

The effect of tooth loss on accurately estimating sex from mandibular features of South Africans

Thesis for Master of Science in Medicine at the School of Anatomical Sciences

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Abstract

In forensic anthropology, the estimation of sex is important for eliminating half of the possible identities the skeletal remains may have, as a result, sexing standards were set from fully dentate mandibles. Edentulous mandibles were excluded from studies that set these standards. Thus, this study intended to determine the effect of tooth loss on accurately estimating sex from the mandibular morphology of black South Africans. The mandibles sampled included 79 (31 males and 48 females) full dentition and 117 (57 males and 60 females) variable degrees of tooth loss mandibles from the Raymond A. Dart Collection of Human Skeletons. Outlines of the non-alveolar regions of the mandibles were digitised. The alveolar regions were rated according to the level of resorption that had occurred. A two block partial least square was performed to determine the effect of tooth loss on the mandibular morphology and a two sample permutation test was conducted to determine the sexing accuracies from all sampled mandibles. Tooth loss had a significant effect on the mandibular morphology. The overall accuracies determined were 85.5% from mandibles with tooth loss and 63.3% from full dentition mandibles. The overall mandible morphology is sexually dimorphic irrespective of the presence of tooth loss. The main factor that may affect the outcome was the mandibular mechanics in males and females. The results suggest that mandibles with high levels of tooth loss could be used in studies of identification. Further studies may want to set sexing standards from both dentate and edentate mandibles.

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Chapter 1: Introduction and literature review

1.1 Introduction

The number of unidentified human remains continues to be a problem around the world for different reasons. One such reason is that this number is constantly growing due to unidentified human remains, the advanced social interaction of communities and countries, and the rise in immigration and the loss of frequent contact with relatives and family (Cattaneo et al., 2000). These reasons could be extended onto the South African population as it represents diverse ethnicities with high levels of migration between provinces and approximately 2.6% of the population comprising of non-citizens (Statistics South Africa, 2012). Countries like South Africa, with its ever growing population, tend to have a great number of unidentified human skeletonised remains (Cattaneo et al., 2000; Evert, 2011).

The percentage of human remains that the South African Medico-Legal Laboratories in Pretoria analyse increases every year (Evert, 2011). The leading reason for the inability to identify the human remains is either that they are decomposed or burned (Evert, 2011). Thus the study and application of human osteological variation is important in simplifying procedures of identification. These procedures may be used in study areas such as forensic anthropology.

Forensic anthropology is the application of biological anthropology to a medico-legal setting where human remains are in the advanced stages of decomposition (Gulec and Iscan, 1994). This field includes the study of external factors and the characteristics of individualisation on skeletal elements (Iscan, 2001). The relation of forensic anthropology to society and the use of evidence from qualitative and quantitative research to substantiate the methods applied in such analyses form part of the application of forensic anthropology (Iscan, 2001). The demographic

characteristics estimated are sex, age at death, population affinity and stature (Iskan, 2001). Sex estimation is usually one of the first steps when undertaking a forensic analysis as it assists in the determination of population affinity, age at death, and helps to eliminate half of the possible known identities (Mays and Cox, 2000; Balci *et al.*, 2005 and Bidmos *et al.*, 2010).

Sex can be estimated from a number of skeletal elements and is more easily accomplished when all skeletal elements are present. Due to the reduced likelihood of all skeletal parts being found, studies have been conducted on the sexual dimorphism of individual skeletal elements (Asala *et al.*, 2004; Bytheway and Ross, 2010; Ramadan *et al.*, 2010; Small *et al.*, 2012). Some of the bones that have been shown to be sexually dimorphic are the cranium and mandible as well as certain postcranial elements such as the os coxa, fourth rib and femur (Asala *et al.*, 2004; Bytheway and Ross, 2010; Ramadan *et al.*, 2010). These bones may have been analysed qualitatively using standardised non-metric methods involving visual observations that define the shape of the features (Loth and Henneberg, 1996). Additionally, quantitative methods involve the analysis of measurements taken using sliding or spreading callipers and osteometric boards. These quantitative analyses also known as metric analyses assess the dimensionality of the structures (Oettle *et al.*, 2005; Franklin *et al.*, 2006; Franklin, 2007a,b; 2008a,b; Coquerelle *et al.*, 2011).

The sexual dimorphism in the mandible is most likely a result of genetic predisposition. Due to this difference in the genetic makeup, at the start of puberty males produce high levels of testosterone and oestrogen in females (Rice, 1984; Sundseth *et al.*, 1992; Rinn *et al.*, 2004; Rinn and Snyder, 2005). Both these hormones maintain bone deposition in the skeleton. Muscle mass is greater in males than females (Raadsheer *et al.*, 1996). The differential muscle mass affect the mandibular morphology of the region they attach to and influence the mechanics of the

mandible. Dietary preferences between sexes have a role in the dimorphism of the mandible (Axelson, 1986). The genetic predisposition, hormonal response, differential biomechanics and diet could be the leading cause to sexual dimorphism in the mandibular morphology.

The mandibular biomechanics are in turn affected by tooth loss and bone resorption. The loss of teeth changes the diet individuals consume and pain felt during mastication (Hylander, 1975; Hildebrandt *et al.*, 1997; Ueno *et al.*, 2008). These characteristics cause mandibular remodelling at specific regions of the mandible (Lonberg, 1951; Enlow and Harris, 1964; Tallgren, 1972; Klemetti and Vainio, 1993; Giesen *et al.*, 2004). The remodelling of these features has direct effects on the sexual dimorphism (Loth and Henneberg, 1996; Balci *et al.*, 2005). However, sex differences are still present in the morphology.

The remodelling could also be age related. Aging leads to reduced bone deposition and increased resorption (Lonberg, 1951). The cortical bone thickness in those with teeth is greater than in mandibles without teeth (Schwartz-Dabney and Dechow, 2002). Thus, the degree to which sexual dimorphism is altered by tooth loss has not been thoroughly studied. This lead to the purpose of the study to be, determining the effect of tooth loss on sexual dimorphism of the mandible and the ability to accurately estimate sex from the mandible using geometric morphometrics.

1.2 Sexual dimorphism in the mandible

The sexual dimorphism in humans is expressed in skeletal parts such as the mandible. The mandible has been studied for sex specific traits as it is able to withstand strong forces and preserves well under unfavourable conditions (Hu *et al.*, 2006; Saini *et al.*, 2011). The reason the mandible is strong is due to the presence of teeth and its bone composition. The mandible is composed of two layered compact cortex, an internal and external cortex, which surrounds a less dense trabecular medulla (**Fig. 1**, Atwood, 1963; Drake *et al.*, 2010).

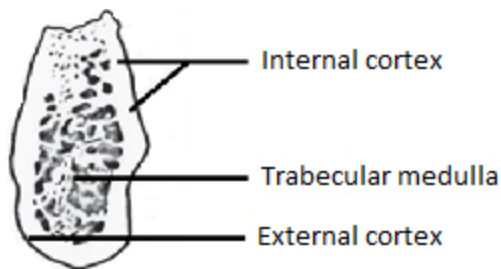


Figure 1: The bone composition of the mandible (adapted from Daegling (1989)).

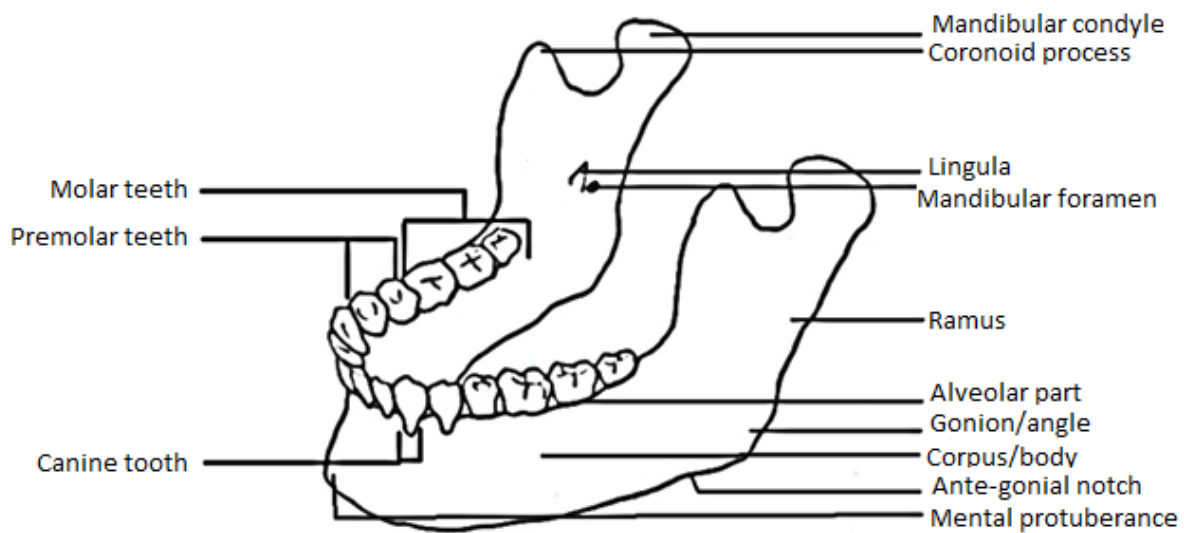


Figure 2: The mandibular features that form part of the mandible (adapted from Netter, 2006).

Like numerous other skeletal elements the mandible is a bone that portrays sex-specific features such as the ramus and coronoid process to mention a few (**Fig. 2**). One mandibular feature that possesses sexual dimorphism is the mental protuberance. This feature is determined to be prominent with a mental symphysis that is drawn backwards in males compared to the female's mental symphysis that was situated more forward and upward. The male mental protuberance is bi-lobed and square shaped compared with the gracile and more rounded female mental protuberance (**Fig. 3**; Rosas and Bastir, 2002; Thayer and Dobson, 2010). The bi-lobed mental protuberance in males may result from wish boning (mandibular arch widening) because the male mandible arch is wider than that of females (Hylander 1975). The strain in the bone during mastication is greatest in those without the mental protuberance than in those with it. Thus the prominent protuberance in males better absorbs the forces applied to the bone (Ichim *et al.*, 2006).

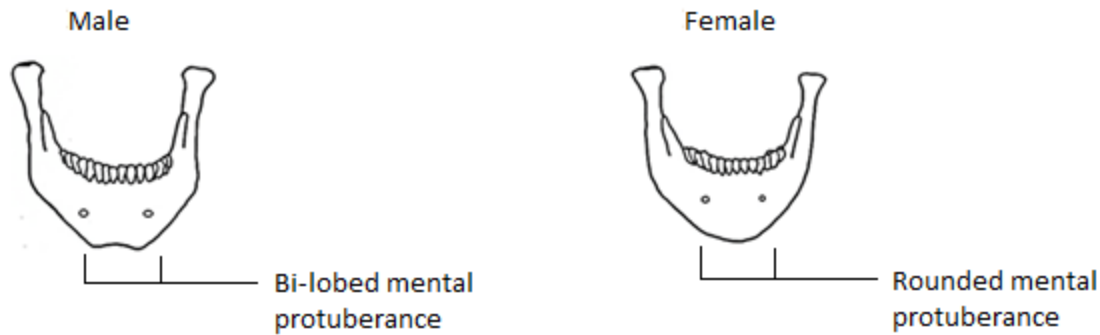


Figure 3: Sexual dimorphism of mental protuberance from anterior view. The males have a bi-lobed mental protuberance/mental region, elongated coronoid process and deep ante-gonial notch. These mandible outlines were adapted from Bass (1995).

The gonion is a mandibular landmark that is also sexually dimorphic, being characterised by the eversion of this feature in males. Eversion is the turning out/flaring of the gonion which may occur due to the large muscle mass and activity of masticatory muscles such as masseter (**Fig. 4**; Raadsheer *et al.*, 1996; Kemkes-Grottenthaler *et al.*, 2002).

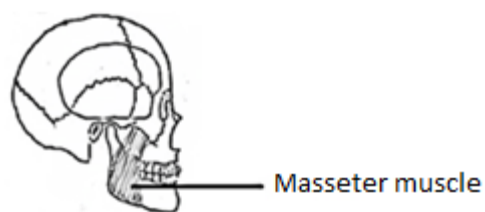


Figure 4: The masseter muscle with its region of attachment on the mandible. Image adapted from Dahlberg and Graber (1977).

The mandibular ante-gonial notch and ramus are also dimorphic features. The male ante-gonial notch and the ramus are respectively deep and flexed (backward slanting of the superior part of the ramus), and the females have shallow or straight ante-gonial notch and ramus flexure (**Fig. 5**; Loth and Henneberg, 1996). The deep ante-gonial notch and ramus flexure including the previously mentioned gonial eversion in males may be a result of muscle action and subsequent bone remodelling (**Fig. 8**; Oettle *et al.*, 2009). The basal aspect of the corpus grows in an anterior direction with majority of bone deposition on the buccal side (Enlow and Harris, 1964; McNamara and Moyers, 1975)

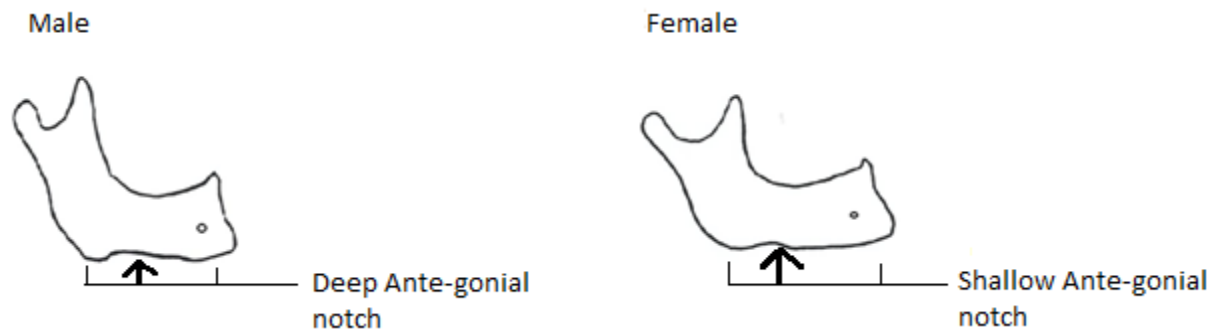


Figure 5: Sexual dimorphism of ante-gonial notch from lateral view. The males have deep ante-gonial notch compares to females. These mandible outlines were adapted from Coquerelle *et al.* (2011).

The male also have longer ramus heights and bigonial breadths (Dayal *et al.*, 2008; Vinay *et al.*, 2013; Ilguy *et al.*, 2014). The evident sexual dimorphism in the ramus could be a result of males having greater muscle mass that exerts larger forces compared to females (Raadsheer *et al.*, 1996). The muscles in males have been shown to generate greater bite forces (Ferrerio *et al.*, 2004). Loading on the mandible may affect the shape of these features. The load could be related

to the type of diet males and females choose to consume. It has been suggested that males tend to have a diet that is fibrous and requires a large amount of chewing than females (Nowjack-Raymer and Sheiham, 2003; Allan, 2005; Kossioni and Bellou, 2011).

The shape and position of the mandibular condyle could be presented as sexually dimorphism. Due to the strong muscle forces, the male condyle experiences high compressive force during mandible depression. These forces change the condyle to a flattened shape. The mandibular condyle length and bicondyle breadths are longer in males (Rosas and Bastir, 2002; Dayal *et al.*, 2008; Coquerelle *et al.*, 2011; Vinay *et al.*, 2013; Ilguy *et al.*, 2014). The observed sexual dimorphism is thought to also be a result of differential muscular forces exerted by males and females through activities such as biting and mastication.

The shape of coronoid process is sexually dimorphic and may also relate to function. Males possess coronoid processes that are more elongated and backwardly positioned than that of females (**Fig. 6**; Franklin *et al.*, 2008b; Coquerelle *et al.*, 2011). The coronoid length and position is affected by the activity of temporalis muscle and bone deposition. With the constantly high muscle pull force in males on the coronoid process, there might be more bone laid down than in females (**Fig. 7**; Enlow and Harris, 1964; McNamara and Moyers, 1975). The growth of the coronoid process is in a superior-medial manner and bone deposition occurs at the lingual side. Resorption in the coronoid process takes place at the buccal and on the anterior aspect (Enlow and Harris, 1964; McNamara and Moyers, 1975). The position of the coronoid process becomes displaced superio-medially.

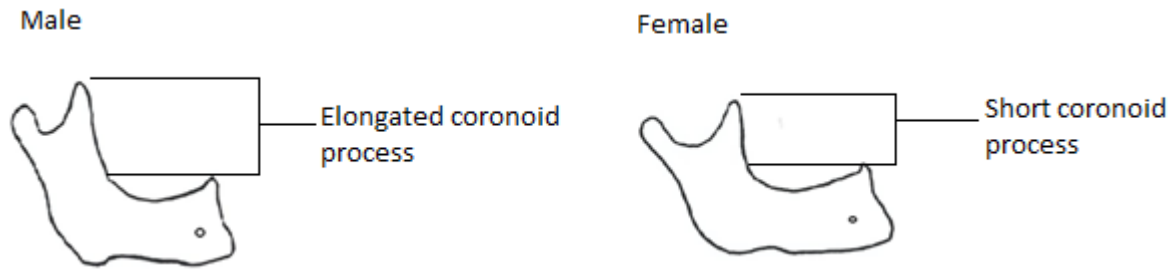


Figure 6: Sexual dimorphism of coronoid process from lateral view. The males have elongated coronoid process than the females. These mandible outlines were adapted from Coquerelle *et al.* (2011).

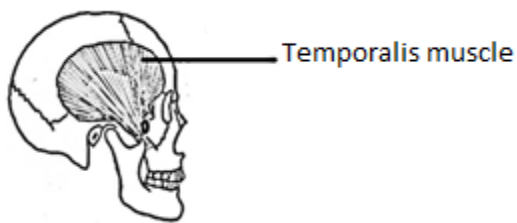


Figure 7: The temporalis muscle with its region of attachments on the mandible. Image adapted from Dahlberg and Graber (1977).

1.3 Sex estimation accuracies

The estimation of sex from the mandible has been characterised through the use of non-metric and metric assessments. The non-metric assessments include the scoring method which is the allocation of a score to the visual assessment of mandibular features such as ramus flexure, gonion eversion and ante-gonial notch shape. This method is used in the first study of sex estimation from the mandibular ramus of a black South African population by Loth and Henneberg (1996). The ramus was scored according to the presence or absence of a flexure (backward sloping of the ramus). The accuracies found using this scoring method to correctly sex individuals were 99.1% in males and 98.8% in females. Other studies that used a similar

method on an American and European populations have lower accuracies ranging between 80.4% -92.6% and 37.5% -60.0% for males and females respectively (Donnelly *et al.*, 1998; Balci *et al.*, 2005). The accuracies reduce for mandibles with loss of posterior teeth (molars) to 85.2% for males and 37.5% for females (Balci *et al.*, 2005). The change in the loading on the mandible may have contributed to the ability to distinguish male from female mandible morphology.

The metric assessment of the mandible generally comprises of linear measurements. Steyn and Iscan (1998) determined that mandibular lengths and breadths were responsible for accurately sexing white South African males at 79.5% and females at 83.3%. Studies on the sexual dimorphism of the mandibular outline using geometric morphometrics have found varying accuracies. The accuracies of correctly estimating sex from the rami of South African adults have a range from 69.6% to 90% for males and 67.8% to 85% for females (Oettle *et al.*, 2005; Franklin *et al.*, 2006; Pretorius *et al.*, 2006). The sexual dimorphism of mandibular outlines of European populations has 97.1% of males correctly sexed and females have 91.7% accuracy (Schmittbuhl *et al.*, 2001).

