PATTERNING OF THE HUMAN DENTITION:
IMPLICATIONS FOR FORENSIC ODONTOLOGY

by

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Please note that images of deceased Australian Indigenous people are contained within this thesis

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List of abbreviations

(All tooth notations in this thesis are presented using FDI notation e.g. 12 for permanent right lateral incisor)

MD = Mesiodistal

BL = Buccolingual

U = Upper

L = Lower

GMA = Geometric Morphometric Analysis

PCA = Principal Component Analysis

DFA = Discriminant Function Analysis

CVA = Canonical Variate Analysis

Abstract

Forensic identification may be required for a number of reasons. The identification process relies on the comparison of information gathered from known records with information from the unknown. Different scientific methods may be employed, but a primary identifier is a comparison of data concerning the status of the teeth. Conclusions regarding identity range from possible to positive identification. The presence of dental treatments or pathological conditions usually adds to the weighting of forensic identification. The availability of dental radiographs also strengthens the opinion where ante-mortem and post-mortem image comparisons can be made. This combination of dental treatments provides a reasonable choice for statistical modelling; however, such forms of variability are on the decline in populations with better oral health.

It is well established that teeth are derived and affected by a complex interplay of genetic, epigenetic and environmental factors, giving rise to significant natural variation in the arrangement, size, and shape of teeth that is generally stable through time. Modelling such variation should provide a useful mechanism for identification in cases where dental treatments are not present in the dentition. Arguments on the issue of individualisation have highlighted an obvious obstacle when tackling this issue as it is impossible to study each and every individual in the world.

The aim of the current project is to display the value of focussing on these normal variations rather than the ‘problems’. The focus is on the measurement and comparison of dental crown size and dental arch size and shape within and between six human populations. This information provides the foundation for future development of a more robust probabilistic model focussing on the normal morphological status of dentition.

Observations were made in six different ethnic groups including Australian Aboriginals, Europeans, and four major ethnic groups in Malaysia; Malays, Indians, Chinese and a Malaysian Indigenous group (*Orang Asli*). Measurements of these variations using both 2D and 3D imaging systems displayed reliable and repeatable methods to measure patterning of the human dentition using the normal morphology of teeth and dental arches. By using standardised eigenvalues derived from metric measurements, a probabilistic model was postulated to assess random match probabilities.

The findings from this current research add to our understanding of the variability of the human dentition and should improve the acceptance of using dental morphology as a means of identification. The results have shown that despite absence of dental treatments, the nature and extent of normal morphological variation in the human dentition can be quantified reliably and then applied in forensic and anthropological situations for identification purposes.

Thesis declaration

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Format of thesis

The thesis will be presented in nine main chapters. An introduction and findings from a literature review are presented in Chapters 1 and 2. A summary from the literature review will then lead to the main aims and objectives of this research. Chapter 4 presents the materials utilized in this research and the methodology employed to achieve aims and objectives highlighted in Chapter 3.

Chapters 5, 6 and 7 cover the results of this current research where Chapter 5 presents data and discussion on dental crown size, Chapter 6 presents data and discussion on dental arch size and shape, while Chapter 7 presents data and discussion on Geometric Morphometric Analysis of dental arch size.

Each chapter of results has a section of discussion and then Chapter 8 presents a general discussion of this research, highlighting its relevance, suggestions for further research and also highlighting collaborative efforts during the conduct of this research. Chapter 9 provides general conclusions. A list of references is provided at the end of this thesis, together with some appendices.

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Chapter 1: Introductory background

1.1 Forensic odontology: the use of teeth for identification purposes

The word ‘*forensic’ is* derived from the Latin word ‘*forensis’,* which means ‘of or before the forum’ (Douglas Harper, 2001). This suggests the need for discussion or presentation of research findings within or to a group. Nowadays, the use of the word forensic remains close to its origin. Issues related to forensic science require the discussion and presentation of evidence to the public and members of the Courts of Law. This discussion may involve different branches within the forensic field and each branch makes its own contribution to the investigative process.

Forensic investigation is known for its detailed analysis of evidence for use in Courts of Law. Over the years, each discipline in the forensic field has undergone major changes and has continually developed in order to play a more effective role. One distinct branch that has evolved in line with developments in technology is forensic odontology.

Forensic odontology is the application of dental sciences to the furtherance of justice (Luntz, 1973). Major responsibilities in this field include identification of deceased persons through dental comparison, when the traditional method of visual identification is not possible, analysis of the face and dentition in cases of trauma, and bite mark analysis.

Identification is important for both legal and social purposes. The basis for decision-making in this field is that the human dentition has many distinguishing features, including presence or absence of teeth, different sizes and shapes of teeth, rotations and angulations of teeth, and also various forms of dental treatment (Bernitz et al., 2006; Pretty and Sweet, 2001).

Teeth are extremely useful for forensic identification purposes due to their ability to resist post-mortem changes (Brace, 1980). They also resist long exposure to soil and water, as well as high temperature (Gustafson, 1966). In mass disasters, teeth are often the most intact structures suitable for examination. The positions of teeth, where the lips and cheeks protect them, make them more resistant to disasters involving fire (Botha, 1986; Whittaker and MacDonald, 1989; Patidar et al., 2010).

The dental identification process includes comparisons between two sets of data to arrive at a conclusion. Ante-mortem data about a presumed victim are sourced from the family, friends, home environment and relevant medical authorities. Post-mortem data are gathered from careful examination of the deceased body. Concordance or discordance of one or several features observed in the data will affect the final conclusion regarding identity.

Previously, it has been suggested that six concordant features need to be identified for a positive match, in accordance with the method applied when comparing fingerprints (Keiser-Nielsen, 1977). However, Acharya and Taylor (2003) highlighted the importance of treating each case separately and not limiting the ability of identifying a match to six concordant features, as for many cases positive identification can be achieved based on a fewer number of concordant features. Due to the availability of a wide range of dental data such as photographs, radiographs or dental casts, it is possible that the identity of a deceased person can be concluded by using only one tooth (Pretty and Sweet, 2001).

Different classifications for reporting identity have been documented (Higgins and James, 2006). Interpol classifications (James, 2005) are widely used in events involving mass casualties. Based on observable features, one of the following Interpol conclusions can be made regarding identity: established, probable identification, possible identification, insufficient data available (inconclusive) or excluded. The degree of certainty is tempered by the available ante-mortem and/or post-mortem evidence.

Following the comparative steps, questions may arise regarding the extent of information available or the prevalence of observed features used to establish an identification outcome. Since the identification process is based on particular dental features, MacFarlane et al. (1974) highlighted the likelihood that forensic odontologists may be asked to indicate the prevalence of such characteristics in the general population. Gustafson and Johanson (1963) also stressed the lack of information within the literature on the value of different characteristics in dental identification.

Whilst the basic tenets remain, one research direction includes the use of computer technology in the analysis process. This has greatly improved the possibility of quantifying various dental features. Furthermore, acceptance of computer technology in Courts of Law, as a requirement for the admissibility of evidence, and within the community has increased with employment of media and social network applications.

1.2 Dental variation

The concept that no two human dentitions are exactly the same is a fundamental tenet in forensic odontology. Interactions between genetic, epigenetic and environment factors affecting the teeth and jaws lead to significant variation within and between human populations. Common genes cause some dental features to be the same between individuals, i.e. almost every individual will have 20 deciduous teeth that are replaced by 32 permanent teeth, except in cases of hypodontia and hyperdontia. However, different genetic makeups and exposure to different environmental factors and stresses result in different expressions of traits on the dental crowns and root surfaces, including the size and shape of teeth and also the position of teeth within the jaws.

Variations in the expression of these different traits, including size and alignment of teeth, make it possible for researchers to identify variation between individuals. Certain dental features can also provide a key to identifying clusters of individuals. Common groupings of individuals may be based on ethnicity, sex, or age. Racial traits, if observable, can help narrow the identification process or give an indicator to a particular geographic location (Keiser-Nielsen, 1965). Recognition of particular dental features that can separate one group from another is of value in the identification process. The more challenging task is to identify a particular individual from within a group.

In the field of forensic odontology, evidence of pathological conditions and any form of dental treatment provides significant weight to the identification process. Dental data can take the form of written records, radiographs, photographs or dental casts. Features that can help in identifying individuals can be observed following thorough dental examination.

The importance of dentists maintaining records of current dental status is acknowledged. However, more often than not, these records capture limited data on the status of the dentition, e.g. missing teeth, caries status and the presence of previous dental restorations (i.e. DMFT score). In cases where a person has no dental treatment, establishing identity can be challenging. It is rare that a dentist will specifically record information on dental crown and dental arch size, although data may be gleaned indirectly from casts. Dental anthropological data is more often recorded for research purposes. The national oral health mission and patients' increasing awareness of oral health benefits suggest that we may soon be required to focus on morphological features (i.e. dental crown size, and dental arch size and shape) rather than treatments when making comparison of dental records. Routine dental impressions and photographs of the dentition may become key components of the forensic identification process.

1.3 From variation to individualisation

Despite the hypothesis that each individual has a different dentition, questions still arise about the possibility that somewhere in the world there may be someone else with similar teeth. Proof of individuality using the dentition is, therefore, a worthwhile topic to explore. Keiser-Nielsen (1977) said “it is impossible to establish the relative importance of a given feature”. This is due to the lack of a statistical basis to discriminate between features.

