanei (5 males, 5 females) from the Black South African population, and 10 left and 10 right calcanei (5 males, 5 females) from the Coloured South African population. See summary of sample sizes in Table 3.1.

Table 3.1 Summary of sample sizes.

Population	Pooled Sample (N)		Intra-observer Error Test (N)		Inter-observer Error Test (N)	
	Male	Female	Male	Female	Male	Female
White South African*	70	69	5	5	5	5
Black South African*	70	70	5	5	5	5
Coloured South African**	70	70	5	5	5	5
Total Number of Individuals ($N_{individuals}$)	210	209	15	15	15	15
Total Number of Calcanei ($N_{calcanei}$)	420	418	30	30	30	30

* Pretoria Bone Collection
** Kirsten Skeletal Collection

3.3.1 Skeletal measurements

Six measurements of the calcaneus were assessed for each left and right calcanei from the White, Black, and Coloured South African populations. These include: Maximum Length (MAXL), Dorsal Articular Facet Length (DAFL), Dorsal Articular Facet Breadth (DAFB), Middle Breadth (MIDB), Middle Articular Facet Length (MAFL), and Middle Articular Facet Breadth (MAFL) (Table 3.2; Figure 3.1; Appendix A). The Maximum Length follows the definitions of Martin (1928) in Steele (1976). The Dorsal Articular Facet Length and Dorsal Articular Facet Breadth follow the definitions of Martin (1988) in Bidmos (2006b). Middle Breadth (also referred to as Load Arm Width) was modified from Martin (1928) in Steele (1976) by the current author for this study. The Middle Articular Facet Length and Middle Articular Facet Breadth were also used. Morphological descriptions of the middle articular facet have been noted in the anthropological (Bidmos 2006b; Orr and Meek 2016) and anatomical (Ergür et al. 2011; Uygur et al. 2009) literature. However, until now, morphometric analyses have not been previously cited in the literature for the middle articular facets. For this project, the current author developed definitions for two new metric variables: Middle Articular Facet

Length (MAFL) and Middle Articular Facet Breadth (MAFB). The current author's inclusion of MAFL and MAFB, and adaptation of MIDB, were included to evaluate the comparison of facet measurements (less asymmetry) to gross size measurements (greater asymmetry) of the calcaneus for pair-matching (Churchill and Formicola 1997; Garroway 2013; Ruff and Jones 1981; Sakaue 1998; Trinkaus, Churchill, and Ruff 1994). All measurements were collected using a digital Vernier caliper with units rounded to the nearest hundredth of a millimeter (i.e. 0.01 mm) and recorded on a paper spreadsheet. The written spreadsheet was later transposed into a digital Excel spreadsheet (Appendix B).

Table 3.2 Description of measurements collected from each calcanei.

Variable	Description	References
MAXL	The distance between the most posteriorly projecting point on the tuberosity and the most anterior point on the superior margin of the articular facet for the cuboid measured in the sagittal plane	modified from Martin 1928 in Steele 1976
DAFL	Distance between the most posterior and the most anterior points on the posterior articular facet of the calcaneus	modified from Martin 1988 in Bidmos 2006b
DAFB	Distance from the most medial to the most lateral points on the posterior articular facet	modified from Martin 1988 in Bidmos 2006b
MIDB	The distance between the most laterally projecting point on the dorsal articular facet and the most medial point on the **middle articular facet***	modified from Martin 1928 in Steele 1976
MAFL	Length of the middle articular facet centered along the long axis of the facet, when middle articular facet is not bipartite, the measurement is taken from the most anterior point to the most posterior point of the entire facet centered along the long axis	Orr (present study)
MAFB	Maximum breadth of middle articular facet perpendicular to MAFL axis	Orr (present study)

*_sustenaculum tali_ in original definition by Martin 1928 in Steele 1976

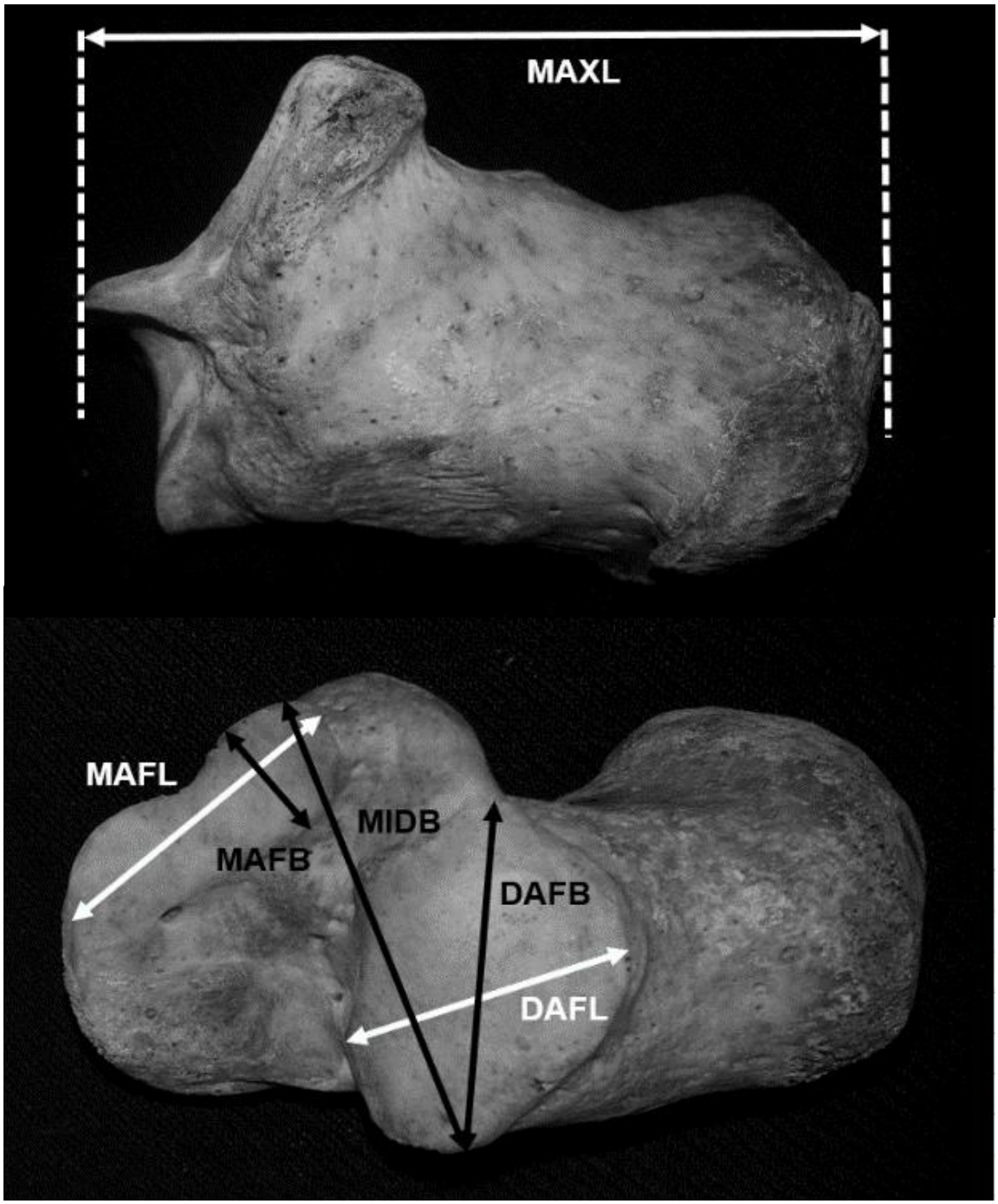

Figure 3.1 Lateral view (top photo) and superior view (bottom photo) of a typical calcaneus depicting the measurements MAXL, DAFL, DAFB, MIDB, MAFL, and MAFB. (Photo by Kayla L. Orr)

3.4 Statistical Analyses

Statistical analyses were performed using MiniTab 17.0 statistical software package, and Microsoft Office Excel 2013. The raw data were first separated into three populations: White, Black, and Coloured South Africans, and then each population group was separated by sex, i.e. the three population groups were analyzed separately and, within these population groups, males and females were analyzed separately. Descriptive statistics were calculated for males and females of each population group. Descriptive statistics were calculated for each measurement of each male calcanei and each female calcanei from each of the three population groups to examine the variation in these morphometric characteristics.

Anderson-Darling tests for normality were performed for each of the six variables (MAXL, DAFL, DAFB, MIDB, MAFL, and MAFB) for South African males. Separate Anderson-Darling tests for normality were performed for each of the six variables for South African females. This method was repeated for males and females of the Black and Coloured South African populations. Normality probability plots were created to examine the distribution of the data and highlight any potential outliers.

A normal distribution is depicted when the plotted measurement points exhibit a linear distribution. A statistical significance level of 5% error rate ($\alpha = 0.05$) to measure normal data distribution was adjusted using a Bonferroni correction. This was completed by dividing the Bonferroni correction ($\alpha = 0.05$) by the number of testable measurement variables ($N_{variables} = 6$) to give a Bonferroni correction of $\alpha = 0.008$. As the number of comparisons between measurement variables increases (i.e. the number of statistical tests), so does the likelihood that a Type 1 error may appear in the statistical outcome. A Bonferroni correction value is used to reduce the rate of Type 1 errors associated with

multiple statistical comparisons. In the current research study, if the p-value was greater than 0.008 ($p > 0.008$), this indicated a normal distribution and parametric tests will be employed for the statistical analyses.

To test for intra-observer error, 30 left and 30 right calcanei of 30 individuals (i.e. $N_{individuals}=30$; $N_{calcanei}=60$) were randomly selected and remeasured from the White (5 males, 5 females), Black (5 males, 5 females), and Coloured (5 males, 5 females) South African population groups. To test for inter-observer error, 30 left and 30 right calcanei of 30 individuals were randomly selected and remeasured from the White (5 males, 5 females), Black (5 males, 5 females), and Coloured (5 males, 5 females) South African population groups, i.e. Kirsten Collection $N_{individuals}=10$; $N_{calcanei}=20$, Pretoria Bone Collection $N_{individuals}=20$; $N_{calcanei}=40$, total $N_{individuals}=30$; $N_{calcanei}=60$. Written descriptions of the measurements and visual demonstrations showing how to collect the data were provided to the research assistants.

The six calcanei variables were tested for intra- and inter-observer measurement errors. Tests for intra-observer error determine if the current author was able to accurately reproduce their measurements for a second time. Tests for inter-observer error determine if the measurements taken by the research assistant are significantly different from those taken by the current author. The measurement variables were evaluated using paired *t*-tests, where if there is no statistically significant difference ($p > 0.008$) between each pair of measurements, the measurement is accurate and reproducible.

Additionally, the measurement variables were evaluated for the technical error of measurement (TEM), relative technical error of measurements (%TEM), and coefficient of reliability (R) for intra- and inter-observers. To evaluate TEM, the calculation is as follows (Ulijaszek and Kerr 1999):

$$\text{TEM} = \sqrt{\frac{\Sigma D^2}{2N}}$$

where D is the difference between the two measurements and *N* is the number of individuals used in the sample. Due to the relationship between the TEM and the size of the measurement (i.e. a difference of 1 mm may be negligible when measuring the length of the femur, while a difference of 1 mm would be significant when measuring the diameter of the radius), the %TEM must be calculated to accurately express the association. The %TEM is calculated as follows (Dahlberg 1940; Perini et al. 2005; Ulijaszek and Kerr 1999):

$$\%\text{TEM} = \frac{\text{TEM}}{(\text{mean})} \times 100$$

using the previously calculated TEM and the mean (i.e. the average of the first and second measurement for each individual, then overall average for all individuals per variable measured). While lower %TEM values indicate good precision of that measurement (Geeta et al. 2009), it is difficult to determine acceptable levels of TEM and %TEM as they may be group-, population-, or age-dependent and vary across measurement types (Ulijaszek and Kerr 1990). Perini and colleagues (2005) presented acceptable %TEM values as between 1% and 7.5% for intra-observers (1.5–7.5% for beginners; 1–5% for skilled observers), and %TEM values between 1% and 10% for inter-observers (2–10% for beginners; 1.5–7.5% for skilled observers).

The coefficient of reliability (R) evaluates the precision of the measurement by assessing the variance between measurements not due to measurement error, and is calculated as follows (Ulijaszek and Kerr 1999):

$$R = 1 - \frac{\text{TEM}^2}{(\text{SD}^2)} \times 100$$

where SD^2 is the total inter-subject variance (i.e. standard deviation for all measurements used when evaluating TEM). The value of R will range from 0 to 1, where the closer the R value is to 1, the better; for example, an R of 0.90 indicates that 90% of the variance is due to factors other than measurement error.

3.4.1 Calcaneal Asymmetry

Asymmetry is present, to some degree, naturally in bilateral skeletal elements. Paired *t*-tests were utilized to test for calcanei asymmetry, i.e. statistically significant differences between paired calcanei. A statistical significance level of 5% error rate ($\alpha = 0.05$) was adjusted using a Bonferroni correction. This was completed by diving the Bonferroni correction ($\alpha = 0.05$) by the number of testable measurement variables ($N_{variables} = 6$) to give a Bonferroni correction of $\alpha = 0.008$. A p-value greater than 0.008 indicates there is no statistically significant difference between the left and right calcanei from a pair, i.e. there is no significant asymmetry.

3.4.1.1 Individual Differences in Calcaneal Asymmetry

The first goal of this research was to investigate the degree of asymmetry between left and right calcanei within each individual when sexes and populations are pooled. To determine the relative amount of asymmetry exhibited in each calcanei pair, the bilateral data were calculated as percentage directional asymmetry (%DA) (Steele and Mays 1995):

$$\%DA = \frac{\text{right-left}}{(\text{average of right and left})} \times 100$$

Percentage directional asymmetry (%DA) indicates the directional bias of a particular dimension, i.e. a dimension is right-biased when the %DA is positive and left-biased when the %DA is negative (Auerbach and Ruff 2006). By converting the directional asymmetry into a percentage, the mathematical formula considers the size of the element; without the conversion to a percentage, the relative significance of the asymmetry could be interpreted incorrectly (Auerbach and Ruff 2006). For example, for larger bones, such as the femora, a 2 mm difference between homologs would be considered insignificant, however, for smaller bones, such as the calcanei, a 2 mm difference between homologs would indicate greater asymmetry. The positive and negative values of %DA were calculated for each pair of measurements for each individual.

Because individual %DA values that are close to zero and exhibit only slight left- and right-biases may not be biologically significant (i.e. bias due to measurement error or fluctuating asymmetry) as true directional asymmetry, only individuals with greater than ± 0.5% directional asymmetry are categorized as having directional asymmetry. The occurrences of left-biased and right-biased individuals were tallied and chi-square (χ^2) tests were used to evaluate whether there were significant differences ($p < 0.008$) between left- and right-biases for the White, Black, Coloured South African, and "Combined South African" groups, i.e. White, Black, and Coloured populations combined, with sexes separated and combined.

To assess the total amount of asymmetry present in each calcaneal dimension, Percentage absolute asymmetry (%AA) was calculated for each variable. This differs from percentage directional asymmetry as the percentage absolute asymmetry disregards the direction (left or right) of the bias (Auerbach and Ruff 2006):

$$\%AA = \frac{\text{maximum-minimum}}{(\text{average of maximum and minimum})} \times 100$$

Percentage absolute asymmetry was calculated for the White, Black, and Coloured South African groups. The %AA was calculated for each of the population groups with males and females separated by sex, and males and females pooled. The %AA was calculated for the South African population groups, i.e. White, Black, and Coloured South African, and "Combined South African" groups, with males and females separated by sex, and males and females pooled.

3.4.1.2 Sex Differences in Asymmetry of the Calcaneus

The second goal of this research project was to investigate sex differences in bilateral asymmetry of calcaneal pairs (populations pooled). Following methods of Storm (2009), the Kruskal-Wallis test was used to calculate differences in %DA and %AA between sex groups, as directional asymmetry and absolute asymmetry violate the assumption of normality. The Kruskal–Wallis was used to evaluate for differences in %DA between sexes, where p-values greater than 0.008 indicate there is no significant difference between groups. The Kruskal-Wallis was used to evaluate for differences in %AA between sexes, where p-values greater than 0.008 indicate there is no significant difference between groups.

3.4.1.3 Population Differences in Asymmetry of the Calcaneus

The third goal of this research project was to investigate population differences in bilateral asymmetry of calcaneal pairs (sexes separated). Following methods of Storm

(2009), the Kruskal-Wallis test was used to calculate differences in %DA and %AA between population groups, as directional asymmetry and absolute asymmetry violate the assumption of normality. The Kruskal–Wallis was used to evaluate for differences in %DA between population groups, where p-values greater than 0.008 indicate there is no significant difference between groups. The Kruskal-Wallis was used to evaluate for differences in %AA between population groups, where p-values greater than 0.008 indicate there is no significant difference between groups.

3.4.2 Calculating the M statistic

The fourth goal of this research was to use the statistic *M* to assess applicability for pair-matching left and right calcanei, and address variances of *M* between sexes and/or ancestry groups. The statistic *M*, introduced by Thomas, Ubelaker, and Byrd (2013), is expressed as:

$$M = \frac{|L-R|}{(L+R)/2}$$

where *L* and *R* are the measurements of the left and the right bone, respectively. The statistic *M* expresses the difference between the right and left measurement as a proportion of the average value of the two measurements. When left and right elements have an *M*-value of zero, they are likely homologs. When testing if two homologs are from the same individual, the *M*-value is examined: if the value of *M* is greater than that from the reference table the null hypothesis is rejected. Therefore, it is unlikely that the two bones being tested originated from the same individual (Thomas, Ubelaker, and Byrd 2013). There will always be some asymmetry between measurements of paired elements but when these measurements are too different in size they will be rejected as a possible

match; the statistic *M* advises the observer how much asymmetry is expected in a particular dimension between pairs of elements, and how much asymmetry would be not be normal for a pair.

The statistic *M* was calculated for each pair of measurements for each individual of the White, Black, and Coloured South African groups. The Excel statistical program utilizes an algorithm, which conducts linear interpolation between data points, calculating the 90^{th} and 95^{th} percentiles of *M* to be tabulated for reference in forensic cases. These percentiles of *M* are standard protocol (Thomas, Ubelaker, and Byrd 2013) and account for natural asymmetry in bilateral skeletal elements, where the 90^{th} and 95^{th} percentiles of *M* and the maximum value of *M* allow for some degree of asymmetry, which is not too stringent nor too lenient. The 90^{th} and 95^{th} percentiles of *M* and maximum *M* were calculated for males and females separately, and for combined sex, for each separate population group (i.e. White, Black, and Coloured South African, and "Combined South African"). The percentiles indicate the size differences that are exhibited in 90%, 95%, and 100% of the individuals in the sample, and are expected and thus an acceptable difference between two calcanei within a pair. The values of *M* were then compared between the sexes using a two sample *t*-test to examine for statistically significant differences. If there is no statistically significant difference between males and females ($p > 0.008$), then the *M*-values can be pooled to calculate the maximum *M* and the 90^{th} and 95^{th} percentiles of *M*. The values of *M* were then compared between population groups using a two sample *t*-test to analyze for statistically significant differences. If there is no statistically significant difference between White, Black, and Coloured South African population groups ($p > 0.008$), then the *M*-values can be pooled to calculate the maximum

M and the 90th and 95th percentiles of *M* for pair-matching without consideration of ancestry.

Assessing potential pair-matches using the statistic *M* was completed by comparing each of the six measurements from one left calcaneus to all right calcanei within the sample, i.e. *M* was calculated for one left calcaneus paired with all right calcanei in the sample. If the value of *M* is greater than the value cited for the 90th, 95th, or maximum *M*, then the right calcaneus can be rejected as a possible match for the left calcaneus. The number of accepted and rejected right calcanei were compared to calculate the reduction rate (percentage) for visually assessing pairs of calcanei. For example, when comparing MAXL of one left calcaneus to 10 right calcanei, if the *M* values for 5 out of the 10 right calcanei were greater than the 90th percentile of *M* for that measurement, there would be a 50% reduction in the number of possible pairs that would need to be visually pair-matched.

The application of the statistic *M* was completed separately for White South African males, White South African females, and pooled sexes for White South Africans. This process was repeated for Black South Africans, with sexes separated and pooled, and Coloured South Africans, with sexes separated and pooled. This process was also repeated for the "Combined South African" group (i.e. White, Black, and Coloured South Africans combined), with sexes separated and pooled. The percentage of possible calcaneal pairs that were accepted, or rejected, as a possible pair were evaluated; differences between sexes and between each ancestral group were assessed, investigating differences in the success of this pair-matching method.

3.4.2.1 Automating comparisons between left and right calcanei

To calculate *M* for all pairwise comparisons, the R statistical computing environment was used (R Core Team 2016; RStudio Team 2016). Firstly, *M* was calculated for all possible pairs based on the measurement of MAXL, e.g. the statistic *M* is calculated for each left MAXL measurement compared to each right MAXL measurement for each individual in the White South African sample. Then, for each reference individual, those results were screened for *M* values that fell under the 90^{th} and 95^{th} percentile and the maximum value of *M*, i.e. the specimens that were considered to be a possible match, based on the 90^{th} and 95^{th} percentile and maximum value of *M*, were stored in a table. The resulting list represented those individuals not rejected as possible pairs. These procedures were conducted for all measurements. The results for each variable were then assessed to determine which measurements performed best for osteometric pair-matching procedures. The analyses in R were repeated for the Black South African and Coloured South African groups.

CHAPTER IV: RESULTS

4.1 Research objectives

The current study focuses on six measurements (maximum length, dorsal articular facet length, dorsal articular facet breadth, middle breadth, middle articular facet length, middle articular facet breadth) of the calcaneus to establish an accurate and reliable osteometric sorting method for pair-matching calcanei in White, Black, and Coloured South African populations. The objectives of this research are to:

(1) Investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled,

(2) Investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled,

(3) Investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations separated, and

(4) Use the *M* statistic to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations.

4.2 Statistical Analyses

4.2.1 Descriptive statistics

Paired calcanei from 419 individuals of White (69 females, 70 males), Black (70 females, 70 males), and Coloured South Africans (70 females, 70 males) were examined to assess the applicability for metric pair-matching in forensic commingling cases. Eight

hundred and thirty-eight ($N_{calcanei}$ = 838) individual calcanei were studied from two cadaveric skeletal collections; contemporary White and Black South Africans were randomly selected from the Pretoria Bone Collection and contemporary Coloured South Africans were randomly selected from the Kirsten Collection.

Six variables of the calcaneus were measured: Maximum Length (MAXL), Dorsal Articular Facet Length (DAFL), Dorsal Articular Facet Breadth (DAFB), Middle Breadth (MIDB), Middle Articular Facet Length (MAFL), and Middle Articular Facet Breadth (MAFL). Table 4.1 shows the descriptive statistics for White South African females and males. Table 4.2 shows the descriptive statistics for Black South African females and males. Table 4.3 shows the descriptive statistics for Coloured South African females and males. The tables list the total number of calcanei assessed ($N_{calcanei}$), minimum measurement length (Min), maximum measurement length (Max), mean ($\overline{X}$), and standard deviation (SD). Overall, for each of the White, Black, and Coloured populations, calcaneal dimensions for females were smaller than calcaneal dimensions for males. White South African females displayed larger calcaneal measurements than Black and Coloured South Africans for most variables (MAXL, MIDB, DAFL, DAFB). Similarly, White South African males displayed larger calcaneal measurements than Black and Coloured South Africans for most variables (MAXL, MIDB, DAFL, DAFB). The variable MAFB displayed the least variation, of all the calcaneal measurements, between population groups and sex groups.

Table 4.1 Descriptive statistics for White South African females and males for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB.

Sex	Variable[a]	Min (mm)	Max (mm)	$\bar{X}$ (mm)	SD (mm)
Female	MAXL-L	71.140	89.475	80.641	3.946
(N = 69)	MAXL-R	71.710	88.840	80.685	3.880
	MIDB-L	34.580	43.840	39.999	2.057
	MIDB-R	34.260	44.490	39.539	2.133
	DAFL-L	24.910	33.530	28.486	1.861
	DAFL-R	24.570	34.720	28.533	2.128
	DAFB-L	24.940	34.140	29.014	2.206
	DAFB-R	24.480	34.160	28.989	2.196
	MAFL-L	11.210	35.310	23.100	7.316
	MAFL-R	11.500	34.870	23.462	6.909
	MAFB-L	8.890	13.760	10.885	0.957
	MAFB-R	9.050	13.790	11.129	1.068
Male	MAXL-L	77.140	103.390	86.261	4.465
(N = 70)	MAXL-R	77.030	104.420	86.313	4.659
	MIDB-L	35.600	49.520	42.882	2.587
	MIDB-R	35.610	49.870	42.926	2.693
	DAFL-L	31.730	36.390	31.615	2.238
	DAFL-R	32.195	36.920	31.849	2.307
	DAFB-L	32.475	39.310	32.748	2.874
	DAFB-R	32.845	39.650	32.729	2.930
	MAFL-L	21.960	38.070	24.416	7.314
	MAFL-R	22.420	38.380	25.018	7.215
	MAFB-L	12.355	14.580	12.021	1.195
	MAFB-R	12.240	14.540	12.028	1.275

[a]MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)

Table 4.2 Descriptive statistics for Black South African females and males for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB.