1.4 Development and biomechanics of the mandible

The displacement of the mandibular features as a result of sexual dimorphism is a reflection of bone resorption and deposition. The resorption and deposition of bone is due to regular growth and development as well as in response to mechanical stimuli as Wolff's law specifies (Chamay and Tschantz, 1972). The mandibular condyle shifts posterior and in a superior position during mandibular growth (**Fig. 8**). The condylar neck of the mandible becomes narrower as a result of

resorption. The mandibular neck descends and becomes the ramus. The deposition of bone at the ramus occurs at the posterior and buccal side. The growth of the coronoid process is in a superior-medial manner and bone deposition occurs at the lingual side. Resorption in the coronoid process takes place at the buccal and on the anterior aspect (Enlow and Harris, 1964; McNamara and Moyers, 1975). The position of the coronoid process becomes displaced superior-medial; and the mandibular corpus becomes posteriorly positioned with bone deposition (Fig. 8). The basal aspect of the corpus grows in an anterior direction with majority of bone deposition on the buccal side.

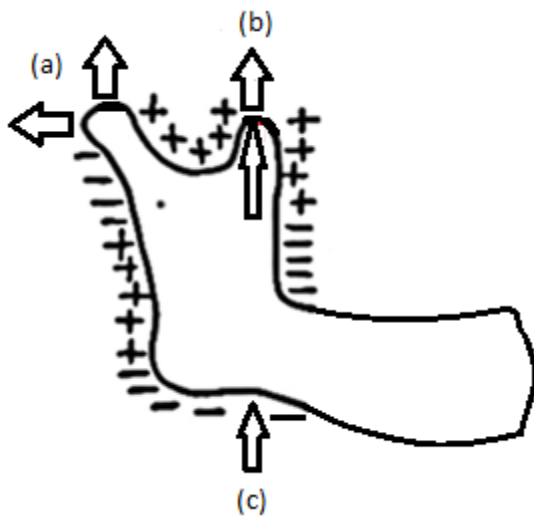


Figure 8: The Illustration of area where bone deposition (+) occurred and resorption occurs (-) adapted from McNamara and Moyers (1975). The arrows indicate the direction the mandibular feature shifts with regard to bone deposition and resorption. (a) The superior displacement of the condyle with bone deposition and posterior movement with resorption. (b) The superior movement or elongation of the coronoid process with bone deposition. (c) The deepening of the ante-gonial notch as a result of bone resorption.

The mandible develops to be an attachment to the cranium articulating with it at the temporo-mandibular joint. This joint involves the mandibular condyle and mandibular fossa (on the base of the cranium) held together by a capsule and ligaments that allow the mandible to function effectively during mastication. Due to this arrangement and muscles of mastication the mandibular features have varied to withstand biomechanical activity (Hylander, 1975).

On one hand, the biomechanics of the mandible may also be considered to be similar to the mechanics of a lever, where lever development and growth would suit the diet, forces and cranial dimensions. On the other hand, the mandible can be described as an articulation to the cranium rather than a lever. Those non-lever mechanics are a result of masticatory muscles exerting the resultant force while the condyle experiences compressive forces (Hylander, 1975). The mandible is classified by Hylander (1975) as a class III lever. The forces applied during the function of the mandible may also be sex specific (Calderon *et al.*, 2006). The sexual dimorphism in the forces may be due to the large muscle mass in males than in females. These sex specific forces are probably what lead to the sexual dimorphism in the mandibular morphology.

1.5 Tooth loss effects on the mandible

Tooth loss affects the mandibular morphology through different processes. There are internal and external bone changes (Atwood, 1963). The internal change occurs in the medulla of the mandible and involves bone resorption. The height of the alveolar region reduces due to resorption (**Fig. 9**; Lonberg, 1951; Tallgren, 1972; Klemetti and Vainio, 1993), as the medulla reduces the surrounding cortical bone narrows.

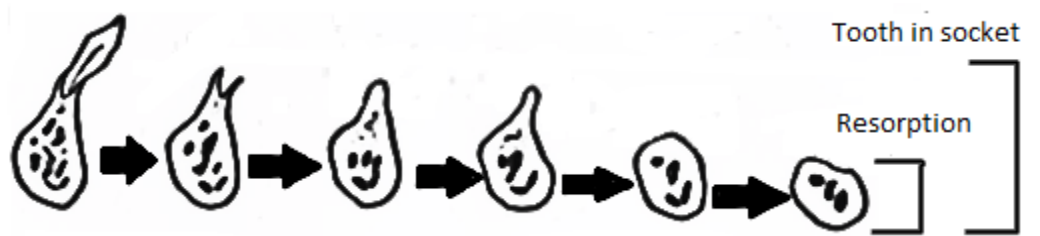


Figure 9: The comparison of bone composition and alveolar heights between mandibles with teeth and those without teeth and resorption has taken place. The remodelling of the alveolar ridge can be seen to occur due to tooth loss. The image was adapted from Atwood, 1963.

The teeth also influence the biomechanics of the mandible. Specific teeth experience differential loading due to their specific form and function (McNeill, 1997). The loading on teeth is converted into forces that are indirectly exposed to the bone. The loading on the alveolar ridge was determined to be larger in the regions of the premolars and molars than incisors and canines (Ferrerio *et al*, 2004; Ichim *et al.*, 2007). The forces are transmitted from the teeth to the bone through structures such as periodontal ligament (**Fig. 10**; Mandel *et al.*, 1986; McCulloch *et al.*, 2000). The forces at the bone adjacent to the socket were greater than the force transferred to the basal regions of the mandible (Daegling and Hylander, 1998). The indirect forces on the mandible are those exerted by muscles that are closely related to the mandibular feature such as masseter muscle on the gonion and ramus. These are some of the features affected by muscle function (Raadsheer *et al.*, 1996).

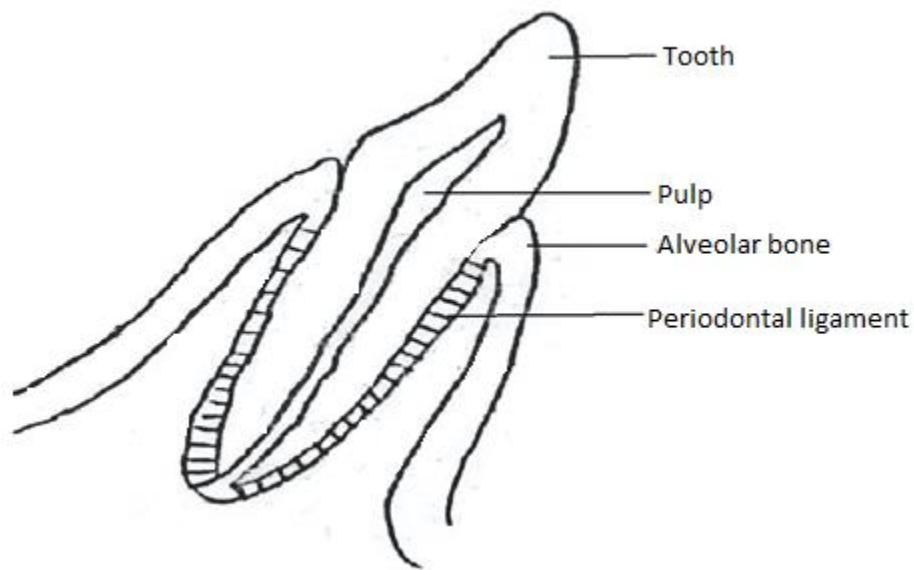


Figure 10: The image of the tooth in a socket (McNeill, 1997).

Age also needs to be considered with tooth loss because young individuals have longer corpora and mental symphyses than the aged individuals (Lonberg, 1951). Differences in the corporal and mental symphyseal heights in young and old dentate mandible result from the young experiencing greater bone deposition. Corpora in old individuals with dentition have greater heights than those who are edentulous because of the sockets containing teeth. The mandibular morphology of the dentate elderly and the young are similar. This could be attributed to a consistent plastic response in mandibles. Fully dentate individuals have a thicker cortex among dentate mandibles (Schwartz-Dabney and Dechow, 2002).

Schwartz-Dabney and Dechow, 2002 compared cortical thickness in dentate and edentate mandibles and found that cortical bone in dentate individuals are unevenly distributed, where

more cortical bone is deposited on the lingual region than labial region. The edentulous mandibles also have thinner cortices than the dentate. It is probably affected by loading on the alveolar bone. The loading is possibly reduced in edentulous mandibles, thus the reduced bone deposition. The reduced loading may also decrease the degree of wish boning, as the tension on the lingual region of the symphysis and compression on the labial side are reduced (Fukase, 2007).

The external changes the mandible undergoes as a result of tooth loss, is the occurrence of a specific pattern of resorption. Resorption on the external parts of the alveolar ridge is greater than the internal parts. The labial aspect of the cortical bone is highly resorptive than the lingual surface (Atwood, 1963; Pietrokovski and Massler 1967). Resorption reduces the size of the cortical thickness. The medullary section reduces immensely in size compared to the cortical thickness (Atwood, 1963). Other internal changes as a result of bone resorption are the reduction in bone density known as osteopenia (Atkinson and Woodhead, 1968; Taguchi *et al.*, 1995; Giesen *et al.*, 2004).

The reduced bone density is also present in aged mandibles and is a confounding factor as tooth loss is prevalent at this stage, together with being prone to osteoporosis. The correlation between bone density and age is due to bone remodelling (Atkinson and Woodhead, 1968; Ulm *et al.*, 1994; Taguchi *et al.*, 1995; Kingsmill and Boyde, 1998; Ledgerton, 1999). The edentulous mandibles were determined to have reduced elasticity compared to dentate mandibles, particularly along the ramus (Schwartz-Dabney and Dechow, 2002).

Regarding specific features of the mandible, the inferior margin of the mandibular corpus, known as the ante-gonial notch, is affected by tooth loss (Atkinson and Woodhead, 1968; Dutra

et al., 2004; 2006). The ante-gonial notch is deeper in edentulous mandibles than in dentate mandibles (Atkinson and Woodhead, 1968; Dutra *et al.*, 2004; 2006). This observation is probably due to the limited amount of muscle attachments in the region below the premolars, and that remodelling of the basal regions of the corpus is a continuous process all through the life span of an individual. Thus notching of this region is expected because of the reduction in cortical bone thickness at the gonion that occurs with aging (Ledgerton *et al.*, 1999; Dutra *et al.*, 2004). It is disputed whether tooth loss affects sexual dimorphism of the ante-gonial notch (Atkinson and Woodhead, 1968). The female ante-gonial notch becomes deep but the ante-gonial notch in males remains deeper with tooth loss. This difference is presumably due to differential muscle mass between males and females (Atkinson and Woodhead, 1968).

Ramus flexure is another of those characters thought to be affected by tooth loss. The entire mandibular ramus experiences remodelling during tooth loss and aging, to accommodate the masticatory function of the mandible by deepening and flexing through resorptive processes (Enlow *et al.*, 1976). The ante-gonial notch and ramus flexure in edentulous mandibles were considered not to be good representations of sex specific features due to the reduced mandibular stress edentulous mandibles experience (Giesen *et al.*, 2004). The mandibular angle is one other mandibular feature that is affected by tooth loss. However, the change in the mandibular angle could be related to masticatory muscle function. The angles of edentulous individuals were larger compared to those from dentate mandibles (Enlow *et al.*, 1976; Dutra *et al.*, 2004). The edentulous mandible was elongated than that of the mandible (**Fig. 11**; Enlow *et al.*, 1976).

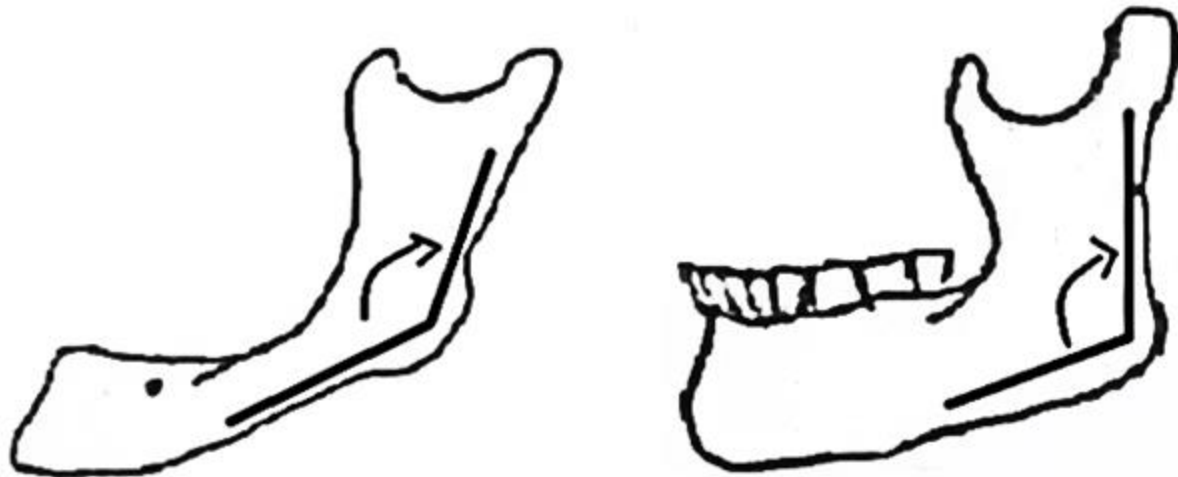


Figure 11: The comparison of edentulous (left) and dentulous (right) mandibles. The mental protuberance in the edentulous mandible is downward and anteriorly positioned than in full dentition mandibles. A deeper ante-gonial notch, backwardly slanted ramus and a coronoid process that is positioned more posterior compared to mandibles with full dentition can be seen in the image. The mandibular angle is obtuse in edentulous mandibles than in dentate mandibles. These mandible outlines were adapted from Lonberg (1951) and Netter (2006).

Another mandibular structure that is affected by tooth loss and age is the condyle. The mandibular condyles from aged individuals were flatter than those from young individuals. The effect of tooth wearing could be taken to resemble that of tooth loss as there is a common change in the occlusal level (Hylander, 1975 and Owen *et al.*, 1991). The retreating occlusal surface present in both tooth loss and wear, especially the loss and wear of posterior teeth, can have a similar effect leading to the increased compressive force being applied by the temporal-mandibular notch on the condyle (Hylander, 1975; Owen *et al.*, 1991). This in turn would result in enlargement of the lateral tubercle of the condyle (Owen *et al.*, 1991). The resorption on the posterior region of the condyle neck affects the condyle, positioning it relatively more anteriorly (Enlow *et al.*, 1976). The anterior region of the condyle neck becomes notched due to the

resorption that takes place along this region (Enlow *et al.*, 1976). The condyle is also affected by forces applied onto it. For example, the force applied onto the condyle is affected by the third molar eruption, where lower hyper eruption leads to increased force applied on the opposite condyle (Zhang *et al.*, 2005). The occlusion of the posterior teeth causes the opposite condyle to reconstruct in such a way the condyle lengthens and elevates (Zhang *et al.*, 2005).

The loss of teeth influences the action of the masticatory muscles that affect the diet consumed and load the mandible experiences. The choice of diet depends on the difficulty or pain felt when consuming certain foods (Hylander, 1975; Hildebrandt *et al.*, 1997; Ueno *et al.*, 2008). The muscles have reduced activity as the mandibular load is decreased. Therefore the force exerted by the masticatory muscles in edentulous mandibles is reduced compared to dentate mandibles.

1.6 Problem statement

The problem with the accuracies and standards of sexing from the mandible at present is that they were conducted on predominantly dentate mandibles (Steyn and Iscan, 1998; Oettle *et al.*, 2005; Franklin, 2007; 2008a; Ongkana and Sudwan, 2010; Coquerelle *et al.*, 2011). Edentulous mandibles were excluded presumably because of the occurrence of resorption, change in mandible biomechanics and diet. These factors may contribute to remodelling of the edentulous mandible.

The application of the sexing standards from full dentition mandibles to mandibles with tooth loss becomes a challenge. The likelihood that the skeletal remains that require identification have a fully dentate mandible is very low. This is because loss of teeth occurs at any stage in a person's life time. The extraction of teeth at a certain stage in life is a lifestyle related practice

(Thorstensson and Johansson, 2010). Being edentulous earlier in life is an indication of a higher social standing in some communities. Removing all teeth by midlife is associated with individuals who are less educated. In South Africa, it seems that those from a lower social standing tend to remove their teeth; with 74.5% being coloured, 39.8% being blacks and 33.6% being white (Friedling and Morris, 2005). Others remove their teeth due to infections and health related illness. These include dental caries and periodontitis which accounted for approximately 55% and 33% of the individuals respectively (Thorstensson and Johansson, 2010). In a South African context, 16% of remains that required identification at the Medico-Legal Laboratories in Pretoria had dentures/dental work and dental deformities (Evert, 2011). Thus the exclusion of edentulous mandibles in studies that set standards for sexing from the mandible might lead to reduced accuracy and precision of correctly sexing from mandibles with tooth loss.

1.7 Aim and objectives

1.7.1 Aim

The mandible has been shown to be susceptible to morphological change with tooth loss. Edentulous mandibles have thus been excluded in studies of sex estimation. Reliable standards are required to estimate sex in the field of forensic anthropology. The estimation of sex from standards requires the variation associated with observable sexual dimorphism. The sexually dimorphic features aid in identifying variation between sexes. Thus the study aims to determine the effects of tooth loss with age on the ability to sex individuals accurately from the combination of mental protuberance, ante-gonial notch, ramus flexure and mandibular condyle in South Africans.

1.7.2 Objectives

1. Determine whether the mandibular features (mental protuberance, ante-gonial notch, ramus flexure and mandibular condyle) are sexually dimorphic and the degree to which they differ in dentulous mandibles
2. Determine the accuracy of sexing individuals quantitatively from these mandibular features in dentulous mandibles
3. Observe the morphological change of the mandibular features with age and tooth loss
4. Determine the accuracy of quantitatively sexing individuals from the mandibular features of edentulous mandibles
5. Determine the accuracy of correctly estimating sex descriptively from mandibular features of both dentulous and edentulous mandibles

Chapter 2: Materials and Methods

2.1 Sample

One hundred and ninety six mandibles were randomly selected from the Raymond A. Dart Collection of Human Skeletons housed at the University of the Witwatersrand Johannesburg. These sampled mandibles consisted of 108 males and 88 females from the Sotho, Tswana and Zulu groups as the South African population is largely comprised of these tribes (Statistics South Africa, 2012). The sampled mandibles included 48 full dentition and 60 mandibles with varying degrees of tooth loss (including edentulous mandibles) from males, and 31 full dentition and 57 mandibles had varying degrees of tooth loss from females. The age range that these mandibles were between was 20 and 80 years (females: range between 20 and 80, mean=42.1, standard deviation=14.6; males: range between 20 and 80, mean=45.1, standard deviation=15.9). This age range was chosen to observe the variation of the mandibular morphology in mandibles with full dentition and tooth loss, and its association with age. Ethical approval is not required as the School of Anatomical Science is covered by the Human Tissue Act no. 65 of 1983.

Mandibles with the third molar unerupted, recognisable orthodontic treatment and pathology were excluded from the study. The unerupted third molar was an indication of ongoing ontogenetic processes, which would affect the mechanical properties of the mandible. Bone remodeling may occur as a result of orthodontic treatment, such as the removal of teeth for alignment purposes (Safdar and Meehan, 1995; Lee and Dodson, 2000).

2.2 Method

The mandibles were positioned with the alveolar process faced towards the horizontal flat table top to enable the curves and landmarks to digitise them at a single sitting without repositioning

the mandible. Eighteen three dimensional fixed landmarks were placed in standard positions while seven curves were captured between fixed landmarks to digitised the mental protuberance, ante-gonial notch, ramus flexure, mandibular condyle and mandibular notch using a MicroScribe G2 digitiser (**Table 1, Fig. 12**). Each curve consisted of a number of landmarks that were resampled to five landmarks for the mental protuberance, fourteen for each ante-gonial notch, nine for the left and right ramus flexures and eight represented each of the mandibular notches. The curves were resampled to these landmarks to conserve the mandibular morphology without redundancy. The resampling was done in Morpheus *et al.* (Slice, 1996; <http://morphlab.sc.fsu.edu/software>).

Table 1: The landmarks and curves to represent the mandibular features (adapted from Franklin *et al.*, 2007).