In cases of forensic identification, experts often arrive at conclusions based on the concept of apparent ‘uniqueness’. Therefore, if an unknown individual ‘X’ is comparable to the known dental data of individual ‘Y’, it can be concluded that ‘X’ is ‘Y’. This is done on a case-by-case basis, with the ‘background’ idea that experts can ‘remember’ that they have never come across a similar case before (Page et al., 2011). Although this approach has long been accepted, new legal directions are now requiring experts to provide supporting statistical probabilities to indicate the likelihood that X is likely to be Y. Saks and Koehler (2005) have urged experts in the forensic community to revise their thinking and make a paradigm shift in forensic identification by providing a more probabilistic foundation when deriving conclusions from their comparisons.

Variability observed in the human dentition provides a theoretical basis for the individualisation of human dentitions. Different dental traits, such as crown dimensions, tooth shape, cusp number, groove and fissure patterns and various other features have been studied by many researchers (Hanihara and Ishida, 2009; Edgar, 2009; Hanihara, 2010) to clarify population origins and patterns. Whilst these studies have provided a wide array of research findings, information on statistical probabilistic evidence is still lacking. A few researchers (Adams, 2003; Martin-de-Las-Heras et al., 2010; Biazevic et al., 2011) have applied information on variability of the human dentition to forensic odontology.

Among the most commonly cited studies when it comes to providing evidence about the individuality of the human dentition in forensic odontology are statistical studies and investigations of twins. Many studies of twins aim to clarify the influence of genetics on various human traits. Twins are excellent subjects because it is impossible to find such genetically related individuals elsewhere in the population. Monozygotic (MZ) twins, or so-called identical twins, share the same genes whereas dizygotic (DZ) twins, also referred to as non-identical or fraternal twins, share half of their genes on average. By studying twins, it is possible to estimate the relative contributions of genetic and environmental factors to observed variation in different traits (Hopper, 1998; MacGregor et al., 2000).

Sognnaes et al. (1982) were among the earliest group of researchers who employed the study of twins to understand variation in dental patterns. This is a commonly cited article in the forensic field. The authors performed their analyses on the anterior dentition and concluded that no identical twin pairs have identical dentitions in terms of arch form or tooth position. However, the number of twin pairs used in the study was very small, with only five pairs of twins considered.

It is acknowledged that it is an impossible task to study each and every human being in the world. Page et al. (2011) highlighted that any work to provide evidence of a feature or features being ‘unique’ is a task to test everyone in the world, including those just born. The issues of time, financial resources and human resources make this task impractical. However, one should also remember that the aim of forensic identification is not to prove that a particular person is the only one in the world to have a particular set of dental features, but that there is no unexplainable discrepancy between ante-mortem and post-mortem data. This is because forensic dental identification requested by authorising bodies is usually based on circumstantial evidence of a presumption that the unknown individual may be X. Records are not blindly drawn from the population at large but sourced based on case-specific investigations. The identification process is made to confirm the presumptive identity.

It is hypothesised that the human dentition can be individualised to the standard required by Courts of Law. The overall aim of this study is to provide information required to develop a model of discriminating individuals using the human dentition and to explore the likelihood that a particular person within a subset of a population will not have the same features as another person within the group. This information consists of dental crown size and dental arch size measured using two dimensional and three dimensional imaging. Information on dental arch shape was also observed and analysed using Geometric Morphometric Analysis. This information provides the foundation for future development of a probabilistic model focussing on the normal morphological status of dentition. It will also contribute to the understanding of the value of human teeth as an identification method. It will assist forensic experts specifically and increase public awareness about the importance of the dentition in forensic cases in general.

1.4 Thesis Format

This thesis will be presented in the following chapters: main body of literature review, aims and objectives, materials and methods, followed by results which will then be separated according to analyses of tooth size, dental arch size and dental arch shape. A general discussion and concluding chapter then follow.

Chapter 2: Literature review

This chapter begins with a summary of the formation of the dentition and dental arches that highlights how variation may arise. It then continues to discuss previous studies looking at both metric and non-metric expression of dental variation. Various methodologies, both two dimensional and three dimensional, used in analyzing this variation are explored. The focus then shifts to review populations previously selected by other researchers, in order to justify the sample employed for this particular research.

2.1 Oral development

2.1.1 Jaw development

The developmental and growth processes of maxillary and mandibular bones will determine the final size and shape of the dental arches. This requires ideal equilibrium of bone remodelling processes (i.e. bone apposition and resorption). Various factors, including genetic and environmental influences, will map the size and shape of the jaws for each individual. Lack of development and growth of jaw structures will ultimately affect the arrangement of the teeth (i.e. a small jaw will cause crowding of teeth).

The jaw and visceral skeleton owe their embryonic origins entirely to the neural crest cells (Hall, 1999; Santagati and Rijli, 2003). The migration of neural crest cells to the region of the maxilla (maxillary process) and mandible (mandibular process) give rise to future maxillary and mandibular bone. These endoskeletal jaw cartilages form a developmental and evolutionary framework for adult vertebrate jaws (Smith and Schneider, 1998; Liem et al., 2001).

In the embryo, the maxillary and the mandibular bones develop through intramembranous ossification, with the mandible using Meckel's cartilage as a scaffold or framework during its development. Whilst this cartilage does not contribute directly to the final mandibular bone, it plays a role in determining the centre of mandibular bone development (de Beer, 1937; Liem et al., 2001; Depew et al., 2002).

2.1.2 Tooth development

To facilitate the understanding of tooth development, this process can be divided into stages which describe different molecular changes during each stage (Nanci, 2008).

Bud stage: This is the initial interaction between epithelium and mesenchyme. Ectomesenchymal cells are packed closely underneath an initial invasion of the epithelial 'bud', hence the term bud stage. Once the interaction between epithelium and ectomesenchyme has been established, the first phase of morphologic differences that will later give rise to different tooth class is initiated. This stage is what it is called *bud-to-cap* transition. Various genes including signalling factors and proteins are expressed and play a significant role in determining the final outcome of the type of tooth.

Cap stage: During this stage, epithelial outgrowth begins to occur, and the presence of a lateral lamina resulting from the movement of this outgrowth begins to develop.

Ectomesenchymal cells present from the previous stage begin to condense creating a so called ‘cap’ appearance. At this stage, the appearance of all elements gives rise to the different anatomical parts of the tooth. The overall structure of the epithelial outgrowth is the enamel organ which forms the enamel of the tooth. The condensation of ectomesenchymal cells underneath the ‘cap’ is comprised of a group of cells called the dental papilla, which contributes to the dentine and pulp. Dental papillae are encapsulated by the dental follicle which then gives rise to the supporting structures of the tooth.

One of the most important structures during this stage is a group of non-dividing epithelial cells called *enamel knots.* Enamel knots appear at the sites of the future cusp tips of the teeth. Their position seems to be influenced by the epithelial signalling molecules, as these molecules regulate the spatial expression of homeobox genes in ectomesenchyme. The enamel knots also seem to stimulate the terminal differentiation of the odontoblasts which then start the deposition of dentine matrix (Thelseff et al., 2001). A number of research projects directed towards understanding the precise role of enamel knots have been conducted, and they are believed to be associated with the control centre where final cusp morphology is derived (Jernvall and Thelsleff, 2000; Nanci, 2008). The primary enamel knots determine the arrangement of cusps and also give rise to secondary enamel knots which determine the cusp tips (Jernvall et al., 1994; Jernvall and Jung, 2000).

Bell stage: Every stage of tooth development has been named due to its histological appearance resembling a certain shape. As the name suggests, the bell stage refers to the continuous growth of the tooth germ which shows a deepening of the epithelial layer to resemble a bell. This is the final stage of morpho-differentiation of the tooth crown. By this time, the resulting tooth has basically developed its signature shape i.e. incisor, canine or molar.

2.1.3 Tooth patterning

There are many theories or models that contribute to the understanding of how teeth are initiated. The understanding on this topic has been continuously refined and has led to further research on a genetic molecular basis. As teeth play an important role in the survival of all vertebrates, Mikkola (2009) postulated that every species should have their own set of teeth, with different classes and morphology, to reflect their survival skills. Unlike other vertebrates, some mammals' teeth developed in one single row and only experience one replacement cycle with some variation between species such as rodents (Mikkola, 2009). Differences in the size, number and morphology of the teeth differentiate different mammals. These variations depend on the patterning of the tooth to accommodate their lifestyles (Ohazama et al., 2010).

The nature of tooth development has been widely studied. It is known that tooth development is initiated by the interaction of ectoderm and mesenchyme (Nanci, 2008). In fact, this specialised nature of tooth patterning in mammals makes them among the most suitable models to study formation of tissue as this ecto-mesenchymal interaction can be predicted and observed (Kapadia et al., 2007).

The first theory to account for variations observed in mammalian dentitions was the ‘field theory’, introduced by Butler (1937), to describe the evolution of teeth as a system and that within each dental arch there is a morphogenetic concentration that can be observed. This morphogenetic concentration causes details on a tooth to resemble its adjacent tooth. At the same time differences in the morphogenetic concentration leads to variation in the resulting tooth morphology. There is a form of gradation or gradient as the morphogenetic concentration moves along a series of tooth groups, depicted in Figure 2.1, causing it to be less concentrated at the extremities (Butler, 1939).