Sex	Variable[a]	Min (mm)	Max (mm)	$\bar{X}$ (mm)	SD (mm)
Female	MAXL-L	66.200	87.430	75.998	4.437
(N = 70)	MAXL-R	66.740	88.490	76.038	4.431
	MIDB-L	33.910	44.160	38.525	2.389
	MIDB-R	33.630	44.460	38.743	2.344
	DAFL-L	22.440	34.320	27.028	2.171
	DAFL-R	21.750	34.650	27.162	2.296
	DAFB-L*	21.780	31.410	26.464	2.195
	DAFB-R*	22.270	30.780	26.060	2.013
	MAFL-L	14.150	34.840	26.889	6.107
	MAFL-R	15.280	34.720	28.503	5.070
	MAFB-L**	7.990	15.090	11.471	1.111
	MAFB-R**	9.210	15.160	11.742	1.175
Male	MAXL-L	70.910	94.310	82.630	4.976
(N = 70)	MAXL-R	71.290	92.790	82.782	4.935
	MIDB-L	35.880	48.450	42.776	2.553
	MIDB-R	35.240	48.430	42.833	2.673
	DAFL-L	21.610	34.850	30.184	2.527
	DAFL-R	22.530	36.020	30.373	2.605
	DAFB-L	23.660	35.340	29.645	2.419
	DAFB-R	23.870	34.890	29.531	2.556
	MAFL-L	14.340	39.650	29.653	6.624
	MAFL-R	22.050	38.830	29.811	6.509
	MAFB-L	9.400	15.130	12.673	1.393
	MAFB-R	9.330	15.280	12.747	1.486

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)

* N = 68

** N = 69

Table 4.3 Descriptive statistics for Coloured South African females and males for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB.

Sex	Variable[a]	Min (mm)	Max (mm)	$\bar{X}$ (mm)	SD (mm)
Female	MAXL-L	64.170	82.810	74.402	3.876
(N = 70)	MAXL-R	64.540	83.210	74.341	3.808
	MIDB-L	31.830	42.730	38.043	2.289
	MIDB-R	30.830	43.720	38.130	2.294
	DAFL-L	23.570	30.810	26.646	1.750
	DAFL-R	23.580	30.980	26.921	1.611
	DAFB-L	21.390	31.150	26.191	2.299
	DAFB-R**	20.640	31.260	26.256	2.280
	MAFL-L	15.560	36.820	27.089	5.574
	MAFL-R	15.910	33.620	27.564	5.027
	MAFB-L	8.890	14.530	11.417	1.171
	MAFB-R**	9.160	14.010	11.559	1.175
Male	MAXL-L	66.780	90.670	79.508	5.260
(N = 70)	MAXL-R	69.680	90.430	79.639	5.063
	MIDB-L	35.320	47.520	41.533	2.619
	MIDB-R	35.240	46.970	41.583	2.538
	DAFL-L	23.240	33.580	29.363	2.026
	DAFL-R	23.770	33.710	29.392	1.941
	DAFB-L	23.800	36.420	29.164	2.635
	DAFB-R**	24.820	36.160	29.303	2.490
	MAFL-L	16.150	39.030	30.145	5.967
	MAFL-R	15.560	37.970	30.615	5.529
	MAFB-L	9.540	15.080	12.135	1.319
	MAFB-R**	8.870	15.280	12.271	1.406

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)
** N = 69

4.2.2 Normality

Normality was assessed for females and males in the White, Black, and Coloured South African populations, for each measurement, using Anderson-Darling tests with the Minitab 17.0 statistical software package. Table 4.4 shows the results of the calculated normality probability for the White South African population. Table 4.5 shows the results of the calculated normality probability for the Black South African population. Table 4.6

shows the results of the calculated normality probability for the Coloured South African population.

Table 4.4 Results of the calculated normality (p-values) for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of the White South African females and males.

Variable[a]	**Sex**	
	Female p-value	**Male p-value**
MAXL-L	0.399	0.153
MAXL-R	0.337	0.533
MIDB-L	0.396	0.033
MIDB-R	0.592	0.513
DAFL-L	0.289	0.645
DAFL-R	0.015	0.375
DAFB-L	0.574	0.845
DAFB-R	0.909	0.890
MAFL-L	< 0.005*	< 0.005*
MAFL-R	< 0.005*	< 0.005*
MAFB-L	0.835	0.058
MAFB-R	0.487	0.190

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)
*Statistically significant ($p < 0.008$)

Table 4.5 Results of the calculated normality (p-values) for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of the Black South African females and males.

Variable[a]	Sex	
	Female p-value	Male p-value
MAXL-L	0.901	0.454
MAXL-R	0.523	0.357
MIDB-L	0.217	0.916
MIDB-R	0.048	0.601
DAFL-L	0.479	0.386
DAFL-R	0.829	0.229
DAFB-L	0.633	0.031
DAFB-R	0.712	0.441
MAFL-L	< 0.005*	< 0.005*
MAFL-R	< 0.005*	< 0.005*
MAFB-L	0.023	0.135
MAFB-R	0.615	0.130

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)
*Statistically significant ($p < 0.008$)

Table 4.6 Results of the calculated normality (p-values) for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of the Coloured South African females and males.

Variable[a]	Sex	
	Female p-value	Male p-value
MAXL-L	0.194	0.572
MAXL-R	0.173	0.260
MIDB-L	0.785	0.482
MIDB-R	0.767	0.317
DAFL-L	0.210	0.742
DAFL-R	0.657	0.530
DAFB-L	0.644	0.398
DAFB-R	0.993	0.495
MAFL-L	< 0.005*	< 0.005*
MAFL-R	< 0.005*	< 0.005*
MAFB-L	0.199	0.845
MAFB-R	0.067	0.527

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth (L = left bone and R= right bone)
*Statistically significant ($p < 0.008$)

Due to the number of variables being assessed, a statistical significance level of 5% (p-value ≤ 0.05) was adjusted using a Bonferroni correction of $\alpha = 0.008$ ($\alpha = 0.05/6$) to account for the possibility of a type-1 error. If a p-value is greater than 0.008, then the data are normally distributed. The results show that the data for females and males in the White South African, Black South African, and Coloured South African samples are normally distributed for variables MAXL, MIDB, DAFL, DAFB, and MAFB. Only the variable MAFL was not normally distributed ($p < 0.008$) for females and males in each South African population; this may be due to variation in the number of talar articular facets on the calcaneus as this feature is highly asymmetrical (this will be discussed further in Chapter 5: Discussion).

4.2.3 Intra- and Inter-observer Error

4.2.3.1 Paired t-tests

Tests for intra- and inter-observer error were evaluated using paired *t*-tests. For the intra-observer error evaluation, the measurement is considered accurate and reproducible if there is no statistically significant difference ($p > 0.008$) between the first recorded measurement and second recorded measurement. The resulting p-values showed no significant intra-observer differences for any of the six variables (see Table 4.7) for all three populations. For the six variables, the average differences ($\overline{X}\ \Delta$) between the first and second measurements taken by the same observer were between 0.084 mm and 0.202 mm. The average intra-observer differences ($\overline{X}\ \Delta$) did not exceed 1%. The greatest measurement differences (Max Δ) between the first and second measurements were

between 0.370 mm and 1.690 mm. The greatest intra-observer error for the measurements was 4.163%.

Table 4.7 Results of the intra-observer error tests for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the White, Black, and Coloured South Africans.

Variable[a]	p-value	$\overline{X}\ \Delta$[b]		Max Δ[c]	
		(mm)	(%)	(mm)	(%)
MAXL	0.218	0.153	0.191	1.370	1.710
MIDB	0.973	0.168	0.411	1.690	4.131
DAFL	0.201	0.202	0.678	1.240	4.163
DAFB	0.124	0.179	0.625	0.830	2.899
MAFL	0.683	0.217	0.813	0.900	3.372
MAFB	0.413	0.084	0.699	0.370	3.079

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
[b] $\overline{X}\ \Delta$ (average difference)
[c] Max Δ (maximum difference)
*Statistically significant ($p < 0.008$)

For the inter-observer evaluation, the measurement is considered accurate and reproducible if there is no statistically significant difference ($p > 0.008$) between the measurement recorded by the first observer and the measurement recorded by the second observer. The resulting p-values showed no significant inter-observer differences for variables MAXL, MIDB, and MAFL, while there were statistically significant differences between the variables DAFB, DAFL, and MAFB (see Table 4.8). For the six variables, the average differences ($\overline{X}\ \Delta$) between the measurements taken by the two observers were between 0.401 mm and 1.222 mm. The average inter-observer differences ($\overline{X}\ \Delta$) did not exceed 5%. The greatest measurement differences (Max Δ) between the first and second observers' measurements were between 1.260 mm and 16.210 mm. The greatest inter-observer error for the measurements was 62.397%; this was attributed to a definition error of the middle articular facet in determining the margins, where the middle articular facet

was divided into two portions, one observer measured the distance between the most anterior to most posterior point, while the other observer measured only the posterior portion of the facet.

Table 4.8 Results of the inter-observer error tests for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the White, Black, and Coloured South African population samples.

Variable[a]	p-value	$\bar{X}$ Δ[b]		Max Δ[c]	
		(mm)	(%)	(mm)	(%)
MAXL	0.133	0.765	0.956	2.870	3.586
MIDB	0.032	0.401	0.998	2.250	5.599
DAFL	0.003*	0.676	2.314	2.490	8.524
DAFB	0.000*	0.629	2.171	2.470	8.526
MAFL	0.095	1.222	4.704	16.210	62.397
MAFB	0.005*	0.319	2.710	1.260	10.705

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
[b] $\bar{X}$ Δ (average difference)
[c] Max Δ (maximum difference)
*Statistically significant ($p < 0.008$)

4.2.3.2 Technical Error of Measurements

To further evaluate intra- and inter-observer error, the technical error of measurements (TEM), relative technical error of measurements (rTEM), and the coefficient of reliability (R) were calculated for each variable. The three population groups were combined for the TEM evaluation of the intra- and inter-observer error. These analyses show that the intra-observer error for all measurements is lower than the inter-observer error for all measurements.

The mean intra-observer TEM and rTEM values are small at 0.175 mm (between 0.085 and 0.229) and 0.584% (between 0.236% and 0.787%) (Table 4.9). These %TEM values are all below the acceptable range for skilled intra-observer error (1%-5%), indicating adequate repeatability of the measurements (Perini et al. 2005). The R-values

are all greater than 0.95 (0.002 to 0.999) for intra-observer error, i.e. there is less than 5% intra-observer error (Table 4.9); R-values greater than 0.95 are acceptable values, indicating accurate repeatability of measurements (Ulijazsek and Kerr 1999).

The mean inter-observer TEM and rTEM are small at 0.821 mm (0.309 to 2.198) and 2.884% (0.952% to 8.461%). For all variables, the inter-observer TEM and rTEM are small except for the variable MAFL (TEM = 2.198 mm; rTEM = 8.461%). Variables MAXL, MIDB, DAFL, DAFB, and MAFB all have %TEM that fall within the acceptable range for skilled inter-observer error (1.5–7.5%), while the %TEM for the variable MAFL fell within the range for beginner observers (2%-10%), indicating adequate repeatability of the measurements for five of the six variables (Perini et al. 2005). All inter-observer R-values are greater than 0.95, with the exception of DAFL (R = 0.935) and MAFL (R = 0.891), i.e. there is less than 5% error for four of the six variables and less than 11% error for all six variables (Table 4.10); R-values greater than 0.95 are acceptable values, indicating accurate repeatability of measurements (Ulijazsek and Kerr 1999).

Table 4.9 Results of the intra-observer evaluation the technical error of measurements (TEM), relative technical error of measurements (rTEM), and the coefficient of reliability (R) for the White, Black, and Coloured South African populations (combined).

Variable[a]	Intra-observer Error		
	TEM[d]	rTEM[e] (%)	R[f]
MAXL	0.189	0.236	0.999
MIDB	0.158	0.385	0.997
DAFL	0.229	0.768	0.992
DAFB	0.177	0.617	0.996
MAFL	0.210	0.787	0.999
MAFB	0.085	0.708	0.995

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
[d] TEM (technical error of measurement)
[e] rTEM (relative technical error of measurement)
[f] R (coefficient of reliability)

Table 4.10 Results of the inter-observer evaluation the technical error of measurements (TEM), relative technical error of measurements (rTEM), and the coefficient of reliability (R) for the White, Black, and Coloured South African populations (combined).

Variable[a]	Inter-observer Error		
	TEM[d]	rTEM[e] (%)	R[f]
MAXL	0.764	0.952	0.982
MIDB	0.437	1.088	0.983
DAFL	0.618	2.115	0.935
DAFB	0.597	2.059	0.959
MAFL	2.198	8.461	0.891
MAFB	0.309	2.627	0.951

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
[d] TEM (technical error of measurement)
[e] rTEM (relative technical error of measurement)

4.3.1 Calcaneal Asymmetry

Asymmetry is present in all bilateral skeletal elements, to some degree (Auerbach and Ruff 2006). Paired *t*-tests were utilized to examine statistically significant differences between paired calcanei (i.e. bilateral asymmetry) for each population group separately, with males and females analyzed separately and with the sexes combined. The p-values

greater than 0.008 indicate no statistically significant differences between the left and right calcanei for the measured variables. The results for the White, Black, and Coloured South Africans are summarized in Tables 4.11, 4.12 and 4.13, respectively.

For White South Africans, there were no statistically significant differences between left and right measurements for most variables when males and females were examined separately and when the sexes were combined. Only the White female MAFB variable showed a statistically significant difference between left and right calcanei (Table 4.11).

Table 4.11 Results of the paired *t*-tests (p-values) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for White South Africans.

Variable[a]	Females	Males	Combined Sexes
MAXL	0.595	0.624	0.474
MIDB	0.035	0.668	0.079
DAFL	0.666	0.025	0.061
DAFB	0.773	0.867	0.757
MAFL	0.403	0.319	0.192
MAFB	0.001*	0.931	0.024

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

For Black females, statistically significant differences between left and right measurements were found for four variables (MIDB, DAFB, MAFL, MAFB). For Black males, there were no statistically significant differences between left and right measurements for all variables. When the sexes were combined, only the DAFB variable showed a statistically significant difference between left and right measurements (Table 4.12).

Table 4.12 Results of the paired *t*-tests (p-values) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for Black South Africans.

Variable[a]	Females	Males	Combined Sexes
MAXL	0.657	0.129	0.698
MIDB	0.004*	0.537	0.990
DAFL	0.216	0.035	0.021
DAFB	0.001*	0.332	0.003*
MAFL	0.002*	0.803	0.042
MAFB	0.000*	0.318	0.262

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

For Coloured females, statistically significant differences were found between left and right measurements for only one variable (DAFL). There were no statistically significant differences between left and right measurements for males nor when the sexes were combined (Table 4.13).

Table 4.13 Results of the paired *t*-tests (p-values) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for Coloured South Africans.

Variable[a]	Females	Males	Combined Sexes
MAXL	0.550	0.285	0.659
MIDB	0.330	0.611	0.301
DAFL	0.007*	0.815	0.058
DAFB	0.578	0.392	0.305
MAFL	0.306	0.423	0.204
MAFB	0.093	0.083	0.016

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

For "Combined South African" females, statistically significant differences were found between left and right measurements for the variables MIDB, MAFL, and MAFB. There were no statistically significant differences between left and right measurements

for males. When the sexes were combined, there were statistically significant differences between left and right measurements for the variables MIDB, DAFL, MAFL, and MAFB (Table 4.14).

Table 4.14 Results of the paired *t*-tests (p-values) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the "Combined South African" group.

Variable[a]	Females	Males	Combined Sexes
MAXL	0.882	0.077	0.146
MIDB	0.001*	0.369	0.004*
DAFL	0.013	0.014	0.000*
DAFB	0.042	0.932	0.166
MAFL	0.003*	0.185	0.003*
MAFB	0.000*	0.089	0.000*

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

4.3.1.1 Individual Differences in Calcaneal Asymmetry

The first goal of this research project was to investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled. To determine the relative amount of asymmetry exhibited in each calcanei pair, the bilateral data were calculated as a Percentage Directional Asymmetry (%DA). The %DA formula compares the measurements of the left and right calcanei of one individual, assessing the percentage difference between the pair with regard to bias (i.e. if the left is larger than the right (left-bias) or vice versa (right-bias)). While the %DA does not change when grouping individuals by population or sex, the data were grouped differently to analyze trends for each of the three South African populations, as well as the "Combined South African" group, with sexes separated and combined.

There were 48 individuals (11%) who exhibited asymmetry in talar articular facet morphology (i.e. the right and left calcanei of the same individual exhibited a different number of facets). This data skews the actual asymmetry in size between pairs in the remainder of the sample (i.e. 371 individuals). Therefore, those who did not exhibit the same number of talar articular facets on both the left and right calcanei were not included for evaluation of the MAFL %DA calculations.

A summary of the calculated Percentage Directional Asymmetry for each population group is presented in Tables 4.15, 4.17, 4.19. The minimum (Min), maximum (Max), and average ($\overline{X}$) values of Percentage Directional Asymmetry are tabulated for females, males, and the combined sexes for each of the White, Black, and Coloured South African populations, and for the "Combined South African" group. The Min %DA is the greatest left-bias in the sample (largest negative number), the Max %DA is the greatest right-bias in the sample (largest positive number), and the $\overline{X}$ %DA is the average bias for the variable in the sample. Table 4.21 summarizes the findings for the "Combined South African" group, separated by sex and when the sexes were combined.

Only individuals with greater than ± 0.5% directional asymmetry were considered for evaluating the propensity of left-bias versus right-bias for each of the six variables. The occurrences of left-bias and right-bias were tallied and chi-square (χ^2) tests were used to evaluate significance when population groups were separated and combined, and with sexes separated and combined. The occurrences (N (%)) of left-bias and right-bias and results of the chi-square (χ^2) tests for significance for the White, Black, Coloured, and "Combined South African" groups are presented in Tables 4.16, 4.18, 4.20, and 4.22.

In the White South African population group, at the individual level, MAFL exhibited the strongest left-bias for females (Min %DA = -28.491%) and strongest right-bias for females (Max %DA = 16.905%), and MAFB exhibited the strongest left-bias for males (Min %DA = -16.552%) and strongest right-bias for males (Max %DA = 11.351%). However, as per the paired *t*-tests (section 4.3.1), only the variable MAFB had statistically significant differences between left and right measurements for the White South African female group, i.e. only MAFB is statistically asymmetrical. On average, the variable with the greatest Percentage Directional Asymmetry was MAFB for females ($\overline{X}$ %DA = 2.581%), MAFB for males ($\overline{X}$ %DA = -0.697%), and MAFL for the combined sexes ($\overline{X}$ %DA = 1.016%). Within the White South African population group, the least left- and right-bias were exhibited by the variables MAXL for the female group, and the variables MIDB and MAXL for the male group, and the variable MAXL for the combined sex group (Table 4.15). Most of the variables did not exhibit a significant difference ($p \geq 0.008$) between occurrences of left-bias and right-bias for the White South African females, males, and combined sex groups, i.e. most variables had no significant difference between the occurrence of left-bias and right-bias. The variable MAFB exhibited a significant difference ($p = 0.001$) between left- and right-bias for the female group; in the female group there were significantly more occurrences of right-bias than left-bias (Table 4.16).

Table 4.15 Calculated Percentage Directional Asymmetry (%DA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for White South Africans.

Females			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-1.546	2.453	0.024
MIDB	-4.764	5.624	0.425
DAFL	-10.983	8.966	-0.020
DAFB	-9.653	6.901	-0.215
MAFL	-28.491	16.905	1.425
MAFB	-7.291	14.957	2.581
Males			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-2.482	3.115	0.077
MIDB	-5.254	5.097	-0.062
DAFL	-8.332	7.827	0.649
DAFB	-7.137	5.757	0.228
MAFL	-7.227	10.778	0.600
MAFB	-16.552	11.351	-0.697
Combined Sexes			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-2.482	3.116	0.051
MIDB	-5.254	5.624	0.184
DAFL	-10.983	8.966	0.312
DAFB	-9.653	6.901	0.004
MAFL	-28.491	16.905	1.016
MAFB	-16.552	14.957	0.955

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.16 Occurrences (N (%)) of left-bias and right-bias for %DA of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for White South Africans and results of the chi-square (χ^2) tests of significance.

Females			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2 (p-value)**
MAXL	14 (47)	16 (53)	0.715
MIDB	17 (37)	29 (63)	0.077
DAFL	25 (52)	23 (48)	0.773
DAFB	27 (57)	20 (43)	0.307
MAFL	23 (42)	32 (58)	0.225
MAFB	14 (26)	39 (74)	0.001*
Males			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	12 (43)	16 (57)	0.450
MIDB	22 (43)	29 (57)	0.327
DAFL	19 (40)	29 (60)	0.149
DAFB	23 (45)	28 (55)	0.484
MAFL	21 (38)	34 (62)	0.080
MAFB	29 (51)	28 (49)	0.586
Combined Sexes			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	26 (45)	32 (55)	0.431
MIDB	39 (40)	58 (60)	0.054
DAFL	44 (46)	52 (54)	0.414
DAFB	50 (51)	48 (49)	0.840
MAFL	44 (40)	66 (60)	0.036
MAFB	43 (39)	67 (61)	0.022

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

In the Black South African population group, at the individual level, MAFB exhibited the strongest left-bias for females (Min %DA = -10.337%), DAFB exhibited the strongest left-bias for males (Min %DA = -9.336%), and MAFL exhibited the strongest right-bias for both females (Max %DA = 18.398%) and males (Max %DA = 13.221%). As per the paired *t*-tests (section 4.3.1), the variables MIDB, DAFB, MAFL, and MAFB had statistically significant differences between left and right measurements for the Black South African female group, and the variable DAFB had statistically significant

differences between left and right measurements for the Black South African combined sex group, i.e. these variables were statistically asymmetrical. On average, the variables with the greatest Percentage Directional Asymmetry were MAFB for females ($\overline{X}$ %DA = -2.390%) and combined sexes ($\overline{X}$ %DA = 1.485%), and MAFB for males ($\overline{X}$ %DA = 0.622%). Within the Black South African population, the least left- and right-bias was exhibited by the variable MAXL for the female group, the variable MIDB for the male group, and the variable MAXL for the combined sex groups (Table 4.17). Most variables exhibited no significant differences ($p \geq 0.008$) between occurrences of left-bias and right-bias in the Black South African females, males, and combined sex groups, i.e. there was no propensity of left-bias over right-bias for most of the variables. The variable MAFB exhibited a significant difference between left- and right-bias for the female group ($p = 0.001$) and combined sex group ($p = 0.006$); in the female group and combined sex group there were significantly more occurrences of right-bias than left-bias. The variable MIDB exhibited a significant difference ($p = 0.006$) between left- and right-bias for the combined sex group; in this population group there were significantly more occurrences of right-bias than left-bias. (Table 4.18).

Table 4.17 Calculated Percentage Directional Asymmetry (%DA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Black South Africans.

Females			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.295	3.322	0.059
MIDB	-4.698	3.872	0.567
DAFL	-6.905	12.634	0.730
DAFB	-9.458	8.407	-1.193
MAFL	-6.795	18.398	0.460
MAFB	-10.337	14.186	2.390
Males			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-1.629	3.498	0.200
MIDB	-4.100	4.314	0.025
DAFL	-4.072	5.754	0.604
DAFB	-9.336	10.733	-0.345
MAFL	-7.002	13.221	0.306
MAFB	-6.241	12.763	0.622
Combined Sexes			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.295	3.498	0.131
MIDB	-4.698	4.314	0.290
DAFL	-6.905	12.634	0.665
DAFB	-9.458	10.733	-0.755
MAFL	-7.002	18.398	0.381
MAFB	-10.337	14.186	1.485

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.18 Occurrences (N (%)) of left-bias and right-bias for %DA of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Black South Africans and results of the chi-square (χ^2) tests of significance.

Females			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2 (p-value)**
MAXL	12 (46)	14 (54)	0.695
MIDB	17 (33)	34 (67)	0.017
DAFL	19 (38)	31 (62)	0.090
DAFB	34 (65)	18 (35)	0.027
MAFL	20 (39)	31 (61)	0.123
MAFB	14 (27)	37 (73)	0.001*
Males			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	16 (43)	21 (57)	0.411
MIDB	22 (45)	27 (55)	0.475
DAFL	20 (39)	31 (61)	0.123
DAFB	28 (52)	26 (48)	0.785
MAFL	27 (56)	21 (44)	0.386
MAFB	24 (45)	29 (55)	0.492
Combined Sexes			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	28 (44)	35 (56)	0.378
MIDB	34 (36)	61 (64)	0.006*
DAFL	39 (39)	62 (61)	0.022
DAFB	62 (58)	44 (42)	0.080
MAFL	47 (46)	55 (54)	0.428
MAFB	38 (37)	66 (63)	0.006*

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

In the Coloured South African population group, at the individual level, MAFB exhibited the strongest left-bias for females (Min %DA = -16.378%) and males (Min %DA = -21.978%), DAFB exhibited the strongest right-bias for females (Max %DA = 12.889%), and MAFB exhibited the strongest right-bias for males (Max %DA = 20.777%). However, as per the paired *t*-tests (section 4.3.1), only the variable DAFL had statistically significant differences between left and right measurements for the Coloured South African female group, i.e. DAFB is statistically asymmetrical. On average, the

variable with the greatest Percentage Directional Asymmetry was MAFB for females ($\overline{X}$ %DA = 1.081%), males ($\overline{X}$ %DA = 1.371%), and combined sexes ($\overline{X}$ %DA = 1.222%). Within the Coloured South African population group, the variable that exhibited the least left- and right-bias were MAXL for the female, male, and combined sex groups (Table 4.19). None of the variables exhibited significant differences ($p \geq 0.008$) between the occurrences of left-bias and right-bias in the Coloured South African female, male, and combined sex groups, i.e. there was no propensity of left-bias over right-bias, nor vice versa, for any of the variables (Table 4.20).

Table 4.19 Calculated Percentage Directional Asymmetry (%DA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Coloured South Africans.