Landmark	Name (abbreviation)	Description
Fixed landmarks		
1	Infradentale (id)	The anterior point between the central incisors or the anterior most point on the alveolar bone estimated to be between the central incisors when absent.
2	Mandibular symphysis (mns)	The deepest region above the mental protuberance.
3	Pogonion (pg)	The point most anterior on the mental protuberance.
4	Gnathion (gn)	The midpoint/point on the inferior border along the mandibular symphysis line.
5	Gonion (go)	The posterior most point on the gonion.
6	Posterior condylion (pcd)	The posterior region of the mandibular condyle.
7	Condylion laterale (cdl)	The lateral tubercle of the condyle.
8	Condylion mediale (cdm)	The medial tubercle of the condyle.
9	Anterior condylion (acd)	The anterior region on the mandibular condyle.
10	Mandibular notch (mn)	The deepest point in the mandibular notch.
11	Coronoid (co)	The superior most point on the coronoid

process.

Mandibular curves

Mental protuberance mns-gn

The curve between the mandibular symphysis landmark and gnathion along the anterior midline of the mandible's mental protuberance.

Mandibular corpus gn-go

The curve between gnathion and gonion along the inferior margin of the mandibular corpus.

Ramus flexure go-pcd

The curve on the posterior margin of the ramus between the gonion and posterior condylion.

Mandibular notch acd-co

The curve is between anterior condylion and coronoid along the superior margin.

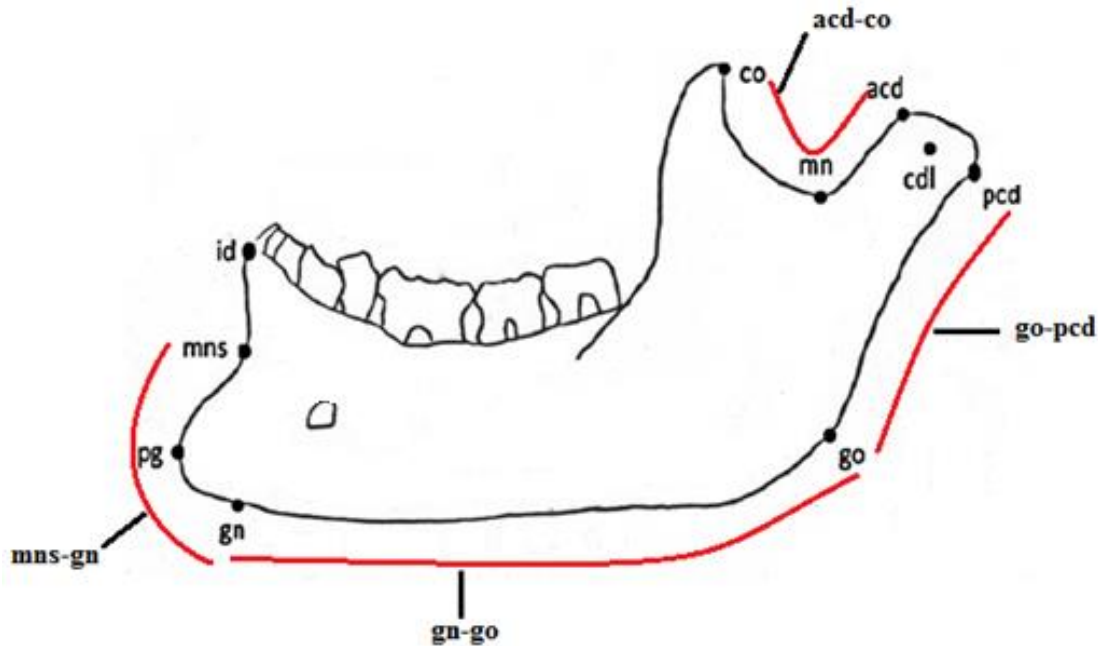


Figure 12: Lateral view of a mandible illustrating fixed landmarks (Abbreviations in **Table 1**).

The curves that were between the fixed landmarks are shown in red.

Intra-observer error was incorporated directly into the analysis by digitising each mandible twice on separate days. The error between the repeat specimens was only considered acceptable if it contributed less than 5% to the variation between specimens.

To assess the effect of tooth loss on shape changes in the mandible morphology socket resorption was scored. Tooth loss and alveolar resorption was assessed qualitatively by scoring the state of tooth socket resorption as a proxy of time since tooth loss. The scores allocated were:

0 – Teeth present post-mortem,

1 – Resorption of the tooth socket with socket visible,

2 – Resorption of the socket with porous bone evident,

3 – Resorption of the socket with bone remodelling.

2.3 Statistical analysis

A Generalised Procrustes Analysis was completed on all sampled specimens and their repeats.

The Procrustes superimposition of landmarks and fixed landmarks was conducted using Morpho package in the software R (The R Foundation for Statistical Computing, <http://r-project.org>). To reduce intra observer error the average shape and size between the repeats were used for subsequent analyses.

To determine whether the mandibular features are sexually dimorphic in dentulous and variably edentate mandibles (objective 1) a two sample permutation test was performed in R on multivariate data from Procrustes Analysis. The test randomly assigns individuals to the groups 10 000 times. This tests whether the actual distance between the sexes exceeds that obtained by random chance. Mean differences of the dentate and variably edentate mandibular morphology were computed to ascertain the dimorphism in variables.

To estimate the accuracy of quantitatively sexing dentulous individuals and those with variable tooth loss (objective 2 and 3), a discriminant analysis was performed in R on principle components (PCs) and not the raw data. This was because the number of variables exceeded the sampled individuals and was thus not invertible, a necessary step in discriminant analysis.

However, the principle components analysis (PCA) method reduced the multivariate data into essential PCs. The number of PCs that represented a significant amount of variation was

determined by 1) the fraction of correctly predicted sex from same sample for the increasing number of PCs; and 2) the difference between fraction of correctly predicting sex and the fraction predicted from randomly assigning individuals to sex 10 times. The latter was computed to prevent over-fitting of the data. This method is similar to the logic of the a-score devised by Jombart (2008) and Jombart and Ahmed (2011) for adegenet R-package. The principle components analysis method can be used to maximise discrimination while avoiding over determination. A line was illustrated using LOESS smoothing to indicate the trend.

To observe the morphological change of the mandibular features with age and tooth loss (objective 4) a two-block Partial Least Squares (PLS) was conducted to illustrate the association between tooth loss and mandibular morphology. This partial least squares test was analogous to the least square regression but between multivariate data that generate covariance to illustrate the association between the data. The permutation test on the residuals using age as a predictor was also conducted to determine whether age influenced mandibular morphology. The permutation test fitted a linear model between age and aligned Procrustes co-ordinates and assess whether the sum of residuals was less than when age was randomly assigned 10 000 times. The degree and distribution of tooth loss between the sexes in mandibles can be biased. Thus, a multivariate analysis of variance was performed on the matrix of tooth scores to ensure that no discernible difference existed between the sexes of mandibles with tooth loss. The multivariate analysis of variance included Wilks' lambda and Pillai tests in PAST3 (PAST3.02; Hammer, 2001; www.folk.uio.no/ohammer/past/).

A quantitative analysis of sexual dimorphism was conducted to determine how accurate the non-metric analysis compared to the metric method was in estimating sex from tooth loss and full dentition mandibles. Each mandibular feature was independently assessed for expression of sex specific traits according to Loth and Henneberg's (1996), and Coquerelle *et al.*'s (2011) descriptive assessments. Each feature on the right and left was assigned to female or male. The sexing criteria used for the descriptive analysis is shown in **Table 2**. The accuracies of correctly independently estimating sex descriptively from mandibular features of both dentulous and edentulous mandibles (objective 5) were calculated.

Table 2: The morphological characteristics used to estimate sex from the individual features of the mandible.

	Male	Female
Mental protuberance	bi-lobed	round and gracile
Ante-gonial notch	deep	straight and shallow
Ramus	flexed and deep	not flexed, shallow and straight
Condyle	flat	round

Chapter 3: Results

The main purpose was to 1) estimate the sexual dimorphism in both dentate and partially edentate mandibles. 2) Estimate the accuracy of correctly sexing in both mandible samples. 3) Determine whether age and tooth loss had an effect on the mandibular morphology. 4) Estimate the sexing accuracies using a descriptive method. The intra observer error was computed to establish the reproducibility of the method.

3.1 Intra-observer error

The distribution of intra-observer error suggested the method was applied in a reproducible manner ($p < 0.05$; **Fig. 13**). The measure of error was least between repeats and greater between specimens.

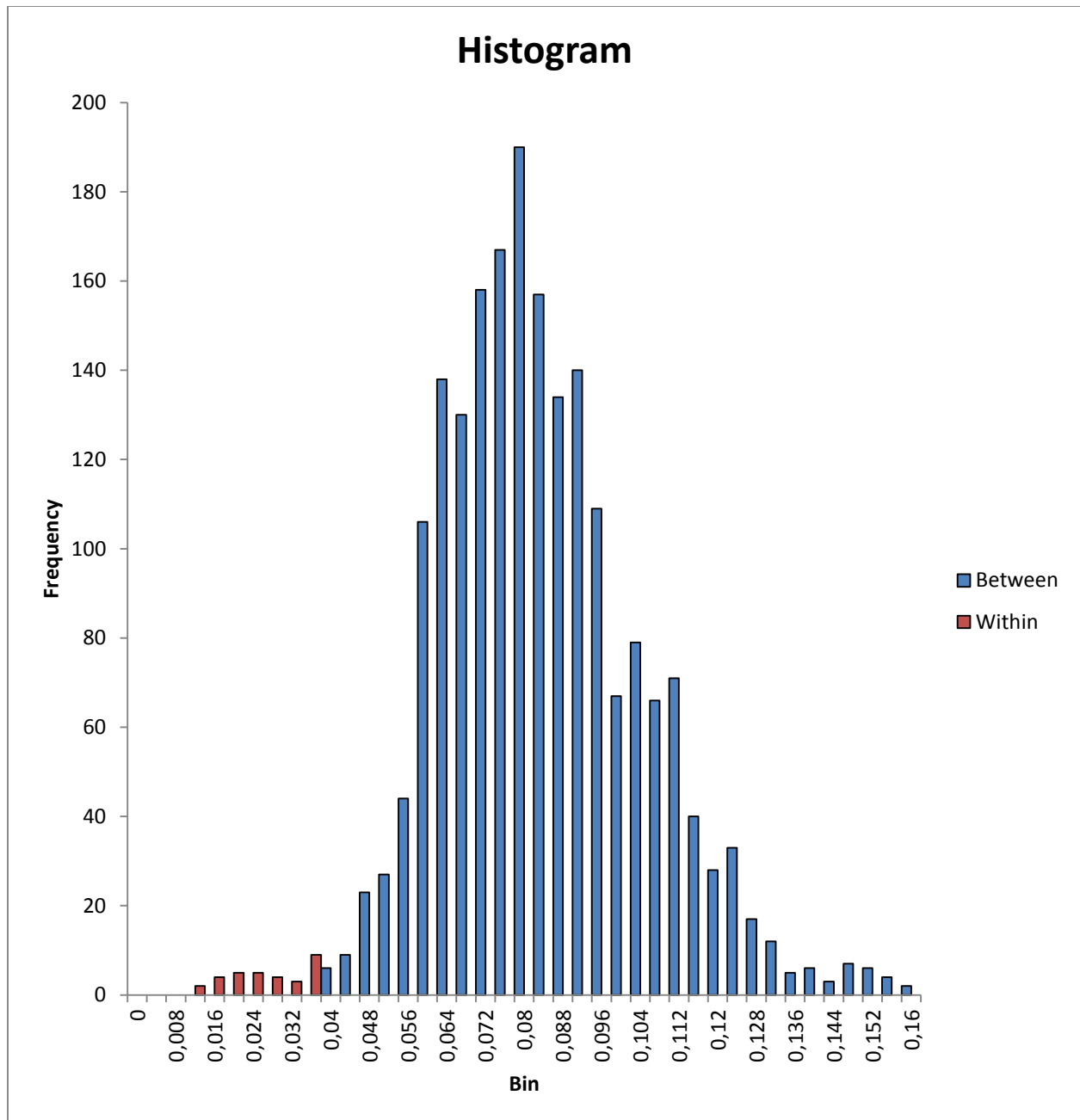


Figure 13: The histogram shows the distribution of the Procrustes distances between specimens and between their repeats. The within error was the difference between the first collected data and the second data from the same specimen. The between error was the difference between different specimens.

3.2 Sexual dimorphism in the mandible using geometric morphometrics

The two-sample permutation test was used for the determination of sexual dimorphism in dentulous and variably edentate mandibles. The test indicated that males were differentially significant from females in both dentate mandibles and those with varying degrees of tooth loss ($p=0.0167$ and $p<0.0001$ respectively). Sexual dimorphism of the overall sample was also significant at $p<0.0001$. The mean difference in the mandibular morphology between males and females was found to be 0.0694 for fully dentate mandibles and 0.0726 for those with variable degrees of tooth loss. These means were significantly different at a p-value of 0.0014. Thus variably edentulous mandibles possess greater sexual dimorphism.

To determine PC's with significant variation the number of PCs was graphically illustrated. Fractions of accurately discrimination for an increase number of PCs. Additionally, a second graph indicating the fraction of correctly discrimination minus the fraction of randomly predicting the sex for increase number of PCs was illustrated. The graphics indicated that a total of 20 PC's for full dentition and 18 PC's for mandibles of tooth loss was optimum for discrimination (**Fig. 14 -Fig. 17**). The 20th and 18th PC that is the end of the ascending consecutive order of PC's is shown by the green line and black arrow (**Fig. 14** and **Fig. 16**). The red line estimated the LOESS smoothing model that indicated the overall trend in changing mandibular morphology. The fractions needed to be considered in light of the results of **Fig. 15** and **Fig. 17**. The first 20 (**Fig. 15**) and 18 PCs (**Fig. 17**) possessed a significant variation and ability to accurately discriminate without over fitting in morphology and is indicated by the green line and black arrow.

3.3 Accuracies for correctly estimating sex

The accuracy that these PC's characterise sexual dimorphism is at 85.4% for full dentition and 89.5% for variably edentate mandibles. The PC that were significant in differentiating males from females in both full dentition and mandibles with tooth loss accounted for similar mandibular features. However, the male and female mandibles morphology with various degrees of tooth loss seems to be exaggerated. Mandibular features represented by males with full dentition mandibles were shortened mandibular corpora, elongated rami and coronoid processes, gonial eversion, reduced mandibular angle and deep ramus flexure than that of females (**Fig. 18 - 19**). Additionally, the fully dentate male mandibular morphology has a broad mandibular notch, less protruding mental protuberance, deep ante-gonial notch and broad mandibular arch when compared to the females mandibular morphology. The mandibular morphology of variably edentate mandibles is similar to the fully dentate mandibles.

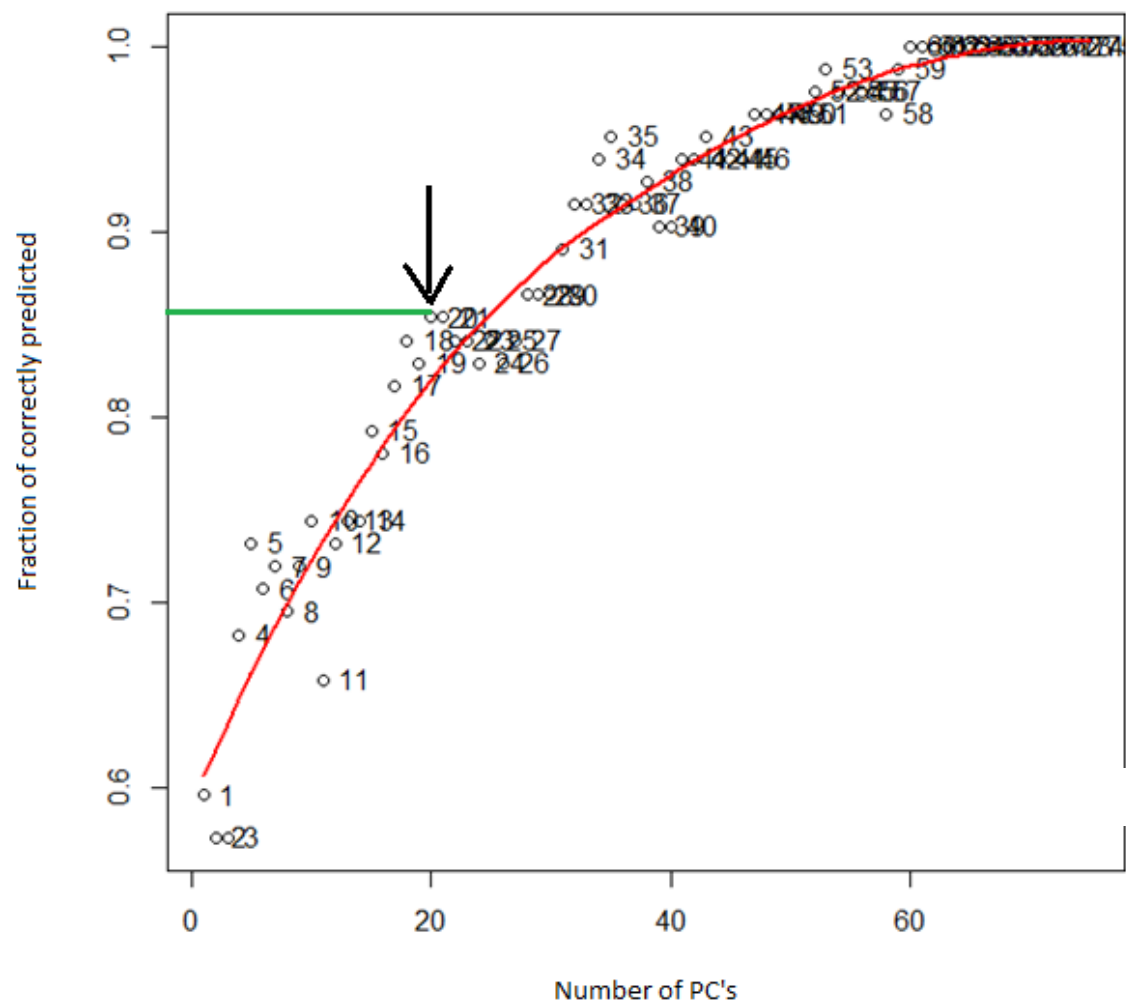


Figure 14: Fraction of correctly predicted sex for the given number of principal components used in discriminant analysis.