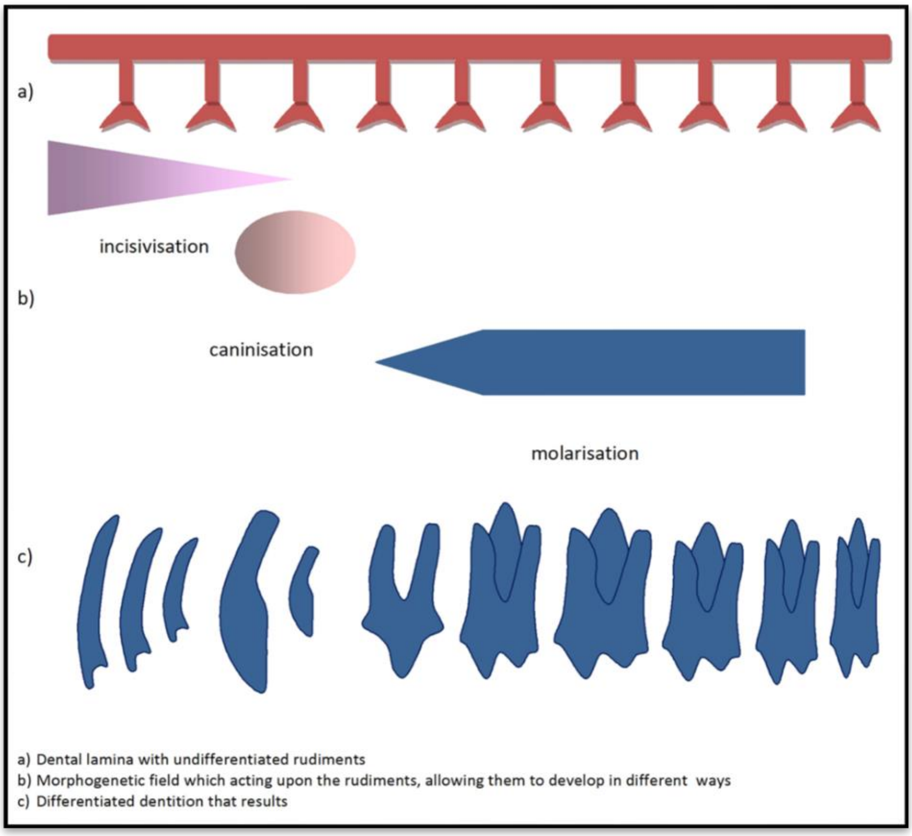


Figure 2.1: Butler’s Field Theory (derived from Butler (1939))

It was not until 1945 that Dahlberg applied the field theory to human development. Dahlberg modified the theory to accommodate the patterning observed in the human dentition, particularly dental features that are present in the permanent dentition. Just like the 'field theory' proposed by Butler, there are similar gradients of morphogenetic concentration that can be observed in humans. Dahlberg (1945) identified four different morphogenetic concentrations present within each jaw: namely incisor, canine, premolar and molar (Figure 2.2). The term 'field' proposed by Butler (1939) and Dahlberg (1945) was adapted from Huxley and de Beer (1934), and referred to areas where differentiation of organs appear.

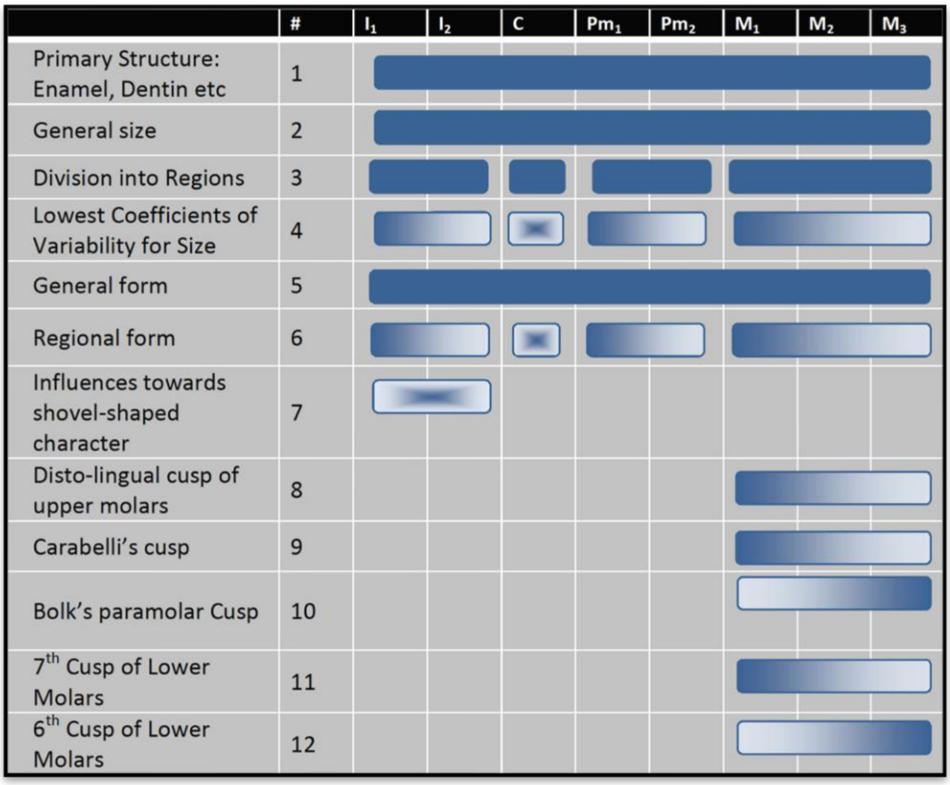


Figure 2.2: Dahlberg's Field Theory (derived from Dahlberg (1945))

It was predicted that this gradient field would be at a peak when the first tooth within each class developed and subsequently reduced to cause variation to the most distal tooth in the group. Therefore, the first tooth of each class is usually the key tooth or the most stable tooth in terms of its morphology. This has formed the basis of most anthropological study of observed variation. Dahlberg (1945) also extended the theory to explain not only the sorts of resultant teeth patterned by these elements, but also other dental features, for example, Carabelli trait.

The ‘field theory’ intimated by both Butler (1937) and Dahlberg (1945) was the initial explanation as to why it is possible to have variation in teeth. Following Butler (1937) and Dahlberg (1945), many studies were directed towards supporting this model in both animals and humans (Henderson and Green, 1975; van Valen, 1961; Lombardi, 1978). Some also found different expression of morphogenetic gradients in terms of tooth size (Kieser et al., 1985a) and dental traits (Townsend et al., 1986; Townsend et al., 1990). This work has initiated more development of theory to enhance and refine understanding on this topic.

Another model known as the ‘gradient pre-pattern model’ initiated by van Valen in 1970 extended Butler’s theory in terms of explaining variation within the same tooth group. He suggested that there is an identical pre-pattern held by all developing tooth buds, however, these similar patterns then evolve into different gradients. Therefore, the gradient affects variation but the magnitude relies on the pre-pattern element.

Osborn (1970) suggested the concepts of different morphogenetic gradient and pre-pattern model within the dental arch by introducing the ‘clone theory’. This theory suggested the presence of three different clones, for incisor, canine and molar, which constitute the human dentition. As growth starts within these clones, gradients are then initiated which explain different variations within the same tooth group.

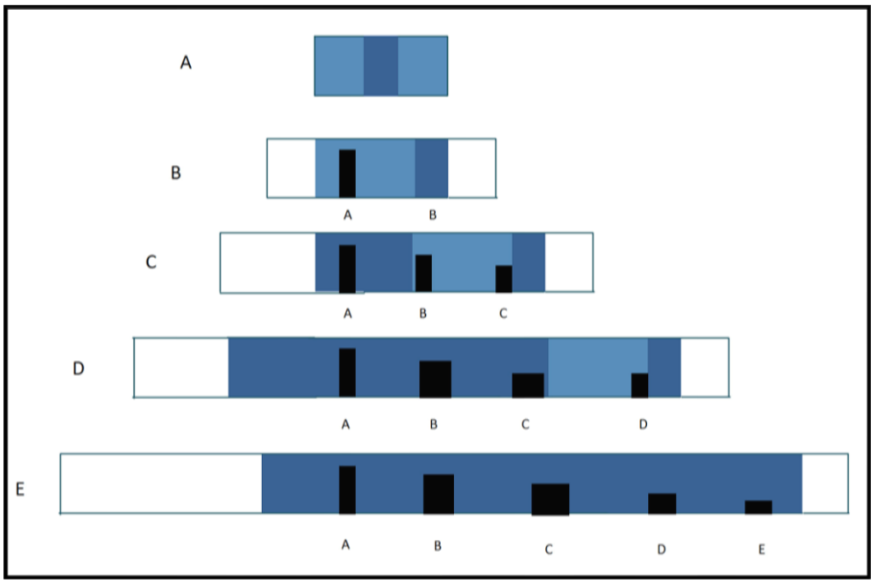


Figure 2.3: Osborn’s Clone Model (derived from Osborn (1970))

Unlike ‘field theory’, this model proposed that every structure is derived from a clone (represent by the heavy stippling in Figure 2.3). As the clone grows distally, new primordia arise from the space available (represent by light stippled in Figure 2.3). These primordia are then differentiated to create the predetermined shape (represent by the black box in Figure 2.3). The movement of the clone cells create a gradient that determines the shape of the resultant primordia. This is different from the field theory model where the primary gradient induces the shape of the primordia (Osborn, 1970).

This model was evident in previous experiments conducted in mice, where the tooth buds continued growth to normal morphology even when they were implanted at different areas, potentially far away from predicted field substance (Glasstone, 1936, 1950; Fisher, 1971).

Following the significant findings of ‘field’ and ‘clone’ theories, more detailed observations focused on the interaction between epithelium and mesenchymal cells (Nanci, 2008; Ohazama, 2010). Studies of the molecular genetic basis of tooth development initiated the ‘homeobox model’.

The ‘homeobox model’ proposed that patterning of teeth is the result of varying expression of several homeobox genes in ectomesenchyme cells. Homeobox genes are recognised for their involvement in controlling multicellular organisms. Each gene contains a 180-base-pair segment (the “homeobox domain”) that encodes a protein domain involved in binding to (and thus regulating the expression of) DNA (Duboule, 1994). There are numerous genes involved in tooth formation (Table 2.1). These genes play a significant role in various stages of tooth development.