Females			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.282	1.884	-0.106
MIDB	-3.192	4.812	0.422
DAFL	-8.099	9.014	0.866
DAFB	-6.411	12.889	0.235
MAFL	-6.470	9.279	0.266
MAFB	-16.378	12.488	1.081
Males			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.325	4.250	0.206
MIDB	-6.965	4.400	0.363
DAFL	-10.849	6.773	0.308
DAFB	-5.052	12.947	0.662
MAFL	-12.947	10.152	-0.236
MAFB	-21.978	20.777	1.371
Combined Sexes			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.325	4.250	0.046
MIDB	-6.965	4.812	0.393
DAFL	-10.849	9.014	0.594
DAFB	-6.411	17.767	0.443
MAFL	-12.947	10.152	0.021
MAFB	-21.978	20.777	1.222

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.20 Occurrences (N (%)) of left-bias and right-bias for %DA of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Coloured South Africans and results of the chi-square (χ^2) tests of significance.

		Females	
Variable[a]	**Left-bias**	**Right-bias**	**χ^2 (p-value)**
MAXL	25 (56)	20 (44)	0.456
MIDB	20 (43)	26 (57)	0.376
DAFL	18 (34)	35 (66)	0.020
DAFB	29 (50)	29 (50)	1.000
MAFL	23 (44)	29 (56)	0.405
MAFB	23 (40)	35 (60)	0.115
		Males	
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	18 (42)	25 (58)	0.286
MIDB	16 (35)	30 (65)	0.039
DAFL	23 (42)	32 (58)	0.225
DAFB	23 (45)	28 (55)	0.484
MAFL	30 (56)	24 (44)	0.414
MAFB	22 (41)	32 (59)	0.174
		Combined Sexes	
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	43 (48)	46 (52)	0.750
MIDB	36 (39)	56 (61)	0.037
DAFL	41 (38)	67 (62)	0.012
DAFB	52 (48)	57 (52)	0.632
MAFL	53 (45)	64 (55)	0.309
MAFB	45 (40)	67 (60)	0.038

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

In the "Combined South African" group (i.e. all three affinities combined), at the individual level, MAFL exhibited the strongest left-bias (Min %DA = -28.491%) and strongest right-bias (Max %DA = 18.398%) for females, and the variable MAFB exhibited the strongest left-bias (Min %DA = -21.978%) and right-bias (Max %DA = 20.777%) for males. On average, the variable with the greatest Percentage Directional Asymmetry was MAFB for females ($\overline{X}$ %DA = 2.011%) and combined sexes ($\overline{X}$ %DA = 1.219%), and DAFL for males ($\overline{X}$ %DA = 0.523%). The variable MAXL exhibited the

least left- and right-bias for the “Combined South African” female, male, and combined sex groups, while all other variables (i.e. dimensions of articular facets) exhibited the greatest left- and right-biases (Table 4.21). None of the variables exhibited a significant difference ($p \geq 0.08$) between left-bias and right-bias for the “Combined South African” males, i.e. there was no propensity of left-bias over right-bias for any of the six variables. The variable MIDB had significantly more occurrences of right-bias than left-bias in “Combined South African” female ($p = 0.003$) and combined sex groups ($p = 0.000$), the variable DAFL had significantly more occurrences of right-bias than left-bias in the “Combined South African” combined sex group ($p = 0.001$), and the variable MAFB had significantly more occurrences of right-bias than left-bias in the “Combined South African” female ($p = 0.000$) and combined sex groups ($p = 0.000$) (Table 4.22).

Table 4.21 Calculated Percentage Directional Asymmetry (%DA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for the "Combined South African" group.

Combined South African Females			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.295	3.322	0.008
MIDB	-4.764	5.624	0.470
DAFL	-10.983	12.634	0.522
DAFB	-9.653	12.889	-0.374
MAFL	-28.491	18.398	0.721
MAFB	-16.378	14.186	2.011
Combined South African Males			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.325	4.250	0.161
MIDB	-6.965	5.097	0.106
DAFL	-10.849	7.827	0.523
DAFB	-9.336	17.767	0.174
MAFL	-12.947	13.221	0.229
MAFB	-21.978	20.777	0.423
Combined South African Combined Sexes			
Variable[a]	**Min %DA**	**Max %DA**	**$\bar{X}$ %DA**
MAXL	-3.325	4.250	0.076
MIDB	-6.965	5.624	0.288
DAFL	-10.983	12.634	0.523
DAFB	-9.653	17.767	-0.100
MAFL	-28.491	18.398	0.476
MAFB	-21.978	20.777	1.219

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.22 Occurrences (N (%)) of left-bias and right-bias for %DA of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for the "Combined South African" group and results of the chi-square (χ^2) tests of significance.

Females			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2 (p-value)**
MAXL	51 (50)	50 (50)	0.921
MIDB	54 (38)	89 (62)	0.003*
DAFL	62 (41)	89 (59)	0.028
DAFB	90 (57)	67 (43)	0.066
MAFL	66 (42)	92 (58)	0.039
MAFB	51 (31)	111 (69)	0.000*
Males			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	46 (43)	62 (57)	0.124
MIDB	60 (41)	86 (59)	0.031
DAFL	62 (40)	92 (60)	0.016
DAFB	74 (47)	82 (53)	0.522
MAFL	78 (50)	79 (50)	0.936
MAFB	75 (47)	86 (53)	0.386
Combined Sexes			
Variable[a]	**Left-bias**	**Right-bias**	**χ^2**
MAXL	97 (46)	112 (54)	0.299
MIDB	114 (39)	175 (61)	0.000*
DAFL	124 (41)	181 (59)	0.001*
DAFB	164 (52)	149 (48)	0.397
MAFL	144 (46)	171 (54)	0.128
MAFB	126 (39)	197 (61)	0.000*

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

To assess the total amount of asymmetry present in each calcaneal dimension for each individual, the calculation for Percentage Absolute Asymmetry (%AA) disregards directional (left or right) bias. The %AA formula compares the measurements of the left and right calcanei of one individual to assess the percentage difference between the pair. Unlike the Percentage Directional Asymmetry, the Percentage Absolute Asymmetry disregards the direction of the bias (i.e. if there is a left-bias or right-bias).

There were 48 individuals (11%) who exhibited asymmetry in talar articular facet morphology (i.e. the right and left calcanei of the same individual exhibited a different number of facets). This data skews the actual asymmetry in size between pairs in the remainder of the sample (371 individuals). Therefore, those who did not exhibit the same number of talar articular facets on both calcanei were not included for evaluation of the MAFL %DA calculations.

The minimum (Min %AA), maximum (Max %AA), and average ($\overline{X}$ %AA) for each variable are summarized in Tables 4.23 to 4.26. The Min %AA is the minimum absolute asymmetry in the sample, the Max %AA is the maximum absolute asymmetry, and the $\overline{X}$ %AA is the average absolute asymmetry for the variable in the sample.

In the White South African population, the variable that exhibited the strongest Percentage Absolute Asymmetry was MAFL for females (Max %AA = 28.491%) and MAFB for males (Max %AA = 16.552%). On average, MAFB exhibited the greatest Percentage Absolute Asymmetry for females ($\overline{X}$ %AA = 4.232%) and males ($\overline{X}$ %AA = 4.484%), and MAFL for the combined sexes ($\overline{X}$ %AA = 3.544%) (Table 4.23).

Table 4.23 Calculated Percentage Absolute Asymmetry (%AA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for White South Africans.

Females			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.026	2.453	0.646
MIDB	0.000	5.622	1.514
DAFL	0.000	10.983	2.320
DAFB	0.000	9.653	1.697
MAFL	0.096	28.491	4.108
MAFB	0.082	14.957	4.232
Males			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	3.116	0.678
MIDB	0.000	5.254	1.545
DAFL	0.000	8.332	2.015
DAFB	0.090	7.137	2.015
MAFL	0.029	10.778	2.972
MAFB	0.075	16.552	4.484
Combined Sexes			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	3.116	0.662
MIDB	0.000	5.624	1.530
DAFL	0.000	10.983	2.166
DAFB	0.000	9.653	1.929
MAFL	0.029	28.491	3.544
MAFB	0.000	16.552	3.100

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

In the Black South African population, the variable that exhibited the greatest Percentage Absolute Asymmetry was MAFL for females (Max %AA = 18.398%) and MAFB for males (Max %AA = 13.570%). On average, MAFB exhibited the strongest Percentage Absolute Asymmetry for females ($\bar{X}$ %AA = 3.956%), males ($\bar{X}$ %AA = 3.675%), and the combined sexes ($\bar{X}$ %AA = 3.815%) (Table 4.24).

Table 4.24 Calculated Percentage Absolute Asymmetry (%AA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Black South Africans.

Females			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.037	3.322	0.733
MIDB	0.087	4.698	1.390
DAFL	0.032	12.635	2.421
DAFB	0.037	14.306	2.917
MAFL	0.033	18.398	2.391
MAFB	0.161	18.168	3.956
Males			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.012	3.498	0.729
MIDB	0.050	4.314	1.421
DAFL	0.032	5.754	1.956
DAFB	0.031	10.733	2.449
MAFL	0.000	13.221	2.437
MAFB	0.146	13.570	3.675
Combined Sexes			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.012	3.498	0.731
MIDB	0.050	4.698	1.405
DAFL	0.032	12.635	2.189
DAFB	0.031	14.306	2.680
MAFL	0.000	18.398	2.415
MAFB	0.146	18.168	3.815

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

In the Coloured South African population, the variable that exhibited the greatest Percentage Absolute Asymmetry was MAFB for females (Max %AA = 21.879%) and males (Max %AA = 16.378%). On average, MAFB exhibited the greatest Percentage Absolute Asymmetry for females ($\bar{X}$ %AA = 4.824%), males ($\bar{X}$ %AA = 4.694%), and the combined sexes ($\bar{X}$ %AA = 4.759%) (Table 4.25).

Table 4.25 Calculated Percentage Absolute Asymmetry (%AA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for Coloured South Africans.

Females			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	4.250	0.983
MIDB	0.000	6.965	1.446
DAFL	0.034	10.849	2.676
DAFB	0.073	17.767	2.790
MAFL	0.032	9.279	2.021
MAFB	0.084	21.879	4.824
Males			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.027	3.282	0.915
MIDB	0.000	5.234	1.482
DAFL	0.035	9.014	2.428
DAFB	0.033	12.889	2.426
MAFL	0.208	12.947	2.833
MAFB	0.090	16.378	4.694
Combined Sexes			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	4.250	0.949
MIDB	0.000	6.965	1.464
DAFL	0.034	10.849	2.552
DAFB	0.033	17.767	2.608
MAFL	0.032	12.947	2.417
MAFB	0.081	21.978	4.759

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

In the "Combined South African" group (i.e. all three affinities combined), the variable that exhibited the greatest Percentage Absolute Asymmetry was MAFL for females (Max %AA = 28.491%) and MAFB for males (Max %AA = 21.978%). On average, MAFB exhibited the greatest Percentage Absolute Asymmetry for females ($\bar{X}$ %AA = 3.449%), males ($\bar{X}$ %AA = 4.325%), and the combined sexes ($\bar{X}$ %AA = 3.889%) (Table 4.26).

Table 4.26 Calculated Percentage Absolute Asymmetry (%AA) evaluating asymmetry for the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the females, males, and combined sexes for the "Combined South African" group.

Females			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.026	3.322	0.765
MIDB	0.000	5.624	1.462
DAFL	0.000	12.635	2.390
DAFB	0.000	14.306	2.344
MAFL	0.032	28.491	2.847
MAFB	0.000	18.168	3.449
Males			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	4.250	0.797
MIDB	0.000	6.965	1.471
DAFL	0.000	10.849	2.216
DAFB	0.031	17.767	2.464
MAFL	0.000	13.221	2.745
MAFB	0.075	21.978	4.325
Combined Sexes			
Variable[a]	**Min %AA**	**Max %AA**	**$\bar{X}$ %AA**
MAXL	0.000	4.250	0.781
MIDB	0.000	6.965	1.466
DAFL	0.000	12.635	2.303
DAFB	0.000	17.767	2.405
MAFL	0.000	28.491	2.796
MAFB	0.000	21.978	3.889

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

4.3.1.2 Sex Differences in Calcaneal Asymmetry

The second goal of this research project was to investigate sex differences in bilateral asymmetry of calcaneal pairs (White, Black, and Coloured South African populations pooled). The Kruskal–Wallis was used to test for differences in %DA between male and female groups and it determined that there were no significant differences ($p > 0.008$) between values of %DA for all variables except for MAFB ($p = 0.003$). The Kruskal–Wallis analysis was used to test for differences in %AA between

male and female groups. It determined that there were no significant differences ($p > 0.008$) between values of %AA for all variables (Table 4.27).

Table 4.27 Results of the Kruskal–Wallis tests (p-values) evaluating sex differences for the %DA and %AA values of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the "Combined South African" group.

Variable[a]	%DA (p-value)	%AA (p-value)
MAXL	0.176	0.792
MIDB	0.196	0.997
DAFL	0.819	0.867
DAFB	0.100	0.363
MAFL	0.148	0.771
MAFB	0.003*	0.610

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

4.3.1.3 Population Differences in Calcaneal Asymmetry

The third goal of this research project was to investigate White, Black, and Coloured South African population differences in bilateral asymmetry of calcaneal pairs (sexes separated). However, as no sex differences were found (see 4.3.1.2), sexes were pooled for the Kruskal-Wallis test. The Kruskal–Wallis was used to test for differences in %DA between population groups and it determined that there were no significant differences ($p > 0.008$) between values of %DA for all variables (Table 4.28). The Kruskal–Wallis analysis was used to test for differences in %AA between population groups. It determined that there were no significant differences ($p > 0.008$) between values of %AA for variables MIDB, DAFL, and MAFB, while there were significant differences between the values of %AA between population groups for variables MAXL, DAFB, and MAFL (Table 4.28).

Table 4.28 Results of the Kruskal–Wallis tests (p-values) evaluating population differences for the %DA and %AA values of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB between White, Black, and Coloured South Africans.

Variable[a]	%DA (p-value)	%AA (p-value)
MAXL	0.732	0.000*
MIDB	0.820	0.763
DAFL	0.518	0.393
DAFB	0.033	0.002*
MAFL	0.104	0.007*
MAFB	0.885	0.170

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

4.3.2 Calculating the M statistic

The fourth goal of this research project was to use the statistic *M* to assess applicability for pair-matching left and right calcanei and to address variances of *M* between sexes and/or ancestral groups. The statistic *M* expresses the difference between the right and left calcanei measurement as a proportion of the average value of the two measurements.

The statistic *M* was calculated for each pair of measurements for each individual within all three populations (i.e. White, Black, and Coloured South Africans). Two sample *t*-tests were employed on the White, Black, and Coloured South African populations, separately, to evaluate sex differences for the *M* values for each variable (see Table 4.29). Within each South African population, there were no statistically significant differences between the *M* values of females and males. Therefore, sexes can be pooled for each population group to calculate the 90^{th} and 95^{th} percentiles of *M* and the maximum *M* to be utilized for pair-matching.

Table 4.29 Results of the two sample *t*-tests (p-values) evaluating sex differences for the *M* values of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the White, Black, and Coloured South Africans.

Variable[a]	White South Africans	Black South Africans	Coloured South Africans
MAXL	0.767	0.968	0.592
MIDB	0.890	0.860	0.868
DAFL	0.390	0.160	0.508
DAFB	0.135	0.265	0.363
MAFL	0.549	0.211	0.520
MAFB	0.695	0.639	0.859

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

Following the standard protocol of Thomas and colleagues (2013), the Excel statistical program was utilized to calculate the 90th and 95th percentiles of *M*. Tables 4.30 to 4.32 summarize the data (i.e. the 90th percentile of *M*, 95th percentile of *M*, and maximum *M*) for the White, Black, and Coloured South African populations, respectively, separated by sex and when the sexes were combined.

Table 4.30 The calculated 90th and 95th percentiles of the statistic *M* and maximum *M* for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of females, males, and combined sexes for White South Africans.

Females			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0143	0.0153	0.0245
MIDB	0.0335	0.0451	0.0562
DAFL	0.0516	0.0642	0.1098
DAFB	0.0347	0.0486	0.0965
MAFL	0.1632	0.1130	0.5984
MAFB	0.0868	0.4542	0.1496
Males			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0180	0.0222	0.0312
MIDB	0.0346	0.0404	0.0525
DAFL	0.0444	0.0620	0.0833
DAFB	0.0475	0.0591	0.0714
MAFL	0.1307	0.5124	1.4416
MAFB	0.1017	0.1109	0.1655
Combined Sexes			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0145	0.0190	0.0312
MIDB	0.0338	0.0417	0.0562
DAFL	0.0495	0.0663	0.1098
DAFB	0.0437	0.0551	0.0965
MAFL	0.1632	0.4681	1.4416
MAFB	0.0744	0.1017	0.1655

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.31 The calculated 90th and 95th percentiles of the statistic *M* and maximum *M* for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of females, males, and combined sexes for Black South Africans.

Females			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0159	0.0202	0.0332
MIDB	0.0261	0.0312	0.0470
DAFL	0.0534	0.0675	0.1263
DAFB	0.0576	0.0879	0.1431
MAFL	0.4344	0.5076	0.6788
MAFB	0.1023	0.1170	0.1817
Males			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0147	0.0171	0.0350
MIDB	0.0304	0.0365	0.0431
DAFL	0.0392	0.0508	0.0575
DAFB	0.0537	0.0640	0.1073
MAFL	0.1376	0.3398	0.5136
MAFB	0.0814	0.0929	0.1357
Combined Sexes			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0152	0.0186	0.0350
MIDB	0.0297	0.0344	0.0470
DAFL	0.0499	0.0577	0.1263
DAFB	0.0570	0.0774	0.1431
MAFL	0.3005	0.4497	0.6788
MAFB	0.0818	0.1042	0.1817

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.32 The calculated 90th and 95th percentiles of the statistic *M* and maximum *M* for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of females, males, and combined sexes for Coloured South Africans.

Females			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0198	0.0283	0.0425
MIDB	0.0331	0.0370	0.0696
DAFL	0.0547	0.0673	0.1085
DAFB	0.0509	0.0578	0.1777
MAFL	0.1575	0.4910	0.8054
MAFB	0.0999	0.1403	0.2198
Males			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0179	0.0188	0.0328
MIDB	0.0320	0.0374	0.0523
DAFL	0.0504	0.0677	0.0901
DAFB	0.0419	0.0641	0.1289
MAFL	0.1154	0.4709	0.5793
MAFB	0.0948	0.1192	0.1638
Combined Sexes			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0182	0.0248	0.0425
MIDB	0.0323	0.0378	0.0696
DAFL	0.0507	0.0683	0.1085
DAFB	0.0501	0.0640	0.1777
MAFL	0.1484	0.4883	0.8054
MAFB	0.1002	0.1220	0.2198

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Two sample *t*-tests were completed to evaluate population differences (sexes combined) between the *M* values of White, Black, and Coloured South Africans. The results of the two sample *t*-tests are summarized in Table 4.33. Only the DAFB showed statistically significant differences between the White and Black South Africans. The MAXL and MAFB exhibited statistically significant differences between the White and Coloured South Africans. There was no statistically significant differences between Black and Coloured South Africans for all six variables. Therefore, *M* values for variables MIDB, DAFL, and MAFL from White, Black, and Coloured South African populations

can be pooled (as they showed no statistically significant differences between all three populations) to calculate the 90th and 95th percentiles of *M* and the maximum *M* to be utilized for pair-matching. Table 4.34 summarizes the data (i.e. the 90th percentile of *M*, the 95th percentile of *M*, and maximum *M*) for the "Combined South African" group, separated by sex and when the sexes were combined.

Table 4.33 Results of the two sample *t*-tests (p-values) evaluating population differences for the *M* values of the variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB for the White, Black, and Coloured South Africans (sexes pooled).

Variable[a]	White vs Black South Africans	White vs Coloured South Africans	Black vs Coloured South Africans
MAXL	0.386	0.001*	0.012
MIDB	0.389	0.678	0.678
DAFL	0.927	0.134	0.145
DAFB	0.004*	0.008	0.804
MAFL	0.592	0.603	0.997
MAFB	0.082	0.000*	0.045

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth
*Statistically significant ($p < 0.008$)

Table 4.34 The calculated 90th and 95th percentiles of the statistic *M* and maximum *M* for variables MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB of females, males, and combined sexes for the "Combined South African" group.

Females			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0170	0.0185	0.0332
MIDB	0.0321	0.0389	0.0562
DAFL	0.0513	0.0681	0.1263
DAFB	0.0517	0.0641	0.1431
MAFL	0.2916	0.4867	0.6788
MAFB	0.0833	0.1095	0.1817
Males			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0178	0.0247	0.0425
MIDB	0.0331	0.0387	0.0696
DAFL	0.0493	0.0575	0.1085
DAFB	0.0504	0.0607	0.1777
MAFL	0.1376	0.4633	1.4416
MAFB	0.0947	0.1081	0.2198
Combined Sexes			
Variable[a]	**90th Percentile**	**95th Percentile**	**Maximum *M***
MAXL	0.0172	0.0207	0.0425
MIDB	0.0324	0.0390	0.0696
DAFL	0.0505	0.0662	0.1263
DAFB	0.0512	0.0640	0.1777
MAFL	0.2058	0.4790	1.4416
MAFB	0.0887	0.1092	0.2198

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

4.3.2.1 Automating comparisons between left and right calcanei

Assessment of potential pair-matches using the statistic *M* was completed by comparing each of the six measurements from one left calcaneus to all right calcanei within their respective South African population, with sexes combined, and within the "Combined South African" group, with sexes combined. As per Thomas and colleagues' (2013) protocol, when making pairwise comparisons, the 90th and 95th percentiles of *M* and maximum values of *M* should exclude no more than 10%, 5%, and 0% of the sample, respectively (Vickers et al. 2015). For the White, Black, Coloured, and "Combined South

African" groups, the pairwise comparisons that resulted in possible matches for each variable are summarized in Tables 4.35 to 4.38, respectively.

When examining the White South African population and utilizing the variable MAXL for pairwise comparisons, there was an 86% reduction in possible pairs by using the 90th percentile of *M* as the cut-off. These calculations resulted in the false rejection of correct pairs for 11% of the individuals in the sample (i.e. 15/139). Using the 95th percentile of *M* as the cut-off for rejection/inclusion decreased the false rejection rates (1% to 6%). However, using the 95th percentile of *M* increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 31% and 83%. Using the maximum *M* as the cut-off for rejection/inclusion decreased the false rejection rate even further (1% to 2%). However, using the maximum value of *M* further increased the number possible pairs to be considered, i.e. decreased the reduction rate to between 1% and 73%. The variable MAXL performed best for each test, i.e. had the greatest reduction in the number of possible pairs while also having acceptable false rejection rates (approximately 10%, 5%, and 0% for the 90th and 95th percentiles of *M* and maximum value of *M*, respectively)(Table 4.35).

Within the Black South African population, when utilizing the variable MAXL for pairwise comparisons, there was an 88% reduction in possible pairs by using the 90th percentile of *M* as the cut-off. These calculations resulted in the false rejection of correct pairs for 10% of the individuals in the sample (i.e. 14/140). Using the 95th percentile of *M* as the cut-off for rejection/inclusion decreased the false rejection rates (5% to 6%). However, using the 95th percentile of *M* increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 22% and 86%. Using the maximum *M* as the cut-off for rejection/inclusion decreased the false rejection rate even

further (0% to 1%). However, using the maximum value of *M* further increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 4% and 74%. The variable MAXL performed best for each test, i.e. had the greatest reduction in the number of possible pairs while also having acceptable false rejection rates (approximately 10%, 5%, and 0% for the 90th and 95th percentiles of *M* and maximum value of *M*, respectively)(Table 4.36).

Within the Coloured South African population, when utilizing the variable MAXL for pairwise comparisons, there was an 84% reduction in possible pairs when using the 90th percentile of *M* as the cut-off. These calculations resulted in the false rejection of correct pairs for 11% of the individuals in the sample (i.e. 15/140). Using the 95th percentile of *M* as the cut-off for rejection/inclusion decreased the false rejection rates (5% to 6%). However, using the 95th percentile of *M* increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 16% and 80%. Using the maximum *M* as the cut-off for rejection/inclusion decreased the false rejection rate even further (0% to 1%). However, using the maximum value of *M* further increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 0% and 65%. The variable MAXL performed best for each test, i.e. had the greatest reduction in the number of possible pairs while also having acceptable false rejection rates (approximately 10%, 5%, and 0% for the 90th and 95th percentiles of *M* and maximum value of *M*, respectively) (Table 4.37).

Table 4.35 Summary of pairwise comparison results within the White South African sample using the 90th and 95th percentiles and maximum values of *M*.

Variable[a]	90th Percentile				95th Percentile				Max M			
	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)
MAXL	19	86	89	11	24	83	94	6	38	73	99	1
MIDB	34	76	88	12	55	60	94	6	55	60	98	2
DAFL	42	70	88	12	42	70	94	6	90	35	98	2
DAFB	32	77	89	11	41	71	94	6	69	50	99	1
MAFL	44	68	89	11	94	32	94	6	138	1	99	1
MAFB	63	55	91	9	96	31	99	1	96	31	99	1

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.36 Summary of pairwise comparison results within the Black South African sample using the 90th and 95th percentiles and maximum values of *M*.

Variable[a]	90th Percentile				95th Percentile				Max M			
	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)
MAXL	17	88	90	10	20	86	95	5	37	74	100	0
MIDB	28	80	89	11	32	77	95	5	43	69	100	0
DAFL	38	73	90	10	44	69	95	5	91	35	99	1
DAFB	42	70	89	11	55	61	94	6	87	38	99	1
MAFL	87	38	89	11	109	22	94	6	135	4	99	1
MAFB	51	64	89	11	63	55	94	6	100	29	99	1

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

Table 4.37 Summary of pairwise comparison results within the Coloured South African sample using the 90th and 95th percentiles and maximum values of *M*.