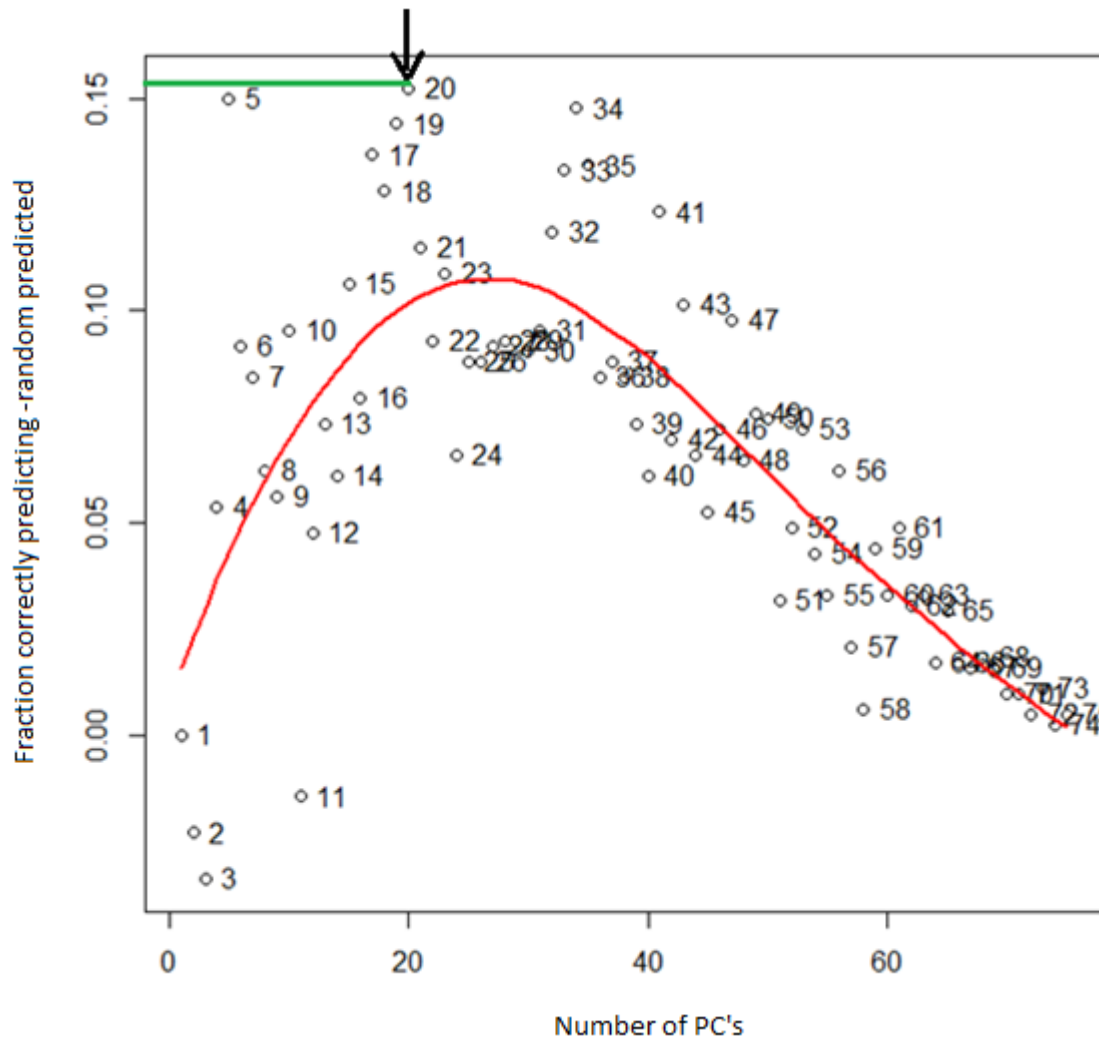


Figure 15: Difference between the fraction correctly predicted sex and the fraction predicted from randomly assigning individuals to a sex 10 times in fully dentate mandibles using discriminant analysis.

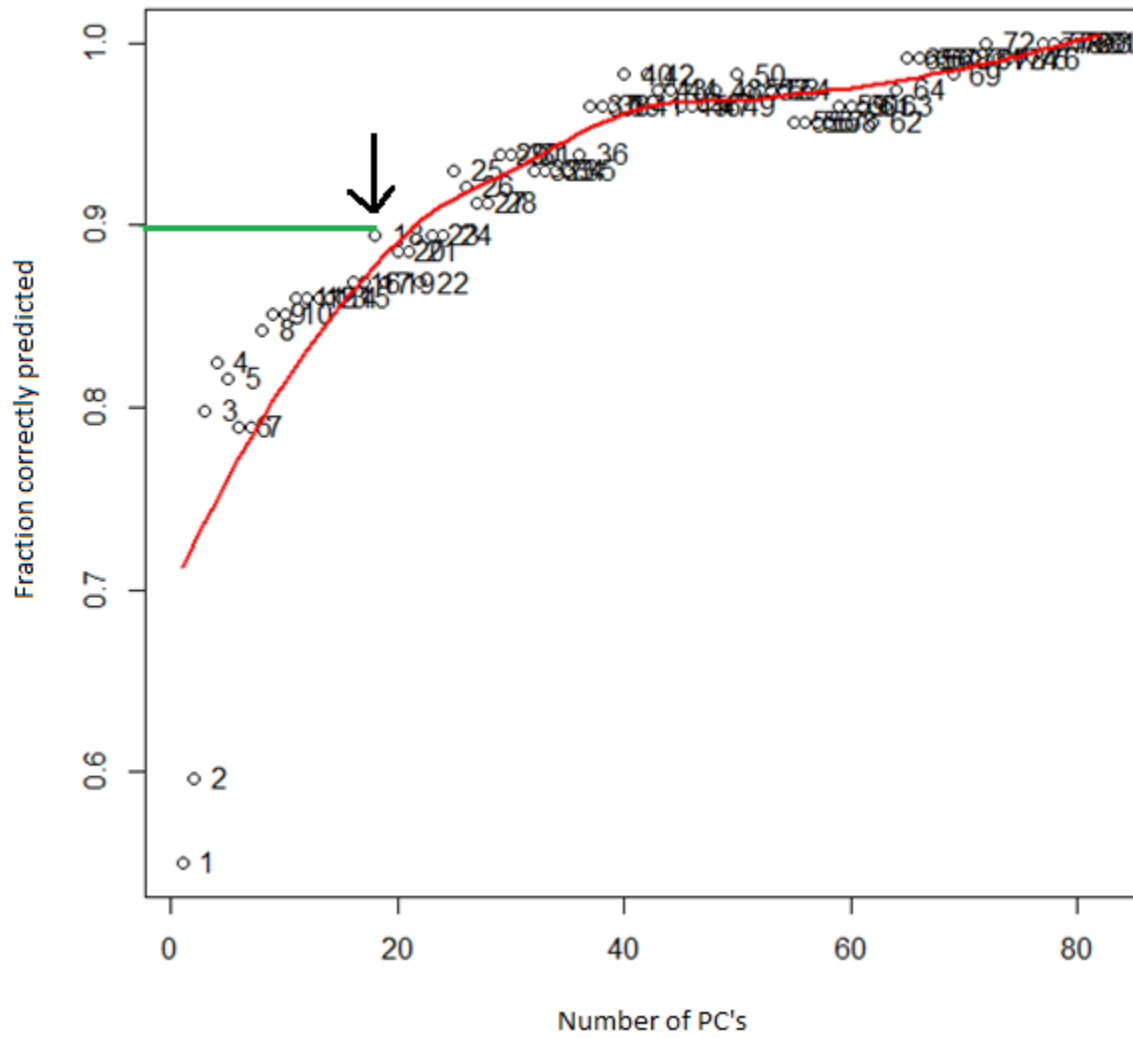


Figure 16: Fraction of correctly predicted sex for the given number of principal components used in discriminant analysis.

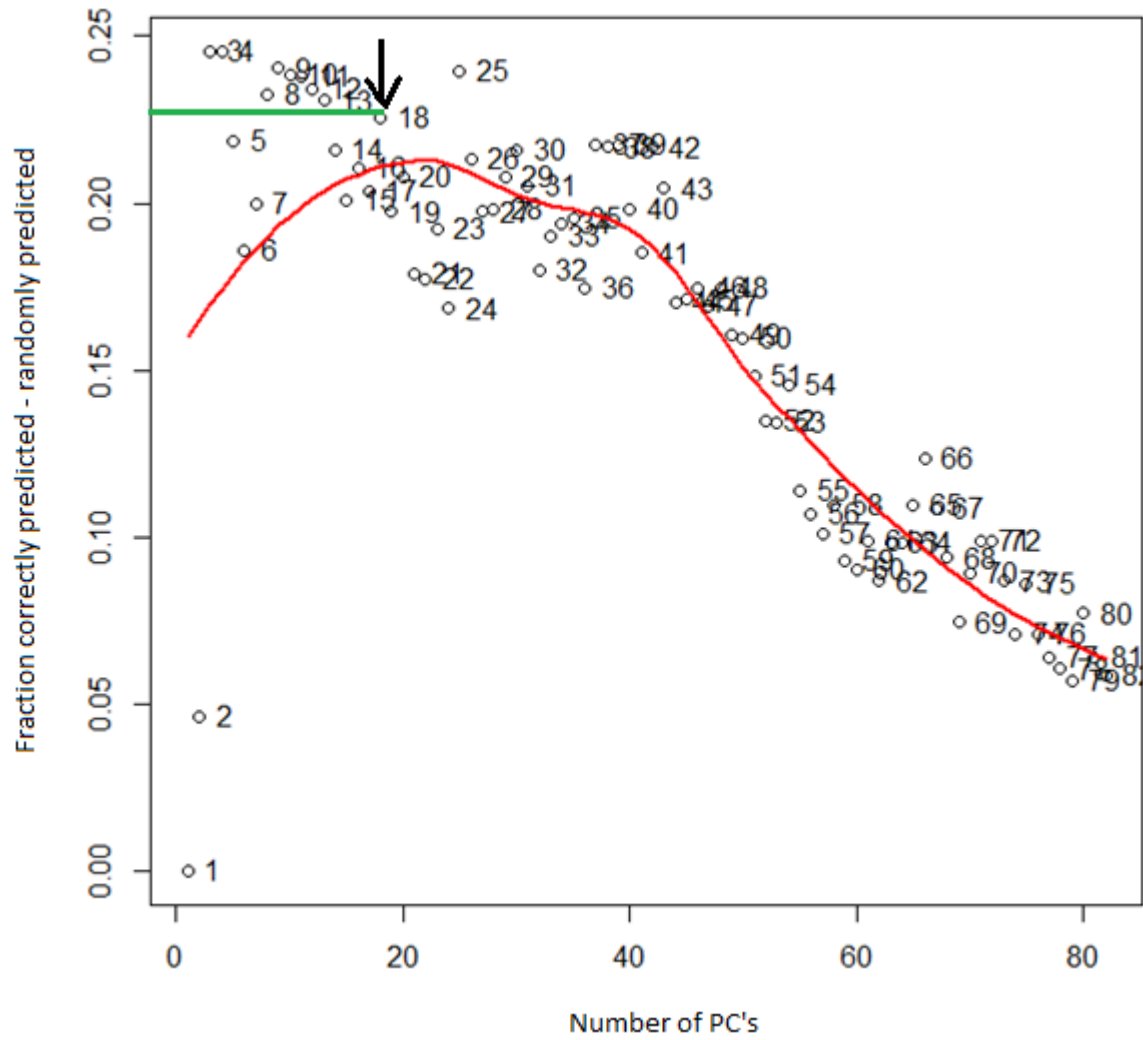


Figure 17: Difference between the fraction correctly predicted sex and the fraction predicted from randomly assigning individuals to a sex 10 times in variably edentate mandibles using discriminant analysis.

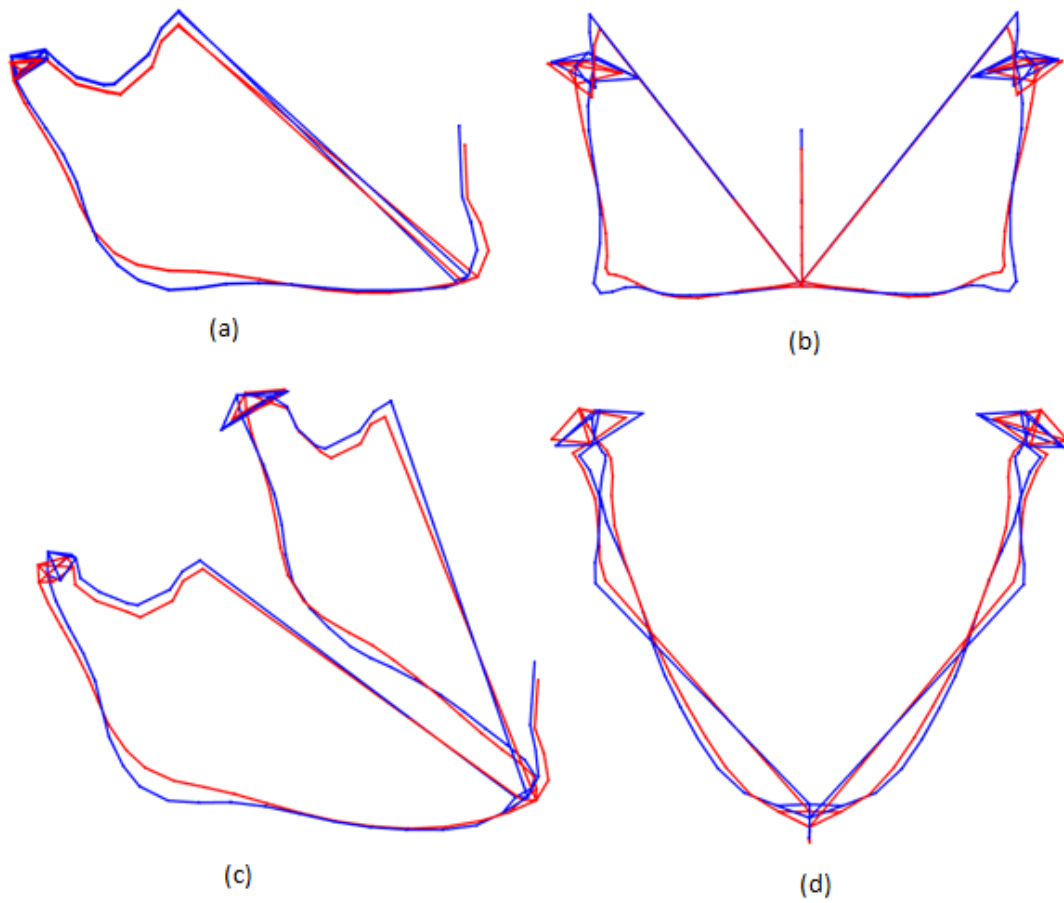


Figure 18: The mandibular morphology that best represents the extreme male and female morphologies of fully dentate mandibles as calculated with discriminant analysis scores of -3 (female) and 3 (male) is shown at four views. a) is the lateral, b) anterior, c) oblique and d) superior view of the fully dentate mandibular morphology. Key: Female-red and Male-blue.

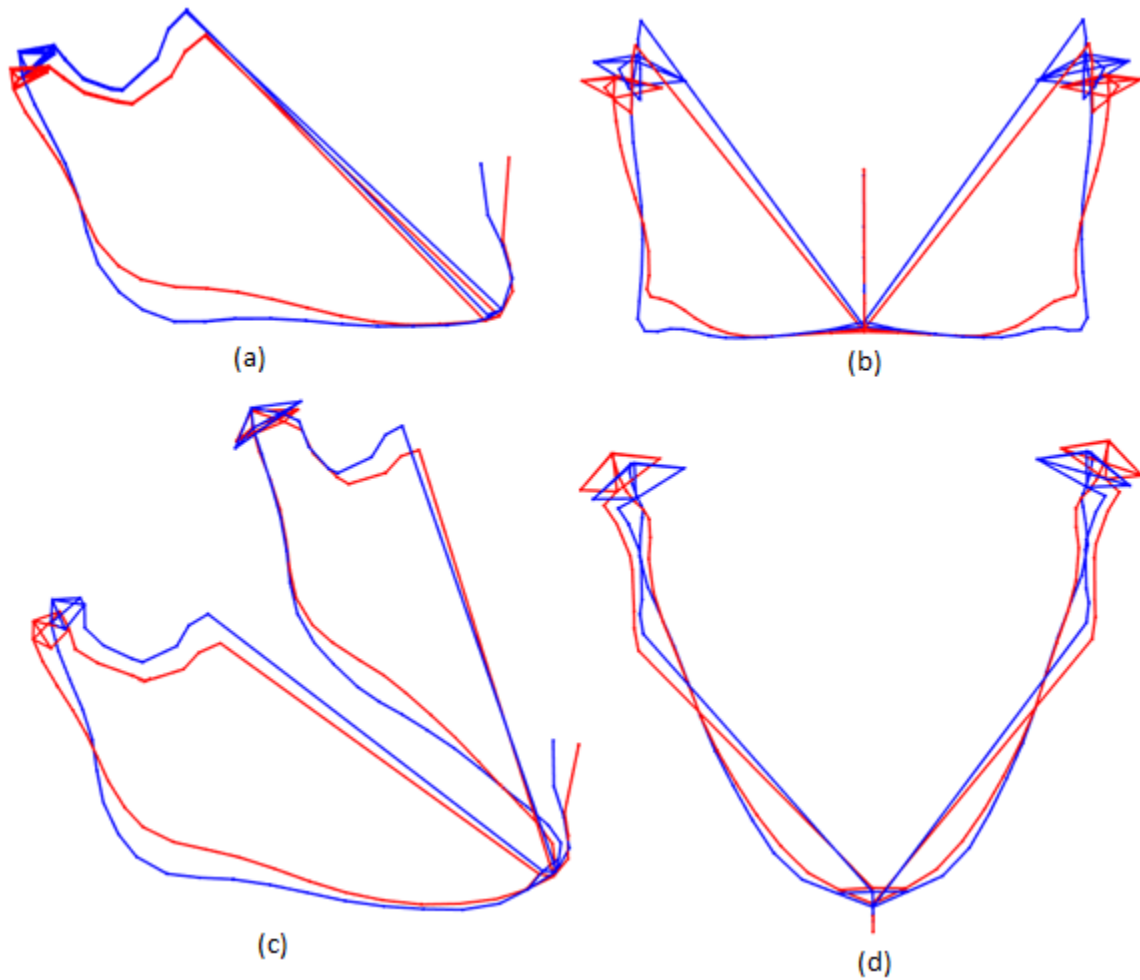


Figure 19: The mandibular morphology that best represents the extreme male and female morphologies of variably edentate mandibles as calculated with discriminant analysis scores of -3 (female) and 3 (male) is shown at four views. a) is the lateral, b) anterior, c) oblique and d) superior view of the variable tooth loss mandibular morphology. Key: Female-red and Male-blue.

The discriminant analysis on PCA plots used to choose PC's for determining the accuracy of sexing correctly from dentulous and variable degrees of tooth loss mandibles yielded overall accuracy of 63.3% for dentate mandibular morphology. A great amount of overlap between males and females mandibles with full dentition was found (**Fig. 20**). The male mandibles with

full dentition had a accuracy of 64.6% and females had 61.3% accuracy of correctly being sexed. The overall sexing accuracy in mandibles with variable degrees of tooth loss was 85.5%. The discriminant analysis showed a distinct discrimination of males and females with minimal overlap between the two sexes (**Fig. 21**). The accuracy of correctly estimating sex in the sampled males and females mandibles with tooth loss was 81.7% and 89.5% respectively.

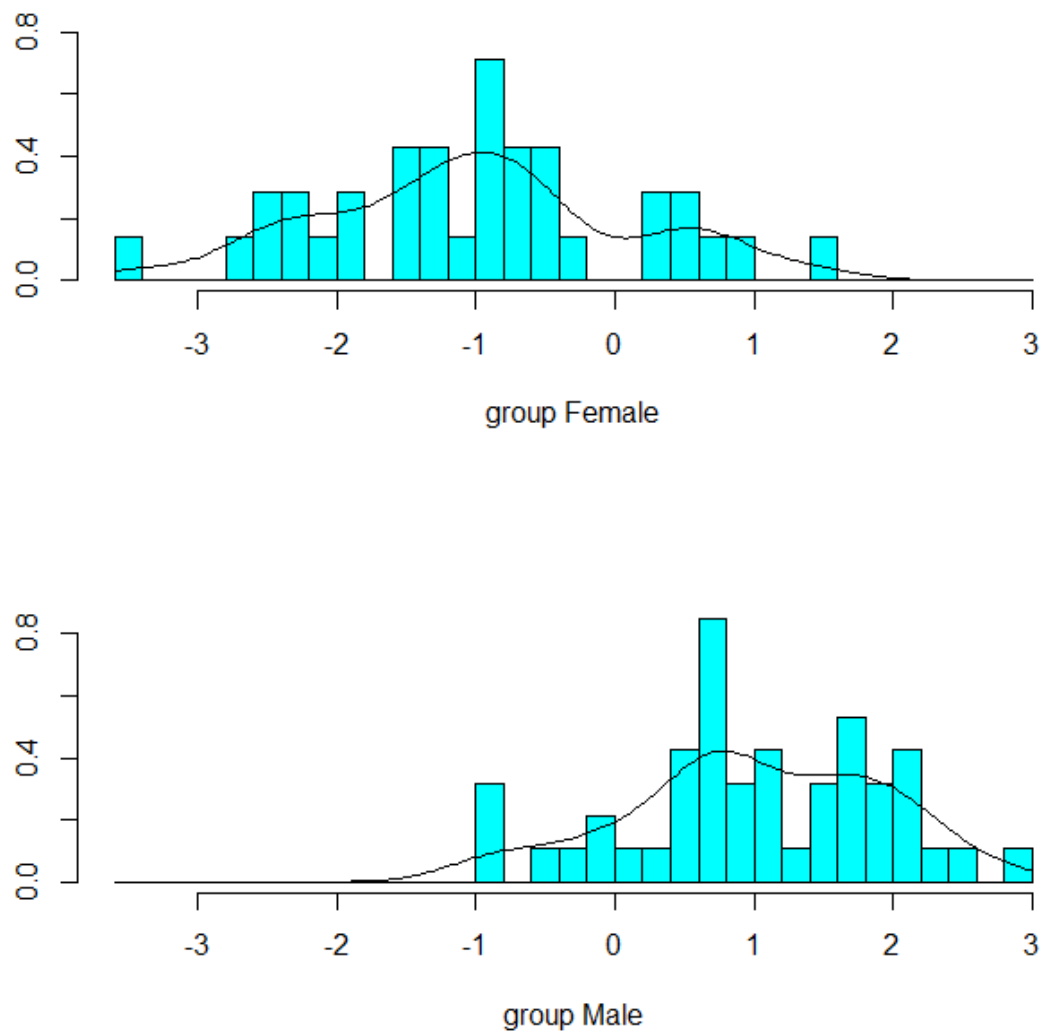


Figure 20: The plot of the discriminant analysis scores for full dentition mandibles. There is a great amount of overlap between male and female mandibular morphology.