Table 2.1: Genes responsible for the tooth development

(adapted from Nanci (2008))

Barx	BarH1 *homolgue in vertebrates (TF)*
Bmp	*Bone morphogenetic proteins (SP)*
Dlx	*Distales homologue in vertebrates (TF)*
Edar	*Ectodysplasin receptor (TF)*
Fgf	*Fibroblast growth factor (SP)*
Gli	*Glioma-associated oncogene homologue (zinc finger protein) (TF)*
Hgf	*Hepatic growth factor (SP)*
Lef	*Lymphoid enhancer-binding factor 1 (TF)*
Lhx	Lim-*homeobox domain gene (TF)*
Msx	Msh-*like genes in vertebrates (TF)*
Otlx	Otx-*related homeobox gene (TF)*
Pax	*Paired box homeobox gene (TF)*
Pitx	*Transcription factor named for its expression in the pituitary gland*
Ptc	*Patched cell-surface receptor for sonic hedgehog (SHH)*
Shh	*Sonic hedgehog (SP)*
Slit	Homologous to *Drosophila slit protein (SP)*
Smo	*Smoothed PTC coreceptor for SHH*
Wnt	*Wingless homologue in vertebrates (SP)*
	TF: Transcription factor; SP: Secreted protein

The two most important homeobox gene candidates involved in specification of neural crest, particularly in odontogenesis, are Msx1 and Dlx (Sharpe, 1995). Msx1 is responsible for the initiation of tooth germs at the incisor and canine regions in humans, whereas Dlx1 is expressed at the multicuspid area (Nanci, 2008). According to this model, the overlapping domains of these homeobox genes with others such as Barx cause positional information for tooth type morphogenesis (Nanci, 2008). This explains the high genetic control in the dentition of every species (Sharpe, 1995).

Whilst the first two landmark models have been applied to the human dentition, the 'homeobox model' was based solely observations in mice (Tucker and Sharpe, 2004). To refine this model, Mitsiadis and Smith (2006) suggested development of another model which incorporated all elements mentioned in those three important models (field, clone and homeobox).

This new ‘Co-operative genetic interaction (CGI) model’ incorporated the homeobox gene model together with field and clone theories. Figure 2.4 shows a pictorial representation of this current concept. According to this concept, every element, including cells, signals and homeobox genes, is acting equally to pattern the resulted tooth at its position. Any disruption of these elements, for examples, defects in cell numbers, defect in signals or defects in genes, will affect the appearance or the presence or absence of a tooth.

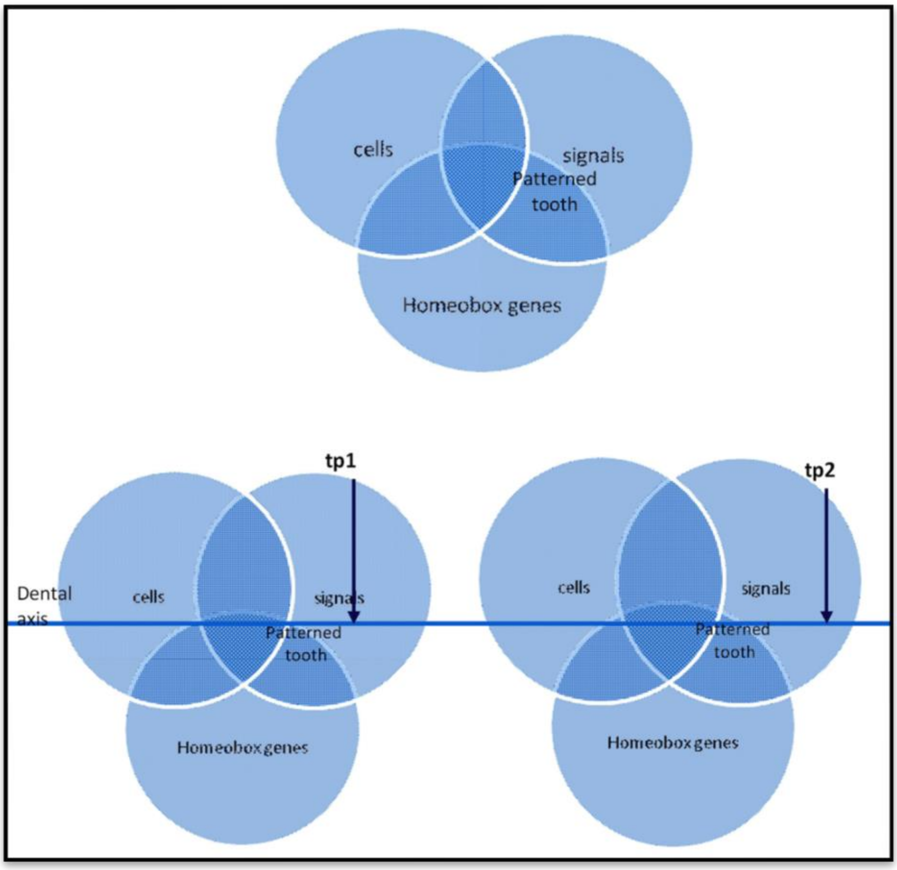


Figure 2.4: Co-operative genetic interaction (CGI) model

(derived from Mitsiadis and Smith (2006))

* tp1 refers to tooth position 1, tp2 refers to tooth position 2

The combination of all three models as one entity was outlined

by Townsend et al., (2009b) and it was proposed that this composite model should be further investigated in a clinical setting.

2.1.4 Genetic and environmental influences

Based on the complex developmental process, it has been suggested that the expression of tooth morphology is influenced by genetic control (Brook et al., 2014a). It was discovered that tooth size and shape are affected by interaction between genetic and environmental factors (Bailit, 1975; Kabban et al., 2001). This is evidenced by studies looking at the effect of genetic and prenatal factors on the expression of tooth anomalies, such as hypodontia (Bailit, 1975), microdontia, megadontia and supernumerary teeth (Brook, 1984; Brook et al., 2014a).

Expression of individual phenotypes results from the interaction of genotype, epigenetic and environmental factors. Genotype is defined as the genetic constitution of an individual and may refer to specific or all gene loci. Additive genetic factors simply mean that the contribution of genetic factors to the resulting phenotype is the sum of the contribution from each allele. There is also a condition where two alleles interact to produce additional genetic contribution but one allele being dominant to another allele at a locus masks the effect of the other allele. Interaction between alleles at different loci on the other hand refers to epistatic effect. Epigenetic factors refer to stable alteration around the cell that does not involve mutations of the DNA itself (Williams et al., 2014).

When genetic factors cannot explain a change in the size or shape of the dental crown, the assumption is that the environment has altered the phenotypic expression. Environmental factors can be partitioned into common and specific components. Common environment refers to the shared environment with family members while specific environment refers to the individual’s experience (Dempsey and Townsend, 2001).

In a study of Scandinavians, the increase in crown size was linked to changes in diet and trace elements (Ebeling et al., 1973). Environmental factors play a smaller role than genetics in causing variations in dental traits. These factors, which affect crown phenotype, act during the odontogenesis stage. The factors that may be associated with crown phenotypic modulation include maternal diabetes, hypothyroidism, hypertension and smoking (Garn et al., 1980). Furthermore, the length of pregnancy and birth weight could also affect crown size and shape (Garn et al., 1980).

The majority of studies to determine environmental influence have been in the permanent dentition. These have generally found that variations in crown size are explained adequately by additive genetic and unique environmental factors (Dempsey and Townsend, 2001).

2.2 Human variation

Variation can be defined as differences that exist among people and populations (Relethford, 2000). People can be differentiated biologically, according to their blood groups or genetic makeup, or they may be differentiated based on their physical appearance, such as height, skin colour or bone structures (Relethford, 2000). Variation in the human dentition, involving both size and shape differences, has been well documented.

2.2.1 Dental arch variation

Human dentitions consist of upper and lower arches. Teeth within the arches occlude to achieve functional movements for various physiological purposes. The term dental arch refers to the collective contour of the dentition or of the shape of the supporting bone (alveolar ridge). The dentition, consisting of either primary or permanent teeth, is attached to the alveolar bone by means of periodontal ligaments and alveolar processes.

The direct relationship between alveolar bone and teeth causes them to complement each other. The growth of alveolar bone and the remodelling process depends on the eruption and also the loss of teeth due to normal physiologic exfoliation in primary teeth or due to pathological conditions such as caries in the permanent dentition. Stability of the dental arch form depends on the maintenance of contact between teeth. The presence of teeth will affect variation in dental arch form in terms of its size or shape. For example, a person with hypodontia or microdontia or perhaps peg-shaped lateral incisor teeth will tend to have a smaller size dental arch to compensate for the overall smaller size and shape of its dentition. Conversely, a person with generally larger size teeth (macrodontia) and extra teeth (supernumerary) will tend to have larger dental arches to try to accommodate the space required for the extra number or size of teeth.

When one or a few teeth are missing, whether congenitally or due to a pathological condition, contact points between the teeth are compromised. However, the general form of the dental arch can usually still be evaluated. Due to direct relativity between dental alveolar bone and teeth arrangement, dental arch shape and size are usually studied by looking at the arrangement of the teeth.

Once teeth have emerged into the oral cavity, the action of muscular activity over the alignment of teeth within their bony crypt is believed to play a role in ‘designing’ the final form of the arch (Brodie, 1954). It has been suggested that the role of lips and cheeks (on the external side of the teeth) and tongue (on the internal side of teeth) act in balance to achieve what is called as equilibrium state or ‘neutral zone’. Weinstein et al. (1963) defined ‘neutral zone’ as “a position in which the resulting dentition will not be moved by natural environmental forces”. This is one of the aims of designing prosthetic removable dentures or when planning treatment modalities to correct malocclusion - to simulate a natural ‘neutral zone’.