Variable[a]	90th Percentile				95th Percentile				Max M			
	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)
MAXL	22	84	89	11	28	80	94	6	49	65	99	1
MIDB	33	76	89	11	38	73	94	6	68	51	99	1
DAFL	47	66	90	10	61	56	95	5	91	35	100	0
DAFB	47	66	90	10	49	65	94	6	108	23	99	1
MAFL	70	49	90	10	117	16	95	5	140	0	99	1
MAFB	64	54	89	11	76	46	94	6	115	18	99	1

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

For the "Combined South African" group, when utilizing the variable MAXL for pairwise comparisons, there was an 87% reduction in possible pairs using the 90th percentile of *M* as the cut-off. These calculations resulted in the false rejection of correct pairs for 11% of the individuals in the sample (i.e. 45/419). Using the 95th percentile of *M* as the cut-off for rejection/inclusion decreased the false rejection rates (5% to 6%). However, using the 95th percentile of *M* increased the number of potential pairs to be considered, i.e. decreased the reduction rate to between 25% and 85%. Using the maximum *M* as the cut-off for rejection/inclusion decreased the false rejection rate even further (0% to 1%). However, using the maximum value of *M* further increased the number of possible pairs to be considered, i.e. decreased the reduction rate to between 0% and 69%. The variable MAXL performed best for each test, i.e. had the greatest reduction in the number of possible pairs while also having an acceptable false rejection rate (approximately 10%, 5%, and 0% for the 90th and 95th percentiles of *M* and maximum value of *M*, respectively) (Table 4.38).

Table 4.38 Summary of pairwise comparison results for the "Combined South African" group using the 90th and 95th percentiles and maximum values of *M*.

Variable[a]	90th Percentile				95th Percentile				Max M			
	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)	Possible Pairs ($\bar{x}$)	Reduction in Possible Pairs (%)	Correctly Paired (%)	Falsely Rejected (%)
MAXL	53	87	89	11	64	85	94	6	128	69	99	1
MIDB	96	77	89	11	114	73	94	6	196	53	99	1
DAFL	120	71	90	10	155	63	95	5	270	36	100	0
DAFB	103	75	89	11	128	69	94	6	303	28	99	1
MAFL	193	54	90	10	314	25	95	5	418	0	100	0
MAFB	169	60	88	12	203	52	94	6	341	19	100	0

[a] MAXL, maximum length; MIDB, middle breadth; DAFL, dorsal articular facet length; DAFB, dorsal articular facet breadth; MAFL, middle articular facet length; MAFB, middle articular facet breadth

CHAPTER V: DISCUSSION

5.1 Context of the Current Study

The goal of a forensic anthropologist is to assist with the identification of unknown individuals through analyzing skeletal remains. Identification is most accurate when the skeleton is complete or nearly complete (Byrd and Adams 2003), which is not always the case, for example in mass graves, or the aftermath of mass disasters, skeletal remains can be found incomplete and/or commingled. In cases of commingling, sorting techniques can be employed to attempt to individualize remains by the reassociation of the skeletal elements. Two common morphological methods used for sorting human skeletal remains are visual pair-matching (evaluating similarities in morphology) and osteometric pair-matching (a quantitative technique) in which left and right skeletal elements are compared to reassociate paired elements. Visual pair-matching relies heavily on the experience of the observer and, thus, is more subjective than osteometric pair-matching, which employs objective measurements and the statistical analysis of data. The Scientific Working Group for Forensic Anthropology (SWGANTH) discussed the need for development and validation of osteometric methods of reassociation of skeletal elements, which are objective and can be evaluated for accuracy and repeatability (SWGANTH 2013a).

Thomas, Ubelaker and Byrd (2013) proposed reference tables for osteometric pair-matching of "major paired bones" (i.e. humeri, radii, ulnae, femora, tibiae, fibulae, clavicles, scapulae, os coxae, and calcanei) of the human skeleton that can be utilized in commingling cases. This study includes mostly individuals of American White descent, and includes smaller samples of American Black, Asian, Hispanic/Mexican, and 'other'

ancestry (the authors did not explain the meaning of 'other' ancestry). This study utilizes a statistic, *M*, which captures the amount of size variation found between homologous bones from single individuals; it establishes the 'normal' variation between bilateral measurements, i.e. asymmetry of skeletal elements, expressed as the statistic *M*. The statistic *M* is presented in tables that can be used for comparison of left and right measurements of skeletal elements to evaluate for possible pairs. When comparisons between left and right measurements exceed the value of *M*, they are eliminated as a possible pair. Bone dimensions that exhibit the least asymmetry between bilateral elements are best utilized for osteometric pair-matching because this narrows the possibility of other matches (Garroway 2013).

The calcaneus was studied in this respect by Thomas et al. (2013). The study included two measurements of the calcaneus, maximum length and middle breadth, and evaluated males and females separately, and combined sexes. They found no sex differences between values of *M* for maximum length or middle breadth of the calcaneus, however, population comparisons were not made as the sample consisted of pooled ancestral data (i.e. individuals of White, Black, Asian, Hispanic/Mexican, and 'other' ancestries were pooled). As their data showed small and unequal representation of ancestral samples, separating the data into smaller ancestral groups would reduce statistical power during the analyses. This research limitation influenced the current author to explore population-specific methodologies for pair-matching the calcaneus as a thesis topic.

South Africa has a history of high rates of violent crime, political violence and human rights abuses by the government under apartheid, as well as rapid, uncontrolled urbanisation and illegal immigration (Nienaber 2015). In 1995, very high rates of political

violence and other violent acts lead to 2,008 unidentified bodies buried in Gauteng province alone (Steyn et al. 1997). Statistics regarding the exact number of unidentified bodies that remain in medico-legal facilities in South Africa is unknown (Evert 2011). However, from January to August 2010, it was reported that there were 846 bodies that remained unidentified and unclaimed at mortuaries in Gauteng province (Evert 2011). After the abolishment of apartheid, South Africa continues to have high rates of violent crime. The country has one of the fastest growing rates of homicide in Africa, a rate of 341 per 1 million people (Statistics South Africa 2017), and a prevalent issue of missing women and children (Isaacs 2017). A new interest in Forensic Anthropology was sparked in South Africa in the mid 1990s to handle the high rates of violence and increasing number of unidentified bodies (Steyn et al. 1997).

Proper recovery of human remains using forensic archaeological methods is imperative for ease and accuracy when attempting to individuate and identify victims. Forensic Anthropology and Archaeology methods are accepted and practiced in many countries, however, that is not often the case in South Africa (Steyn et al. 1997). While South African academic institutions are active in physical anthropological research and are equipped with the understanding of archaeological excavations, they are rarely utilized by law enforcement for such cases; there is no set standard for recovery or application of archaeological methods for use in forensic cases (Nienaber 2015). Therefore, when contacted for forensic anthropological analyses, the forensic recovery has already been completed.

There are many examples of forensic cases in which human remains are commingled. Steyn et al. (1997) reported commingling in several cases due to the improper recovery of human remains. In one case, skeletal remains that were suspected to

be one individual, by police, were actually the skeletal remains of two adult individuals. In another case, skeletal remains of an adult male were commingled with those of a 7 to 8 month old fetus. L'Abbé (2005) describes a grain bag that was recovered by police in a forest containing a number of skeletonized individuals. The author determined a minimum number of individuals (MNI) of 10, although it was estimated that as much as 80% of skeletal elements were missing. A combination of visual pair-matching, taphonomy, articulation, and the process of elimination techniques were applied, but most of the elements could not be individuated. Osteometric pair-matching research on South African populations may therefore assist in reassociation, and thus contribute with identification of unknown human remains, when cases of commingling occur.

The calcaneus was chosen for this project because it has been understudied in osteometric sorting. The calcaneus is resistant to taphonomic changes, and they are usually found intact as they are often protected within shoes and/or socks in forensic cases (Bidmos and Asala 2003; Pickering 1986; Peckmann et al. 2015; Anastopoulou et al. 2018). Most of the literature about osteometric pair-matching concentrates on larger skeletal elements, such as long bones, for reassociation and identification in commingling cases (Adams and Byrd 2006, 2008; Byrd 2008; Byrd and Adams 2003; Chew 2014; Garroway 2013; LeGarde 2012; Rodriguez et al. 2015; Thomas, Ubelaker, and Byrd 2013). In a commingling context, the goal is the reassociation and identification of human remains, even if all victims have been accounted for (Byrd and Adams 2016; Kontanis and Sledzik 2014). The lack of calcanei research, in osteometric pair-matching, may impair personal identification of the deceased and prevent the return of the totality of the remains to the next of kin (Adams and Byrd 2008). Futhermore, previous research has shown that the calcaneus can be used to provide accurate sex and stature estimations

when there is an absence of other most often used skeletal elements (Anastopoulou et al. 2018). The calcaneus can be used to assist with creating the biological profile of the unknown South African individuals; methods for estimation of sex from the calcaneus in White South Africans (Bidmos and Asala 2003) and Black South Africans (Bidmos and Asala 2004), estimation of stature from the calcaneus in White South Africans (Bidmos 2006a) and Black South Africans (Bidmos and Asala 2005), and estimation of ancestry from the calcaneus of White and Black South Africans (Bidmos 2006b) have been published.

The maximum length (MAXL), middle breadth (MIDB), dorsal articular facet length (DAFL), and dorsal articular facet breadth (DAFB) measurements of the calcaneus were chosen by the current author because they have been used in previous research for estimating sex, stature, and ancestry of White and Black South Africans (Bidmos 2006a, 2006b; Bidmos and Asala 2003, 2004, 2005). Since these measurements have previously been used for creating the biological profile in South African populations, the author chose to investigate whether these variables could also be employed for osteometric pair-matching of commingled calcanei in South African populations.

Previous research has found that articular surfaces of other skeletal elements exhibit little asymmetry (Churchill and Formicola 1997; Garroway 2013; Ruff and Jones 1981; Sakaue 1998; Trinkaus, Churchill and Ruff 1994). Therefore, articular surfaces of calcanei may provide accurate measurements for osteometric pair-matching. The author included the DAFL and DAFB because they have been used in previous research for estimating sex, stature, and ancestry of White and Black South Africans (Bidmos 2006b; Bidmos and Asala 2003, 2004, 2005) and may be useful for osteometric pair-matching. The author also chose to include newly developed metric measurements, middle articular

facet length (MAFL) and middle articular facet breadth (MAFB), because the morphology of this facet has been examined for estimation of ancestry in South African populations (Bidmos 2006 b; Orr and Meek 2016) and may be useful for osteometric pair-matching.

The current study focuses on six measurements of the calcaneus (MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB) to establish an accurate method for osteometric pair-matching of calcanei in three populations, White, Black, and Coloured South Africans. The objectives of this research are to 1) investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when populations and sexes are pooled, 2) investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled, 3) investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured populations separated, and 4) use the statistic *M* to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations. The results from these investigations could highlight how ancestry influences asymmetry. If this research finds that ancestry influences asymmetry, and thus osteometric pair-matching, future studies should also evaluate for differences before pooling their data.

5.1.1 Analysis of Normality

It is important to test data for normal distribution before further statistical analyses can be completed. Data that have normal distribution may then be analysed using parametric tests. All measurements exhibited statistical normality except for the MAFL

dimension. This is attributed to the variation in the morphology of the middle articular facet dimension. Orr and Meek (2016) found that the number of articular facets of the calcaneus vary; individuals can have three facets, two facets, or one facet that articulates with the talus. Furthermore, some individuals have, for example, three facets on one calcaneus while its pair has two facets. In cases where the individual has three facets, the middle articular facet is separated into anterior and posterior portions, which means that the middle articular facet would be shorter in length in comparison to a middle articular facet that was not separated into two portions. The variation in length of the middle articular facet, therefore, does not comply with statistically normal distribution. As this variable has not been investigated in previous research, it is unclear why some middle articular facets are divided into anterior and posterior portions.

5.1.2 Analysis of Observer Error

Reliability and repeatability of forensic anthropology methods is extremely important. Descriptions of morphological features and definitions of metric measurements must be well defined so that researchers are able to reproduce anthropological assessments. Morphological assessment of skeletal remains relies heavily on the experience of the observer, whereas metric assessment provides objective analyses (Introna et al. 1997; Peckmann et al. 2015; Spradley and Jantz 2011). Therefore, the forensic community has been producing more objective and quantifiable techniques to assist in the identification of unknown human remains (Christensen and Crowder 2009; Lesciotto 2015). The current study utilized osteometrics, an objective method, for pair-matching calcanei which provides data on the accuracy and repeatability.

In the current study, the paired-*t* tests found there were no significant intra-observer differences for any of the six variables and no inter-observer differences for the variables MAXL, MIDB, and MAFL, while there were significant inter-observer differences for the variables DAFL, DAFB, and MAFB (see Table 4.7). Calculation of the average differences of measurements and evaluating the Technical Error of Measurements (TEM) (see table 4.10) determined that mean intra-observer TEM and rTEM were small, and the %TEM values were within the acceptable range for skilled intra-observer error (1%-5%), indicating adequate repeatability of the measurements (Perini et al. 2005). The mean inter-observer TEM and rTEM were also small for each variable, except for MAFL; the %TEM for the variable MAFL was the only variable that did not fall within the acceptable range for skilled inter-observer error (1.5%-7.5%) (Perini et al. 2005). All intra- and inter-observer R-values are greater than 0.90, i.e. there is less than 10% intra- and inter-observer error, except for the inter-observer R-value of MAFL (11% error), indicating accurate repeatability of all measurements except MAFL.

The increased inter-observer error of the MAFL variable could be due to ambiguity in the definition of the variable MAFL or because the measurement points may have been unclear. For example, some individuals have a bipartite middle articular facet or a facet that is almost completely separated into posterior and anterior portions. It is, therefore, possible that the two observers used different measurement points for this variable. Therefore, caution should be taken when using the MAFL variable in the future for osteometric pair-matching.

5.2 Test of Statistically Significant Asymmetry in Calcaneal Dimensions

In the current study, paired *t*-tests were conducted to test for statistically significant bilateral asymmetry of six calcaneal dimensions (MAXL, MIDB, DAFL, DAFB, MAFL, and MAFB) for the White, Black, and Coloured South African populations. The MAFL and MAFB variables from the current study were found to be statistically symmetrical for White, Black, and Coloured South Africans; these variables have not been examined in the published literature and, therefore, comparisons to other research is not possible. For White South Africans, there were no statistically significant differences between left and right measurements for all variables, i.e. all variables were statistically symmetrical (Table 4.11). Previous research of White South African calcanei found that MAXL, MIDB, DAFL, and DAFB were statistically symmetrical (Bidmos and Asala 2003), which is consistent with the findings of the current study.

For Black South Africans, only the DAFB variable showed a statistically significant difference between left and right measurements (Table 4.12). Previous research of Black South African calcanei found that MAXL, MIDB, DAFL, and DAFB were statistically symmetrical (Bidmos and Asala 2004). In the current study, statistical symmetry in the MAXL, MIDB, and DAFL is consistent with previous research, however, the findings of DAFB are inconsistent with Bidmos and Asala (2004) as it was not statistically symmetrical. This inconsistency may be due to the sample sizes utilized for evaluating bilateral asymmetry. Bidmos and Asala (2004) collected data from 116 Black South Africans, however, the authors did not specify the number of individuals that were selected when testing for bilateral asymmetry (most research tests only a small subsample for bilateral asymmetry). In the current study, data was collected from 140 Black South Africans and all individuals were tested for bilateral asymmetry.

For Coloured South Africans, there were no statistically significant differences between left and right measurements for all variables (Table 4.13), i.e. all variables were statistically symmetrical. Currently, there is no published research that investigates bilateral asymmetry of Coloured South African calcanei and, therefore, comparisons to other studies are not possible.

Though calcaneal measurements may be statistically symmetrical, there is still some degree (i.e. percentage) of asymmetry in calcaneal dimensions. This, in turn, influences pair-matching comparisons. Osteometric pair-matching is most accurate with the use of bone dimensions that exhibit the least asymmetry between bilateral elements (Garroway 2013). When paired elements exhibit a low degree of asymmetry, the criteria for pair-matching can be more stringent, i.e. exclude bones that are too different in size. Therefore, in the current research, the percentage of asymmetry exhibited in each calcaneal dimension was investigated.

5.3 Individual Differences in Calcaneal Asymmetry

The first objective of this research project was to investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled. To determine the relative amount of asymmetry exhibited in each calcanei pair, the percentage directional asymmetry was calculated. Table 4.21 summarizes the directional asymmetry of the White, Black, and Coloured South African pooled populations; this was called the “Combined South African” group.

In the "Combined South African" group (combined sexes) the MAXL of the calcaneus exhibited the smallest range of directional asymmetry. The MIDB also exhibited a small range of directional asymmetry, but it was greater than that of MAXL. However, dimensions of the articular facets (DAFL, DAFB, MAFL, and MAFB) exhibited greater ranges of directional asymmetry compared to MAXL and MIDB. The results of the current study can only be compared to those of Storm (2009), as no other studies, to date, have calculated directional asymmetry in calcanei. However, Storm's (2009) study and the current study only share two common variables: MAXL (cited as CZL in Storm 2009) and MIDB (cited as CZB in Storm 2009). Therefore, no statistical comparisons could be made between these studies because of the risk of method bias from the limited number of variables used for comparison (McClave et al. 2013; Watt and van den Berg 1995). The results of the current study are consistent with those of Storm (2009) insofar as the MAXL ('CZL') exhibited a smaller range of directional asymmetry (between -3.33% and 4.25%) than the MIDB ('CZB') (between -6.97% and 5.62%). Storm (2009) found that MAXL ('CZL') exhibited a range of directional asymmetry between -4.32% and 5.0% and MIDB ('CZB') exhibited greater directional asymmetry, between -8.0% and 8.52%.

In the current study, chi-square (χ^2) tests were used to evaluate whether there were significant differences between occurrences of left- and right-biases for the "Combined South African" group (Table 4.22). For the "Combined South African" group (combined sexes), the variables MAXL, DAFB, and MAFL did not have statistically significant differences in the occurrences of left- or right-biases. However, the variables MIDB, DAFL, and MAFB had significantly more occurrences of right-bias. However, when looking at White, Black, and Coloured South African populations separately, occurrences

of left- and right-biases were not found to be significantly different for most calcaneal variables. The only variables that had statistically more occurrences of right-bias than left-bias were MIDB and MAFB in the Black South African population. These differences occur in the samples because small but insignificant side-biases present within each South African populations become magnified when pooled into the "Combined South African" group (Meek, personal communication April 2019).

The results of the current study can only be compared to those of Storm (2009), as no other studies, to date, have tested for side-bias in calcanei. However, Storm's (2009) study and the current study only share two common variables: MAXL (cited as CZL in Storm 2009) and MIDB (cited as CZB in Storm 2009). Therefore, no statistical comparisons could be made between these studies because of the risk of method bias from the limited number of variables used for comparison (McClave et al. 2013; Watt and van den Berg 1995). The results of the current study are consistent with Storm (2009) insofar as the MAXL ('CZL') did not exhibit a side-bias, i.e. did not have more occurrences of left-bias than right-bias or vice versa. However, Storm (2009) found that MIDB ('CZB') had statistically more occurrences of left-bias than right-bias. This is inconsistent with the results of the current study as MIDB did not have more occurrences of left-bias, but rather more occurrences of right-bias only in the Black South African population.

Percentage absolute asymmetry was also calculated to assess the total amount of asymmetry present in each calcaneal dimension of the "Combined South African" group. Table 4.26 summarizes the absolute asymmetry of the "Combined South African" group. In the "Combined South African" group (combined sexes), the MAXL of the calcaneus exhibited the smallest average percentage absolute asymmetry. The MIDB also exhibited

a small average percentage absolute asymmetry, but greater than that of MAXL. Dimensions of the articular facets (DAFL, DAFB, MAFL, and MAFB) exhibited greater ranges than MAXL and MIDB.

The results of the current study can only be compared to those of Storm (2009), as no other studies, to date, have calculated absolute asymmetry in calcanei. However, Storm's (2009) study and the current study only share two common variables: MAXL (cited as CZL in Storm 2009) and MIDB (cited as CZB in Storm 2009). Therefore, no statistical comparisons could be made between these studies because of the risk of method bias from the limited number of variables used for comparison (McClave et al. 2013; Watt and van den Berg 1995). The results of the current study are consistent with those of Storm (2009) insofar as the MAXL exhibited a smaller average percentage absolute asymmetry (0.78%) than MIDB (1.47%), and Storm (2009) also found that MAXL ('CZL') exhibited smaller average percentage absolute asymmetry (0.84%) than MIDB ('CZB') (1.56%).

5.3.1 Causes of Asymmetry within Individuals

The results of the current study, to this point, have presented the directional and absolute asymmetry exhibited in calcaneal dimensions at the individual level (i.e. pooled sexes and population groups) (Tables 4.21 and 4.26). The paired *t*-tests showed that most calcaneal dimensions exhibited statistical symmetry (Tables 4.11-4.13). The results of percentage directional asymmetry and percentage absolute asymmetry showed that, on average, MAXL and MIDB variables are more symmetrical than DAFL, DAFB, MAFL, and MAFB. These results also showed that all individuals exhibited directional and

absolute asymmetries close to 0% in MAXL and MIDB, while there was a wide range of directional and absolute asymmetries in DAFL, DAFB, MAFL, and MAFB (i.e. some exhibit percentage asymmetries close to 0%, while others exhibit percentage asymmetries up to 21.98%). The expression of asymmetry in bone dimensions is influenced by a complex interaction of genetics and hormones, biomechanics, and environmental stress (Burwell et al. 2006; Plochocki 2004; Shaw and Stock 2009; Steele and Mays 1995), which will be discussed in the next three sections.

5.3.1.1 Genetics and Asymmetry

The results of the current study (with pooled sexes and populations) show that MAXL and MIDB are more symmetrical than DAFL, DAFB, MAFL, and MAFB (articular surface measurements). The developmental process of the foot throughout ontogeny can explain these results. Bone length is more canalized (i.e. genetically controlled) during growth (Auerbach and Ruff 2006; Biewener and Bertram 1994, 1993; Lanyon 1980; Lieberman et al. 2001; Ruff 2003) than other bone dimensions. Research has shown that articular surfaces follow a similar growth pattern to bone length (Ruff et al. 1994). However, in comparison to bone lengths, articular growth is more mechanically sensitive. Articular growth is also more canalized than diaphyseal breadth growth (Auerbach and Ruff 2006). That is to say, growth of articular surfaces are somewhat genetically controlled but are also influenced by mechanical stress throughout ontogeny. The varying influence of stress upon the different dimensions of the developing calcaneus support the findings of the current study. When MAXL was compared to articular surface dimensions, it showed lesser degrees of asymmetry possibly because they are influenced

more by genetic control. The articular surface dimensions exhibited greater degrees of asymmetry possibly because they are influenced more by mechanical or environmental factors.

Although genetics controls bone development through ontogeny to maintain symmetry, genetics also plays a role in causing asymmetry, though the degree of this influence is not well understood (Storm 2009). Research has established the following genetic causes of skeletal asymmetry: loss in variation of genes, protein heterozygosity, mutant genes, directional selection, and the disruption of co-adapted gene complexes through hybridization (Møller and Swaddle 1997). Human and animal studies by Clarke et al. (1986), Livshits and Kobyliansky (1991), and Mazzi et al. (2002) have demonstrated that inbreeding, i.e. the loss in variation of genes, increases the chances and the degree of asymmetry. The relationship between asymmetry and the level of heterozygosity or homozygosity has had contradictory results (Storm 2009). Many studies have found evidence that a loss of heterozygosity increases levels of fluctuating asymmetry, and low levels of homozygosity may increase an organism's buffering ability against environmental insults, therefore reducing asymmetry (Storm 2009). However, human and animal studies by Hutchison and Cheverud (1995), Livshits and Kobyliansky (1991), Møller and Swaddle (1997), and Palmer and Strobeck (1992, 1986) report no relationship between homozygosity and increased asymmetry. High levels of asymmetry have also been associated with congenital conditions (Naugler and Ludman 1996). This may be a result of the breakdown of developmental stability due to environmental stress (Naugler and Ludman 1996). It is also possibly a reflection of a predisposition of the genetic disorder producing an increased susceptibility to asymmetry (Naugler and Ludman 1996).

The large degree of asymmetry expressed in calcaneal dimensions by some individuals in the sample may be attributed to genetic factors. While pathological calcanei were excluded from the current study, it is possible that individuals in the sample had genetic factors, such as loss in genetic variation, influencing asymmetry. These genetic factors would not have been known to the current author as no genetic testing was performed on the individuals in the sample.

5.3.1.2 Biomechanics and Asymmetry

In the current study, there was no statistically significant asymmetry (with sexes and populations pooled) and no significant differences in occurrences of left- or right-bias for most calcaneal dimensions (with populations separated and sexes pooled). These results can be attributed to biomechanics of the human body. Mechanical stress, i.e. the exertion of more strain, on the dominant side of the limbs is associated with bilateral asymmetry; the dominant limb has more developed musculature, therefore increased bone development to support the increased use (Krishan et al. 2010; Schell et al. 1985; Plato, Wood and Norris 1980) causing disparity between bilateral bone dimensions. However, the function of the lower limbs requires relatively equal mechanical loading (Auerbach and Ruff 2006; Plochocki 2004), i.e. similar biomechanical stress upon both left and right feet. Though right-footedness has been found to be more prevalent (Bell and Gabbard 2000; Gentry and Gabbard 1995), the contralateral non-preferred foot supports activities of the dominant foot (e.g. kicking) to provide stability (Auerbach and Ruff 2006; Bell and Gabbard 2000; Gentry and Gabbard 1995). Therefore, the dominant foot and contralateral non-preferred foot are subjected to similar mechanical loading, maintaining symmetry

with little to no side-bias (Tümer et al. 2019). The similar mechanical loading on both feet explain why most calcaneal dimensions do not exhibit statistically significant asymmetry and why most calcaneal dimensions do not have more occurrences of left-bias than right-bias, or vice versa, in the current study.