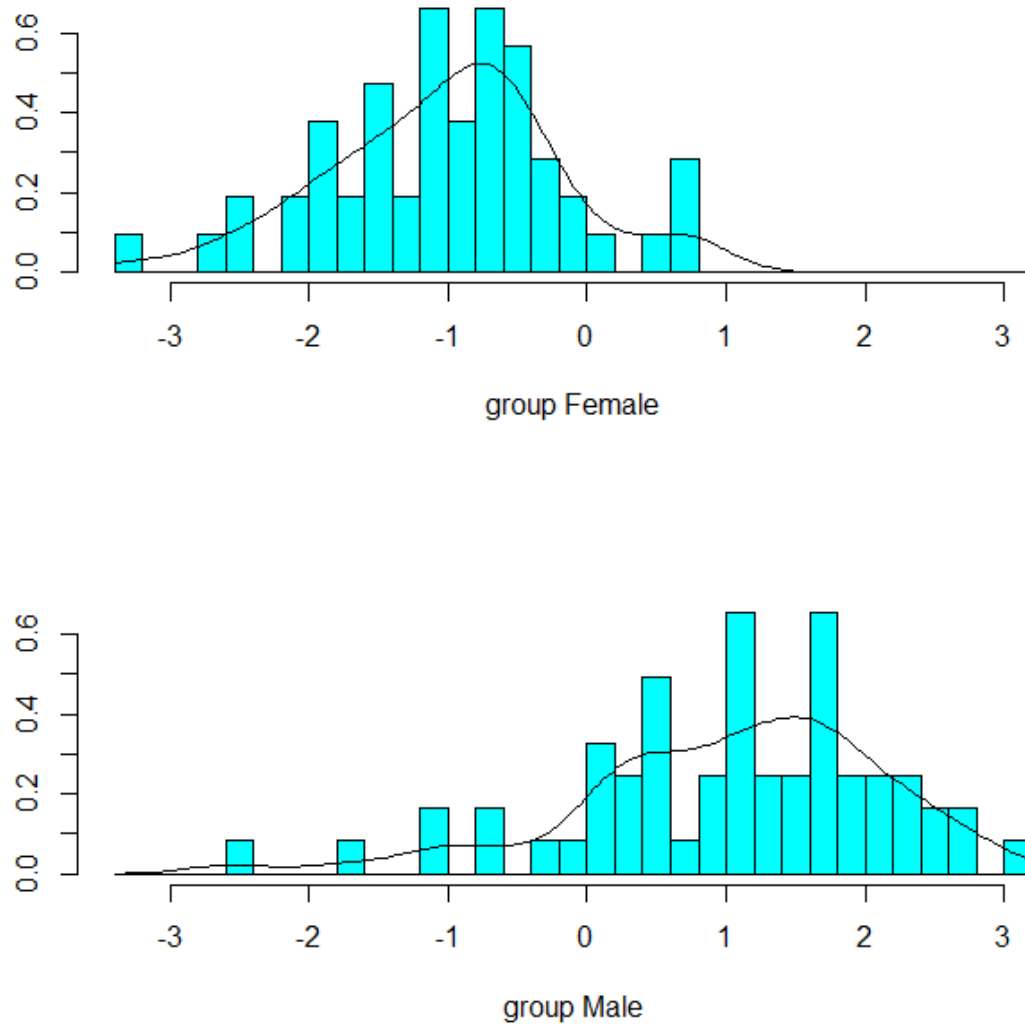


Figure 21: The plot of the discriminant analysis scores for mandibles with tooth loss. There is reduced overlap between male and female mandibular morphology.

3.4 Tooth loss and age effects on mandibular morphology

When analysing the association between mandibular morphology and tooth loss, it was initially observed that the landmarks of the mental region dominated the PLS analysis, and would create a

Pinocchio effect on the remaining landmarks (Klingenberg and McIntyre, 1998). The anterior and protruding mental protuberance seem to adversely affect the shape of the coronoid process, condyle and ramus (**Fig. 22**). Thus, the landmarks over the mental region were excluded from further analyses.

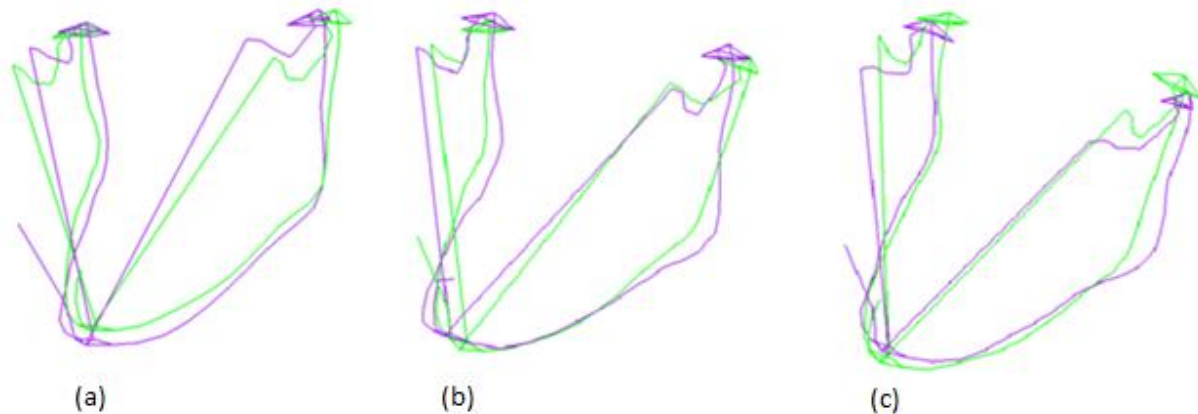


Figure 22: (a) The mandibular shape in tooth loss and full dentition mandibles that was represented by PLS 1. (b) The mandibular morphology represented by PLS 2. (c) The mandibular morphology represented by PLS 3. Key: maximum=green, minimum=purple.

After removal of the mental landmarks and the resuperimposition of the configurations, the permutation test on age as a predictor of mandibular morphology was performed. The results suggests that age does not significantly influence the mandible ($p=0.6319$). Thus the analysis of the two block partial least square used to associate mandibular shape with levels of tooth loss was insignificant. It was assumed to be affected by the inclusion of the full dentition mandibles in the analysis. The mandible's Generalised Procrustes Analysis superimposition was conducted

again after the exclusion of full dentition mandibles and landmarks on the mental protuberance (Rohlf and Slice, 1990). The superimpositions of the mandible outline are shown in **Fig. 23**.

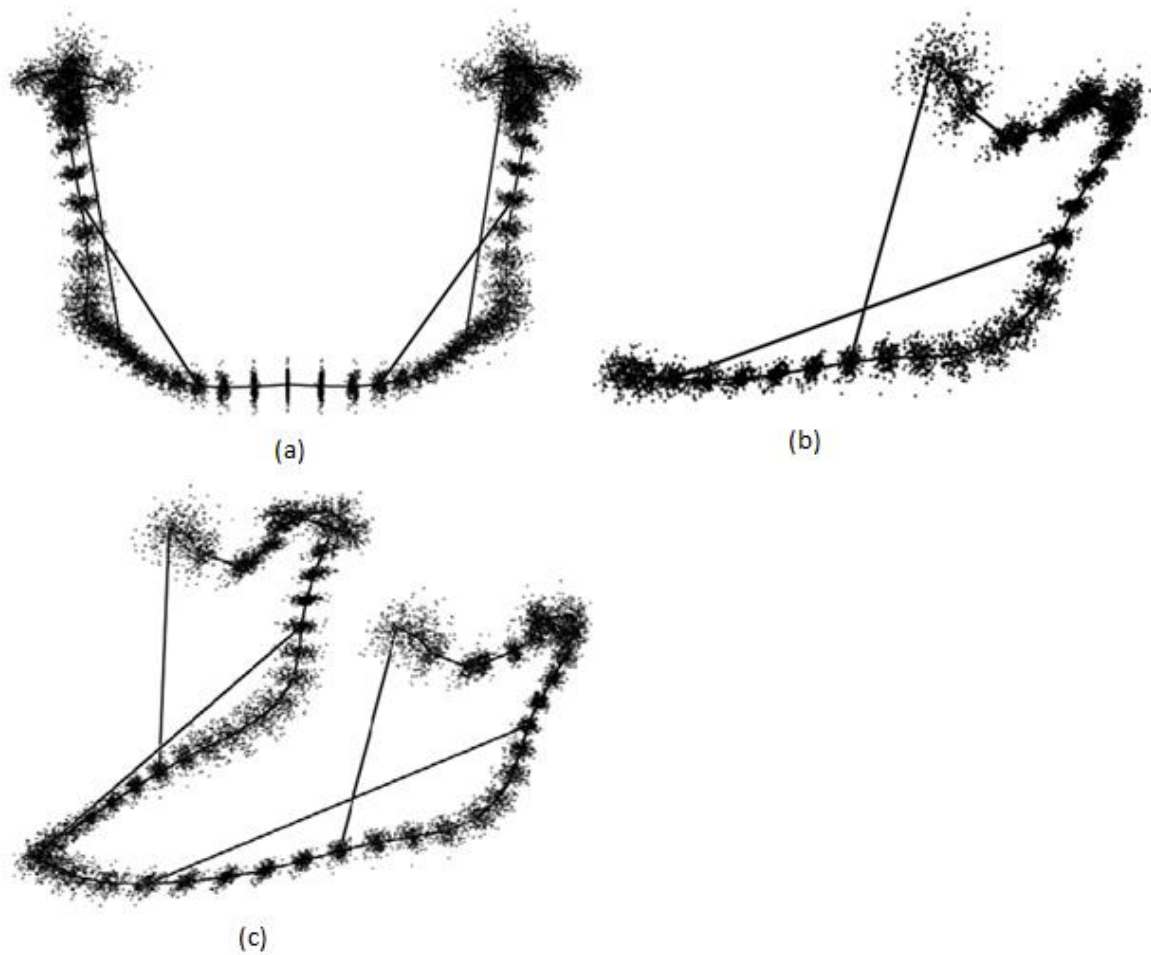


Figure 23: a) Anterior view of the superimposed mandibular landmarks from the sampled mandibles. b) Lateral view of the superimposed mandibular landmarks from outlined mandibles. c) Oblique of the superimposed mandibular landmarks of all sampled mandibles.

The removal of the full dentition mandibles and the mental region landmarks resulted in the analysis being marginally significant at a $p = 0.0474$ (**Fig. 24**). The comparison of mandibular

shape between those with various degrees of tooth loss were represented by PLS graphs in **Fig. 24**. PLS graphs were interpreted in relation to the tooth loss scale on the left. The first graph (top left) represents the PLS 1, PLS2 graph (top right), PLS 3 graph (bottom left) and 4th PLS graph (bottom right). The graphs are shown in relation to the tooth loss scale on the left (y-axis). The tooth loss scale is as follows: tooth loss with full resorption was represented by black, tooth loss with partial resorption represented grey, and white represented presence of teeth. The PLS 1 graph showed the general association of tooth loss and mandible shape (**Fig. 25-27**). The first PLS graph represented a shortened and broad mandibular arch, and a shortened coronoid process in variably edentate mandibles. PLS2 graph illustrated the relationship between the losses of anterior teeth with mandible shape. The mandibular shape represented by the second PLS graph was a more anteriorly positioned coronoid process with the mandibular angle being acute in tooth loss mandible than in observed in mandibles with teeth. The gonion is also eversed in variably edentate mandibles shown by PLS 2. While PLS 3 graph indicated no logical association between tooth loss and mandibular shape. Thus was excluded from further analysis. The 4th PLS graph suggested a relationship between the mandible shape and loss of anterior teeth. This PLS graph demonstrated a posteriorly positioned coronoid process in variably edentate mandibles. The condyle and superior aspect of the ramus was more laterally positioned than the mandibular shape and ante-gonial notch is present in mandibles with teeth.

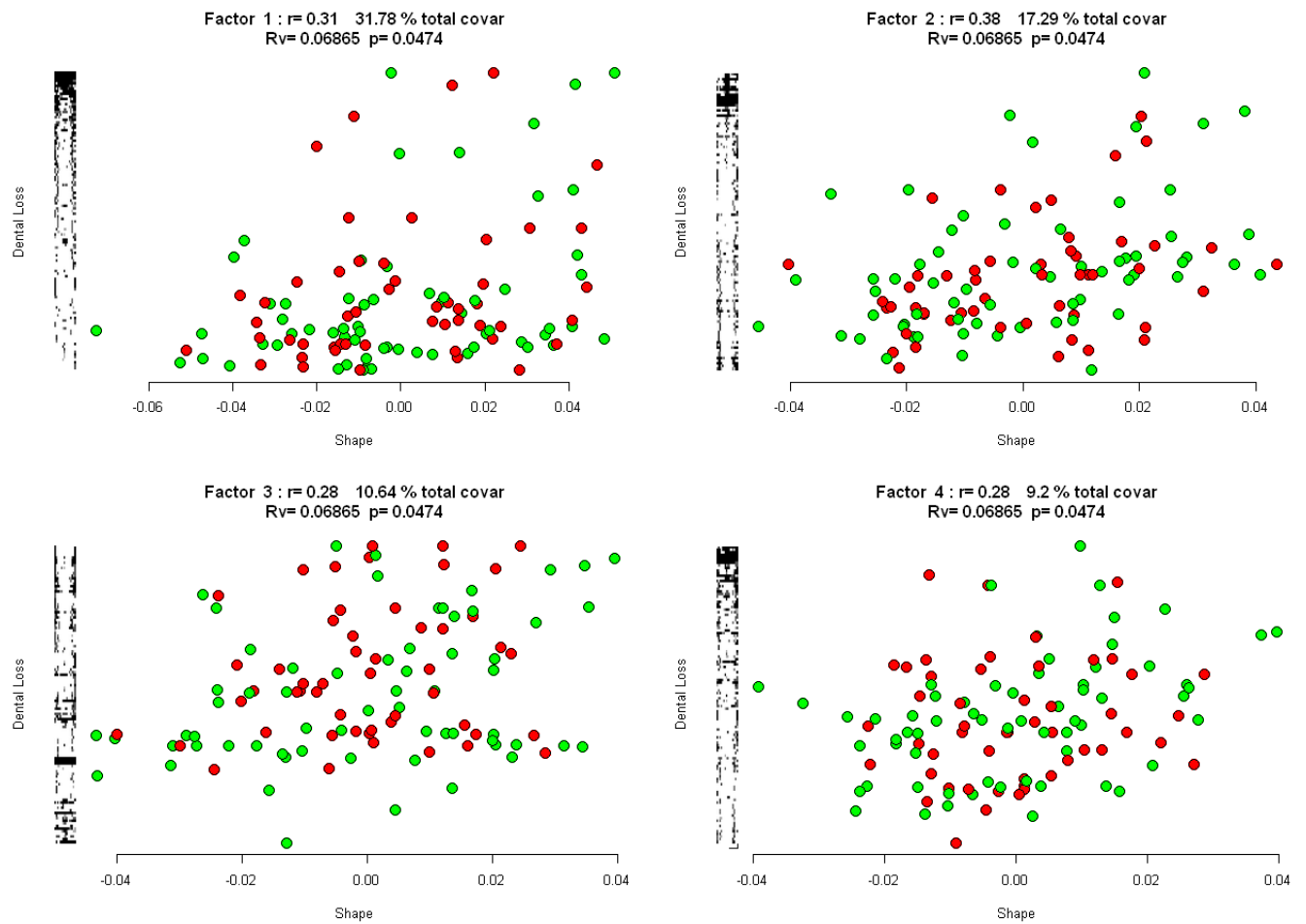


Figure 24: The PLS graphs that represent the association between tooth loss and mandibular morphology. The PLS graph interpretation was related to the tooth loss scale on the left. PLS graph Key: male=Green, female=red.

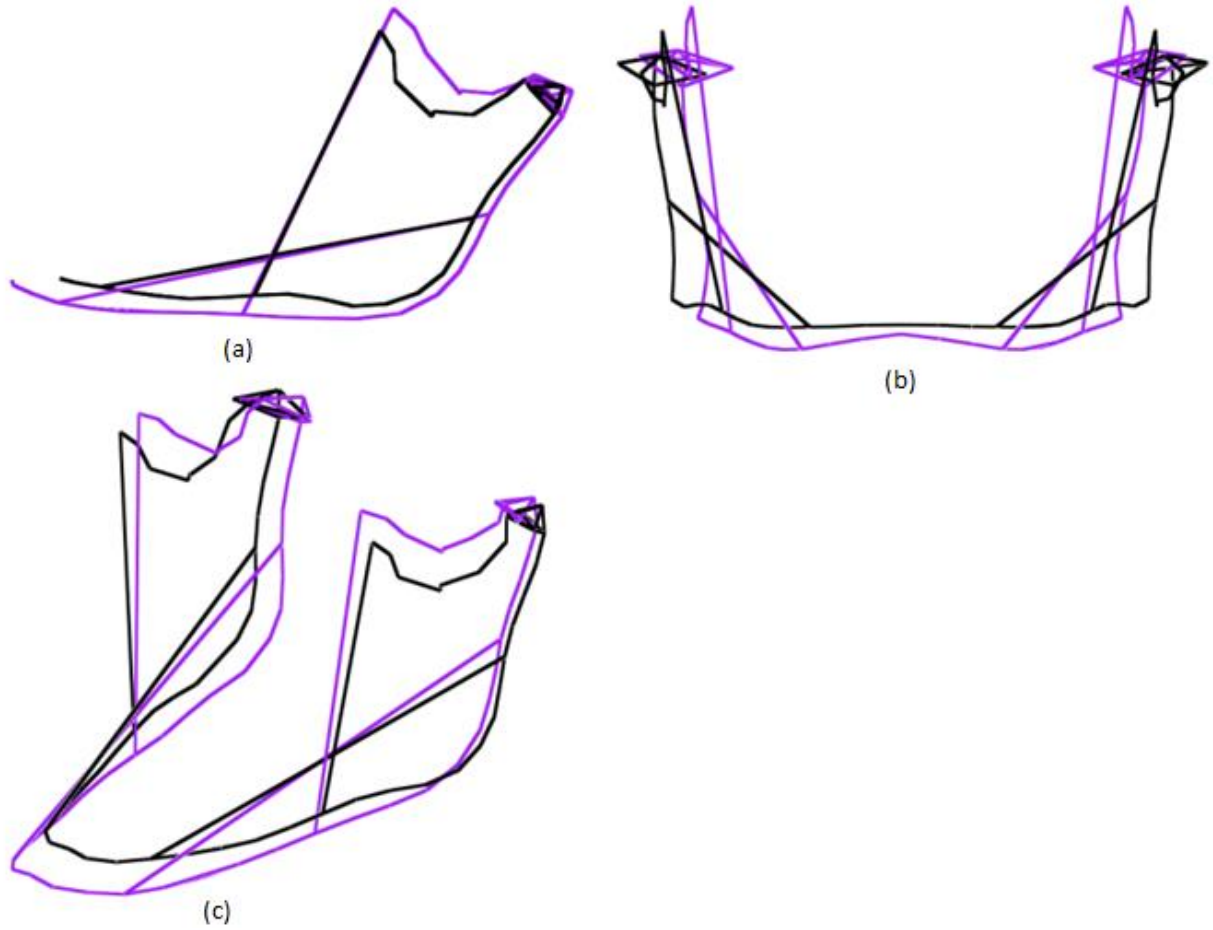


Figure 25: PLS1 graph represented the general association of tooth loss and mandible morphology. The coronoid process of those with tooth loss but teeth present was relatively longer than the edentulous mandibles. (a) is the lateral, (b) anterior and (c) oblique view of the mandibular morphology. See text for descriptions. Key: edentulous= black, teeth present=purple.