Scott (1957) disagreed with the concept of ‘moulding’ the dental arch by the control of muscular activity, suggesting instead that the shape of the dental arch is predetermined and whilst soft tissue also has an impact on the shape, it is only a minor role. However, the theory of achieving equilibrium within the dental arch, that is; dental arch form is predetermined but consequently shaped by muscular activity, has been accepted by many (Harris and Johnson, 1991; Bran et al., 1998). It also should be noted that the balance is not a simple equation between internal and external muscles but also the effect of jaw movements and the forces of mastication are also equally involved (Proffit, 1978; Moss, 1980).

Dental arches exhibit considerable variability in size and shape within and among human groups. It is believed that there is interplay between genetic and environmental factors influencing the final form of dental arches (Proffit, 1986). The influence of genetic factors on dental arch size and shape has been highlighted by several authors (Lundstrőm, 1948; Stein et al., 1956). More recently, researchers have explored the causal component of phenotypic variability and noted environmental contributions to arch size and occlusal traits (Corrucini and Potter, 1980; Harris and Smith, 1980).

Hu et al. (1991) stated that inheritance of dental arch dimensions is essentially polygenic and can be influence by jaw, tooth size and dental occlusion. Due to such compounding factors, determination of whether dental arch form is primarily genetic or environmental is important for establishing the cause of malocclusion to ensure better treatment modalities (Lavelle, 1978). It will also be beneficial in forensic situations where variation and individualisation across populations is a concern.

The dental arch has undergone continuous adaptation throughout human evolution. From the Paleolithic era to the modern era, the overall trend has been from prognathism to orthognathism congruent with a reduction in form, size and number of teeth (Dahlberg, 1945). While these changes have substantially slowed, no two dental arch forms are believed to be alike.

2.2.2 Tooth variation

2.2.2.1 Dental crown size variation

The best model for variation in crown size is that a combination of genes or additive genetic effects contributes to phenotypic modulation (Hughes et al., 2000; Dempsey and Townsend, 2001). This involves both autosomal and sex-linked genes. The involvement of autosomal genes was implicated by the size reduction of permanent crown sizes in individuals with autosomal syndromes such as Down syndrome (Townsend, 1983).

2.2.2.2 Dental asymmetry

Other than variation observed in individual dental crown size, variation of the human dentition can also be observed in dental crown size patterns between the left and right teeth. Asymmetry between left and right teeth can be divided into directional and fluctuating asymmetry. Directional asymmetry refers to a condition where dental crown size on one side is consistently larger than the dental crown size on the opposite side within a single population (Hillson, 1996). Fluctuating asymmetry, on the other hand, shows varying degree of size differences on left or right sides.

2.2.2.3 Sexual dimorphism

A common finding across populations suggests that the most dimorphic tooth in the permanent dentition is the canine (Liversidge and Molleson, 1999) while others have also found evidence of sexual dimorphism in molars (Hughes et al., 2000). In terms of differences of size dimension, it was found that the buccolingual dimension of the dental crown tends to exhibit more sexual dimorphism than the mesiodistal dimension (Liversidge and Molleson, 1999; Liu et al., 2000).

The first implications that the sex chromosomes were involved in determining crown size were from sibling studies which compared crown size between sisters, brothers and sister-brother pairs (Garn, 1965). The involvement of X-linked genes in crown size was revealed by the higher correlation for crown size between sister-sister pairs compared to brother-sister pairs (Garn, 1965). Evidence that genes for crown size were located on Y-chromosomes was supported by similar crown size in male cousins who share the same Y-chromosomes and different X chromosomes (Alvesalo, 1971).

The differential effect of sex chromosomes on amelogenesis and dentinogenesis causes sexual dimorphism to become evident. This was revealed by a study of sex chromosome anomaly patients (Alvesalo, 1971). The dosage effect of the X chromosome is evident in the thicker enamel and larger crown size in females with extra X chromosomes, e.g. 47,XXX (Alvesalo et al., 1987) and also in males with extra X chromosomes, such as those with Klinefelter's syndrome (47,XXY) (Alvesalo and Portin, 1980). The increased crown size in males compared to females is attributed to the growth-promoting effect of the Y-chromosomes on dentinogenesis. Y-chromosomes also stimulate amelogenesis in a similar manner to that of X-chromosomes (Alvesalo and Kari, 1977).

2.2.3 Statistical evidence for the diversity of dental patterns

It is generally accepted held concept that humans differ in many ways, including their dentitions. Approaches used to address the issue of individuality of the human dentition can be observed in the different array of research work undertaken. Researchers in anthropology are often interested in describing morphological traits of teeth whilst researchers in forensic odontology have particular interest in developing a statistical concept of the variation of the human dentition. Early works by Butler and Dahlberg, who introduced the concept of morphogenetic fields in the mammalian and human dentitions, stimulated interest in studies of dental variation (Butler, 1939; Dahlberg, 1945). Since then, many studies have been directed to more in-depth investigations on these various dental traits.

Although many studies have been carried out on dental morphology, forensic dental experts still cannot come to agreement about how to prove that human teeth differ between individuals beyond reasonable doubt. Scott and Turner (1997) stated that in comparison to other developmental processes in other parts of the body, teeth are developed within a highly conserved evolutionary process and possess very strong genetic control. Shields and John (1996) also pointed out that teeth are not prone to destruction and therefore provide valuable information to study variation among populations and are particularly useful in forensic investigation.

If the issue of individualisation were to be documented chronologically from the perspective of forensic odontology, the earliest approach to studying variability of the human dentition was by MacFarlane and colleagues (1971) using 200 dental casts obtained from patients. The main focus of this research was to stress positive and negative features in the human dentition. The authors referred to positive features as individualising features observed on teeth, while negative features referred to the absence of a tooth (MacFarlane et al., 1971). It was concluded that human teeth could be differentiated. They also noted that certain dental features were not independent but rather associated with other features.

Various studies have been conducted to identify the diverse information derived from the human dentition which allows the use of these data for forensic purposes. Forensic researchers have a particular interest in relating the issue of individuality of the human dentition to identification of individuals and to bite mark investigations.

The status of the human dentition can be classified into missing, filled or restored to assess overall health. These are common criteria used by many researchers involved in oral health research throughout the world. The first research utilising the combination of these traits was presented by Sognnaes (1975). Treating different characteristic independently, and multiplying them to obtain a final value, he calculated the diversity of dental patterns. For example, four missing teeth could create 35,960 combinations and four teeth with fillings could create 20,475 possible combinations, giving a total value of 730,281,000 possible combinations.

A similar approach to calculate possible combinations of tooth conditions was presented by Keiser-Nielsen (1977). Based on the three conditions (*C)* and the number of teeth present (*n*), i.e. C = missing, filled or unrestored and n = 32 (all teeth present), possible combinations would be 3^{32} which would be equal to 1,853,020,188,851,841 different patterns. If the combination were limited to only a few teeth, for example, only posterior teeth were considered, it would still gave the value of 3^{20} which is equal to 3,486,784,401. Therefore, it was suggested that the human dentition presented with a very diverse pattern judging by the possible combinations of the number and condition of teeth. This study has initiated the possibility of addressing dental pattern discrimination potential as a combination rather than looking at single feature. However the limitation of the study highlighted by Adams (2003) is that this combination may change over time.

Keiser-Nielsen (1977) also highlighted an example considering six features, which he suggested occur independently. He proposed that when these features carried 10% frequency, this would make a particular individual one of at least a million. This finding, upon which a decision was based, stated that forensic identification required at least ‘six concordant features’ to achieve meaningful comparison for forensic identification purposes.

Keiser-Nielsen (1980) then introduced a mathematical equation in an attempt to ascertain the maximum possible combinations present within the human dentition. He developed an equation as follows:

$$\boldsymbol{K}(M,X) = \frac{M}{1} \text{ x } \frac{M-1}{2} \text{ x } \frac{M-2}{3} \text{ x } \frac{M-\ (X-1)}{X}$$

where *M* is the number of teeth considered, usually 32, and *X* is the number of entities i.e. number of teeth missing or number of teeth filled.

This equation was introduced for application to missing and restored teeth. However, it did not take into account possible combinations for other morphological traits. The way the equation was generated is based on the assumption that, within populations, teeth that are missing and restored are equally probable. Because of this design flaw it is rarely used.

A different approach to understanding the individuality of the human dentition was explored by Sognnaes et al. (1982) by stressing the value of using twins to understand more about variability in the human dentition. Five pairs of twins underwent dental examinations and their upper and lower arch impressions were obtained. Testing of bite mark registrations was performed using various media including dental waxes, plaster and silicone. The study concluded that, despite their similar genotypes, there were significant variations between MZ twin pairs in relation to various dental features (Sognnaes, 1982). However, the limited number of twin pairs included in the study was a weakness in the study design.

An article used widely in citing the individuality of the human dentition is by Rawson et al. (1984), where the authors proposed the need for statistical evidence to understand individuality. This work was directed specifically at bite mark investigation. Bites of 397 individuals were obtained and, through mathematical evaluation, the authors claimed they could demonstrate the uniqueness of the human dentition beyond reasonable doubt. This rather bold statement not only initiated concern about the nature of ‘uniqueness’ in the human dentition, but it led to more debate. The authors stressed the need to explore further the determination of matches between teeth and bite marks on skin as this was not addressed in their study.

Kieser (1990) suggested different ways to study variability in the human dentition by either performing a retrospective study on the developmental process of teeth or through a prospective study by formulating a mathematical relationship. The author also suggested that the best outcome would be to incorporate both approaches.