In the current study, articular surface dimensions of the calcaneus exhibited greater degrees of asymmetry than other calcaneal variables. This can be attributed to biomechanical stress, as calcaneal articular surfaces are more susceptible to biomechanical stress than the length and breadth variables (Auerbach and Ruff 2006). Mechanical loads from the leg are transferred to the forefoot through the calcaneus (Jung et al. 2016). The load arm on the subtalar joint (i.e. dorsal articular facet and middle articular facet) is the medium for the weight-bearing axis (Jung et al. 2016:44). Therefore, when calcaneal dimensions exhibit higher degrees of asymmetry, it is possible that these individuals may participate in activities that require unequal use of their lower limb (e.g. sports) or may have pathologies or injuries that require more mechanical loading on one foot over the other for stability (Kanchan et al. 2008).

5.3.1.3 Environment and Asymmetry

The results of the current study showed that there was no statistically significant asymmetry for most calcaneal dimensions (with sexes and populations pooled). Other research on bilateral asymmetry has also found calcaneal dimensions to be statistically symmetrical (Bidmos and Asala 2004, 2003; DiMichele and Spradley 2012; Peckmann et al. 2015b; Scott et al. 2017). These findings suggest that the process of developmental stability is a factor in maintaining symmetry in the calcaneus. Under conditions of

environmental stress, the body will use more resources to maintain its optimal homeostasis (i.e. symmetry) in the lower limb, for stability and locomotion, at the expense of traits that can function without symmetry, such as those of the upper limbs, cranium, and dentition (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997). The calcaneus requires symmetry for stability and locomotion. The results of this study show that, while the South African individuals may have experienced environmental stress (as they all lived the majority of their lives during the Apartheid era), the body maintains optimal homeostasis (i.e. symmetry) in the calcaneus, possibly at the expense of other skeletal elements that do not require symmetry for function.

Although there was no statistically significant asymmetry for most calcaneal dimensions, there were individuals in the current study who exhibited higher degrees of asymmetry in calcaneal dimensions compared to others; this analysis was completed with sexes and populations pooled. Research by DeLeon (2007), Guatelli-Steinberg et al. (2006), Kujanova et al. (2008), Özener 2010, Schaefer et al. 2006, and Storm (2009) has illustrated that skeletal asymmetry may be attributed to socioeconomic differences. Low socioeconomic status is associated with a number of environmental stresses including nutritional stress, diminished living conditions, and inadequate access to health care. Nutritional stresses and poor fitness and health cause an increase in skeletal asymmetry as the body lacks the resources to buffer against developmental disruptions (Gangestad and Thornhill 1999; Leamy and Klingenberg 2005; Møller and Swaddle 1997). The individuals with greater degrees of asymmetry in calcaneal dimensions may be from low socioeconomic status and high levels of environmental stress. That is to say, individuals who experienced higher levels of environmental stress may have lacked the resources to buffer against developmental disruptions, because of their low socioeconomic status, thus

leading to more bilateral asymmetry in calcaneal dimensions. Conversely, individuals with low degrees of asymmetry in calcaneal dimensions may be from high socioeconomic status and have experienced low levels of environmental stress. As sexes and populations were pooled for this analysis, there is no way to know which exact individuals were expressing high or low degrees of asymmetry. However, environmental stress and socioeconomic status will be revisited in sections 5.4.1.2 and 5.5.1.3 as they relate to sex and population differences, respectively.

5.4 Sex Differences in Asymmetry of the Calcaneus

The second objective of the current study was to investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled. The Kruskal–Wallis test was used to evaluate for significant differences in directional asymmetry between sexes of the White, Black, and Coloured South African pooled populations (i.e. the "Combined South African" group). In the current study, there were no statistically significant differences in directional asymmetry between the sexes for most measurements (Table 4.27). Only the MAFB variable exhibited a statistically significant difference in directional asymmetry between sexes. For the "Combined South African" female group, MAFB exhibited a range of directional asymmetry between -16.38 and 14.19%, while the "Combined South African" male group exhibited a range of directional asymmetry between -21.98% and 20.78% for MAFB (Table 4.21).

The results of the current study can only be compared to those of Storm (2009), as no other studies, to date, have calculated directional asymmetry in calcanei. However,

Storm's (2009) study and the current study only share two common variables: MAXL (cited as CZL in Storm 2009) and MIDB (cited as CZB in Storm 2009). Therefore, no statistical comparisons could be made between these studies because of the risk of method bias from the limited number of variables used for comparison (McClave et al. 2013; Watt and van den Berg 1995). While Storm (2009) did not explicitly state the ranges of directional asymmetry present in males and females, the results of the current study are consistent with those of Storm (2009) insofar as there were no statistically significant differences in directional asymmetry between sexes for the MAXL ('CZL') and MIDB ('CZB') measurements.

The Kruskal–Wallis test was also used to evaluate for significant differences in absolute asymmetry between sexes of the White, Black, and Coloured South African pooled populations (i.e. the "Combined South African" group). In the current study, there were no statistically significant differences in absolute asymmetry between sexes for any calcaneal dimension (Table 4.27). The results of the current study can only be compared to those of Storm (2009), as no other studies, to date, have calculated absolute asymmetry in calcanei. However, Storm's (2009) study and the current study only share two common variables: MAXL (cited as CZL in Storm 2009) and MIDB (cited as CZB in Storm 2009). Therefore, no statistical comparisons could be made between these studies because of the risk of method bias from the limited number of variables used for comparison (McClave et al. 2013; Watt and van den Berg 1995). While Storm (2009) did not explicitly state the average percentage absolute asymmetry present in males and females, the results of the current study are consistent with those of Storm (2009) insofar as there were no statistically significant differences in absolute asymmetry between sexes for the MAXL ('CZL') and MIDB ('CZB') measurements.

5.4.1 Causes of Sex Differences in Asymmetry

The results of the current study, to this point, have presented the directional and absolute asymmetry exhibited in calcaneal dimensions with sexes separated and populations pooled (Tables 4.21 and 4.26). The results of the Kruskal-Wallis tests showed no statistically significant differences in directional asymmetry between sexes for five of the six variables and no statistically significant differences in absolute asymmetry between sexes for all six variables (Table 4.27). Sex differences in biomechanical (activity/labour) and environmental (e.g. nutrition) stresses may create differences in osteometric asymmetry between males and females (Storm 2009). These differences can then influence the applicability of osteometric methods for pair-matching human skeletal elements. Evaluating sex differences in bilateral asymmetry is, thus, a necessary step in developing an osteometric method for pair-matching skeletal elements.

5.4.1.1 Biomechanics and Asymmetry

The results of the current study (with separated sexes and pooled populations) showed most calcaneal variables did not exhibit statistically significant differences in directional asymmetry between the sexes (Table 4.27). There were no statistically significant differences in directional asymmetry between the sexes for five variables (MAXL, MIDB, DAFL, DAFB, and MAFL). However, there was a statistically significant difference in directional asymmetry between the sexes for one variable (MAFB).

Similarly, Storm (2009) found no statistically significant differences in directional asymmetry between the sexes in MAXL ('CZL') and MIDB ('CZB'). Storm (2009) reported that males in their sample were employed in more physically demanding occupations, such as farming or industrialised factory work, compared to females who were engaged in less physically demanding occupations, mostly in the domestic sphere (Storm 2009). Storm's (2009) study found that sexual division of labour/activity was reflected in directional asymmetry in some skeletal pairs, however, these sex differences were not reflected in the calcaneus. The MAXL and MIDB variables in the current study also showed no statistically significant differences, which is consistent with the results of Storm (2009). During apartheid, White, Black, and Coloured South Africans would have participated in different labour activities; White South Africans (males and females) would have been employed in professional office jobs, Black and Coloured South African males would have performed strenuous labour activities (i.e. farming), while Black and Coloured South African females would have been employed in the domestic sphere (Thompson 2001).

As discussed in section 5.3.1.2, the stability and locomotor function of the lower limb requires relatively equal mechanical loading (Auerbach and Ruff 2006; Plochocki 2004). In the current study, most of the calcaneal dimensions do not exhibit statistically significant asymmetry (Tables 4.11-4.13). This could be attributed to equal mechanical loading on both feet. The requirement for similar mechanical loading on both feet, even under different labour conditions, may explain the lack of differences in directional asymmetry, for most calcaneal dimensions when males and females are compared.

In the current study, the MAFB dimension was the only calcaneal dimension that had statistically significant differences in directional asymmetry between the sexes. As

discussed in section 5.3.1.2, articular surface dimensions exhibit greater degrees of asymmetry than other calcaneal variables. This was attributed to articular surfaces being more susceptible to biomechanical stress than length and breadth variables (Auerbach and Ruff 2006). However, the other articular facets (DAFL, DAFB, and MAFL) did not exhibit a statistically significant difference in directional asymmetry between the sexes. This may indicate that the MAFB is more susceptible to biomechanical stress. The middle articular facet is the articular surface of the sustenaculum tali that articulates with the talar head. The middle articular facet occupies a key position in providing stability, as the sustenaculum tali functions as a bracket for the talar head and allows the transmission of force towards the lateral arch (Harris 1983; Kapandji 1970; Lamy 1986; Mann 1991; Olson and Seidel 1983). Therefore, biomechanical differences in mechanical loading related to stability may influence the MAFB variable more than other articular facets. Therefore, in the current study, sex differences in labour/activity, while not reflected in most calcaneal dimensions, may account for the statistically significant difference in directional asymmetry between the sexes for MAFB.

5.4.1.2 Environment and Asymmetry

The results of the current study (with separated sexes and pooled populations) showed no statistically significant differences in absolute asymmetry between sexes for all six calcaneal dimensions (Table 4.27). The MAXL and MIDB variables in the current study also showed no statistically significant differences, which is consistent with the results of Storm (2009). Storm's (2009) study found no statistically significant differences in absolute asymmetry between sexes in MAXL ('CZL') and MIDB ('CZB'). Storm

(2009) reported that significant differences between the sexes in absolute asymmetry were widely distributed throughout the skeleton, however absolute asymmetry was not exhibited in calcaneal dimensions.

As discussed in section 5.3.1.3, under conditions of environmental stress, the body will use more resources to maintain its optimal homeostasis (i.e. symmetry) in the lower limb for stability and locomotion (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997). As the calcaneus requires symmetry for stability and locomotion, the body maintains symmetry in the calcaneus possibly at the expense of other skeletal elements that do not require symmetry for function. In the current study, South African males and females may have experienced different degrees of environmental stress, however, this did not result in statistically significant differences in absolute asymmetry between sexes in calcaneal dimensions. Therefore, the requirement for optimal homeostasis in the lower limb, even under varying degrees of environmental stress, may explain the lack of differences in absolute asymmetry of calcaneal dimensions between sexes.

5.5 Population Differences in Asymmetry of the Calcaneus

The third goal of the current study was to investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured populations separated. In the current study, there were no statistically significant sex differences in the directional asymmetry for most calcaneal dimensions and no statistically significant sex differences in the absolute asymmetry for all six calcaneal variables, therefore, sexes were pooled for the investigation of population differences. The Kruskal–Wallis test was used to evaluate for significant differences in directional asymmetry between the White, Black, and Coloured South African

populations (with sexes pooled). In the current study, there were no statistically significant differences in the directional asymmetry for all six calcaneal dimensions between the White, Black, and Coloured South African population groups (see Table 4.28). However, statistically significant differences in absolute asymmetry for three calcaneal dimensions (MAXL, DAFB, and MAFL) were found between the White, Black, and Coloured South African populations (see Table 4.28). In the White South African population, the variables MAXL, DAFB, and MAFL exhibited an average percentage absolute asymmetry of 0.66%, 1.93%, and 3.54%, respectively (Table 4.23). In the Black South African population, the variables MAXL, DAFB, and MAFL exhibited an average percentage absolute asymmetry of 0.73%, 2.68%, and 2.42%, respectively (Table 4.24). In the Coloured South African population, the variables MAXL, DAFB, and MAFL exhibited an average percentage absolute asymmetry of 0.95%, 2.61%, and 2.42%, respectively (Table 4.25). As no other studies, to date, have compared directional or absolute asymmetry of calcanei between populations, no direct comparisons could be made.

5.5.1 Causes of Population Differences in Asymmetry

The results of the current study found no statistically significant differences in directional asymmetry between White, Black, and Coloured populations for all calcaneal variables. Statistically significant differences in absolute asymmetry between White, Black, and Coloured populations were found for three calcaneal variables (MAXL, DAFB, and MAFL) (Table 4.28). The expression of asymmetry in bone dimensions is influenced by a complex interaction of genetics and hormones, biomechanics, and

environmental stress (Burwell et al. 2006; Plochocki 2004; Shaw and Stock 2009; Steele and Mays 1995). Population differences in genetic, biomechanical (activity/labour), and environmental (e.g. nutrition) stresses may create differences in osteometric asymmetry between populations. These differences can then influence the applicability of osteometric methods for pair-matching between population groups. Evaluating population-specific differences in bilateral asymmetry is necessary when developing osteometric methods for pair-matching skeletal elements. To date, no studies have investigated population differences in bilateral asymmetry of calcaneal dimensions, therefore, direct comparisons to other studies was not possible. However, the results of the current study suggest that genetic, biomechanical, and environmental stresses influenced the differences exhibited between the White, Black, and Coloured South African populations.

5.5.1.1 Genetics and Asymmetry

The results of the current study (with pooled sexes and separated populations) show that there were no statistically significant differences in directional asymmetry between the White, Black, and Coloured South African populations for all six calcaneal variables. However, the results of the current study (with pooled sexes and separated populations) show that three variables (MAXL, DAFB, and MAFL) exhibit statistically significant differences in absolute asymmetry between the White, Black, and Coloured South African populations. The significant differences in absolute asymmetry between White, Black, and Coloured South Africans may be explained by the role of genetics.

While no significant differences in directional asymmetry were found, statistically significant differences in absolute asymmetry between White South African and Black and Coloured South African groups were found for MAXL, DAFB, and MAFL. These statistically significant differences in absolute asymmetry may be attributed to the inherent genetic differences, i.e. the ancestral genetic contributions, of the three South African populations. South Africa is comprised of multiple ancestries with a variety of parent groups, contributing genetically to the contemporary population groups (L'Abbé et al. 2011; Tishkoff et al. 2009). Bone growth is strongly influenced by genetics, as genes carry information that is necessary for mesenchymal stem cell development to mature bone cells (O'Connor et al. 2010). The distinct genetic backgrounds may have influenced differences in growth and skeletal asymmetry between the White, Black, and Coloured South African populations.

White South Africans are descendants of a small group of European settlers, with almost equal genetic contributions from Dutch, British, German, and French settlers (Sutherland 2015). Black South Africans are mainly descendent from the indigenous Bantu-speaking Nguni and Sotho-Tswana groups (Thompson 2014). Coloured South Africans are descendent from populations from Africa, Europe, and Indonesia, with the greatest genetic contributions from indigenous Khoe-San and Bantu-speakers, White Europeans and Indians (Henneberg, Brush, and Harrison 2001; Patterson et al. 2010; Peterson et al. 2013; Quintana-Murci et al. 2010; Stull 2014; Stull, Kenyhercz, and L'Abbé 2014; Tishkoff and Williams 2002). This demonstrates that there are distinct genetic differences between the White, Black, and Coloured South African populations. However, there are also some genetic similarities, particularly between Black and Coloured South Africans. The inherent genetic differences may explain why some

calcaneal variables (MAXL, DAFB, and MAFL) exhibited statistically significant differences in absolute asymmetry between populations. The inherent genetic similarities may explain why some variables (MIDB, DAFL, and MAFB) did not exhibit statistically significant differences in absolute asymmetry in the current study.

The statistically significant differences in absolute asymmetry, for some calcaneal variables, between White, Black, and Coloured South African populations could also be attributed to the influence of genes. Quinto-Sanchez and colleagues (2015) cited that different patterns of asymmetry may be found between different ancestral groups. In their study, they attributed asymmetry to the ways in which different populations throughout the world were founded and developed, i.e. human populations are differentially affected by gene flow or genetic drift (Gonzalez et al. 2014; Quinto-Sanchez et al. 2015). As discussed in section 5.3.1.1 of the current study, a loss in variation of genes is one of the genetic causes of skeletal asymmetry (Møller and Swaddle 1997). The influence of genetic variation on skeletal asymmetry presented by Quinto-Sanchez and colleagues (2015) supports this statement. The authors investigated the relationship between genetic admixture and facial asymmetry in a Latin American admixed sample. They found that Latin American individuals with lower levels of fluctuating (i.e. absolute) asymmetry corresponded to greater heterozygosity (i.e. individuals who are 'more admixed'), compared to those with greater homozygosity (i.e. individuals who are 'less admixed') (Quinto-Sanchez et al. 2015).

The White, Black, and Coloured South African populations have different degrees of genetic variation, due to how the groups were founded. This may explain why there are significant differences in absolute asymmetry between the three South African populations for some calcaneal variables. As discussed in Chapter 1 (section 1.5), the

social and geographical laws imposed by apartheid restricted gene flow between the White, Black, and Coloured groups in South Africa (Morris 2012; Ross 2008; Sutherland 2015; Thompson 2014). These barriers for gene flow allowed for the preservation of distinct morphological differences that exist among these three population groups (McDowell 2012).

White South Africans are descendants of a small group of European settlers (Sutherland 2015). The introduction of the Prohibition of Mixed Marriages Act in 1949 outlawed 'mixed-race' marriages (i.e. marriage between Whites and 'non-Whites') (Jacobson, Amoateng, and Heaton 2004; Stull, Kenyhercz, and L'Abbé 2014) reinforcing gene flow restrictions within the White population. White South Africans are, therefore, a prime example of the Founder Effect, which is characterized by a loss in genetic variation within a new population when a small number of individuals founded the population (Greeff 2007).

Indigenous Bantu-speakers and Khoe-San are the foundational populations of the contemporary Black and Coloured South African population groups. While the Bantu-speakers and Khoe-San are considered distinct population groups (Barbieri et al. 2013; Herbert 1990; Liebenberg et al. 2015; Petersen et al. 2013; Stynder 2009), it has been shown that Bantu-speakers and Khoe-San interacted and mated before the European colonization of South Africa. This increased genetic diversity of these populations before colonization (Sutherland 2015).

After colonization, 'mixed-race' unions between female slaves (mainly Khoe-San) and White European males resulted in the uniquely admixed (i.e. genetically diverse) Coloured South African population. The Black South African population are mainly descendant from indigenous Bantu-speaking groups. However, during apartheid the Black

and Coloured South African populations were not restricted from mating with each other. That is to say, the Black and Coloured South African populations experienced less barriers for gene flow during apartheid (Posel 2001). Therefore, the Black and Coloured South African populations show an increase in genetic diversity because of the interactions and mating between these populations (i.e. Bantu-speakers and Khoe-San, Khoe-San and White Europeans, and Black and Coloured South Africans).

Møller and Swaddle (1997) attributed the loss of genetic variation as a cause of asymmetry. This is not consistent with the results of the current study. The White South African population, which has low levels of genetic admixture, exhibited less asymmetry in the MAXL and DAFB dimensions and a higher degree of asymmetry in the MAFL dimension than the Black and Coloured South Africans. According to the research by Møller and Swaddle (1997), the White South Africans should exhibit greater degrees of absolute asymmetry in MAXL and DAFB as well as MAFL due to the populations' loss in genetic variation, while Black and Coloured South Africans should exhibit lesser degrees of absolute asymmetry due to their increased genetic variation (i.e. heterozygosity). Therefore, in the current research, there are factors other than genetics, e.g. biomechanical and environmental stresses, which are influencing the differences in calcaneal asymmetry between the three South African populations.

5.5.1.2 Biomechanics and Asymmetry

The results of the current study (with pooled sexes and separated populations) show that there were no statistically significant differences in directional asymmetry between the White, Black, and Coloured South African populations for all six calcaneal

variables (Table 4.28). The lack of statistically significant differences in directional asymmetry between White, Black, and Coloured South Africans may be explained by biomechanics of the calcaneus.

Previous studies have shown that division of labour/activity is reflected in directional asymmetry of some skeletal pairs (Garrido-Varas 2013; Storm 2009). During apartheid, White South African males and females were employed in clerical and managerial occupations, whereas, Black and Coloured South African males were employed in manual positions and females were employed as domestic help (Thompson 2001; Treiman et al. 1996). However, in the current study, there were no statistically significant differences in directional asymmetry between White, Black, and Coloured South Africans for all six calcaneal variables.

This may be explained by similar mechanical loading on both feet. As discussed in section 5.3.1.2, the stability and locomotor function of the lower limb requires relatively equal mechanical loading (Auerbach and Ruff 2006; Plochocki 2004). Therefore, even under different labour conditions, the requirement for equal mechanical loading on both feet may explain the lack of statistically significant differences in directional asymmetry, for all six calcaneal dimensions, when White, Black, and Coloured South African populations are compared.

5.5.1.3 Environment and Asymmetry

The results of the current study (with separated sexes and pooled populations) showed statistically significant differences in absolute asymmetry between White, Black, and Coloured South African populations for three (MAXL, DAFB, and MAFL) calcaneal

dimensions. However, the results of the current study found three calcaneal variables (MIDB, DAFL, and MAFB) did not exhibit statistically significant differences in absolute asymmetry between White, Black, and Coloured South African populations. These results can be explained by the role of environmental stress on bilateral asymmetry.

As discussed in section 5.4.1.2, an increased level of social status and wealth is associated with less skeletal asymmetry (Storm 2009). Populations of higher socioeconomic status have higher genetic fitness, i.e. have increased buffering capabilities and, therefore, lower levels of skeletal asymmetry (Storm 2009). Conversely, those in low socioeconomic standing have higher levels of skeletal asymmetry, which has been shown to be related to a lack of access to adequate nutrition and health care, diminished living conditions, and higher risk of disease (Storm 2009).

Acute socioeconomic contrasts separated South African population groups under apartheid (Cameron 2003; Henneberg and Lavelle 1999). The different environmental stresses experienced by each South African ancestral group may explain the statistically significant differences in absolute asymmetry, for some of the calcaneal dimensions, between the White, Black, and Coloured South African populations. During apartheid, White South Africans were of high socioeconomic status (Thompson 2001); they experienced low infant mortality rates (14.9/1000 individuals) and long life expectancies (64.5 years for males, 72.3 years for females) (Thompson 2001). White South Africans experienced optimal environmental conditions throughout life, favouring skeletal maturation (Liebenberg 2015; Sutherland 2015) and symmetry. Black South Africans were of low socioeconomic status during apartheid and experienced high levels of poverty, malnutrition, and disease (Thompson 2001). Evidence of their increased environmental stresses is shown in their high infant mortality rates (110/1000 individuals)

and low life expectancies (51.2 years for males and 58.9 years for females) (Seedat 1984; Thompson 2001); Thompson (2001) cites that the statistics for Black South Africans are only estimates as these kind of data were only collected for White South Africans during apartheid. The unfavourable living conditions experienced by Black South Africans likely retarded skeletal growth and maturation (Norris et al. 2006; Vindulich et al. 2006) and negatively influenced skeletal asymmetry. Coloured South Africans also experienced high levels of poverty, malnutrition, and disease during apartheid (Thompson 2001); their socio-economic status was slightly higher than Black South Africans but much lower than White South Africans during apartheid. Evidence of their increased environmental stress is shown in their high infant mortality rates (80.6/1000 individuals) (Seedat 1984; Thompson 2001) and low life expectancies (58 years for males and 66 years for females) (Bradshaw, Dorrington, and Sitas 1992). The unfavourable living conditions experienced by Coloured South Africans negatively influenced skeletal growth and development (Liebenberg 2015; Sutherland 2015).

The statistically significant differences in absolute asymmetry between the White, Black, and Coloured South African population groups for some calcaneal dimensions may, therefore, be due to their differences in socioeconomic status during apartheid. While White South Africans had optimal living conditions, favouring skeletal growth, Black and Coloured South Africans were in unfavourable living conditions, which would have contributed to greater levels of asymmetry in bone dimensions. Not all calcaneal dimensions exhibited statistically significant differences in absolute asymmetry between the three South African populations. However, Black and Coloured South Africans, who were of lower socioeconomic status, exhibited greater degrees of absolute asymmetry than White South Africans for most calcaneal dimensions (Tables 4.23-4.25). The

environmental stress and socioeconomic status experienced by the three South African populations may explain the differences in absolute asymmetry between the White, Black, and Coloured populations.

The results of the current study found that three (MIDB, DAFL, and MAFB) of the six calcaneal variables did not exhibit statistically significant differences in absolute asymmetry when the White, Black, and Coloured South African populations were compared. This may be attributed the body trying to maintain optimal homeostasis. As discussed in section 5.3.1.3, under conditions of environmental stress, the body will use more resources to maintain its optimal homeostasis (i.e. symmetry) in the lower limb for stability and locomotion (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997). As the calcaneus requires symmetry for stability and locomotion, the body maintains symmetry in the calcaneus possibly at the expense of other skeletal elements that do not require symmetry for function. In the current study, White, Black, and Coloured South Africans have experienced different degrees of environmental stress, however, this did not result in statistically significant differences in absolute asymmetry between populations for some calcaneal dimensions. Therefore, the requirement for optimal homeostasis in the lower limb, even under varying degrees of environmental stress, may explain why not all calcaneal dimensions exhibited statistically significant differences in absolute asymmetry between the White, Black, and Coloured populations.

5.6 Osteometric Sorting Using the Statistic *M*

The fourth objective of the current study was to use the statistic *M* to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations. The statistic *M* expresses the difference between the left and

right calcanei measurements as a proportion of the average value of the two measurements; the statistic *M* is the equivalent of absolute asymmetry, without conversion to a percentage. Tables 4.30-4.32 summarize the calculated values of *M* for the six calcaneal variables of White, Black, and Coloured South African populations, with sexes separated and sexes pooled.