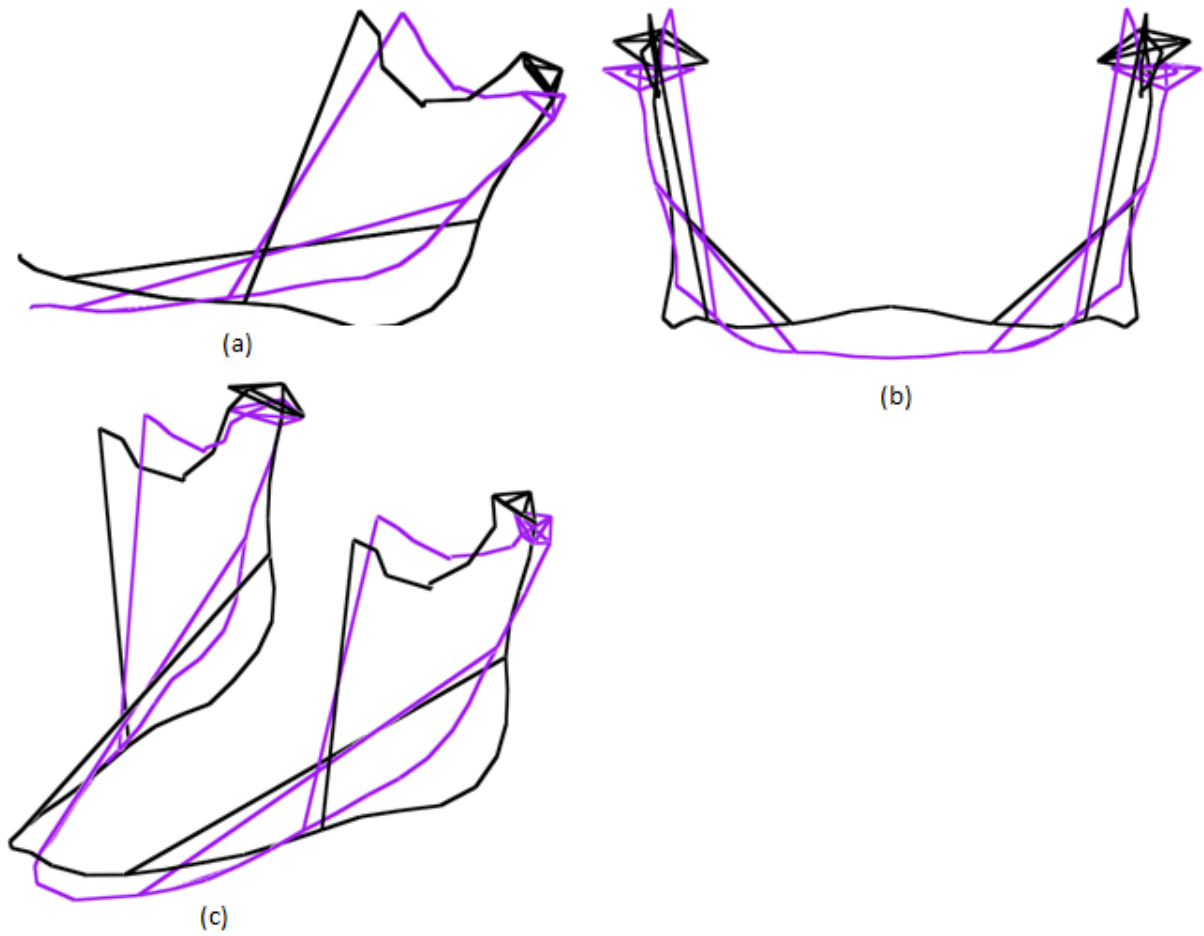


Figure 26: The PLS 2 graph showed that the mandibular morphology represented here was associated with the loss of anterior teeth. (a) is the lateral, (b) anterior and (c) oblique view of the mandibular morphology. See text for descriptions. Key: edentulous= black, teeth present=purple.

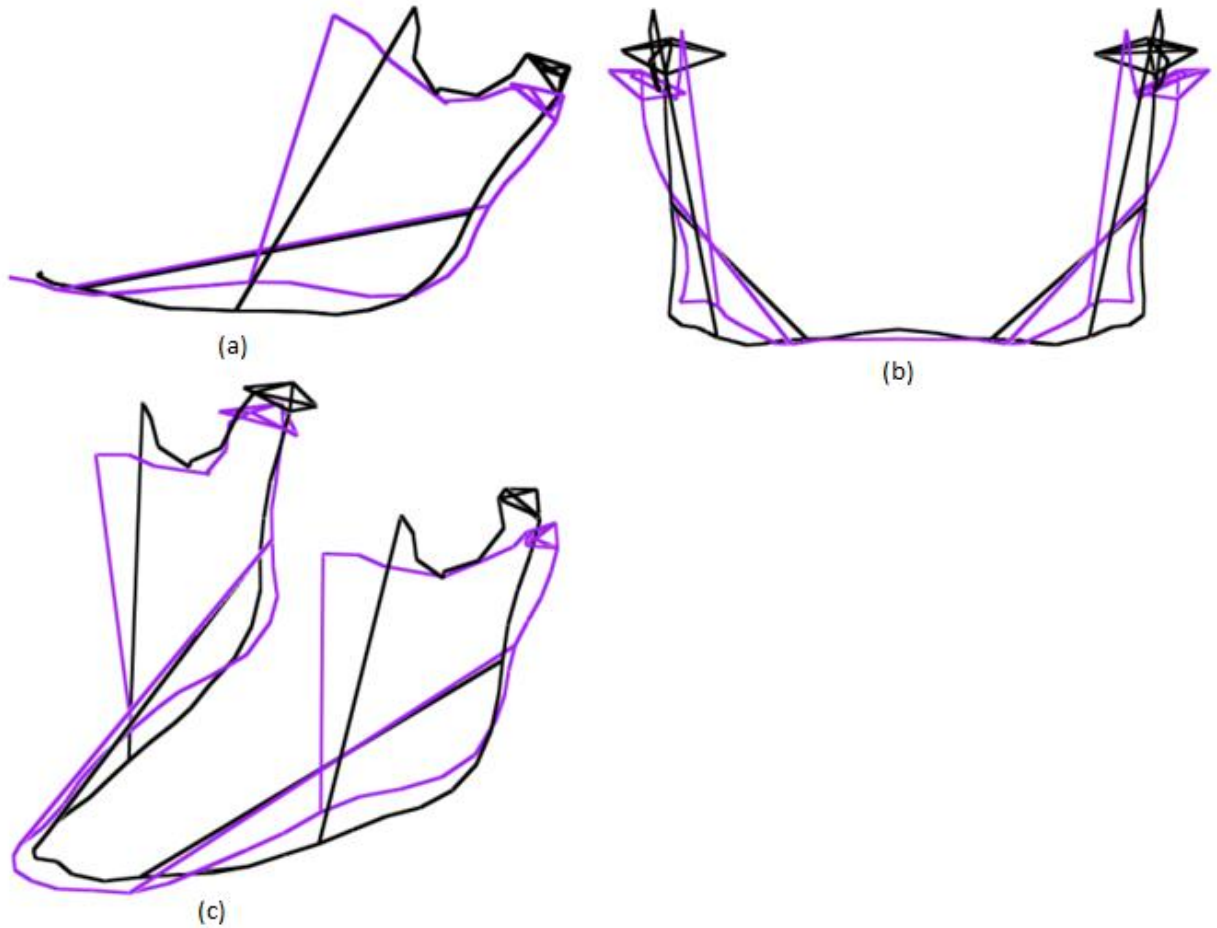


Figure 27: The PLS4 graph represented the relationship between the mandibular morphology and loss of posterior teeth. (a) is the lateral, (b) anterior and (c) oblique view of the mandibular morphology. See text for descriptions. Key: edentulous= black, teeth present=purple.

A multivariate analysis of variance was performed on the matrix of tooth scores to test whether differences between the sexes of mandibles with tooth loss existed. The level of tooth loss was found to be slightly different as evidenced by the significance of Wilks' lambda and Pillai test ($P=0.0366$ in both tests).

3.5 Sexual dimorphism in the mandible using descriptive method

To determine the non-metric accuracies of these features, the characters were independently scored. The accuracies of correctly estimating sex descriptively from mandibular features of both dentulous and edentulous mandibles from a quantitative analysis are shown in **Table 3**. The overall accuracies were lower than the accuracies found from the discriminant analysis of the quantitative analysis.

Table 3: Quantitative analysis of each mandibular feature independently.

Mandibular feature	Accuracy	Accuracy
	Left	Right
Mental protuberance	64.25	64.25
Ante-gonial notch	55.44	52.33
Mandibular ramus	58.03	57.00
Mandibular condyle	48.71	45.60
Overall average	56.61	54.79

Chapter 4: Discussion

Many studies of sexual dimorphism exclude mandibles with high levels of tooth loss because the effect of tooth loss on accurately estimating sex from the mandibles is not understood. Thus it was the study's aim to prove this hypothesis.

4.1 Sexual dimorphism in the mandible

The sexual dimorphism on the mandibular morphology found was consistent with that determined in other sexual dimorphism studies (Steyn and Iscan, 1998; Oettle *et al.*, 2005; Pretorius *et al.*, 2006; Franklin *et al.*, 2008; Oettle *et al.*, 2009). However, the high estimate of sexual dimorphism from mandibles with tooth loss was unexpected and could not be compared with any other similar study. This finding could be because mandibles with high levels of tooth loss were excluded from previous studies of sexual dimorphism for example in Steyn and Iscan (1998), Oettle *et al.* (2005), Franklin (2007) (2008a), Ongkana and Sudwan (2010) and Coquerelle *et al.* (2011). The study of sexual dimorphism of mandibles with tooth loss indicate that these mandibles display equally if not greater dimorphism as observed in full dentition mandibles. Mandibles with tooth loss should not be excluded from identification studies especially when their aims are to identify standards for sex estimation.

The degree of sexual dimorphism in the mandible outlines are influenced by factors responsible for morphological variation such as genetics, physiology and its mechanics affecting the morphology. The different genetic predisposition in males and females during development is responsible for the sexual dimorphism (Rice, 1984; Sundseth *et al.*, 1992; Rinn *et al.*, 2004; Rinn and Snyder, 2005). This genetic predisposition leads to the males producing testosterone and

females oestrogen at the start of puberty. The differential hormone production may have affected the bone growth. The testosterone is an androgen while oestrogen contains small amounts of androgens (Dorfman and Shipley, 1956; Hohn, 1966; Sims *et al.*, 2003; Tulandi and Gelfand, 2006). Androgens present in male sex hormones account for the secondary characteristics which include increased bone growth through nitrogen retention for protein build-up (Dorfman and Shipley, 1956; Hohn, 1966; Notelovitz, 2002; Vanderschueren *et al.*, 2004). Males also have a larger muscle mass that apply greater mechanical forces on the mandible compared to that in females.

Regarding the masticatory complex and osteological structures, the effect of testosterone on muscle was experimented upon in a study conducted on emasculated rodents. Androgens such as testosterone were administered to these rodents resulting in the strengthening of the hypotrophied masticatory muscles (Scow and Roe, 1953). Young and adult human males aged between 6-20 years have a significantly larger bite forces than females which could be attributed to the larger muscle mass in males (Dean *et al.* 1992; Braun *et al.* 1995; 1996). An increased muscle mass affects the facial morphology and thus the differential muscle mass in males and females as a result of genetics could contribute to the sexual dimorphism in fully dentate mandibles and the revelation in variably edentate mandibles (Raadsheer *et al.*, 1996).

The lower sexing accuracies in the fully dentate than in variably edentate mandibles is translated to a large overlap in the former (**Fig. 20** and **21**). The overall sexing accuracies determined in this study were relatively higher when compared with other studies on black South Africans using discriminant analyses (Steyn and Iscan, 1998; Oettle *et al.*, 2005; Pretorius *et al.*, 2006; Franklin *et al.*, 2008; Oettle *et al.*, 2009). The accuracies that these studies found from full dentition mandibles using mandibular features such as gonial eversion were 73.9% for males and

71.4% for females (Oettle *et al.*, 2009); ramus accuracies ranged between 69.6% - 69.2% for males and 67.8% - 81.9% for females (Steyn and Iscan, 1998; Oettle *et al.*, 2005; Pretorius *et al.*, 2006); symphysis were 62.5% for males and for females 54.8% (Franklin *et al.*, 2008). The high sexing accuracies in this study might be due to curves being used to outline the mandibular features as they best define the characters instead of fixed landmarks across multiple features for example gonion, ramus and condyle. Exception could be made to the accuracies for correctly estimating sex from the ramus using linear measurements that were 97.4% in males and 95% for females (Franklin *et al.*, 2006). The great difference in the sexing accuracies between linear methods and the geometric morphometrics used in this study could be because linear measurements include shape and size of the mandibles, while geometric morphometrics only considers the shape of the mandibles.

Very few studies have considered the effect of tooth loss on mandibular morphology and sexual dimorphism. Loth and Henneberg (1996) found reduced accuracies of 93% in males and 88% in females using the ramus flexure for mandibles with molar tooth loss compared with accuracies of 99.1% in males and 98.8% for females in their fully dentate sample. It can be deduced that tooth loss negatively affects the qualitative method as the accuracies are lower than those found in full dentition mandibles. This could be that the method is based on the subjective ability of the observer to identify the flexure. Another qualitative study on accuracies estimated from mandibles with posterior tooth loss yielded higher sexing accuracies for males at 85.2% and were lower at 37.5% for females (Balci *et al.*, 2005). The large difference in the accuracies between studies could be that the method used in Balci *et al.* (2005) is best at correctly estimating sex from males than females and is thus biased toward males. The identification of ramus flexure presence as a male characteristic may have resulted in most males being correctly

sexed than females. This method could become positively and negatively biased to males and females respectively. Other reasons may be that the resorption in the mandible affects mandibular features such as the ramus flexure, ante-gonial notch and the elongation of the coronoid process. Due to this, the mandibular features in females remodel and become masculinise to resemble those of males. Hence the sexing accuracies using qualitative methods are more likely to sex females incorrectly compared to males. This is supported by the difference in the mandibular morphology between full dentition and mandibles with variable tooth loss found in the current study. The mandibles with tooth loss had similar but exaggerated mandibular sexual dimorphism in mandibular morphology than the full dentition mandibles.

The overall sexing accuracies found here were not only higher than that of the South African samples but are similar to the accuracies determined in studies of non-South African populations (Schmittbuhl *et al.*, 2001; Balci *et al.*, 2005; Kharoshah *et al.*, 2010). The use of qualitative methods to accurately estimate sex from linear measurements of Egyptian mandibles yielded 83.6% for males and 84.2% for females (Kharoshah *et al.*, 2010). The accuracies from a European population using geometric morphometrics have 97.1% of males sexed correctly and females at 91.7% (Schmittbuhl *et al.*, 2001). The Turkish population yielded male accuracies of 95.6% and 70.6% for females from full dentition mandibles, while those from mandibles with tooth loss are 85.2% for males and 37.5% for females (Balci *et al.*, 2005). The similarities in the accuracies of correctly estimating sex in populations other than South Africans suggest that the high level of sexual dimorphism in the mandible is a trend in most populations around the world.

The male and female mandibles were characterised by specific mandibular shapes. The male mandible was determined in this study to have a broader mandibular arch, an elongated coronoid process compared to the narrow mandibular arch in females similar to the findings of Franklin *et*

al. (2008) and Coquerelle *et al.* (2011). Other features include the flexed ramus, deep ante-gonial notch and gonial eversion in males that is in concordance with Loth and Henneberg (1996) and Oettle *et al.* (2009) respectively. The mandibular shapes in male and female studied in the current study were similar to those determined by other studies (Loth and Henneberg, 1996; Steyn and Iscan, 1998; Rosas and Bastir, 2002; Franklin *et al.*, 2008; Coquerelle *et al.*, 2011; Lestrel *et al.*, 2011; Bejdova *et al.*, 2013). These mandibular features also illustrate that the male and female mandibles from black South Africans portray features similar to those found in studies of sexing from the mandible on European populations.

When compared with other cranial elements the human mandible is greatly affected by mechanical activity and loading. This could be an important differentiating factor that causes sexual dimorphism (Raadsheer *et al.*, 1996). The mechanical activity is considered to be brought on by muscle action. The large muscle mass in males (as previously mentioned) may have accounted for the broad mental region and mandibular arch. These features might have conformed in relation to the muscle actions associated with these regions. The activity of other muscles that might have caused the widening of the mandibular arch are those that attach on the lateral aspect of the mandible (**Fig. 28**). These include the masseter muscle and the temporal muscle. The large muscle mass of the temporal muscle may explain the elongated coronoid process in the mandibular morphology of males (**Fig. 29**).

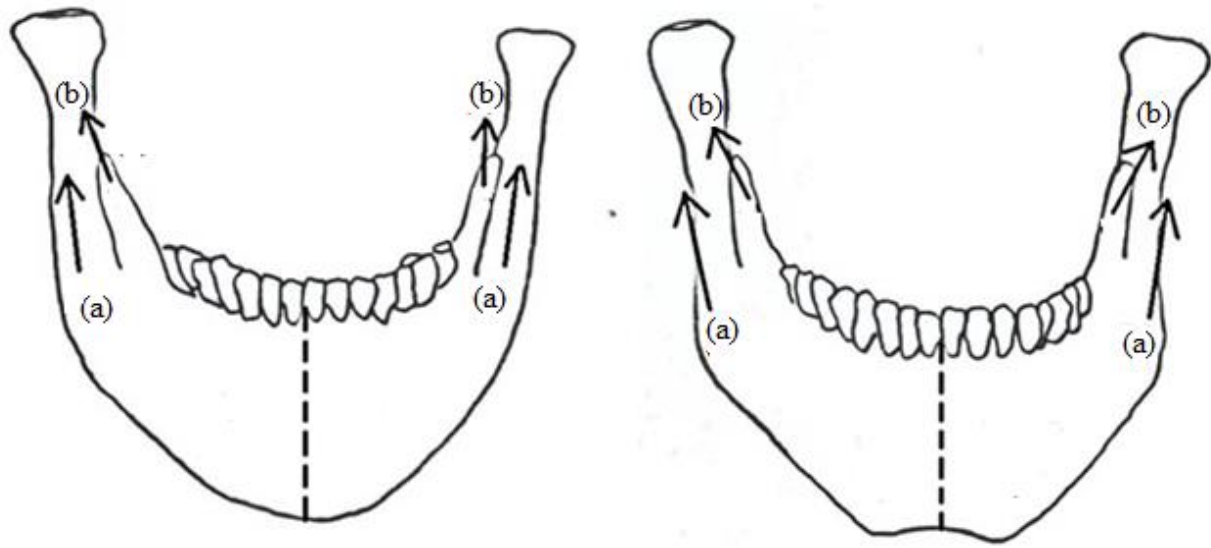


Figure 28: The effect muscles may have on the broadening of the mandible. The female (left) experience less muscle activity thus no widening of the mental region and mandibular arch or lengthening of the coronoid process. The large muscle mass in male mandibles (right) account for the morphology male mandibles had. The directional effect of: (a) masseter and (b) the temporal muscle. Image adapted from Bass (1995).