Adams (2003) argued against the use of Keiser-Nielsen’s mathematical equation in forensic situations. He considered that the concept of random and equal occurrence needs a more detailed explanation than provided by the equation that was formulated. The author then conducted a study in which he proposed that by using a large dataset of dental records empirical comparisons could be made and thus an accurate estimate could be achieved within the population. By performing pairwise comparison (using a computer program) of two large datasets comprised of adults from a civilian United States population and United States military personnel, the study demonstrated that diversity of dental patterns based on missing, filled and unrestored teeth was on the scale that is comparable to mtDNA (Adams, 2003). A limitation of the study design was that the datasets did not reflect current oral health trends. In addition, normal morphological elements of the dentition such as dental crown size was not included as part of the overall assessment.

In 2005, Kieser et al. undertook a study aimed at quantifying information gained from the anterior dentition. For the purpose of this investigation, data on the shape of the anterior dentition, both general arch shape and individual shape made by teeth, were utilised. The authors obtained dental casts from 50 randomly selected individuals who had undergone orthodontic treatment, with the rationale that this group of individuals would have fairly similar occlusions. The approach of this research differed from previous studies by employing Geometric Morphometric Analysis rather than a subjective analysis. Whilst the focus of the study was its application in bite mark investigation, the approach was different from previous research looking at identifying individuals, and gave a new perspective to studying dental diversity. The authors concluded that the concept of the individuality of the human dentition was well supported.

Bernitz et al. (2006) collated a number of dental features that are widely used in bite mark examination and these same features have widely been recognised in a number of articles. The features included crowding, rotations, asymmetry, pathological displacement, extraction, unerupted teeth, fillings, attrition and grooves on incisal edges, supernumerary teeth, fractured teeth, diastema and the relative position of one tooth to the next. All of these variables could occur randomly and contribute to individuality in the human dentition.

Johnson et al. (2007) reported research to quantify the individual characteristics of the human dentition. The group conducted a power study and determined that 400 samples were required. Data were collected, using computerised programs, on similar variables to those mentioned in other studies (e.g. tooth width, degree of rotation, diastema, missing teeth). They reported that based on their data set it was possible to provide an evidence-based statement on the individuality of the dentition (Johnson et al., 2007).

There are various concepts in understanding dental variation. Many studies have been conducted worldwide observing expression of different dental traits in certain populations. The work is now being directed towards placing these different elements within a more recognised statistical probability that will incorporate amalgamation of all possible traits.

2.3 Population diversity

The building of human diversity is based firstly on the phenotypic similarities that cluster people according to their respective group and, secondly, on phenotypic differences that separate them into different groups within a population. These variations are an important key to further discussion of the concept of individualisation.

2.3.1 Ethnicity versus race

In the study of human variation, population separation was often conducted in the past based on the grouping widely referred to as ‘race’. According to AAPA Statement on Biological Aspects of Race (1996), the concept of race first arose in the early 19th century and involved categorising people based on their visible traits, including skin colour, features of the face, body size and shape, and also underlying skeletal features (AAPA Statement on Biological Aspects of Race, 1996).

There have been ongoing debates over the use of the term race or ethnicity within research communities. ‘Race’ suggests a biological basis for socially constructed categories and implies genetic homogeneity within broadly defined, heterogeneous population groups (AAPA Statement on Biological Aspects of Race, 1996; Kaplan and Bennet, 2003). Other definitions include the use of race as a taxonomic group of people who are believed to belong to the same genetic stock, which commonly arises as a consequence of geographical isolation (Richardson, 1980). One of the issues among scientists is that the number of races is often not easily agreed upon. Some people were not easily classified into a certain group because of their features suggested overlapping of several racial groups.

Generally, human races were clustered into three major groups namely Europeans, Africans and Asians, also referred to as “Caucasoid”, “Negroid” and “Mongoloid” (Mayhall et al., 1982). Another group of native Australians, believed to not belong to any of the other groups, was introduced as “Australoid” (Townsend et al., 1990). Due to the possibility of overlapping of features between these groups, there can never be a clear separation among them. However, groupings are necessary for the purpose of understanding variation among humans so that particular features can be recognised as belonging to a particular group.

Other scholars proposed clustering that corresponded roughly with the geographical division of human beings. This led to division of sub-Saharan Africans; Europeans, western Asians, and northern Africans; eastern Asians; Polynesians and other inhabitants of Oceania; and Native Americans (Risch et al., 2002).

Because the term 'race' can suggest elements of discrimination, AAPA statement on biological aspects of race (1996) has highlighted a few points to revise the old statement on race. Other alternative terminology to describe different population groups is the word 'ethnicity'. Indeed, Richardson (1980) questioned whether more than one race exists for humans, preferring instead to refer to ethnic groups who are separated by cultural, climatic and geographical boundaries.

Ethnicity can be defined differently according to the context of use. Commonly, ethnicity refers to membership of a group defined by culture, heritage or national origin (Kaplan and Bennet, 2003). Ethnicity can also refer to people of the same nationality who share a distinctive common bond, such as geographical location, a culture or language and who are historically related.

There are clearly issues to consider when applying the terms ‘race’ or ‘ethnicity’. Kaplan and Bennett (2003) suggested guidelines for the use of these terms in biomedical research: The following points, among others, should be noted when conducting research where ‘race’ or ‘ethnicity’ is included:

1. *When race/ethnicity is used as a study variable, the reason for its use should be specified*
2. *In citing race/ethnicity data from any source, authors should describe the way in which individuals were assigned to racial/ethnic categories.*
3. *Race/ethnicity should not be used as a proxy for genetic variation. Statements about genetic differences should be supported by evidence from gene studies.*
4. *In stating hypotheses and describing results, authors should distinguish between race/ethnicity as a risk factor or as a risk marker.*
5. *In the interpretation of racial/ethnic differences, all conceptually relevant factors should be considered.*

Whilst the guidelines use either race or ethnicity, the main issue is that the authors tried to highlight the role of researchers in ensuring that groupings of the subjects are well defined. These points are important to make the study outcome more beneficial. The author would like to highlight that the term used within this thesis will be **‘ethnicity’** due to the grouping of subjects based on their defined culture, heritage or national origin who share a distinctive common bond, such as geographical location, a culture or language and are historically related.

2.3.2 Phenotypic differences

Due to the nature of grouping people according to their similarities, variation within groups tends to be less than variation between groups (Relethford, 2000). One of the widely employed methods in segregating human diversity is to look at craniofacial structures. Early craniofacial analyses and major longitudinal growth studies were based mainly on people of European ancestry. However, due to the significant differences noted between diverse ethnic groups, a large number of cephalometric studies were followed (Altemus, 1960; Riolo et al., 1974; Broadbent et al., 1975; Harris et al., 1977; el-Batouti et al., 1994; Johannsdottir et al., 1999).

Differences within and among groups can also be observed according to sex (Riolo et al., 1974; Bhatia and Leighton, 1993) and across different age groups (Riolo et al., 1974; Broadbent et al., 1975; Bishara, 1981). Differences in craniofacial morphology within and between populations of different backgrounds result from complex interactions between genetic and environmental factors. These affect both formation and growth of the skull.

Differences in the facial skeleton are more complex due to the effects of masticatory function (Kasai et al., 1993). Australian Aboriginals, for example, were observed to have larger dental arch size and more powerful musculature (Kasai et al., 1993). They are known to have been hunter-gatherers who lived under harsh conditions. Their teeth were generally utilised as tools for the manufacturing of cultural items, for food preparation and for eating a high fibre diet with added abrasives (Barrett, 1976). On the other extreme, people who have lived in a lifestyle that is less demanding in terms of life survival present with less robust features. For example, Japanese people (in comparison to the Australian Aboriginal) tend to display smaller facial and dental dimensions and less robust facial muscles due to the fact that they have more advanced food processing technology (Kasai et al., 1993).

In reference to the earlier groupings of humans, physical anthropologists have observed various craniofacial differences among four different groups. Caucasoids are characterised by a high cranial vault, receded zygoma, large brow ridge and narrow nasal aperture. Mongoloids present with medium height, brachycephalic skull, absent brow ridges, small nasal aperture and projecting zygoma. Negroids have a short dolicephalic skull shape, receded zygomas and wide nasal aperture. Australoids fall between the Negroid and Caucasoid groups. At this point, it is important to emphasise that this thesis is solely based on variation observed within the human dentition rather than within other bony traits.

Observed dental morphological variations have also led to the identification of specific dental complexes. These complexes have been formulated to support the general characteristics observed in bony features of the skull. The term *dental complex is* based on non-metric features found on teeth. Expression of these dental traits may be observed more frequently in one population compared with another. For instance, Mongoloid ethnic groups have been noted to have high frequencies of shovel shape or shovelling of incisor teeth, entoconid (cusp 6), metaconid (cusp 7) and prostostylids. On the other hand, Caucasians have been observed to have low frequencies of shovelling, cusp 6 and 7 and prostostylids but high frequencies of Carabelli trait and bilateral counter winging of central incisors (Mayhall et al., 1982).

Tooth size and morphology have been widely used in the assessment of population affinities and histories (Hanihara and Ishida, 2005), genetics (Townsend et al., 1992) and forensic applications (Lasker and Lee, 1957). In an attempt to characterise people based on their dentitions, several researchers have proposed dental complexes that may be ethnically discriminating. It was hypothesised that groups of people who shared the same genetic background should have approximately the same frequencies and expressions of dental traits.