In the current study, two sample *t*-tests were employed to evaluate sex differences for the values of *M* for each variable within each South African population group (Table 4.29). Results of the current study found that sex differences in values of *M* were not statistically significant for all calcaneal variables for the White, Black, and Coloured South African population groups. Therefore, combined sex tables can be utilized for osteometric pair-matching of calcanei for White, Black, and Coloured South Africans. Thomas and colleagues (2013) examined osteometric pair-matching of "major paired bones" (i.e. humeri, radii, ulnae, femora, tibiae, fibulae, clavicles, scapulae, os coxae, and calcanei). Their measurements included two calcaneal variables (MAXL and MIDB). The authors combined population data (American Black, American White, Asian, Hispanic/Mexican, and 'other') for their pair-matching study. The authors found no statistically significant sex differences in the values of *M* for either the MAXL or MIDB calcaneal variables. The results of the current study are consistent with those of Thomas et al. (2013). The current study found that the values of *M*, for the White, Black, and Coloured South Africans (with sexes combined) are acceptable for osteometric sorting of calcanei as sex differences in values of *M* were not statistically significant for all calcaneal variables for the three South African populations.

Because the results of the statistic *M* calculations are equivalent to absolute asymmetry, the same conclusions can be drawn from the statistic *M* results as the results

of absolute asymmetry discussed earlier in this chapter. As discussed in section 5.4.1.2, under conditions of environmental stress, the body will use more resources to maintain its optimal homeostasis (i.e. symmetry) in the lower limb for stability and locomotion possibly at the expense of other skeletal elements that do not require symmetry for function (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997). There were no statistically significant differences in absolute asymmetry between sexes in all three South African population groups. Therefore, it was concluded that, even though males and females may have experienced varying degrees of environmental stress, this was not reflected in calcaneal dimensions.

As no statistically significant differences for values of *M* were found between sexes in the White, Black, and Coloured South African groups, the same conclusion can be drawn. Although males and females may have been under varying degrees of environmental stress, sex differences in values of *M* are not reflected in calcaneal dimensions. Therefore, as no statistically significant differences in values of *M* were found between sexes for any of the six calcaneal dimensions, sexes can be combined for pair-matching calcanei in the White, Black, and Coloured South African populations.

In the current study, two sample *t*-tests were employed to evaluate population differences for the values of *M* for each calcaneal variable between the White, Black, and Coloured South African population groups (Table 4.33). The values of *M* for DAFB exhibited statistically significant differences between White and Black South Africans, and the values of *M* for MAXL and MAFB exhibited statistically significant differences between White and Coloured South Africans. There were no statistically significant differences for all six calcaneal variables for values of *M* between Black and Coloured South Africans. Thomas and colleagues (2013) did not evaluate the influence of ancestral

differences in their methodology as they combined their population data (i.e. American Black, American White, Asian, Hispanic/Mexican, and 'other') for their pair-matching study; no formal tests were employed to evaluate differences between the ancestral groups. The statistically significant differences for values of *M* of calcaneal dimensions between White, Black, and Coloured South Africans demonstrates there are differences in asymmetry between ancestral groups, and thus evaluations of these differences should be completed before combining populations for pair-matching methods.

Because the results of the statistic *M* calculations are equivalent to absolute asymmetry, the same conclusions can be drawn from the statistic *M* results as the results of absolute asymmetry discussed earlier in this chapter. As discussed in section 5.5.1.1, there were statistically significant differences in absolute asymmetry between the White, Black, and Coloured South African populations for three calcaneal variables (MAXL, DAFB, and MAFL). This was attributed to genetic differences between the three South African populations; bone growth is strongly influenced by genetics as genes carry information that is necessary for mesenchymal stem cell development to mature bone cells (O'Connor et al. 2010). White South Africans are descendants of European settlers, Black South Africans are descended from indigenous Bantu-speakers, and Coloured South Africans are descended from indigenous Khoe-San and Bantu-speakers, White Europeans and Indians. Therefore, the distinct genetic backgrounds of the three South African populations may have influenced growth and skeletal asymmetry between the White, Black, and Coloured South African populations. There were no statistically significant differences in absolute asymmetry between the three South African populations for three calcaneal variables (MIDB, DAFL, and MAFB). The lack of statistically significant differences in absolute asymmetry for MIDB, DAFL, and MAFB

were attributed to the inherent genetic similarities between the three South African populations.

In section 5.5.1.2, the statistically significant differences in absolute asymmetry between the three South African population groups for three calcaneal dimensions (MAXL, DAFB, and MAFL) was also attributed to differences in environmental stress. Populations of higher socioeconomic status have higher genetic fitness, i.e. have increased buffering capabilities and, therefore, lower levels of skeletal asymmetry (Storm 2009). Conversely, those in low socioeconomic standing have higher levels of skeletal asymmetry, which has been shown to be related to a lack of access to adequate nutrition and health care, diminished living conditions, and higher risk of disease (Storm 2009). The statistically significant differences in absolute asymmetry between the three South African populations were attributed to the acute socioeconomic differences (i.e. environmental stress) between the groups. White South Africans had favourable living conditions (high socioeconomic status), resulting in lower degrees of absolute asymmetry, while Black and Coloured South Africans had unfavourable living conditions (low socioeconomic status), resulting in higher degrees of absolute asymmetry. However, the lack of statistically significant differences in absolute asymmetry between the three South African populations for three calcaneal variables (MIDB, DAFL, and MAFB) were attributed to the body maintaining optimal homeostasis; under conditions of environmental stress, the body will use more resources to maintain symmetry in the lower limb for stability and locomotion (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997).

As statistically significant differences in values of *M* were found between the three South African groups, the same conclusions can be drawn. The inherent genetic

differences between the White South Africans and Black and Coloured South Africans could have been reflected in the values of *M* for DAFB, which exhibited statistically significant differences between White and Black South Africans, and for MAXL and MAFB, which exhibited statistically significant differences between White and Coloured South Africans. The lack of statistically significant differences in values of *M* for all of the six calcaneal variables between Black and Coloured South Africans can be attributed to the genetic similarities between these two population groups. It is also possible that the varying degrees of environmental stress experienced by White South Africans and Black and Coloured South Africans were reflected in values of *M* for DAFB, which exhibited statistically significant differences between White and Black South Africans, and for MAXL and MAFB, which exhibited statistically significant differences between White and Coloured South Africans. The lack of statistically significant differences in values of *M* between Black and Coloured South Africans for all of the six calcaneal variables can be attributed to the similar environmental stresses experienced by these two populations. It is also possible that the requirement for optimal homeostasis in the lower limb, even though environmental stresses varied between the three South African populations, may explain why not all calcaneal dimensions exhibited statistically significant differences in values of *M*.

Therefore, when developing methods for osteometric pair-matching of calcanei, caution should be given when combining the three South African populations for calculating the statistic *M* for MAXL, DAFB, and MAFL variables, as these variables exhibited statistically significant differences in the values of *M* between White, Black, and Coloured South Africans. However, the three South African populations could be combined when using the statistic *M* for MIDB, DAFL, and MAFB variables as these

variables did not exhibit statistically significant differences in values of *M* between the White, Black, and Coloured South Africans.

5.6.1 Comparisons of left and right calcanei

Assessment of potential pair-matches using the statistic *M* was completed by comparing each of the six measurements from one left calcaneus to each of the six measurements from all right calcanei within each South African ancestral group, with sexes combined. Tables 4.35-4.37 summarize the results of the pairwise comparisons for the White, Black, and Coloured South African populations, respectively. The MAXL variable performed best, i.e. had the greatest reduction in the number of possible pairs while also having an acceptable false rejection rate (approximately 10%, 5%, and 0% for the 90^{th} and 95^{th} percentiles of *M* and maximum value of *M*, respectively) for each pair-matching test within each South African group.

These results can be explained by the low degree of absolute asymmetry in the MAXL dimension for White, Black, and Coloured South Africans. Bone dimensions that exhibit the least asymmetry between bilateral elements are best utilized for osteometric pair-matching because this narrows the possibility of other matches (Garroway 2013). As the MAXL dimension exhibits the lowest degree of asymmetry, in all three South African populations, this variable should be utilized first for osteometric pair-matching within the White, Black, and Coloured South African groups. The MIDB dimension also exhibited a low degree of asymmetry, though a higher degree of asymmetry than MAXL, in all three South African populations. This variable should be utilized second (if MAXL is not available) for osteometric pair-matching within the White, Black, and Coloured South

African groups. Articular surface dimensions, which exhibit greater degrees of asymmetry in all three South African populations, should be utilized for osteometric pair-matching if MAXL and MIDB are not available.

Because MAXL did not exhibit statistically significant differences in absolute asymmetry and values of *M* between sexes, this variable should be utilized first when pair-matching White, Black, and Coloured South African calcanei, with sexes pooled. However, when pair-matching pooled South African populations (i.e. the "Combined South African" group), the MIDB variable should be utilized. Although the MAXL variable performed best, MAXL exhibited statistically significant differences in absolute asymmetry and values of *M* between South African population groups. The MIDB variable had a large reduction in the number of possible pairs while also having an acceptable false rejection rate for each pair-matching test within each South African group. The MIDB variable also exhibited a low degree of asymmetry and did not exhibit statistically significant differences in absolute asymmetry and values of *M* when the three South African population groups were combined. Therefore, the MIDB dimension should be utilized first for osteometric pair-matching calcanei for the "Combined South African" group.

CHAPTER VI: CONCLUSION

The current study focused on six measurements of the calcaneus (Maximum Length (MAXL), Middle Breadth (MIDB), Dorsal Articular Facet Length (DAFL), Dorsal Articular Facet Breadth (DAFB), Middle Articular Facet Length (MAFL), and Middle Articular Facet Breadth (MAFB)) to establish an accurate method for osteometric pair-matching of calcanei in three populations, White, Black, and Coloured South Africans. The goals of this project were to: 1) investigate the degree of asymmetry between left and right calcanei within each individual of the White, Black, and Coloured South African populations, when sexes and populations are pooled, 2) investigate sex differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations pooled, 3) investigate population differences in bilateral asymmetry of calcaneal pairs with sexes separated and White, Black, and Coloured South African populations separated, and 4) use the *M* statistic to assess applicability for pair-matching left and right calcanei in the White, Black, and Coloured South African populations.

The current study utilized two skeletal collections: the Pretoria Bone Collection for the examination of White and Black South African individuals, and the Kirsten Collection for examination of Coloured South Africans. This study examined 419 paired calcanei (419 left calcanei and 419 right calcanei; $N_{calcanei} = 838$) from 419 skeletal cadaveric individuals of White South Africans (70 males, 69 females), Black South Africans (70 males, 70 females) and Coloured South Africans (70 males, 70 females). Individuals were selected at random. The sample consists of adult individuals between the age of 20 years and 103 years of age. Juveniles (<20 years of age) were excluded from

this study because they are not skeletally mature. Individuals were excluded from the sample if there were any trauma, taphonomic damage, or pathologies present to one or both calcanei that would affect the accuracy of calcaneal measurements.

All measurements exhibited statistical normality except for the MAFL dimension, which was attributed to variation in the morphology of the middle articular facet dimensions (see section 5.1.1). The results of the intra-observer and TEM error analyses showed no significant intra-observer differences. The results of the inter-observer error and TEM error analyses showed that only one of the variables (MAFL) showed a significant inter-observer difference and was not within the acceptable range for skilled inter-observer error. It was suggested that caution should be taken when measuring the MAFL variable. Overall, the analyses indicated accurate repeatability of all measurements except MAFL.

The primary conclusions of this thesis are:

- When sexes and populations were pooled, the results showed that, on average, MAXL and MIDB variables are more symmetrical. The variable MAXL exhibited the smallest range of directional asymmetry and smallest average percentage absolute asymmetry. The variable MIDB also exhibited a small range of directional asymmetry and small average percentage absolute asymmetry. The results demonstrated that MAXL and MIDB are more genetically controlled during growth and development of the foot throughout ontogeny.
- When sexes and populations were pooled, the variables DAFL, DAFB, MAFL, and MAFB exhibited larger ranges of directional asymmetry and absolute asymmetry than

MAXL and MIDB. These results demonstrated that articular surface dimensions are influenced more by biomechanical and environmental stress than MAXL and MIDB.

- When sexes were pooled and populations were separated, side-bias (i.e. left- or right-bias) was not statistically significant in most calcaneal dimensions, which was attributed to relatively equal mechanical loading on both feet to maintain symmetry (Auerbach and Rudd 2006; Plochocki 2004).
- When sexes were separated and populations were pooled, differences in directional asymmetry between males and females was only exhibited in the MAFB dimension. These results demonstrated that sex differences in labour/activity were not reflected in most calcaneal dimensions. This was attributed to the requirement for similar mechanical loading on both feet, even under different labour conditions (Auerbach and Ruff 2006; Plochocki 2004).
- When sexes were separated and populations were pooled, differences in absolute asymmetry between males and females were not exhibited in any of the six calcaneal dimensions. These results demonstrated that while males and females may experience different environmental stresses, they are not reflected in calcaneal dimensions. This was attributed to the body using more resources to maintain optimal homeostasis in the lower limb under conditions of environmental stress (Clarke 1993; Møller and Swaddle 1997; Pomiankowski 1997).
- When sexes were pooled and populations were separated, differences in directional asymmetry between White, Black, and Coloured South African populations was not exhibited in any of the six calcaneal dimensions. These results demonstrated that population differences in labour/activity were not reflected in most calcaneal

dimensions. This was attributed to the requirement for similar mechanical loading on both feet, even under different labour conditions (Auerbach and Ruff 2006; Plochocki 2004).

- When sexes were pooled and populations were separated, differences in absolute asymmetry between the three South African populations was exhibited in three calcaneal dimensions (MAXL, DAFB, and MAFL). This was, in part, attributed to inherent genetic differences between the three South African populations. These results were also attributed to acute socioeconomic differences; White South Africans had favourable living conditions (high socioeconomic status), resulting in lower degrees of absolute asymmetry, while Black and Coloured South Africans had unfavourable living conditions (low socioeconomic status), resulting in higher degrees of absolute asymmetry.
- Pair-matching calcanei of White, Black, and Coloured South Africans populations is possible using the 90^{th} and 95^{th} percentiles of *M* and maximum *M* for calcaneal dimensions (Tables 4.30-4.32). The MAXL variable performs best, i.e. had the greatest reduction in the number of possible pairs (up to 88%) while also having an acceptable false rejection rate (approximately 10%, 5%, and 0% for the 90^{th} and 95^{th} percentiles of *M* and maximum value of *M*, respectively) for each pair-matching test within each South African group.
- When sexes were separated and populations were pooled, sex differences in values of *M* were not statistically significant for any of the six calcaneal variables. Therefore, pair-matching of calcanei can be completed using the values of *M* for pooled sexes in the White, Black, and Coloured South African groups.

- When sexes were pooled and populations were separated, population differences in values of *M* were statistically significant for variables MAXL, DAFB, and MAFB. Therefore, when pair-matching calcanei of pooled South African populations (i.e. the "Combined South African" group), the values of *M* for MIDB should be utilized.

As the calcaneus has been understudied for osteometric sorting methods, this research provides a more extensive evaluation of bilateral asymmetry in the calcaneus. Overall, the results of the current study demonstrated that the calcaneus, though influenced by genetic, biomechanical, and environmental stressors, maintains a low degree of asymmetry in its dimensions due to canalization, bipedal locomotion, and developmental stability. When developing a method for pair-matching, bone dimensions that exhibit the least asymmetry between bilateral elements are best utilized for osteometric pair-matching because this narrows the possibility of other matches (Garroway 2013). Therefore, variables MAXL and MIDB, which exhibit the least amount of asymmetry and are more canalized than articular facet dimensions of the calcaneus, should be utilized for osteometric pair-matching.

The results of this study highlight the need for evaluating sex differences and population differences in asymmetry when developing methods for osteometric pair-matching. While sex differences in calcaneal asymmetry were not found in the current study, evaluating for sex differences is an important step in future studies. Some calcaneal dimensions exhibited statistically significant differences in absolute asymmetry between the White, Black, and Coloured South African population groups, therefore future research should test for population differences in skeletal asymmetry. As genetic, biomechanical, and environmental stress may differ significantly between population

groups, this may negatively influence the establishment of a “typical” size relationship (i.e. asymmetry). Therefore caution should be taken in the future when developing osteometric pair-matching methods using pooled population data.

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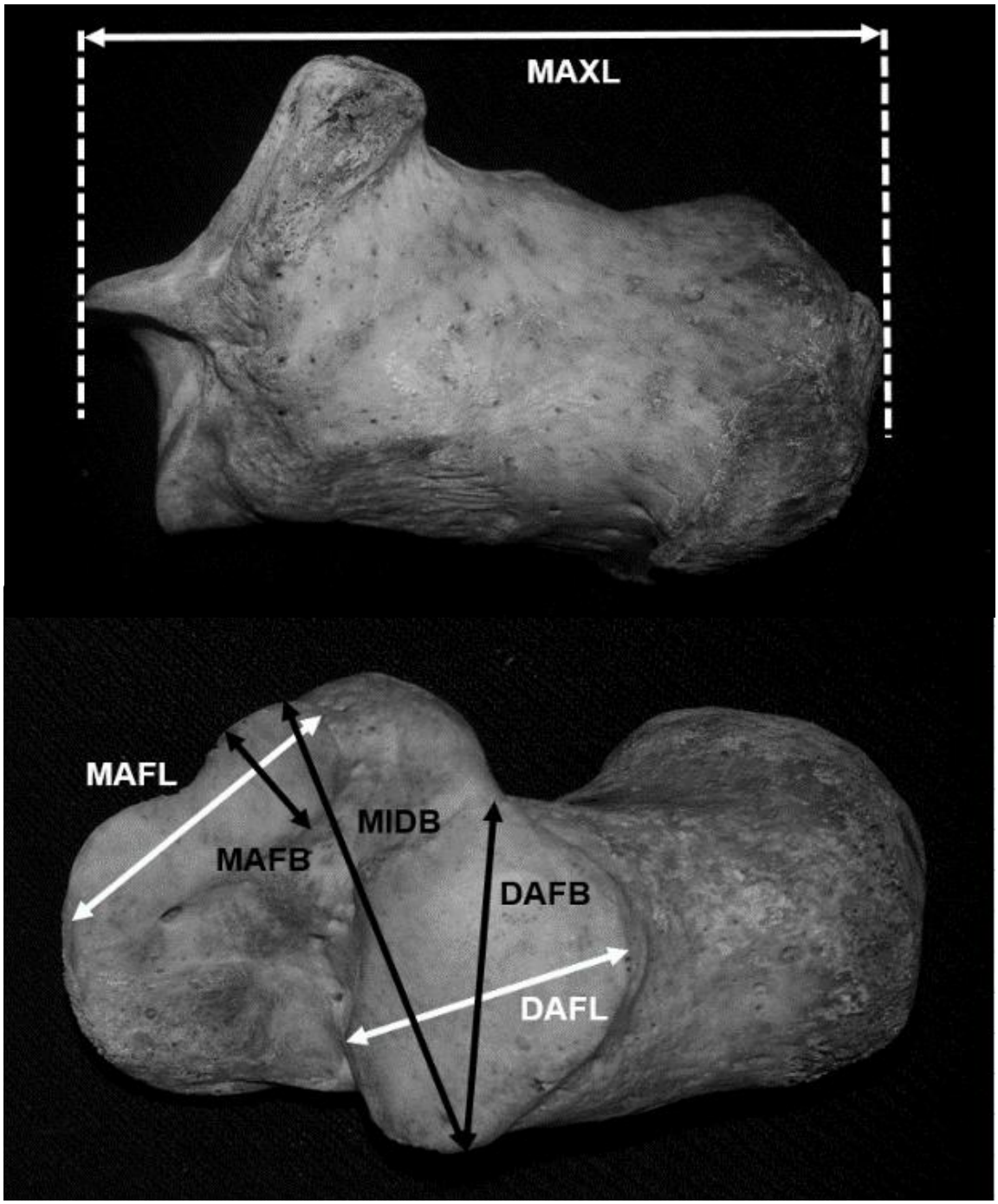
APPENDICES

APPENDIX A: MEASUREMENT DEFINITIONS

Variable	Description	References
MAXL	The distance between the most posteriorly projecting point on the tuberosity and the most anterior point on the superior margin of the articular facet for the cuboid measured in the sagittal plane	modified from Martin 1928 in Steele 1976
DAFL	Distance between the most posterior and the most anterior points on the posterior articular facet of the calcaneus	modified from Martin 1988 in Bidmos 2006b
DAFB	Distance from the most medial to the most lateral points on the posterior articular facet	modified from Martin 1988 in Bidmos 2006b
MIDB	The distance between the most laterally projecting point on the dorsal articular facet and the most medial point on the **middle articular facet***	modified from Martin 1928 in Steele 1976
MAFL	Length of the middle articular facet centered along the long axis of the facet, when middle articular facet is not bipartite, the measurement is taken from the most anterior point to the most posterior point of the entire facet centered along the long axis	Orr (present study)
MAFB	Maximum breadth of middle articular facet perpendicular to MAFL axis	Orr (present study)

**sustenaculum tali* in original definition by Martin 1928 in Steele 1976



Lateral view (top photo) and superior view (bottom photo) of a typical calcaneus depicting the measurements MAXL, DAFL, DAFB, MIDB, MAFL, and MAFB. (Photo by Kayla L. Orr)

Appendix B. Raw data collected from Pretoria Bone Collection and Kirsten Collection
(Biological Affinity: W = White South African, B = Black South African, C = Coloured South African; Sex: 1 = male, 2 = female)

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1014	W	1	85.63	84.77	41.81	42.07	33.06	33.42	31.34	32.18	21.52	22.39	12.48	12.17
1016	W	1	85.36	85.58	44.67	44.30	30.24	30.13	32.21	32.51	23.37	21.74	14.15	14.54
1444	W	1	84.47	85.26	45.41	44.39	33.12	33.92	35.86	35.67	20.40	19.28	13.02	12.56
1419	W	1	82.75	81.98	42.24	42.55	30.68	29.54	30.15	29.92	32.95	31.27	10.89	10.87
1442	W	1	77.17	77.03	39.18	38.86	28.70	28.29	29.26	29.36	16.42	16.32	11.22	10.45
1417	W	1	80.63	80.12	38.86	39.53	28.80	29.61	26.38	25.73	20.28	20.44	10.93	10.56
1347	W	1	87.51	86.24	42.63	42.87	32.86	33.88	34.33	34.16	19.22	19.60	12.84	13.32
1436	W	1	85.64	85.29	42.78	44.03	29.83	32.26	29.38	29.92	32.99	32.37	10.99	11.08
1290	W	1	88.60	88.32	45.75	46.81	33.96	34.88	31.37	29.53	21.35	37.53	12.92	13.25
1292	W	1	85.14	85.24	43.76	44.95	31.57	31.69	33.42	33.45	22.72	21.63	11.50	11.46
1139	W	1	77.83	77.32	35.60	35.61	25.22	25.13	26.24	26.64	13.84	15.01	10.09	10.66
1256	W	1	89.49	89.28	44.99	44.34	35.43	35.18	37.58	37.96	19.93	20.99	12.48	12.46
1522	W	1	85.48	86.32	43.59	44.03	29.84	29.53	33.82	35.01	20.89	21.23	10.86	10.37
1218	W	1	82.31	82.11	40.46	40.93	30.59	31.27	32.39	34.31	15.19	14.93	9.91	9.54
1468	W	1	88.93	86.75	41.42	40.36	31.91	31.58	36.98	36.48	16.57	16.72	10.92	10.20
1435	W	1	86.63	85.47	43.94	44.60	33.61	33.17	30.91	29.39	19.98	21.77	13.13	14.04
1285	W	1	86.42	85.89	44.90	45.08	32.22	32.32	27.72	27.76	22.59	36.35	13.25	13.15
1122	W	1	83.71	84.54	44.61	44.36	31.61	31.38	29.37	30.21	23.54	23.92	12.36	12.38
1075	W	1	86.85	86.54	39.31	39.45	32.39	32.21	31.61	30.52	16.35	16.36	11.62	11.47
1753	W	1	79.01	79.77	38.43	37.98	27.83	29.83	31.49	31.35	4.66	28.72	10.26	11.32
1272	W	1	82.43	83.41	42.72	41.80	32.66	33.03	33.30	33.45	21.87	22.53	12.70	13.00
1907	W	1	77.14	77.14	40.79	41.18	27.90	27.75	31.21	31.28	20.55	19.93	11.46	12.42
1086	W	1	79.73	79.66	40.22	40.68	28.44	28.50	30.80	31.51	29.48	30.21	10.92	11.57
1536	W	1	88.79	91.60	44.91	45.16	34.54	35.00	33.17	33.12	22.34	23.19	12.36	13.16