Masticatory muscles that attach on the lateral aspects of the gonion and ramus may also define the deep ramus flexure in males. Including the medial pterygoid muscle that inserts on the medial aspect of the mandible around the gonion region, this muscle may have affected the ramus and ante-gonion features of the mandible during the elevation of the mandible. The elevation of the mandible by the masseter (**Fig. 29b**), the temporal (**Fig. 29a**) and medial pterygoid muscles (**Fig. 30b**) during mastication to allow for maxilla to occlude with the mandible, these muscles apply forces in a direction that may have caused the ramus to flex as observed in the male morphology (**Fig. 29**). The males may have had broader condyles due to the high compressive force they experience. The great muscle mass of the lateral pterygoid muscle in males could as well be the explanation for the anterior displacement of the condyle that males possessed. The lateral

pterygoid muscle shifts the mandible in lateral motions during mastication and that it inserts at the neck of the mandibular condyle could affect the position of the condyle (**Fig. 30a**).

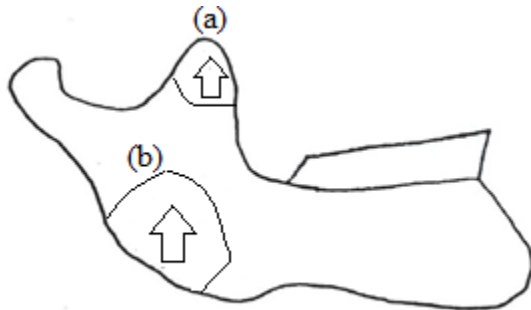


Figure 29: The (a) temporal muscle and (b) masseter muscle attach at these regions and contract in the directions specified by the arrows. The contraction of muscles results in the modelling of the mandibular feature that they are attached to. The coronoid process is posteriorly placed in males with a notched ramus and ante-gonial notch. Image adapted from Lonberg (1951).

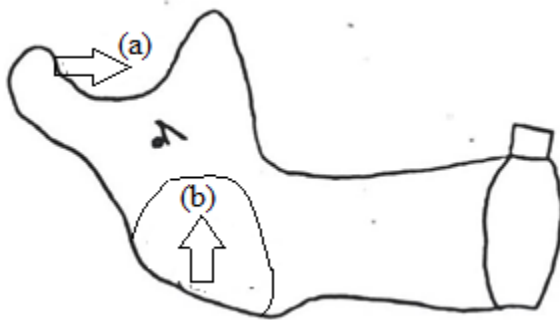


Figure 30: The direction in which the function of (a) lateral pterygoid and (b) medial pterygoid muscle contract.

The large muscle mass males had, that was previously mentioned, may have contributed to the shape mandibular features had. The consideration of the masticatory muscles that act upon the mandibular features, specifically muscles on external aspects of the mandible, could have caused

lateral widening of the arch. The observed widening is called wish boning of the mandible. For instance, when the temporal and masseter muscle function they pull the mandibular feature they attach to superiorly and laterally respectively. This notion was supported by Hylander and colleagues (1998) including Vineyard and Ravosa, (1998) who studied how the consistency of food (hard or soft) affected the force the mandibles experienced. These studies were conducted on primate mandibles. The mandibles of humans and primates are similar in function; however, the functions of specific teeth such as canines are different. The shared function included the lever mechanics of the mandibles linked to masticatory purposes. They determined that the mandibular arch widened when hard foods were consumed. The lateral widening of the mandible was due to the high pressure applied triggering the elastic properties of mandible to flare out. The bone material moves away from the region at which pressure was applied (Chamay and Tschantz, 1972). In the case of a solid and fixed shape formed, the pressure had to be applied constantly over a long period. Thus widening of the male mandible due to the high masticatory forces they apply on bone, as Wolff's law specifies.

The sexual dimorphism in the mandibular morphology may have been affected by lever mechanism of the mandible. The mandible was considered to be a lever that assisted an individual in reducing the size of food portions in the mouth (Hylander, 1975). The condyle is taken as the fulcrum, the coronoid process and gonion are regions where muscles apply force and cause an effect of mandible through its elevation and depression (Mcevoye, 2013; **Fig. 31**). The alveolar region that is located directly above the corpus is where the food eaten applies its load (Mcevoye, 2013). The female mandibular morphology that was studied had a shorter ramus and a longer corpus than male morphology. This could be due to the mechanics of the mandibular lever; the longer the handle between the effort and load (length between gonion and load which

could be the mandibular corpus) the handle bends in the direction of the load. Thus, the female's mandibular morphology had a deeper ante-gonial notch than in males. A similar effect is expected in males where the elongated ramus could possess a deep flexure and be a mechanically linked response of bone to the muscle mass. Thus, the long corpus in females could possibly be associated with the lever mechanics of the mandible.

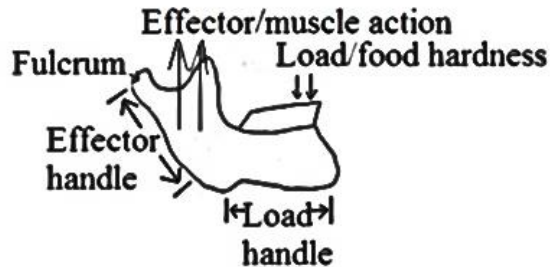
Lever

1. Normal

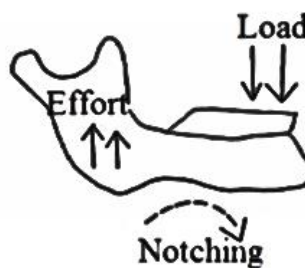
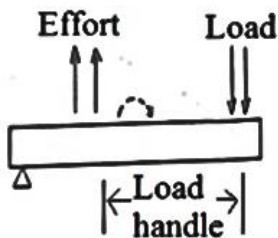


Mandible as a lever

1. Normal



2. Elongation of corpus



3. Elongation of ramus

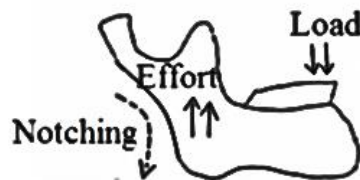
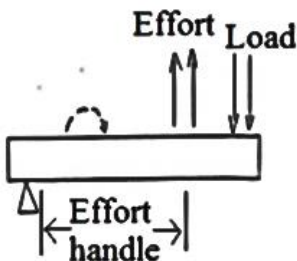


Figure 31: 1. The lever that represents the function of the mandible. The fulcrum is the mandibular condyle, the effector is the coronoid, ramus and gonion regions, the load is the teeth region that are used during mastication. 2. The representation of the elongation of the mandibular corpus. The broken arrow indicates the direction at which that section is able to curve in. 3. The representation of the elongated ramus with its notching (broken arrow) causing the change in morphology. (Mandible outlines adapted from Lonberg, 1951)

This premise of notching in the ante-gonion region and the ramus as a result of lever mechanics of the mandible is supported by Hylander (1975) and Davidovits (2013). They suggest that the mandible is a lever that remodels as a result of loading. This suggestion classified the mandible as a class III lever (**Fig. 32**; Ryan, 2009). However, Taylor (1986) suggests the mandible as a three dimensional lever and considered it to be the integration of left and right units. These mandibular units articulate with the base of the cranium at the condyle. The mandibular condyle experiences compressive forces during events such as mastication. When the load on the teeth was applied, the condyle was not only acting as a fulcrum but was an effector region as well (Taylor, 1986). With such a configuration in mind, the mandible is still however recognized as a lever (class I lever; Ryan, 2009).

It was considered that the gonion is a fulcrum that was suspended by muscles allows for the acceptance of the mandible as a lever (Hylander, 1975). This fulcrum separates the loading (alveolar) region and the effector (ramal) region. Due to this arrangement, the same result, regarding remodelling and notching, is expected to occur when the fulcrum was thought to be the condyle. The lengthening of the loading handle could cause the notching of ante-gonial notch in class I lever scenario. The expected ramus flexure also goes for the lengthening of the effector handle. In the scenario of mastication, the food that required being grind exerts a downward load. As a result of this the opposite side of the apparent lever, the effector (ramus, coronoid process and condyle) moves upwards to cause a compressive force on the regions that articulated with the cranium. Thus, the relative posterior positioning of the condyle in females was due to a shortened handle of the ramus. The posterior position of the mandibular condyle was considered to be a result of a confined articular surface with the cranium. The observed female condyle position could be assumed to be due to a small size of the temporo-mandibular joint (Hesse *et*

al., 1997). The joint might restrict the condyle to move within the joint thus the change in position.

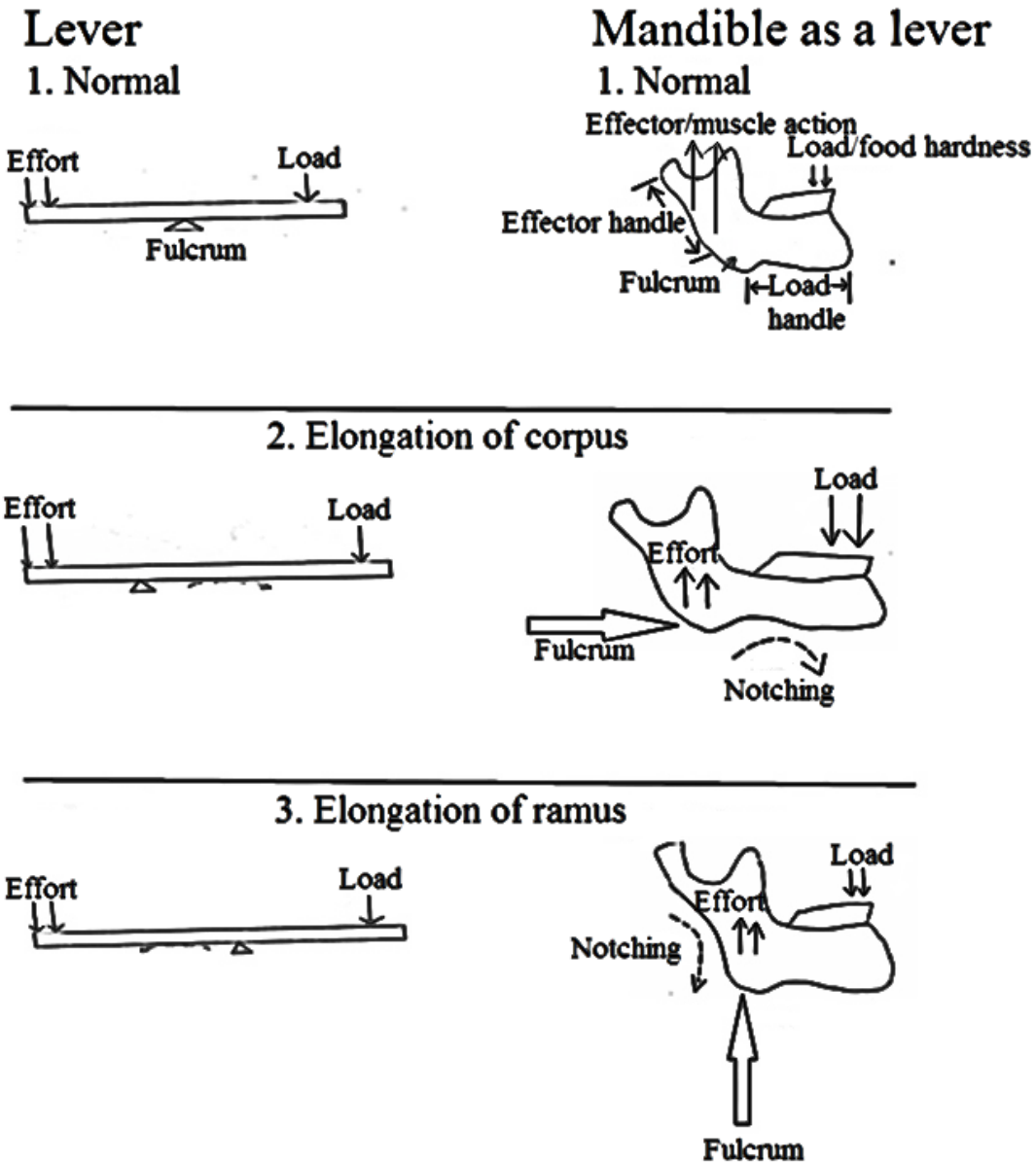


Figure 32: 1. The class I lever. The fulcrum could represent the gonion region, the applied effort be at the condyle and load at the dentition region. 2. The elongation of the ramus (between condyle and gonion) may lead to the notching of the ramus. As indicated by the broken arrow. 3. The elongation of the corpus may lead to the notching of this region. (Mandible outlines adapted from Lonberg, 1951).

The length of the corpus and ramus in males and females could also be explained by the lever effect of the mandible. From the understanding of how levers function, the longer the load lever handle is from the fulcrum the lesser the force required to lift the load (Newing, 1963). This kind of a lever could best describe the mandibular dimensions of the female. The shorter the distance from the condyle (fulcrum) to the loading region (corpus), the less work is required of the muscles for the mandible to function. Clegg *et al.* (2009) briefly discusses the basics of lever function. He states that the force applied as an effector, named torque, is the product of the load (force perpendicularly applied) and the distance of load from the fulcrum (Herrick and Karnow, 1962; Clegg *et al.*, 2009). The understanding of this formula and lever mechanics suggests that the longer the lever handle is from the fulcrum the more effort required for effective function (Newing, 1963; Rutland, 1973; Oxlade, 2008). This could explain the observed male and female ramus and condyle length.

The long ramus in male was probably to accommodate the large muscle mass. The great loading during mastication in males may cause the large muscle mass, which could lead to the mandible remodelling to withstand these factors. The longer the load is from the fulcrum the more work is required. The long corpus in female is most probably to allow the mandible to be effective during reduced muscle mass. Therefore sexual dimorphism of mandibular shape could function to compensate for the small muscle mass in females or the large muscle mass in males.

The sexual dimorphism determined in mandibular morphology could also be a result of differences between male and female dietary preference (Nowjack-Raymer and Sheiham, 2003; Allan, 2005; Kossioni and Bellou, 2011). The mandibles sampled could have once belonged to individuals who could have lived in rural villages, informal settlements or townships, which is probable as the acquisition of skeletons for the Dart Collection of Human Skeletons began in the

1920s. This was during the time when South African black individuals living in urban environment could earn a middle or upper class income. As a result of the class group they lived in, their diet was distinct and cultural differences played a great role in their diet. Thus culturally, males had sizeable portions of meals and the foods they chose to eat required an extensive amount of chewing (Jensen and Holm, 1999). The males could also prefer to eat foods such as meat. These two factors may contribute to the muscle activity that exerted forces on the mandible during mastication. This could result in the males being able to maintain the large muscle mass through diet they may have taken. While females culturally consume small meal portions due to cultural practices and probably because of their bodies demanding less than that of males. Thus the smaller and gracile mandibular features observed in females.

The studies on South African populations that were divided into divergent classes of living studied their food consumption (MacIntyre *et al.*, 2002; Vorster *et al.*, 2005). These studies found that females generally received smaller amounts of nutrient intake than males. Food preferences were determined, where females preferred and consumed more fruits and vegetables in contrast to meat products for males (Axelson, 1986; Logue and Smith, 1986). The male diet required a lot of chewing compared to females. Thus, the mandible is sexually dimorphic through dietary preferences.

The sexing accuracies of full dentition and mandibles with tooth loss may also be explained by dietary preferences. The mandibles with tooth loss have a morphology that is distinct from the morphology of mandibles with full dentition. The difference could be a result of individuals who are partially edentulous preferring soft foods including fluids over hard, fibrous foods that require a large amount of chewing (Nowjack-Raymer and Sheiham, 2003; Allan, 2005; Kossioni and Bellou, 2011). The fully dentate individuals could have been able to eat a variety of foods

resulting in differential mechanical stresses on the mandible. For example, full dentition individuals might prefer a more variable diet. These individuals are most probably able to chew structures that require a large amount of muscle force. The food taken exerts high loadings on the mandible bone, example nuts. The diet could also include softer foods, such as banana slices, that do not need as much effort as chewing on nuts. In general, there's reduced loading on the mandible because the diet that tooth loss individuals choose to consume might need less muscle force.

The loading on the mandible has been studied by Paradis *et al.* (2013) on the mandibular shape of mutant mice. They observed that edentulous mandibles possessed less-variable mandibular shapes. This mandibular morphology could have been a result of the reduced biomechanical activity edentulous mandibles experienced. People who had most of their teeth removed were found to prefer foods that required less mechanical activity (Nowjack-Raymer and Sheiham, 2003; Allan, 2005; Kossioni and Bellou, 2011). The diet in full dentition mandibles was assumed to be less restricted by the number of teeth and ability to chew. The diet chosen by individuals with tooth loss might be similar as a result of such restrictions. Under these assumptions, tooth loss in relation to reduced mechanics of the mandible may decrease the variability of the mandibular morphology, compared to the diet in full dentition individuals that might have exerted fluctuating forces and load on the mandible. Thus, the increased variability in diet of fully dentate individuals would result in variable morphology and reduced sexual dimorphism (**Table 4**).

The less variable mandibular morphology of tooth loss and increased sexual dimorphism may be caused by the less variable diet these individuals consumed. Hence, the mandibles with tooth loss are less variable morphology, and accuracies for correctly sexing in them were high.

Table 4: Sexual dimorphism in the morphology

	Fully dentate	Variably edentate
Diet	Increases variation	Decreases variation
Morphology	Decreases sexual dimorphism	Increases sexual dimorphism

The mandible shape variation in both full dentition and tooth loss might have been affected by the muscle mass. The preferred diet that individuals with variable edentulism had was softer than that of full dentition mandibles, as previously stated. The soft diet might result in lesser muscle mass because of the reduced mechanical activity by the muscles. The lesser mechanical activity may be to the extent that the muscle and bone mass could not be maintained in their original form. Thus the mandible's mass becomes reduced with tooth loss and resorption, leading to the conformation of mandible shapes with tooth loss compared with full dentition. According to evidence that supports this thought, differential forces are used for the consumption of food with variable consistency (Slagter *et al.*, 1993). Mandibles with dentition had higher muscle contraction activity when hard diets were taken compared with softer diets (Slagter *et al.*, 1993). Thus, the variable muscle mass due to mechanical activity could have led to variable mandibular shapes in full dentition mandibles as a result of variable diet.

The association between mandibular morphology and the cranial dimensions is considered to contribute to the sexual dimorphism of mandibles. The cranium and mandible developed together to be articulated and occluded with one another. For the mandible to form a proper occlusion with the maxilla and articulate with the cranium base width and height of both these bony parts have to be similar. The broad mandibular arch the males were observed to have been

most probably due to broader midfacial breadths (Ursi *et al.*, 1993; Rosas and Bastir, 2002). The long rami in males may adjust its shape to accommodate the long faced male as it articulates with the crania. While the short ramus and long corpus noted in the female morphology might be to accommodate the short and narrow facial dimensions.

Franklin *et al.* (2005) and Steyn and Iscan (1998) studied sexual dimorphism of cranial dimensions of black and white South Africans, respectively. They found that males of both populations had longer cranial lengths and breadths. Other studies on cranial dimensions of South Africans and non-South Africans confirmed that there are distinct sex differences (Steyn and Iscan, 1998; Ursi *et al.*, 1993; Rosas and Bastir, 2002; Franklin *et al.*, 2005). The articulated cranium and mandibular dimensions were measured and compared between the sexes. The distance between the mandibular gonion and cranium base were longer in males than in females (Bishara *et al.*, 1984). The mandibles and maxilla are also elongated in males. The midfacial dimensions and the cranial length are also determined to be longer in males than females (Ursi *et al.*, 1993; Rosas and Bastir, 2002). These relationships between the cranial base and mandibular dimensions could help clarify the observed mandibular sexual dimorphism. The dimensions of the mandible complement the maxilla and base of the cranium. The longer maxillofacial and mandibular lengths in males could result from their obtuse gonial angles. Thus, the observed male mandibular features included a backward slanted ramus and longer mandible lengths.