The working tenet is that people who have similar frequencies of occurrence of particular dental complexes could be identified as belonging to a particular race or group of people. However, racial dental complexes have been criticised by some researchers, with doubt expressed about their validity (Mayhall, 1999). Several dental complexes will be reviewed such as the Mongoloid (Hanihara, 1967; Turner,1990), Caucasoid (Mayhall et al., 1982) and Australoid complexes (Townsend et al., 1990) and the limitations that may arises when using dental complexes will be highlighted.

The first researcher to apply the concept of dental complexes was Hanihara (1967). He proposed the Mongoloid dental complex which is comprised of six primary crown morphologies that occur at high frequency, namely shovel shape on the upper central and lateral incisors, deflecting wrinkle, prostostylid, seventh cusp on the lower second molar and metaconule on the upper second molar. These traits are believed to be characteristic of Mongoloid people and Hanihara suggested further exploration and application of the notion of dental complexes in other racial groups.

In addition to the work by Hanihara, Turner (1990) found Mongoloid people could be further subdivided into Sinodonts and Sundadonts. Sinodonts are represented by Northern Asians and Native Americans and Sundodonts by people of South East Asia. Turner identified several dental traits in several East Asian samples, namely; winging of upper central incisors, shovelling of upper central incisors, double shovelling and interruption grooves on lateral incisors, mesial ridge of upper canine, distal accessory ridge, hypocone, cusp 5 of upper first molar, Carabelli trait of upper first molar, parastyle of upper third molar, enamel extensions of upper molars, root number of upper first premolar, root number of upper second molar, peg-shaped lateral incisors, congenital/absence of upper third molar, lingual cusp of number of lower second premolar, groove pattern of lower second molar, cusp number of lower first molar, cusp number of lower second molar, deflecting wrinkle of lower first molar, distal trigonid crest of lower first molar, prostostylid of lower first molar, root number of lower second molar, and odontome of upper and lower first and second premolars.

Turner concluded that East Asians could be divided into those people who lived in the North and South East of East Asia. In addition to the major clusters, the South East Asian (Sundadont) division could be further sub-divided into two minor clusters. The first cluster consists of Nepalese, Philippinos, and people from the East Malay Archipelago, Indomalaysians and Burmese. The second cluster consists of prehistoric Taiwanese, Thailanders, early mainland South East Asians, early Malay Archipelago and recent South East Asian (people from Indochina). There was no exact definition provided of these clusters. However, it is believed that the Sundadont appearance originated due to the admixture of people from the first minor cluster with neighbouring Caucasoids, or influence from Arab and Indian traders, missionaries and colonists.

Mayhall et al. (1982) proposed a "Caucasoid dental complex" consisting of a low frequency of occurrence of shovelling, prostostylids, occlusal tubercles on the lower premolar and high frequency of Carabelli trait, hypocone reduction of the upper second molar, and bilateral counter winging. Another dental complex was proposed by Townsend et al. (1990). They found that Australian Aboriginals were characterised by a high frequency of occurrence of the entoconulid, also referred to as cusp 6. The frequencies were approximately 70% on the lower first molar, 80% on the lower third molar and 50% on the lower second molar.

Evidence of differences observed in the expression of different dental traits has led to separation of populations into different groups. Evidence from other studies has also suggested the benefit of using metric traits in separating humans into different population groups. Metric traits simply refer to features that can be measured.

Odontometric analyses are useful and biologically meaningful in assessing worldwide inter-population relationships. The results from odontometric analyses (mesiodistal and buccolingual diameters) are consistent with those based on genetic and craniometrical data (Hanihara and Ishida, 2005). From the 72 major populations, the authors were able to characterise human populations into three main streams using mesiodistal and buccolingual diameters as follows; microdontic, mesodontic and megadontic.

Microdontic populations consist of Native Americans, Philippinos, Negritos, Jomon/Ainu, and Western Eurasian while Polynesian and East/Southeast Asians are mesodontic and Australian Aborigines, Melanesians, Micronesians, sub-Saharan and Africans are megadontic. Hanihara and Ishida (2005) noted that their results did not support the Mongoloid subdivision proposed by Turner (1987, 1990). The Chinese and Japanese, who are Sinodonts according to Turner, were found to be closest to the Southeast Asians, while prehistoric Jomonese were closer to Australian and Papuan populations.

Hanihara (1977) calculated phenetic distance with multivariate analyses and found that Australian Aboriginals were closer to Caucasians and American Whites than to Mongoloids. Matsumara and Hudson (2005) used C-score data that represent shape components and found that Malays, South Chinese and South Indians have a narrower mesiodistal diameter than Philipinos or Negritos, (based on the first principal component that attributes variance for relative size of mesiodistal against buccolingual). The second and third principal components placed Malay and South Chinese between

Negritos and South Indians. The Negritos possessed larger relative molar and incisor size.

Marked dissimilarity in different ethnic groups can be observed in the patterns of tooth sizes. Australian Aboriginals and Melanesians have been reported to show large teeth while the Philipinos, Indians and Yeminites have small teeth. Australian whites and Taiwan Aboriginals have intermediate tooth size (Hanihara, 1967). Moreover, the Mongoloid group is characterised by relatively large lateral incisor teeth compared with their centrals. American blacks were reported not only to have significantly larger tooth crown dimensions than American whites (Richardson and Maholtra, 1975; Harris and Rathburn, 1989) but also large arch size and arch form that was squarer and less tapered in the canine–premolar region dental (Burris and Harris, 2000).

Tooth size may be a manifestation of functional demands on the teeth and these demands can vary with local adaptations. As discussed earlier, Australian Aboriginals' life adaptation caused them to also have larger teeth with evidence of tooth wear (Barrett, 1976). On the other hand, the Japanese tend to have relatively smaller teeth (Kasai et al., 1993).

The ability of dental complexes to highlight separate ethnic groups shows the potential application of these features for human identification. Possible application would be by direct comparison of observed non metric traits with extreme frequencies and degrees of expressions. It is proposed that the value of this evidence could be maximised by combining them with metric traits.

2.3.3 Challenges

Complexity of individual identity and the lack of clear-cut boundaries between ethnic categories make it difficult to write about race or ethnicity with precision. The first major challenge in writing about race or ethnicity is to avoid implying that every individual has racial or ethnic identity that can be easily determined.

Human populations who are relatively homogenous genetically are generally becoming less common because of migration and inter-racial marriages. Racial or ethnic self-identification can be complex. While many individuals identify with a single racial or ethnic category, others identify themselves as biracial or multiracial, confirming their connection to more than one group. Membership in a given racial or ethnic group may be an indicator from a particular trait if the incidence or prevalence of the condition is higher in that group than in other racial or ethnic groups. The likelihood of having a set of features may vary considerably among members of the group and those who are actually having distinct features may share relevant characteristics with people in other racial or ethnic groups.

This has led to the need to explore different traits observed in different ethnic groups and perform various measurements using the same standard. This is important to verify current understanding and at the same time formulate a useful indicator for the process of individualisation.

2.4 Recording variation

Documenting variation in dental arch and tooth form may involve written documentation, image capture or a physical record in the form of a dental cast.

2.4.1 Two-dimensional imaging

Photographic records, besides being easy to obtain, provide advantages for detailed studies such as accuracy, permanence and comprehensibility. Coloured photographs can provide relative images of the intraoral conditions of the person. Common photographic records of patients include occlusal views of the upper and lower arches and when the both arches are in occlusion. Other forms of photographs taken in dental clinics include frontal view with the subject smiling. This form of record is low in cost, easily stored and can be done quickly.

2.4.2 Three-dimensional imaging (3D)

A relatively new concept involves the use of 3D imaging. This literature review underlines many issues related to the application of 3D technology in dentistry and forensic science generally and also stresses the importance of the research potential of 3D technology, particularly in human odontometrics.

2.4.2.1 Principles of 3D scanners

The principle of most non-contact scanners is based on a triangulation method. The light, sensor and the object to be scanned are connected to form the shape of a triangle hence the name '*triangulation'.* Sources of light (which can be from laser, white light or optical light) are projected onto the surface of the object. A CCD sensor then receives the reflected light from the object and converts it to a series of point clouds (Figure 2.6). These point clouds are registered in a 3D coordinate system. The ability of this system to estimate the exact size of an object depends on the mechanics of the triangulation process. The process is similar to human vision, where the eyes estimate the size of an object based on the distance between the eyes to the object and the fixed distance between the two eyeballs.

Whilst the discovery of 3D imaging was initially used in the entertainment and photographic industries, it has now evolved for use in a multitude of industries. This type of imaging allows direct analysis from images on a computer monitor and storage of data for future use.

Physical objects are the best source of information. Direct observation and the ability to touch the objects can give a wide spectrum of information. However, not all objects can be passed around for the purpose of information sharing and, with time, the question of storage will definitely be a concern. Due to these issues, the use of three-dimensional imaging is appealing as it allows 360 degree data extraction from an object, which is not possible to achieve in two-dimensional photographs. Maximum data output allows application in many industries including engineering, entertainment and health sciences.