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1126	W	1	84.18	83.85	38.33	38.79	30.44	29.96	32.42	32.47	17.48	17.80	10.87	9.82
1291	W	1	85.69	83.97	43.62	43.72	31.82	33.01	31.85	33.47	33.72	33.69	13.22	12.54
1909	W	1	79.86	81.38	45.12	44.89	30.87	31.53	32.85	32.66	19.55	19.25	10.72	12.01
1091	W	1	89.02	87.00	43.70	42.16	36.07	36.92	35.56	33.25	18.18	18.71	10.55	11.58
1221	W	1	85.57	85.43	41.39	40.69	29.46	30.33	30.92	31.80	18.97	18.70	11.30	11.09
1475	W	1	89.10	91.68	43.78	46.07	31.50	33.10	35.67	35.16	34.28	36.88	10.93	11.43
1231	W	1	83.21	83.29	41.04	41.31	31.76	32.16	32.49	32.96	19.28	19.05	13.28	12.37
1229	W	1	79.28	79.20	40.05	41.66	27.77	27.88	31.95	31.65	18.52	33.09	10.57	10.97
1759	W	1	91.12	92.07	44.54	44.39	31.93	33.03	35.86	37.24	20.15	19.88	11.69	11.22
1214	W	1	79.46	78.65	42.44	42.59	29.03	29.57	31.92	31.89	19.03	19.67	12.48	12.89
1213	W	1	82.64	82.66	40.48	39.83	28.86	27.01	33.07	32.89	31.54	30.79	13.37	13.27
1305	W	1	88.76	86.89	44.90	43.24	29.56	29.28	33.26	33.17	25.44	24.43	12.59	11.02
1242	W	1	88.60	88.62	41.99	42.47	30.21	31.11	32.11	31.54	30.29	14.34	11.89	12.79
1099	W	1	87.93	87.94	43.40	43.36	31.10	31.34	31.72	32.94	38.07	38.34	12.52	12.23
1565	W	1	85.64	85.71	44.63	44.25	33.01	33.28	30.37	29.17	21.77	22.88	12.71	12.01
1501	W	1	85.67	85.39	41.14	40.72	30.72	30.24	30.30	31.75	31.34	29.71	11.52	11.13
1355	W	1	82.33	82.29	41.45	41.56	32.31	32.44	33.41	33.21	31.00	31.44	10.04	10.10
1377	W	1	90.18	90.18	44.32	44.89	33.43	33.42	36.35	35.29	31.27	22.25	11.46	12.48
1637	W	1	84.61	84.65	44.25	44.61	31.47	31.03	34.97	34.20	33.24	21.75	13.13	13.56
1657	W	1	88.00	88.43	45.56	46.15	34.46	34.49	28.36	27.91	34.27	34.26	13.44	13.28
1101	W	1	84.31	84.29	38.83	39.08	27.37	28.51	28.21	28.24	28.49	29.24	11.68	11.74
1997	W	1	95.39	95.18	46.53	47.46	33.85	35.37	35.65	36.84	21.76	22.45	12.80	13.20
1130	W	1	91.59	91.84	47.46	48.58	34.50	34.01	39.31	39.65	21.73	22.79	13.08	13.09
1394	W	1	87.71	88.88	40.72	39.47	30.91	30.97	32.72	31.36	16.60	17.29	11.80	11.30
1526	W	1	90.78	91.97	45.08	46.06	32.95	32.95	35.93	37.62	35.20	35.43	11.56	11.83
1954	W	1	87.90	88.05	44.73	44.92	32.81	32.72	33.55	34.07	22.05	22.88	12.86	12.89
1215	W	1	90.84	91.31	46.16	45.41	34.01	34.51	36.02	35.27	35.14	35.58	14.58	13.09

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1995	W	1	103.39	104.42	46.79	47.76	34.69	35.05	38.06	38.43	34.63	34.76	11.22	12.47
1671	W	1	87.58	87.18	45.41	43.58	33.38	30.71	34.97	32.80	22.95	22.31	12.85	12.81
1212	W	1	85.48	85.84	39.73	39.64	32.76	32.19	29.78	30.15	11.83	11.82	8.89	7.57
1530	W	1	89.52	90.58	40.86	41.26	34.31	35.62	33.08	34.68	18.79	19.45	12.35	12.25
1298	W	1	90.85	90.90	43.30	43.37	31.45	31.32	30.68	29.56	20.51	21.87	12.52	12.41
1082	W	1	90.52	90.48	44.62	44.92	32.67	34.08	32.46	33.41	34.12	34.26	13.63	13.78
1471	W	1	81.48	81.27	38.77	40.13	28.72	29.97	28.82	28.53	28.62	28.82	11.21	12.18
1861	W	1	88.36	89.09	42.62	43.40	31.29	33.12	34.45	34.41	34.18	35.54	13.36	13.35
1411	W	1	90.19	89.71	43.96	42.67	33.03	33.08	34.77	35.32	33.86	32.51	12.40	11.18
1385	W	1	87.60	87.71	43.40	42.23	32.26	32.95	31.30	31.05	32.12	33.16	13.39	13.21
1230	W	1	89.92	90.05	44.77	44.42	31.09	32.20	36.62	35.08	19.43	19.95	13.38	13.88
1624	W	1	84.14	84.20	45.00	45.39	33.83	33.39	34.16	33.82	37.82	38.38	13.76	14.25
1513	W	1	87.31	87.52	44.71	45.08	33.36	33.27	38.79	38.54	34.50	34.47	12.14	12.95
1992	W	1	88.61	88.46	38.14	38.14	31.70	31.41	33.52	31.21	16.12	15.76	10.05	9.90
1775	W	1	92.42	94.09	49.52	49.87	36.39	34.66	38.33	37.56	26.29	24.69	13.07	12.41
1068	W	1	82.25	82.26	42.97	40.77	30.96	30.97	33.53	33.80	19.50	18.48	9.83	10.32
1149	W	1	87.54	88.18	43.01	43.67	30.02	30.29	30.02	31.32	23.33	22.24	11.73	11.80
1455	W	1	82.76	82.94	41.13	41.92	33.59	33.50	30.40	30.58	35.01	35.56	12.38	12.96
1224	W	1	91.33	90.58	44.39	42.36	28.35	28.00	31.52	31.68	18.17	20.24	13.41	11.36
1982	W	2	83.49	84.41	38.91	38.14	29.28	29.97	31.00	30.57	18.96	18.85	10.95	12.38
1853	W	2	85.41	85.23	41.23	43.56	31.63	32.68	29.81	31.41	33.12	34.87	11.27	11.45
1927	W	2	77.56	78.40	37.10	38.66	25.53	26.36	27.14	27.75	31.79	19.52	11.64	12.49
1792	W	2	78.26	78.81	36.99	36.79	28.25	27.83	26.63	26.36	14.32	16.17	10.31	11.03
1440	W	2	88.64	87.28	42.10	43.51	29.31	29.33	30.15	31.20	19.03	20.66	10.38	11.22
1415	W	2	82.93	83.29	41.84	41.29	30.83	30.38	31.66	31.98	21.67	22.11	10.27	10.38
1304	W	2	83.82	83.34	39.87	40.09	26.42	28.90	29.05	29.52	18.14	16.75	10.67	10.25
1134	W	2	78.24	78.39	37.36	37.20	28.84	28.92	28.63	28.75	30.91	32.46	11.58	12.78

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1278	W	2	79.36	79.15	41.13	41.54	26.63	27.23	27.93	28.35	30.71	30.65	10.60	11.65
1182	W	2	76.38	76.53	35.94	36.28	27.05	26.25	28.58	28.30	13.76	15.13	10.92	10.80
1266	W	2	80.64	80.54	41.00	40.79	30.03	28.30	29.57	29.89	14.66	16.25	11.45	12.16
1566	W	2	75.00	75.57	38.35	37.22	27.71	27.61	28.65	29.04	29.64	28.80	10.87	10.13
1172	W	2	79.06	77.94	39.10	37.85	28.02	27.97	25.88	25.54	17.69	17.86	11.35	12.91
1174	W	2	74.44	74.25	41.12	41.58	28.23	28.61	24.94	25.92	32.07	31.94	13.76	13.79
1892	W	2	76.79	75.72	39.86	40.96	27.03	27.90	26.96	26.16	17.78	19.03	11.32	13.15
1948	W	2	73.47	73.55	36.94	36.78	26.59	26.33	26.71	26.19	31.21	31.24	11.24	11.33
1106	W	2	81.79	81.48	36.51	36.29	27.46	27.86	30.71	30.72	17.13	19.25	10.46	11.39
1873	W	2	80.77	80.85	40.91	41.08	25.96	25.66	31.00	30.17	29.66	30.66	10.99	11.58
1896	W	2	82.59	81.90	37.97	38.41	27.44	25.65	29.83	29.53	19.69	19.02	12.07	12.55
1107	W	2	78.12	80.06	39.68	38.12	28.43	25.47	25.40	24.58	18.71	19.18	11.77	11.92
1205	W	2	78.51	79.76	39.60	39.45	27.50	29.14	25.56	24.48	29.71	29.48	12.60	12.52
1324	W	2	79.36	79.21	36.96	38.11	28.84	29.85	28.37	27.46	14.66	15.21	10.09	10.87
1227	W	2	80.31	80.71	37.46	37.94	28.64	28.21	26.42	27.41	30.20	31.02	9.67	9.98
1757	W	2	77.82	78.83	37.32	37.31	30.53	30.61	32.32	32.04	30.06	29.94	10.84	11.41
1207	W	2	82.82	82.12	38.26	39.10	26.81	26.24	29.03	29.04	32.87	33.07	10.02	10.18
1337	W	2	86.22	85.89	39.08	39.50	32.10	34.52	31.84	31.59	17.21	16.16	10.22	11.22
1339	W	2	79.46	80.11	39.06	39.19	28.97	29.00	28.62	28.73	28.68	28.28	10.44	10.86
1211	W	2	78.43	78.07	40.34	40.21	25.55	26.52	30.14	29.59	27.82	27.18	10.30	10.34
1410	W	2	80.13	80.76	37.54	37.15	27.58	27.53	25.55	25.81	13.74	14.66	10.52	9.78
1819	W	2	83.46	82.41	41.40	41.03	30.65	30.38	33.48	33.07	18.03	17.94	9.33	9.05
1209	W	2	79.35	79.15	38.24	38.70	25.87	24.57	26.22	27.06	29.73	30.70	11.46	11.26
1722	W	2	84.31	84.96	37.46	36.22	26.75	27.56	27.68	26.83	15.47	28.68	10.96	10.20
1818	W	2	85.75	85.45	42.48	42.71	28.48	28.04	31.23	31.47	30.98	31.17	11.44	11.88
1264	W	2	77.20	76.99	38.54	38.71	27.80	27.63	30.34	30.88	14.74	15.71	10.39	10.94
1341	W	2	82.06	82.13	39.67	40.01	29.12	28.95	29.76	30.54	19.02	19.06	11.08	10.38

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1503	W	2	76.28	76.26	40.89	40.93	26.73	26.78	30.37	30.97	20.91	20.76	9.02	9.22
1832	W	2	79.92	80.25	38.35	38.35	29.76	30.21	30.45	29.83	32.16	31.64	11.14	11.12
1201	W	2	79.93	80.19	41.52	41.46	27.01	26.91	28.19	29.78	20.37	32.58	12.41	11.50
1908	W	2	80.95	80.88	40.04	40.35	29.32	28.14	31.57	30.91	33.33	32.52	10.34	10.57
1550	W	2	80.78	80.89	39.44	40.34	27.29	26.77	28.68	30.73	18.56	19.06	10.96	10.69
1145	W	2	85.65	86.89	40.40	38.52	26.10	27.21	28.46	28.03	18.16	17.07	10.60	10.56
1340	W	2	89.48	88.84	43.33	44.49	33.53	34.72	34.14	34.16	17.93	17.95	11.83	11.94
1177	W	2	83.50	83.54	41.89	41.96	29.18	29.05	31.68	31.86	34.87	33.82	10.16	10.13
1094	W	2	78.97	78.91	39.04	39.85	28.32	28.56	29.18	29.47	17.25	18.30	10.90	10.27
1088	W	2	78.13	78.33	39.72	40.43	29.94	31.46	28.81	28.82	28.35	21.28	11.58	11.86
1751	W	2	77.89	77.91	36.39	36.06	26.75	25.93	25.85	25.65	30.43	29.94	9.57	9.67
1096	W	2	86.37	86.99	37.67	39.85	29.21	28.22	28.07	28.02	13.61	14.37	9.95	10.28
1237	W	2	78.33	78.44	38.25	39.55	29.72	29.65	28.88	28.96	12.27	12.13	9.64	10.13
1928	W	2	78.23	79.28	40.47	41.30	29.39	28.74	28.07	27.95	33.64	33.84	12.06	12.99
1273	W	2	79.99	79.81	40.91	40.89	28.86	28.06	29.97	29.97	18.50	18.19	10.83	10.79
1457	W	2	80.51	79.56	37.45	38.23	28.88	28.67	27.11	26.93	11.55	11.50	11.45	12.41
1703	W	2	79.63	79.55	37.84	38.92	26.20	26.49	27.51	27.46	17.44	18.93	8.89	10.28
1049	W	2	86.94	86.71	43.28	42.95	33.49	34.30	32.41	31.79	19.41	19.47	11.98	11.94
1756	W	2	71.14	71.71	35.97	36.33	24.91	25.56	28.16	28.43	25.29	25.20	10.22	9.73
1143	W	2	75.28	74.20	38.21	38.28	28.89	29.05	28.82	28.32	19.01	20.04	10.19	10.00
1797	W	2	85.39	85.08	42.08	42.14	29.46	30.55	28.89	28.43	32.29	32.96	10.71	10.69
1960	W	2	86.03	86.20	41.99	42.68	31.36	32.08	31.89	32.01	35.31	22.49	12.24	12.25
1898	W	2	75.51	75.93	36.41	36.74	26.97	26.86	28.96	28.81	30.50	30.21	9.35	9.25
1664	W	2	79.95	80.75	41.89	41.65	31.94	31.92	29.72	29.74	29.30	29.56	13.20	13.25
1890	W	2	80.90	80.07	37.73	38.11	30.57	30.57	29.45	29.44	11.21	13.28	9.03	9.64
1352	W	2	82.42	82.73	43.84	42.79	30.74	29.97	34.10	30.96	32.87	32.56	10.82	11.45
1971	W	2	82.02	83.54	40.60	40.41	28.23	28.79	33.54	33.46	17.12	16.85	11.86	11.64

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1460	W	2	83.21	82.72	38.64	38.31	30.14	30.29	29.37	29.32	29.19	28.72	10.75	11.09
1263	W	2	84.42	83.15	39.96	40.59	27.63	26.95	29.11	28.35	15.79	16.01	11.60	11.65
1362	W	2	87.16	88.38	41.10	41.34	28.49	28.45	27.36	27.46	18.46	18.83	11.88	12.03
1807	W	2	79.47	79.51	36.16	38.22	26.31	26.66	26.87	26.85	16.14	27.14	11.66	11.63
1127	W	2	76.48	76.74	39.59	39.60	26.77	27.45	25.14	25.34	15.00	15.82	10.84	10.26
1121	W	2	88.45	87.44	41.06	40.86	28.97	28.67	28.21	28.66	24.78	29.14	10.65	10.96
1727	W	2	72.99	72.67	34.58	34.26	28.59	27.14	26.19	25.44	29.30	28.04	9.50	9.83
1042	B	2	81.66	80.51	41.39	40.68	28.34	28.49	27.49	27.30	21.86	19.35	11.84	11.86
1905	B	2	82.11	81.78	39.62	39.21	28.51	28.32	28.18	26.88	34.84	34.07	10.57	10.94
1903	B	2	75.01	74.94	37.19	36.97	27.53	28.33	26.82	27.85	29.98	30.16	11.19	12.88
1656	B	2	72.88	73.90	38.11	37.92	27.26	27.90	26.61	26.58	30.02	30.24	11.33	11.37
1902	B	2	75.74	75.65	40.57	40.67	26.79	27.86	28.97	28.21	33.12	32.86	11.63	11.95
1623	B	2	73.67	73.42	38.45	38.79	25.98	25.48	26.96	25.87	30.02	30.11	12.73	13.23
1901	B	2	70.76	70.95	36.98	37.82	24.24	24.46	24.39	24.79	29.63	29.95	11.98	11.85
1780	B	2	78.55	78.58	43.07	42.93	29.39	29.44	29.59	29.82	32.21	33.02	12.96	13.53
1779	B	2	83.71	83.93	44.16	43.86	29.45	29.52	28.62	28.38	32.99	33.18	12.53	13.21
1778	B	2	77.42	77.66	38.54	38.35	26.84	26.15	24.35	24.68	27.75	27.81	13.48	13.38
1777	B	2	79.04	78.94	37.99	39.49	27.77	28.45	26.48	25.81	32.35	33.52	11.81	11.83
1820	B	2	78.57	79.58	41.36	41.65	29.42	29.90	26.86	27.41	17.65	16.97	10.97	10.53
1817	B	2	73.43	72.81	38.79	39.25	25.92	24.71	29.21	27.48	28.07	28.37	10.43	10.61
1636	B	2	76.46	77.68	41.79	41.17	29.27	28.87	26.80	26.81	19.94	21.34	12.27	12.37
1825	B	2	75.14	73.76	36.78	37.33	25.53	26.91	24.96	24.23	17.19	29.65	11.21	10.43
1732	B	2	69.75	70.81	34.29	34.17	23.24	21.75	23.01	23.02	17.57	29.47	10.74	9.94
1719	B	2	71.55	71.50	38.71	38.48	24.52	25.53			31.02	31.53	11.79	12.80
1771	B	2	72.82	72.87	37.34	38.57	27.00	28.36	23.96	22.67	31.43	31.84	11.94	12.13
1755	B	2	86.75	86.41	40.01	39.43	26.82	25.03	29.67	28.33	18.00	17.41	11.03	11.52

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1710	B	2	77.94	77.97	36.34	36.50	26.76	27.30	24.16	23.87	30.03	29.23	11.85	11.41
1840	B	2	75.48	75.61	38.56	36.79	25.91	26.59	26.95	25.45	28.10	27.12	10.01	9.82
1026	B	2	80.89	81.56	40.29	40.88	30.01	31.59	29.04	28.92	21.30	31.01	12.17	12.35
1885	B	2	79.86	79.96	41.91	41.11	29.87	28.12	27.94	26.98	33.78	34.38	12.36	11.91
1881	B	2	71.49	71.63	36.55	37.47	24.75	25.14	28.15	28.78	28.25	29.48	10.95	10.79
1043	B	2	75.48	75.74	39.20	38.79	27.44	27.23	25.05	23.79	16.92	16.50	11.03	10.40
1883	B	2	74.66	72.24	38.44	38.64	27.03	27.97	26.54	27.00	29.25	29.64	11.09	10.00
1185	B	2	79.76	79.65	38.06	38.32	27.91	27.74	26.67	26.41	31.47	31.92	10.46	10.81
1045	B	2	81.58	81.42	42.73	43.28	29.52	29.95	25.51	25.84	18.94	19.71	15.09	15.16
1467	B	2	73.67	73.16	35.05	35.88	25.85	26.20	24.17	22.95	30.05	31.17	10.32	10.13
1275	B	2	79.10	79.91	37.87	38.38	26.93	27.86			17.18	28.91		
1532	B	2	80.35	80.23	40.25	40.93	31.55	31.56	28.87	28.18	19.49	19.23	11.85	12.86
1381	B	2	71.14	70.68	36.56	36.60	23.57	23.43	22.55	23.65	17.50	27.17	9.10	10.08
1313	B	2	81.29	80.83	37.37	37.04	27.74	27.59	27.16	26.18	31.99	29.94	11.41	11.45
1429	B	2	75.99	76.60	36.51	36.77	25.12	25.01	23.17	23.12	30.53	29.71	11.49	11.46
1002	B	2	70.36	71.51	34.50	35.32	23.79	24.21	25.97	26.22	26.13	26.62	10.13	10.53
1013	B	2	77.48	76.73	38.07	38.61	27.42	27.41	26.06	25.42	30.29	30.75	12.10	12.14
1019	B	2	72.23	74.67	36.00	36.33	30.17	30.05	27.51	26.96	24.62	24.03	7.99	9.21
1020	B	2	76.38	76.28	38.77	38.94	26.08	26.10	25.83	25.27	31.73	31.13	12.88	12.92
1015	B	2	74.71	74.86	36.32	36.76	26.82	26.36	27.47	26.77	18.87	17.63	11.58	12.40
1017	B	2	66.20	66.74	36.17	36.56	22.44	22.83	22.43	22.27	29.71	29.36	11.06	11.39
1021	B	2	72.35	72.28	36.76	37.18	25.23	24.91	25.58	23.27	28.29	29.00	12.07	11.91
1022	B	2	72.88	73.18	35.90	37.14	26.12	26.61	27.11	28.09	29.43	30.87	9.06	10.04
1024	B	2	74.33	75.12	40.40	40.19	23.95	27.18	24.70	25.04	31.36	31.05	11.67	11.54
1025	B	2	81.10	81.07	39.00	39.72	26.61	26.50	28.00	25.35	18.28	30.00	11.01	10.89

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1028	B	2	78.10	78.24	39.96	38.79	25.00	24.46	27.98	26.39	32.99	32.32	10.89	11.28
1409	B	2	72.44	73.28	37.68	38.47	29.22	27.39	29.81	25.83	18.65	29.41	12.01	14.41
1003	B	2	67.46	67.64	38.09	38.45	25.15	25.35	23.91	23.57	28.75	28.81	10.85	10.93
1034	B	2	81.24	80.72	40.95	40.68	30.03	30.15	27.47	26.86	30.54	28.92	12.42	12.40
1570	B	2	73.47	73.23	37.36	36.98	28.03	29.03	23.54	23.10	30.62	30.61	11.91	12.44
1673	B	2	76.65	76.91	37.35	38.18	25.71	25.50	21.78	22.29	31.96	32.81	11.72	12.30
1413	B	2	74.03	73.32	38.51	39.58	26.28	26.45	26.89	27.34	15.25	18.34	11.46	11.77
1545	B	2	77.19	78.00	40.32	41.38	27.77	29.02	25.56	25.11	32.32	32.30	12.14	12.32
1399	B	2	73.74	72.50	39.60	40.19	25.86	26.42	30.06	28.43	30.14	30.01	11.20	12.53
1041	B	2	87.43	88.49	43.10	44.32	34.32	34.65	31.41	30.78	18.12	18.73	11.21	11.66
1670	B	2	85.40	86.20	43.14	43.41	29.55	27.59	29.72	27.16	17.98	33.33	13.94	14.36
1039	B	2	75.16	74.26	39.33	39.02	27.60	26.24	26.66	27.05	14.15	28.69	11.02	10.98
1593	B	2	74.51	74.05	38.22	37.58	28.37	28.03	24.67	25.08	30.80	31.97	12.17	12.64
1708	B	2	78.43	76.73	37.05	37.31	25.32	24.28	24.69	23.91	31.01	31.52	11.61	11.75
1602	B	2	77.48	77.21	39.38	38.49	27.84	27.72	23.36	25.41	31.91	32.06	11.26	11.28
1607	B	2	75.27	75.39	35.99	36.63	24.34	24.03	24.75	24.99	27.86	27.98	11.10	11.90
1544	B	2	76.36	77.12	43.78	44.46	29.53	31.74	28.25	29.49	20.00	20.15	13.94	13.85
1574	B	2	69.53	70.23	33.91	33.63	24.87	25.44	23.98	23.90	15.99	15.28	10.07	10.34
1697	B	2	69.68	70.27	35.38	36.14	23.82	23.93	24.33	24.83	29.23	29.15	11.45	11.71
1688	B	2	71.79	70.26	37.93	38.34	26.01	26.76	26.20	25.48	32.20	31.91	11.98	11.78
1617	B	2	67.10	67.82	34.31	34.34	27.52	27.15	26.40	26.24	29.76	30.21	11.09	11.32
1005	B	2	74.61	74.13	36.37	36.52	24.77	25.17	24.30	23.92	29.41	29.08	11.48	12.36
1006	B	2	78.83	79.16	37.19	37.75	29.55	29.90	28.88	28.94	34.21	34.72	10.35	10.86
1485	B	2	74.34	74.21	37.13	37.79	29.28	29.48	26.34	26.33	33.05	33.26	10.70	12.07
1642	B	2	78.12	78.39	40.41	40.89	27.96	28.97	28.21	28.17	32.94	33.33	12.16	12.62

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1427	B	2	79.77	79.62	41.60	41.80	25.88	25.60	30.89	29.58	33.27	33.90	10.19	10.39
1294	B	1	83.57	83.46	43.55	44.21	33.83	32.48	29.94	29.41	20.46	22.47	12.47	14.17
1040	B	1	81.46	81.86	42.19	42.28	26.36	26.10	28.01	28.03	19.90	19.13	12.34	12.43
1372	B	1	74.21	74.24	36.31	35.24	27.99	28.57	26.01	24.75	28.96	28.01	10.24	9.67
1018	B	1	77.64	77.49	42.35	43.15	28.74	28.24	28.05	28.26	20.09	24.21	11.53	10.69
1387	B	1	82.32	81.36	46.84	46.62	28.28	28.41	27.46	26.73	34.39	25.41	15.13	15.09
1306	B	1	79.46	80.24	42.11	41.31	29.99	30.87	28.75	28.11	32.26	32.91	13.73	13.75
1281	B	1	89.66	88.89	43.57	44.01	30.63	30.91	33.84	34.48	30.88	18.26	13.21	14.01
1314	B	1	82.46	83.94	41.87	42.11	30.58	29.65	30.34	29.40	34.10	37.67	12.97	13.57
1184	B	1	86.88	86.89	43.66	43.16	29.10	30.64	28.01	28.52	31.97	31.25	12.04	11.49
1206	B	1	79.44	79.03	43.81	42.33	30.05	30.98	29.34	29.64	21.24	21.19	12.88	12.93
1120	B	1	80.41	81.59	41.17	42.37	28.48	28.50	28.21	26.14	22.35	32.63	11.26	12.42
1368	B	1	85.13	86.02	42.18	41.95	29.78	29.40	28.78	28.27	35.35	34.58	13.78	14.78
1528	B	1	78.58	78.26	39.61	41.31	30.01	30.75	27.49	26.93	34.99	35.71	10.29	11.24
1208	B	1	87.47	88.63	45.94	46.48	34.17	36.02	33.79	34.89	34.28	34.41	14.90	14.44
1142	B	1	92.44	91.42	46.83	47.84	34.85	35.28	32.60	34.51	22.95	22.86	14.58	14.70
1523	B	1	81.15	82.29	39.66	39.99	28.56	28.53	27.82	28.72	30.29	30.14	10.23	10.18
1196	B	1	77.26	77.63	43.48	43.95	28.80	28.04	29.53	29.64	34.55	35.20	11.89	11.94
1170	B	1	79.56	78.89	39.58	39.37	26.10	26.64	29.97	29.62	29.53	32.39	12.29	12.61
1116	B	1	81.33	82.88	44.23	44.42	31.54	32.63	28.36	28.59	19.93	19.49	13.46	13.42
1863	B	1	80.65	80.05	41.33	40.78	28.04	28.45	28.84	29.08	30.02	30.25	11.44	11.56
1396	B	1	89.20	91.86	47.80	48.03	32.29	34.13	31.23	31.42	34.29	38.83	12.57	12.91
1092	B	1	75.47	76.06	39.58	40.05	29.82	29.25	26.09	26.18	20.33	20.71	13.05	13.23
1090	B	1	84.95	85.05	42.02	40.56	29.69	30.69	29.41	30.48	35.54	35.43	11.17	10.56
1859	B	1	86.37	86.30	44.84	44.94	32.43	32.64	29.32	28.68	35.83	26.44	13.25	12.63