Other dimensions of cranial features such as bizygomatic breadth and upper facial heights were greater in males than in females (Steyn and Iscan, 1998; Dayal *et al.*, 2008). The males therefore had wide mandibular arches. The study of the interaction between mandible and the cranium of non-South Africans found that the mandible changed shape in relation to the base of the cranium (Alarcon *et al.*, 2013). Individuals with elongated faces had obtuse mandibular angles. They also

found that cranial base was more vertically displaced with the maxilla being short and deeper than in short faced individuals. The elements making up the skull are integrated so as to function as a whole. Therefore, the mandibular morphology could be directed to conform to the already sexually dimorphic cranial dimensions. Thus, the males had a broad mandibular arch and the mandibles were sexual dimorphic.

4.2 Age differences

The lack of significance between age and mandibular morphology was unexpected particularly as the age group was between 20 and 90 years. With further reflection on the age composition of the sample, the lack of relationship between mandibular morphology and age may have been due to an unequal representation of mandibles from each decade. However, the mandible was shown in previous studies to be affected by age (Kemkes-Grottenthaler *et al.*, 2002; Popa *et al.*, 2009; Aragao *et al.*, 2014). Thus, age having no effect on the mandible can be debated for a number of reasons. One such expectation for this lack of significance is no effect by the masticatory muscle activity on the mandible (Peyron *et al.*, 2004). Due to muscle activity being similar throughout life, the mandible shape might stay unchanged. At the same time it is not understandable why age had no effect on bone remodelling. It might be that tooth loss dependent mandibular shape modifications was not a result of age.

In addition, age related mandibular shape change might have been imprecise as factors, such as hormonal levels, muscle activity, nutrition and diet supplement or medication, related to aged individuals were not considered in the analysis. These factors may either help or hinder the maintenance of the bone structure (Haddadin *et al.*, 1999; Caldas *et al.*, 2000; Chestnutt *et al.*,

2000). With aging, it is expected that the production of the bone material might be reduced due to response to hormonal reception, impact of diet on bone and old age disorders. The impact of hormones (oestrogen and testosterone) on bone was previously discussed. Due to the reduced activity of muscles individuals who have aged their dietary portions might be lesser. The reduced activity might also be translated to muscle function that is required to keep the mandible in its original shape. While the loading could be inferred onto the body not provide necessary nutrients to retain the bone shape. These factors may also be caused by the loss of teeth. Hence a significant association was found between tooth loss and mandibular morphology and not with age. Additionally, if tooth loss is correlated with age, the effect of tooth removal may have obscured the effect of age on bone.

A number of studies were performed to understand the reasons tooth extraction was done in non-South African populations. The extraction of teeth (specifically permanent teeth) was distributed over all the age groups (Haddadin *et al.*, 1999; Caldas *et al.*, 2000; Chestnutt *et al.*, 2000; Taani, 2003; Aida *et al.*, 2006; Al-Shammari *et al.*, 2006 and Da'ameh, 2006). The exception being a study of Dutch mandibles which determined that the loss of posterior teeth was related to aging (Mays, 2014). They found that the density and mass of bone becomes reduced with aging individuals and bone deposition was greatest during development and growth. Additionally, the bone growth plateaued and bone deposition reduced after the age of 35 years. This reduction of bone deposition may be affected by oestrogen and testosterone levels, and whether the individual was using the masticatory muscles as frequently as they once did when young, as general activity preserves the mandibular shape (Frost, 1997; Lane, 2006; Link, 2012). Therefore age may not affect the mandibular morphology when tooth extraction is not age related and daily activities are similar throughout life.

4.3 Tooth loss effect on mandibular morphology

The large morphological variation in full dentition mandibles might have resulted from the differential loading on the mandibular bone. Supposedly, when a similar force is applied, the divergent shape of full dentition mandibles was a derivative of the mandible experiencing lower loading than mandibles with varying degrees of tooth loss. The extraction of teeth from the socket initiates resorption and acts as the beginning of mandibular bone remodelling. After a tooth is extracted from the socket, the surrounding bone socket undergoes resorption. The resulting alveolar ridge resorption after tooth loss affects the height of both the alveolar ridge and the corpus (Lonberg, 1951; Tallgren, 1972; Klemetti and Vainio, 1993). Due to tooth loss and height reduction, the corpus may experience higher stress. This could result from the periodontal ligament being lost when a tooth was removed from its socket. During occlusion in full dentition mandibles the periodontal ligaments experience strain leading to reduced stress transferred to the corpus (Mandel *et al.*, 1986; McCulloch *et al.*, 2000). During an event such as mastication, a load is probably applied on teeth. The force exerted, as a load, on the crown of the teeth is transferred to the root and then the periodontal ligament. The expectation with tooth loss and resorption of bone is that the corpus is now directly exposed to the stresses that would have been transferred through the teeth and periodontal ligaments. Thus, the mandibles with tooth loss were less variable in morphology and yielded high sexing accuracies than full dentition mandible. This hypothesis regarding the role of teeth and periodontal ligament was supported by evidence that indicated teeth and periodontal ligaments absorb the mechanical forces during dental occlusion, limiting the exposure of the corpus to such strains. Thus the mandibular morphology of fully dentate mandibles is less likely to be affected by these forces compared to variably edentate mandibles. This could result in the less variable mandibular morphology in the latter.

The variable mandibular morphology and low sexing accuracies in fully dentate mandibles could also be affected by the presence of teeth. Each tooth type has its function that may have led to differential strain on bone. The application of a load on a tooth with a narrow and flat occlusal surface such as incisors and canines might transfer a relatively small strain in comparison with premolars and molars. The molars can withstand a greater load compared to premolars (Ferrerio *et al.*, 2004). It is understood that teeth with more than one cusp and/or roots and are broad act as dissipaters of strain. Thus, a variable loading in full dentition mandibles can result from the different kinds of teeth they possess. While mandibles with varying degrees of tooth loss probably have similar loads exerted on to it. During events such as biting, the permanent teeth that experienced the least force were determined to be the incisors (Ferrerio *et al.*, 2004). The molars were recorded with the greatest bite force. Posterior teeth (premolars and molars) compared to anterior teeth (incisors and canines) had the largest measure of bite force.

Furthermore, the maximum bite force between the sexes was in males (Ferrerio *et al.*, 2004). The relation of socket resorption to height of alveolar ridge was made (Atwood, 1963; Klemetti and Vainio, 1993). It was understood that after the extraction of a tooth, the tooth socket underwent resorption resulting in a diminished alveolar ridge of the mandible. The periodontal ligaments that keep the tooth in its socket were determined to have elastic properties and thus absorb much of the mechanical stress. As a result the bone it connected the teeth with (specifically the bone directly below the socket) experienced less pressure (Mandel, 1986; Natali, Pavan and Scarpa, 2004). Additionally, the force experienced by the periodontal ligament at the base of the root is greater than the force experienced by the apex of the root (**Fig. 33**; Mandel, 1986).



Figure 33: The probable force transfer. The force may have been greater when applied to the tooth. Due to the periodontal ligament the force experienced by the adjoining bone might have been less. Key: Solid arrow=large force, Broken arrow=lower force. Image adapted from McNeill (1997).

The large variation and the low accuracies in full dentition mandibles may be a result of bone constitution. The mandibular bone changes its composition with the occurrence of tooth loss and resorption (Ulm *et al.*, 1997; Seong *et al.*, 2009). The bone composition in mandibles with tooth loss was considered to be different than that in mandibles with all their teeth present (Seong *et al.*, 2009). Tooth loss and subsequent resorption can significantly affect the bony constitution of the mandible resulting from normal adult remodelling process. Seong *et al.* (2009) studied dry edentulous human mandibles. They found that elastic modulus of the mandible was correlated with bone hardness and with apparent cortical density. Mandibular bone density reduced with bone resorption that resulted from tooth loss (Ulm *et al.*, 1997).

The consideration that the bone making up the mandible is more elastic before tooth loss, than after tooth loss and resorption was made. This could be translated to the reduced elastic bone composition in mandibles with tooth loss being less susceptible to morphological change as a result of muscle function, leading to more homogenous mandibular morphology in tooth loss than in fully dentate mandibles. The other reason is probably that with tooth loss the diet becomes similar among individuals than in fully dentition individuals. Due to such, the muscles exert similar forces on the less elastic mandible leading to a convergence of the morphology. Thus, the mandibles with variable tooth loss had similar mandibular morphology compared to full dentition mandibles.

The less variable mandibular morphology in mandibles with tooth loss may result from reduced usage due to pain. This pain is not a factor when considering the diet of fully dentate mandibles may have consumed. The pain can result from exposed nerves, and inflammation modulates pain often increasing its perception. Note that some sockets were rated as one or two (not fully resorbed socket) in tooth loss mandible could have experienced the pain. The perception of pain in such cases may depend on the duration at which the socket is not resorbed. The pain that was possibly felt may have been caused by the exposed nerve endings in the partially resorbed tooth socket being stimulated. The pressure felt during occlusion of nearby teeth may have innervated the nerves through food particles and fluids consumed. As a result of the pain an individual might have preferred a diet that did not require a large amount of mechanical force.

The evidence found suggested that the avoidance of certain foods could have also been a preventative measure to keep the socket from filling with food particles and reduce the healing process (Blum, 2002; Vickers, 2005). The dental pain might have been caused by a dry socket known as alveolar osteitis (Blum, 2002; Vickers, 2005). Alveolar osteitis is a condition that

could occur after a tooth was extracted. In addition, the exposed socket might be subjected to pain from external stimuli (Blum, 2002; Vickers, 2005). The pain could result in individuals choosing softer foods (Stoller *et al.*, 2001). Such foods do not need a large amount of chewing and may lead to reduced pain. The change in diet might expose the mandible to a reduced mechanical activity of muscles. The mandible of those with tooth loss experiences reduced muscle activity and causes minimal morphological changes in the mandible. Thus the less variable mandibular morphology in mandibles with tooth loss compared to that of full dentition.

A distinct mandibular morphology related to the loss of anterior teeth was found in this study. The morphology observed could be the response of bone to the more frequent use of posterior teeth than what would occur had the anterior teeth been present. The increased use of posterior teeth may have led to the remodelling of the mandibular morphology, increasing its efficiency for posterior processing of foodstuffs. Thus, the presence of the ante-gonial notch, gonion eversion, ramus flexure, posteriorly positioned condyle, more acute mandibular angle and anteriorly positioned coronoid process in mandibles with anterior tooth loss (**Fig. 34**).

The more upright coronoid, acute mandibular angle and condyle positions observed for variably edentulous mandibles in the results may be due to bone experiencing high muscle activity. The constant use of posterior teeth with loss of anterior teeth leads to increased function of masseter and posterior temporalis muscle than anterior temporalis muscle (Blanksma and Van Eijden, 1990). The decreased use of the anterior temporalis muscle and a greater reliance on masseter could lead to a less upright coronoid process. Thus, change in muscle function as a result of posterior teeth use could present a mandibular morphology with an ante-gonial notch, gonion eversion, ramus flexure, posteriorly positioned condyle, acute mandibular angle.

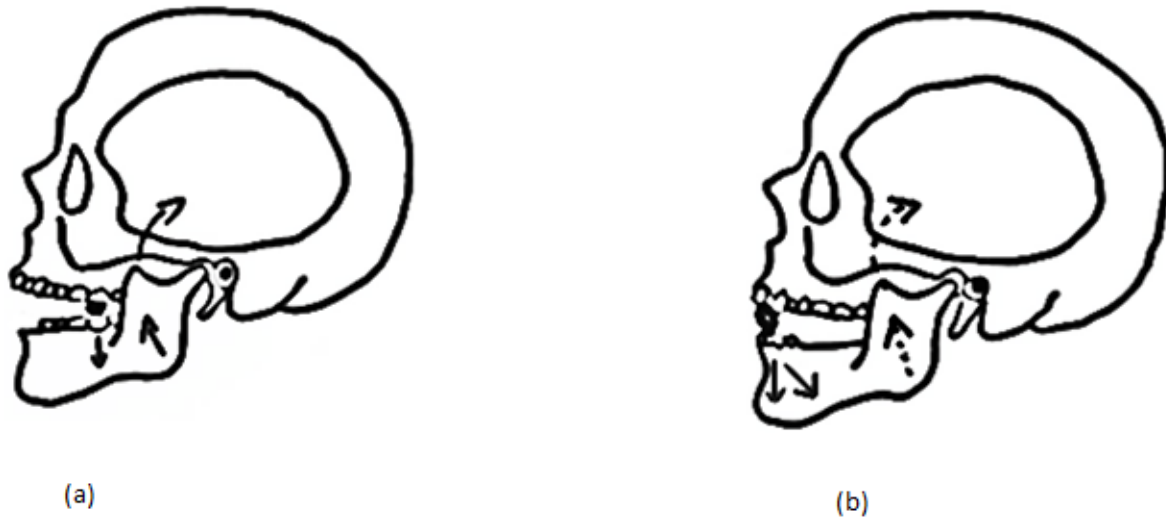


Figure 34: (a) Shows how masseter and temporal muscle function may account for the mandible shape that was related to the loss of anterior teeth. (b) Illustrate the effect of anterior teeth use on the mandible. Temporalis muscle and masseter muscles might have exerted reduced forces compared to muscle use when chewing with posterior teeth. Key: Solid arrow=high forces, Broken arrow=reduced forces. Image adapted from Dahlberg and Graber (1977).

The position of the coronoid process and lack of ante-gonial notch with the loss of posterior teeth may be explained by the bone resorption that occurred. The shift of the coronoid process to be less upright in edentulous mandibles might be due to the resorption that may have occurred on the antero-inferior region of the coronoid process (**Fig. 35, Fig. 36**; Goose, 1982). The absent notch in the ante-gonial region of those without teeth in the mandible morphology related to posterior tooth loss may be explained by reduced bone resorption occurring at this region. This might be due to the presence of posterior teeth. Thus the lack of ante-gonial notch associated with posterior tooth loss.

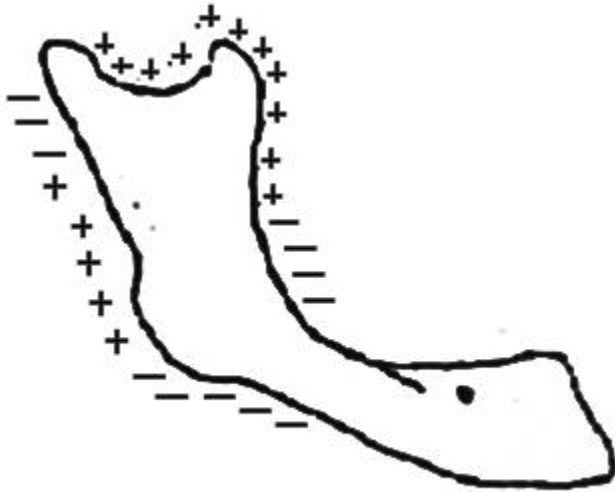


Figure 35: Illustrate the regions that resorption (-) and bone deposition (+) generally occur. Image adapted from McNamara and Moyers (1975) and Netter (2006).



Figure 36: Illustrate the shift of the mandible features as result of the resorption. The solid lined mandible shape represents shape of mandibles with teeth while the broken line shape those with tooth loss. The solid line arrows indicate the direction at which the mandible region shifted with bone deposition. While the broken arrow indicated the direction the feature shifted with resorption. Image adapted from McNamara and Moyers (1975).

The association of the absent ante-gonial notch and posteriorly positioned coronoid process with loss of posterior teeth may have been affected by resorption and mechanical changes. The observe notch at the ante-gonial region in mandible morphology may have been due to mechanical changes that result from resorption of bone at the inferior region of the corpus (Pietrokovski and Massler, 1967; Goose, 1982). In addition, reduced activity of masseter and temporal muscle may explain the more posteriorly positioned coronoid process related to loss of posterior teeth of mandibles with teeth present. The loss of posterior teeth might have prevented the individuals from consuming foods that require great amount of mastication. Thus the reduced activity of muscles that exerted limited forces but with decreased effects on the mandible. Individuals with anterior teeth present choose foods that are not crunchy, dry and solid (Hildebrandt *et al.*, 1997; Ueno *et al.*, 2008). This is because of the high mechanical activity required to consume them. Therefore, due to the reduced temporalis and masseter muscle function, the mandible had an absent ante-gonial notch and posteriorly positioned coronoid process.

The multivariate analysis of variance on the tooth loss matrix found a difference between the sexes. Although a difference exists, the significance was marginal. This slight difference in tooth loss scores between the sexes may complicate interpretation of the results, as there may be the introduction of bias in this study. The difference does not take away the significance of this study but highlights potential problems that need to be considered for future analyses.

4.4 Sexual dimorphism using qualitative method

The comparison between the accuracies found using discriminant and descriptive analyses demonstrated that the discriminant analysis had higher accuracies than descriptive analysis. The comparison implied that discriminant analyses are a more accurate method to correctly estimate sex. This might be that, the descriptive analysis relies mainly on the observer's prior knowledge of sexual dimorphism characteristics may bias the outcome. The discriminant analysis maximises the difference between the sexes resulting in an ultimate benchmark mandibular morphology.

The accuracies for correctly estimating sex using descriptive analysis were much lower than those determined by other studies of South African populations. Loth and Henneberg (1996) studied the ramus flexure of South Africans using a similar method and found overall accuracy of 99%. The accuracies found in the current study were similar to those determined on an American population using a qualitative method (62.5 %; Donnelly *et al.*, 1998). The large differences between the sexing accuracies using the various descriptive methods could be due to a number of reasons. One such reason is the observer's ability to identify the features well. The other being, that each mandibular feature in this study was sexed independently from the other features. Thus, the descriptive method yielded accuracies that were lower than other similar studies

Conclusion

This study examined the effect of tooth loss on accurately estimating sex from black South African mandibles using geometric morphometrics. Additionally the effect of age and the accuracy of qualitatively sexing mandibles compared to quantitative methods was tested. The study was conducted due to majority of sexual dimorphism studies on the mandible excluded mandibles with high levels of tooth loss and there is minimal understanding of how tooth loss affects the sexual dimorphism.

Both mandibles that were fully dentate and variably edentate portrayed sexual dimorphism. The mandibles with varying degrees of tooth loss were significantly more dimorphic than full dentition mandibles. The evident sexual dimorphism in mandibular morphology may be a result of genetics and hormonal physiology on bone. The mandibular morphology was similar in both full dentition and mandibles with tooth loss. Though, the morphology was exaggerated in mandibles with tooth loss as they possess more masculine features. The differential accuracies and mandibular morphology between fully dentate and mandibles with tooth loss could be explained by the lever mechanism of the mandible, muscle activity and diet. The distinctly high accuracies and decreased variability in mandibles with tooth loss may be due to the reduced bone response to external forces and diet consumed. Although age was not found to affect mandibular morphology, the distribution of age between the samples was not comparable and thus age related change may have been obscured by other factors, and thus an age-restricted sample would be better suited. The sexing accuracies from the use of descriptive analysis were lower than quantitative sexing accuracies. According to this study, geometric morphometrics was a more accurate estimate of sex from the mandible than the descriptive analysis. The low sexing accuracies using descriptive analysis was probably dependent on the observer's ability to

distinguish the demarcation of males from females and the determination may bias the final decision.

The direct change as a result of tooth loss from independent mandibular features that are used to estimate sex is not thoroughly understood. Further research could be conducted on such a topic using geometric morphometrics. The mapping of resorptive fields associated with tooth loss could as well be determined. Additionally, studies on identification from the mandible could include mandibles with tooth loss as they do possess sexually dimorphic features as tooth loss is a commonly occurring factor that needs to be considered in forensic anthropology. The increasing number of unidentified remains with tooth loss requires sex estimation standards that may be set from the mandibles with tooth loss to help in the identification of individuals.

Thus, the study was quantitative to avoid prejudice and bias during sex estimation, and although the exact method cannot presently be applied in the forensic context, the results are hoped to have bearing on the non-metric method currently in use for estimation of sex. Therefore, black South African mandibles with high levels of tooth loss are highly dimorphic and yield high sexing accuracies using a qualitative method.

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