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1573	B	1	84.55	87.56	42.44	43.21	28.52	29.24	31.64	31.93	22.77	22.58	11.75	11.12
1154	B	1	77.61	78.59	40.24	40.33	26.93	27.07	23.66	23.87	34.61	34.80	13.22	13.20
1998	B	1	92.64	92.74	41.19	41.53	27.29	27.57	26.00	26.18	23.65	23.47	14.54	13.66
1575	B	1	86.99	86.93	44.78	44.74	28.70	29.33	28.63	27.03	37.93	37.49	14.69	14.42
1592	B	1	82.78	82.89	42.92	43.71	28.37	28.00	30.57	30.47	37.30	37.44	12.87	12.65
1110	B	1	87.52	88.02	41.45	41.67	30.95	30.91	28.58	29.43	21.38	20.77	11.26	11.04
1595	B	1	82.61	83.54	45.03	45.39	29.41	28.55	33.55	33.77	34.84	35.49	13.17	13.14
1543	B	1	90.11	90.16	43.77	42.75	34.09	33.53	28.86	29.38	21.40	21.29	12.70	13.41
1072	B	1	74.74	75.88	35.88	35.95	26.72	26.21	27.69	27.59	14.34	14.34	10.31	10.06
1552	B	1	82.73	82.77	40.31	40.33	28.46	28.32	27.22	27.10	21.10	20.78	13.42	13.68
1618	B	1	79.46	79.71	41.96	43.81	31.26	31.53	29.66	31.11	33.40	33.51	10.23	10.01
1614	B	1	79.82	78.53	43.61	43.79	28.13	27.53	29.36	29.83	35.51	35.30	11.26	11.31
1661	B	1	86.62	86.77	44.56	45.92	33.27	33.60	31.16	31.49	18.86	21.53	13.18	14.52
1029	B	1	88.64	88.83	43.28	42.70	34.32	33.74	31.89	32.89	20.58	20.46	13.00	12.28
1033	B	1	70.91	71.29	38.54	38.20	26.49	26.87	25.35	24.93	32.12	32.89	13.33	12.83
1493	B	1	89.70	90.50	43.94	44.24	32.34	33.38	29.30	28.12	39.65	38.42	13.77	14.49
1494	B	1	78.17	79.32	42.08	42.71	27.46	27.47	28.27	28.48	33.68	34.32	12.27	12.47
1500	B	1	87.05	85.93	43.35	43.40	30.48	30.95	33.38	32.45	34.61	34.47	12.82	12.89
1855	B	1	94.31	92.79	46.52	47.25	31.12	32.36	32.82	32.81	35.26	35.03	9.40	10.08
1651	B	1	87.67	88.20	45.67	46.18	32.47	32.42	29.06	29.85	36.04	34.59	14.74	14.89
1951	B	1	85.50	85.61	43.06	42.45	32.10	32.16	27.79	28.05	36.41	36.65	14.02	14.29
1620	B	1	81.39	81.97	45.38	44.29	33.84	32.85	31.24	30.26	21.32	21.92	13.32	14.45
1539	B	1	74.26	74.76	41.32	40.99	26.50	28.07	28.65	28.27	29.83	29.29	13.07	12.93
1956	B	1	77.87	77.59	41.33	41.63	31.15	31.16	27.95	27.03	29.56	31.43	11.63	11.20
1981	B	1	87.49	86.48	45.72	46.72	31.86	32.36	29.36	32.69	36.29	35.64	13.08	12.85

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
1741	B	1	82.88	82.32	43.46	43.76	29.75	29.06	29.45	30.57	35.00	34.87	13.52	12.73
1985	B	1	83.47	83.51	45.22	45.17	30.35	29.66	34.78	33.76	32.93	32.77	13.11	12.83
1944	B	1	82.20	82.62	44.11	44.44	29.99	29.72	32.54	31.78	34.77	34.27	13.48	13.52
1800	B	1	82.18	81.98	40.44	41.14	29.59	30.73	27.87	27.40	32.26	32.96	13.51	14.04
1834	B	1	84.66	83.69	43.56	41.81	33.71	32.64	33.93	33.12	34.51	34.83	13.09	14.20
1959	B	1	79.57	79.38	42.19	42.07	29.03	29.85	30.46	30.22	22.52	22.76	11.30	11.71
1831	B	1	81.33	82.38	43.79	44.22	33.16	33.26	32.27	32.41	23.01	35.87	15.03	13.12
1793	B	1	81.05	80.56	40.96	41.11	30.34	30.43	30.74	29.96	32.68	32.13	12.15	11.89
1946	B	1	76.66	76.67	38.07	39.05	27.85	27.75	26.78	26.73	32.64	32.55	11.53	11.35
1376	B	1	83.37	82.83	40.79	41.69	27.69	26.65	27.94	28.55	33.16	33.86	11.41	11.54
1893	B	1	90.69	90.10	48.45	48.04	32.72	32.80	35.34	33.67	38.16	37.44	14.58	13.85
1957	B	1	82.44	82.45	43.21	42.23	33.85	33.32	29.89	29.34	34.31	33.89	12.32	12.66
1936	B	1	81.99	82.00	46.30	45.98	32.86	33.87	34.36	33.48	37.72	36.24	14.47	14.28
1799	B	1	82.33	81.63	44.59	42.95	27.83	28.09	28.53	26.69	22.21	22.22	14.88	15.15
1715	B	1	81.89	81.27	39.88	39.98	32.16	32.70	28.64	30.21	20.21	20.16	9.71	9.33
1629	B	1	74.30	74.35	40.99	41.09	21.61	22.53	29.65	30.01	20.90	30.42	12.16	12.97
1833	B	1	77.08	77.66	42.57	41.19	29.80	29.51	32.14	31.82	34.17	31.87	12.61	12.10
1823	B	1	77.40	76.69	40.54	39.34	31.01	31.04	27.45	27.53	35.58	34.49	11.98	12.49
1766	B	1	80.10	80.25	44.97	44.16	32.89	32.84	31.11	30.42	21.35	21.38	10.53	10.56
1113	B	1	91.18	91.37	47.18	48.43	33.64	35.36	31.84	29.00	23.65	22.05	14.69	15.28
1282	B	1	79.12	79.32	40.19	40.14	30.71	31.35	26.59	25.02	37.07	36.29	13.29	14.42
356	C	1	82.15	83.65	44.31	43.74	31.29	28.07	33.85	33.91	35.86	37.87	13.14	14.01
370	C	1	79.18	79.23	41.38	41.69	30.39	29.78	28.19	27.02	33.79	34.48	11.14	13.42
378	C	1	74.75	75.96	39.95	38.25	30.17	29.70	27.86	27.22	33.14	32.35	12.96	11.86
382	C	1	88.66	88.66	45.64	46.03	32.65	32.52	36.22	36.16	38.17	37.97	12.49	13.64

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
385	C	1	83.34	85.83	41.86	43.01	29.58	30.63	29.29	28.67	33.02	32.54	12.85	14.12
389	C	1	79.46	78.96	40.64	40.87	29.55	27.26	25.62	26.06	30.62	32.26	11.79	11.67
390	C	1	76.84	77.06	41.38	41.38	27.24	27.31	26.16	26.53	20.75	20.66	11.88	12.05
391	C	1	80.24	79.32	43.10	42.94	29.77	31.31	28.27	28.45	21.33	19.74	11.45	11.22
394	C	1	80.74	81.32	40.27	40.52	28.68	29.87	27.56	27.54	31.82	30.54	12.72	12.36
396	C	1	82.97	83.06	41.02	42.36	31.26	30.97	29.83	30.41	33.62	33.55	13.98	14.41
397	C	1	86.52	87.03	45.53	45.88	30.85	30.96	30.05	28.34	22.22	23.51	13.05	13.22
398	C	1	76.96	76.23	41.47	41.82	28.94	30.28	29.54	30.77	33.81	32.24	13.36	12.36
404	C	1	70.56	70.04	36.33	36.35	28.66	28.99	23.80	25.02	29.75	29.44	10.71	10.95
407	C	1	84.83	82.58	41.76	41.37	27.24	25.72	27.60		36.44	34.68	14.51	
409	C	1	76.56	78.48	37.63	37.86	26.95	28.81	27.54	32.91	16.15	15.56	9.54	9.59
411	C	1	81.13	80.75	42.59	43.02	31.69	31.91	28.90	30.88	31.54	31.19	13.22	14.60
414	C	1	73.48	72.93	44.90	44.01	27.14	28.13	32.20	31.23	21.03	35.16	10.92	11.24
423	C	1	71.41	71.19	40.56	42.05	29.19	28.74	26.37	28.95	30.22	32.72	10.67	11.36
424	C	1	76.72	75.80	41.96	42.28	27.76	27.96	28.20	28.90	29.52	31.16	11.85	11.86
437	C	1	76.88	77.56	36.78	37.41	26.29	27.40	27.94	28.13	31.48	31.13	9.88	10.50
445	C	1	73.61	74.36	40.90	42.74	30.09	30.98	29.81	31.45	21.60	23.91	12.63	13.64
447	C	1	78.97	79.18	41.28	41.02	30.93	28.25	27.39	27.43	34.03	32.96	12.66	12.79
449	C	1	86.76	85.58	47.52	45.96	30.33	29.65	36.42	35.40	37.83	33.23	11.49	11.20
452	C	1	76.48	76.65	37.18	37.51	29.05	29.01	27.41	27.82	33.65	33.23	10.38	9.68
454	C	1	87.84	86.21	44.50	44.37	30.80	30.99	29.37	30.86	33.72	33.42	14.64	13.21
458	C	1	74.67	75.54	39.42	39.55	29.82	29.47	25.81	25.35	33.84	34.25	11.75	11.62
1173	C	1	78.45	78.74	41.30	41.66	30.49	30.71	26.57	27.54	36.11	35.78	15.08	15.28
881	C	1	79.52	80.07	40.50	41.41	29.79	28.86	28.45	29.98	32.00	31.86	11.83	13.18
877	C	1	86.66	86.39	46.65	46.97	31.83	32.51	31.17	31.68	39.03	37.72	14.46	14.28

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
874	C	1	86.47	86.99	42.07	43.38	29.60	30.64	30.85	29.33	36.13	36.26	11.47	12.11
873	C	1	77.62	78.22	43.99	44.27	29.36	29.52	29.36	31.07	31.76	31.43	13.61	13.28
869	C	1	82.90	82.24	42.41	43.05	29.42	30.79	30.02	28.70	32.97	32.85	11.79	12.14
867	C	1	85.24	85.30	46.10	44.60	32.01	31.22	33.33	33.04	33.38	22.02	12.58	13.43
866	C	1	82.61	81.93	40.76	39.25	30.51	30.03	28.41	29.17	31.32	31.85	10.65	11.64
863	C	1	81.33	81.68	44.68	44.31	31.71	32.06	29.71	30.45	37.11	36.78	14.02	14.09
861	C	1	66.78	69.68	36.95	37.84	23.24	23.77	24.99	25.19	19.61	18.68	10.97	10.94
856	C	1	70.24	70.83	36.07	36.71	28.31	28.87	27.64	27.85	28.89	30.29	12.26	12.39
855	C	1	88.56	89.10	41.85	43.06	31.98	31.15	33.53	33.42	19.19	20.79	11.30	13.92
823	C	1	70.11	70.62	40.11	39.48	27.16	26.98	27.38	27.98	31.24	31.16	10.94	11.06
818	C	1	76.96	76.41	40.02	41.30	26.59	27.93	29.23	28.51	30.30	31.18	12.83	13.12
809	C	1	90.67	90.43	40.82	41.42	33.20	31.09	31.62	30.13	21.23	22.50	12.53	12.55
808	C	1	76.71	76.67	39.83	39.79	28.32	28.09	31.68	30.74	29.53	30.13	10.81	11.48
813	C	1	78.33	78.82	39.78	39.50	28.00	27.46	28.94	29.61	17.88	32.91	12.23	11.56
810	C	1	82.74	82.03	42.76	42.37	30.21	30.46	27.53	27.20	34.66	33.85	12.34	12.01
811	C	1	71.79	72.86	38.79	39.35	29.52	29.32	27.86	27.06	28.81	29.39	13.05	12.88
801	C	1	79.94	78.41	43.36	42.09	29.60	29.01	30.46	31.96	21.84	35.50	10.45	10.96
806	C	1	83.73	84.66	43.40	44.08	31.38	32.46	30.03	30.22	33.68	33.29	14.14	13.56
804	C	1	89.33	89.95	43.97	45.56	33.35	33.71	28.21	28.12	23.08	23.25	13.96	14.64
803	C	1	75.83	77.16	38.66	38.77	29.42	29.43	26.09	27.05	31.20	28.95	10.46	10.30
802	C	1	70.87	70.45	38.89	38.19	25.87	25.55	30.14	29.42	28.67	28.51	9.67	9.53
258	C	1	82.33	81.68	44.88	44.92	31.79	32.31	31.58	30.95	37.10	36.75	14.29	14.34
795	C	1	81.72	82.45	41.87	42.58	28.67	30.68	31.64	30.73	32.11	31.57	13.35	13.47
794	C	1	78.76	78.58	39.84	40.14	25.85	26.55	26.43	27.07	32.65	31.65	12.17	10.92
793	C	1	77.23	79.08	40.82	40.76	30.84	32.08	28.24	27.51	17.61	17.62	10.82	11.15

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
792	C	1	79.11	79.46	44.39	43.97	29.69	30.38	31.55	30.80	34.22	34.58	12.40	12.17
790	C	1	77.42	76.84	42.08	42.13	28.64	28.15	24.73	24.82	36.43	35.63	12.21	12.99
787	C	1	84.02	83.58	44.87	41.85	29.87	29.69	31.27	30.59	20.80	19.37	13.13	10.53
785	C	1	78.12	78.43	41.45	41.22	27.77	28.50	30.44	29.88	33.05	34.29	11.97	12.44
778	C	1	85.14	85.29	42.95	42.05	33.58	32.48	33.31	32.04	36.66	15.61	10.43	8.87
772	C	1	79.26	79.85	41.50	41.29	30.37	28.87	33.47	34.25	32.82	33.71	11.85	12.21
771	C	1	89.79	87.06	45.11	45.32	29.09	28.31	29.81	29.72	34.90	35.11	13.61	13.42
770	C	1	77.45	78.35	38.27	38.26	25.36	26.64	27.91	28.02	29.81	30.14	10.36	11.31
767	C	1	73.38	70.98	38.16	37.93	28.27	28.11	25.62	25.30	32.71	32.02	10.96	11.05
766	C	1	78.13	77.45	41.84	41.68	26.97	28.31	30.52	29.49	30.89	29.63	12.72	12.76
765	C	1	78.81	78.91	41.88	41.37	30.21	28.61	24.83	25.90	33.44	33.61	11.36	11.29
762	C	1	80.46	80.62	40.97	40.24	25.74	25.29	25.65	26.17	17.78	32.89	12.30	13.17
749	C	1	75.06	76.29	42.61	42.95	30.84	30.64	28.51	28.01	21.19	33.81	12.16	12.73
746	C	1	75.05	75.93	35.32	35.24	28.35	28.68	28.53	28.01	30.83	31.01	9.64	10.00
743	C	1	76.63	77.77	42.82	42.32	28.51	28.58	30.57	29.83	31.51	31.67	11.77	11.30
741	C	1	82.62	83.31	42.07	42.21	27.80	28.27	32.48	32.00	35.09	35.67	12.84	13.70
352	C	2	75.80	77.19	38.21	37.76	27.85	26.46	23.29	22.77	30.79	31.09	12.29	11.91
373	C	2	81.77	79.13	39.07	38.51	29.29	27.01	26.61	26.89	20.15	20.52	13.57	13.62
375	C	2	77.38	77.70	37.08	37.62	29.63	28.17	24.63	23.10	32.25	32.35	13.47	13.91
376	C	2	71.33	71.39	35.61	36.53	25.41	25.94	26.78	27.59	29.30	29.26	10.99	11.21
381	C	2	71.81	72.21	37.51	36.96	26.07	27.41	24.49	23.95	30.18	29.74	11.57	11.34
383	C	2	78.67	79.46	39.52	39.21	24.32	24.66	25.18	24.68	33.65	33.58	12.53	13.15
399	C	2	78.28	79.76	39.33	39.38	26.23	27.53	27.39	27.80	28.25	28.62	13.49	13.59
402	C	2	70.40	71.24	35.89	36.14	23.72	24.49	21.69	21.98	29.22	27.89	12.16	11.58
416	C	2	75.96	74.67	39.10	40.49	28.51	29.57	30.45	29.77	16.39	17.56	10.67	11.98

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
417	C	2	73.35	73.04	38.73	38.63	27.64	27.76	26.27	25.40	31.19	32.02	11.10	11.09
428	C	2	72.27	73.51	38.35	38.88	26.59	27.16	24.85	25.78	31.18	30.49	11.83	11.58
441	C	2	75.18	75.80	37.22	38.70	26.46	26.84	21.63	24.61	16.91	16.26	10.17	9.42
442	C	2	82.81	83.21	40.87	41.96	27.67	28.76	27.53	27.94	19.32	21.20	10.94	11.05
457	C	2	81.25	80.70	40.95	41.32	30.81	30.98	31.15	30.46	22.02	20.64	13.62	13.44
884	C	2	73.93	74.38	35.33	34.62	26.41	25.78	23.26	24.01	29.94	29.36	11.35	11.21
872	C	2	74.06	73.40	40.35	40.23	25.15	24.93	26.35	26.95	31.17	31.43	12.21	13.29
871	C	2	76.45	75.95	36.81	37.52	27.03	27.10	27.82	28.34	29.73	30.32	11.47	11.04
865	C	2	76.25	75.37	38.58	39.05	23.97	25.14	28.40	28.75	17.96	18.65	10.39	9.65
864	C	2	67.48	68.70	36.90	35.99	25.07	25.49	21.77	21.09	28.54	29.50	12.40	12.00
859	C	2	72.16	73.10	37.01	36.61	26.67	27.13	24.80	24.34	29.70	30.31	11.11	10.79
854	C	2	74.42	73.85	37.78	38.18	23.84	25.04	25.73	25.65	27.44	28.13	10.96	11.38
852	C	2	74.76	73.84	36.47	35.52	28.21	28.12	28.35	27.51	30.87	31.09	11.16	10.22
792	C	2	75.63	73.74	40.48	39.83	29.83	29.04	27.56	27.37	33.16	33.41	9.94	11.14
796	C	2	75.07	75.34	37.21	37.51	26.21	28.34	24.76	25.55	18.52	31.04	10.97	11.01
783	C	2	70.39	69.56	40.89	40.33	26.12	25.59	26.71	25.62	34.72	33.62	11.92	12.27
780	C	2	72.65	73.48	38.26	37.97	24.51	24.96	25.26	25.01	30.24	30.36	11.59	12.15
779	C	2	76.12	75.80	39.03	37.80	24.42	24.91	25.48		20.30	27.99	10.90	
755	C	2	80.00	79.04	41.70	41.02	26.66	26.98	26.17	26.50	33.06	31.96	12.81	12.13
754	C	2	72.70	72.88	38.21	38.09	27.85	27.16	26.70	26.86	31.04	31.59	11.06	11.50
753	C	2	64.17	64.54	31.83	30.83	23.57	23.58	21.39	20.64	24.31	23.95	8.89	9.16
752	C	2	72.61	73.90	37.63	37.77	25.33	26.55	24.65	24.94	30.50	30.87	11.22	11.51
751	C	2	78.08	78.51	37.65	37.45	29.54	29.25	30.11	31.26	28.67	29.67	11.23	9.53
748	C	2	75.49	74.72	37.35	37.46	27.77	28.19	27.12	26.31	28.97	28.55	12.20	13.16
747	C	2	81.95	82.19	41.96	39.82	30.22	30.57	28.86	26.77	36.82	23.28	11.76	12.13

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
725	C	2	67.42	67.23	33.14	33.54	25.71	24.64	23.22	23.37	25.30	26.36	9.35	9.98
714	C	2	75.03	74.65	38.74	38.78	26.63	26.48	23.28	23.39	30.18	30.71	11.48	12.02
706	C	2	68.86	68.64	32.51	32.69	24.00	25.24	23.18	23.40	28.73	28.28	10.02	10.14
705	C	2	73.56	72.30	37.29	38.51	28.86	28.87	26.60	25.68	28.74	29.11	9.61	10.89
702	C	2	76.16	74.85	40.02	39.25	25.53	25.05	29.62	29.32	30.82	30.35	10.62	10.03
685	C	2	75.63	75.41	42.73	43.72	30.62	30.29	30.28	30.98	30.48	30.58	12.61	12.39
619	C	2	80.80	79.15	39.19	39.19	26.18	25.91	25.17	24.78	19.76	19.36	11.05	12.48
602	C	2	68.73	69.45	36.08	35.99	23.92	24.94	26.00	26.83	15.56	15.91	10.34	11.21
576	C	2	73.38	72.72	40.49	40.51	25.62	27.84	24.72	23.73	31.12	30.73	13.99	13.85
529	C	2	72.05	72.84	36.02	36.69	25.67	25.90	26.98	27.38	27.81	27.57	10.24	10.12
502	C	2	75.09	75.27	38.94	39.41	28.87	28.85	28.70	28.46	18.48	18.56	14.53	13.24
463	C	2	75.44	74.75	36.01	37.77	28.20	28.31	24.62	24.86	31.42	31.43	11.62	11.78
462	C	2	68.71	68.83	35.27	36.26	27.75	28.98	25.20	25.37	29.10	29.55	9.78	9.98
347	C	2	69.06	68.78	38.51	38.38	26.79	26.57	25.48	24.80	30.13	30.31	10.64	10.97
346	C	2	73.12	73.14	40.39	39.95	27.03	27.36	26.83	28.46	32.84	31.43	12.25	12.78
328	C	2	70.36	69.89	37.81	38.87	27.12	27.27	26.38	25.76	16.30	16.96	10.74	11.37
309	C	2	80.53	81.94	41.77	41.82	26.94	26.53	29.22	28.92	30.57	31.57	11.05	11.09
306	C	2	75.06	75.14	39.59	41.02	28.97	28.98	28.12	28.11	32.26	31.44	11.53	12.52
298	C	2	72.34	72.96	36.75	36.55	26.42	27.35	27.42	27.25	17.62	31.99	9.42	10.89
267	C	2	75.73	76.03	39.98	39.64	28.76	29.10	27.88	27.72	33.35	33.01	11.83	11.40
243	C	2	74.87	75.46	37.21	37.22	25.87	26.20	27.94	27.91	18.27	31.67	9.45	10.36
265	C	2	70.64	70.07	35.90	37.67	26.48	26.53	25.29	27.05	29.53	29.38	11.69	11.79
282	C	2	73.49	72.89	35.95	35.89	24.98	26.39	26.29	27.19	19.43	27.53	10.96	10.05
277	C	2	68.47	67.24	35.06	34.79	25.78	26.66	24.97	24.44	25.99	25.36	11.54	10.90
276	C	2	81.45	80.76	41.50	40.96	27.51	27.97	29.66	28.96	21.86	21.61	13.56	13.86

ID	Biological Affinity	Sex	MAXL-L	MAXL-R	MIDB-L	MIDB-R	DAFL-L	DAFL-R	DAFB-L	DAFB-R	MAFL-L	MAFL-R	MAFB-L	MAFB-R
253	C	2	76.00	76.45	42.10	42.21	26.06	28.52	30.15	30.14	30.43	30.52	11.59	11.87
880	C	2	75.66	75.51	40.33	40.26	27.38	26.20	29.70	29.18	28.43	29.03	11.02	11.50
719	C	2	70.98	72.33	35.58	34.81	26.62	26.95	24.23	24.83	27.40	27.90	11.16	11.46
698	C	2	75.11	75.42	40.10	40.40	27.10	27.52	24.21	25.81	19.65	19.79	9.73	10.78
679	C	2	72.16	72.80	36.24	36.78	25.57	25.42	22.38	22.84	17.84	17.58	11.94	11.51
671	C	2	78.86	78.30	39.33	39.32	26.14	26.36	25.09	26.19	30.41	30.45	11.83	11.80
669	C	2	74.49	73.72	37.26	38.46	25.20	26.05	26.01	26.99	30.59	30.86	13.04	14.01
663	C	2	75.54	75.80	36.51	37.15	26.24	26.30	26.71	26.35	28.24	28.36	11.74	11.78
656	C	2	68.67	67.82	36.28	36.17	26.32	26.75	28.36	28.12	29.87	29.99	10.48	10.00
645	C	2	75.91	76.07	38.93	38.01	26.17	25.77	24.67	25.19	32.27	19.62	12.01	11.42
640	C	2	78.14	77.98	34.66	34.80	23.64	23.80	25.60	25.71	19.01	18.30	10.81	11.20