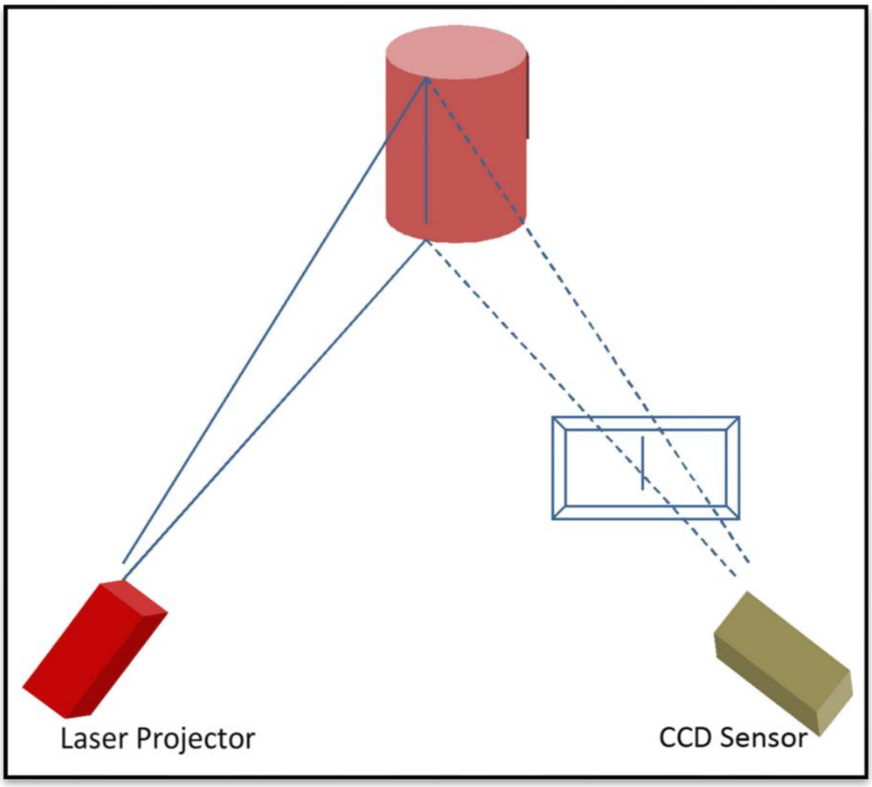


Figure 2.6: Principles of laser triangulation (derived from Optix 400S manual)

2.4.2.2 3D Technology

A range of data acquisition hardware for producing 3D images is available. Generally, 3D scanners can be divided into contact and non-contact 3D scanners. Non-contact 3D scanners reduce the risk of damaging the object that needs to be scanned (Bachrach et al., 2010). There is a range of 3D technology in each of these groups of scanners.

Scanners utilise either laser or white light technology. Each technology has its own advantages and limitations. Laser scanners have wider potential application in terms of their flexibility in scanning different objects. White light technology on the other hand has the ability to scan an object faster than a laser scanner. Together with the hardware, various software used for image analysis is available in the market. It largely depends on the interest of the end user in purchasing software that may be of most benefit to them.

The reliability of using three-dimensional imaging as an alternative to direct measurement of dental casts and two-dimensional imaging has been studied extensively by many researchers (Smith et al., 2009a; Abizadeh et al., 2012; Sousa et al., 2012). For those involved in studying human phenotypes, particularly teeth in this case, it allows the ability to document and gain better understanding of variation. It allows the researcher to perform various measurements and observations of a virtual dental cast as if it is real, and at the same time preserve the information obtained in a quantitative format.

Utilising intelligent three-dimensional scanning technologies to measure various dental traits will enhance the way individualisation of human dentition can be explored. In addition, combining 3D technology and the methods of statistics will also contribute to the understanding of human teeth and their variation.

2.4.2.3 The use of 3D scanners in dentistry

Dentistry involves providing services to patients who require the practitioner to make educated decisions using diagnostic inferences and treatment planning options to deliver oral health care. 3D technology in dentistry is an excellent tool to aid diagnosis and treatment planning. This is evident in the work of prosthodontists, who require virtual planning for restorative work such as bridge and crown constructions; orthodontists, who are required to perform various measurements on patients' dental casts to make correct judgement on space analysis, tooth width and others features; and oral and maxillofacial surgeons, who use 3D imaging in surgical treatment planning.

Accurate representation of patients' dentitions and arches is crucial to ensure they receive the best treatment for their individual needs. Replicas of patients' dentitions are acquired by making dental impressions and converting them to plaster models. Use of such models allows dental practitioners to make necessary measurements and formulate treatment options. Dental models also aid communication between practitioners and patients.

The stability of dental casts as a replica of patients' dentitions has been widely researched and is not the focus of this discussion. There are three important issues to consider when carrying out measurements on patients' dental casts. These issues have been researched widely by many and include validity, reliability and reproducibility (Naidu et al., 2009; Nouri et al., 2009). Measurements made directly on dental models have been regarded as the 'gold standard'. However, as research and dentistry progress, the method of acquiring various measurements of dental variables could be performed via two or three-dimensional images.

2.4.2.4 3D imaging in forensic science

In forensic science, 3D technology applications could be useful in investigations involving comparison of pattern injury, analysis of trauma and tool mark investigations (Sansoni et al., 2009, Bachrach et al., 2010). Other applications may include identification from video surveillance and facial construction.

Quite often, forensic cases need to be investigated by several experts. Physical evidence may sometimes need to be transported from one location to another. This evidence is subjected to extra care as it might be fragile and any damage while *en route* will hamper the quality of investigation. To overcome this, digital 3D data allow authorised forensic experts to gain quick access to the information they need, regardless of location.

3D scanning bridges this gap between physical and digital, capturing highly detailed and accurate 3D models of physical objects. While 3D scanning is not a new concept, the availability of affordable, portable and easy to operate 3D scanners is now putting this capability within widespread reach.

There are two types of 3D scanners widely employed in forensic investigation. Crime scene scanners capture a large overview map of a crime scene. This overview map is helpful in understanding the relative position of objects, but the objects themselves are rough 3D shapes. New ‘close up’ 3D scanners capture individual objects in full colour and high resolution 3D (Ma et al., 2010).

Most 3D scanners today use lasers to measure 3D information. A laser stripe or dot is moved across a target, and is photographed by a camera at a slight angle to the laser source. Depending on how far away the laser strikes a surface, it will appear at different places in the camera's field of view. This type of capture method is non-contact, meaning it does not touch or affect the original physical sample. For fragile or important forensic samples, this is very important.

It is possible to create castings, but for some items there is a danger of damage to the original in this process. Optically capturing of the shapes using a 3D laser scanner provides a portable digital 3D model without any damage to the original. Plaster casts work very well for some applications but are still physical objects that are difficult to share across locations and take up physical storage space. Plaster casts are easily captured by a 3D scanner and can be converted into digital models to solve these issues.

In forensic odontology, particularly, the use of 3D images will greatly improve the presentation of evidence in Courts of Law so that members of the court can appreciate detail compared to two-dimensional displays or a small size dental casts.

2.5 Analysing variation

Traditionally, analysis of objects has involved measurement or scoring of features. Lestrel (1989) defined morphology or form as equating to size and shape. Size refers to the spatial extent of an organism or part, its magnitude or dimensions. Size can be measured in different ways, such as area or width. A widely used size measure for real organisms is a length measurement.

The term 'size' has usually referred to metrical analysis describing measured dimensions. Measurement of size can usually be carried out to measure arch breadth (arch width), depth (arch length) and circumferences. The component of size is relatively straightforward and can easily be quantified. However, the component of shape can be challenging to be quantified. Words from everyday language, such as ‘size’ and ‘shape’ have received new technical meanings, which can caused some difficulties (Bookstein, 1989).

'Shape' refers to the proportions of a structure and to the relative sizes and arrangement of its parts. For a simple shape, this can be defined easily. For objects that are more complicated, a single description may not be enough to describe its shape completely.

From this point on, the author would like to stress that whenever the term ‘form’ is used, it refers to the combination of size and shape. This term is widely used by other authors (Richtsmeier and Lele, 1993; Slice et al., 1996; Lele and Richtsmeier, 2001). Our basic mathematical knowledge tends to lead us to say that two objects are fundamentally the same if they are geometrically similar.

As an extension of the use of dental traits when assessing human population diversity for anthropological study, Dahlberg (1963) highlighted the possibility of expanding its application for forensic human identification purposes. Dental traits proposed by Dahlberg (1963) as suitable for use in forensic analysis were cusp size, number and location, simple and complex occlusal groove pattern, individual tooth measurements, number and arrangement of teeth, root systems, occlusal and bony relationship and palatal rugae pattern. Since this project only focuses on the use of dental casts, only some of these features will be studied.

2.5.1 Dental crown size

Studies involving tooth size have been well documented (Moorrees et al., 1957; Kieser, 1990; Hanihara et al., 2005; Townsend et al., 2009a). Depending on the availability of instruments and equipment to a research group, various researchers will employ different methodologies. However, the definition of the parameters involved in the measurement of tooth size is generally the same.

Measurements of dental crown size have been employed directly on dental casts or indirectly through measurement on two dimensional and three dimensional imaging. Measurement of mesiodistal dimensions has been defined as the greatest distance between the mesial and distal surfaces of the crown (Moorrees and Reed, 1954). Buccolingual diameter has been defined as the greatest distance between buccal and lingual surfaces of the crown measured at right angles to the mesiodistal line. Some researchers have also looked at measuring tooth size diagonally, i.e. from the mesiobuccal cusp to the distolingual cusp (Karaman et al., 2006).

2.5.2 Dental arch size and shape

Dental arch classifications are important in formulating dental treatment modalities, for example in the field of orthodontic. There is not uniform agreement among orthodontists about how to classify dental arch shape (Lee et al., 2011). Traditionally, dental arch shape has been categorised by subjective evaluation. This depends solely on individual interpretation in reference to a list of available shapes. Thompson (1915) classified dental arches shapes as: square, round square, round or round V-Shaped.

A descriptive morphological study by Yamazaki (1934) added epsilon, elliptic, parabolic and hyperbolic to the list. McCohnail and Scher (1949) combined the earlier findings to present a classification that is commonly used, shown in Figure 2.7. Categories used by McCohnail and Scher include parabolic, ovoid, hyperbolic, elliptic, trapezoidal and catenary.

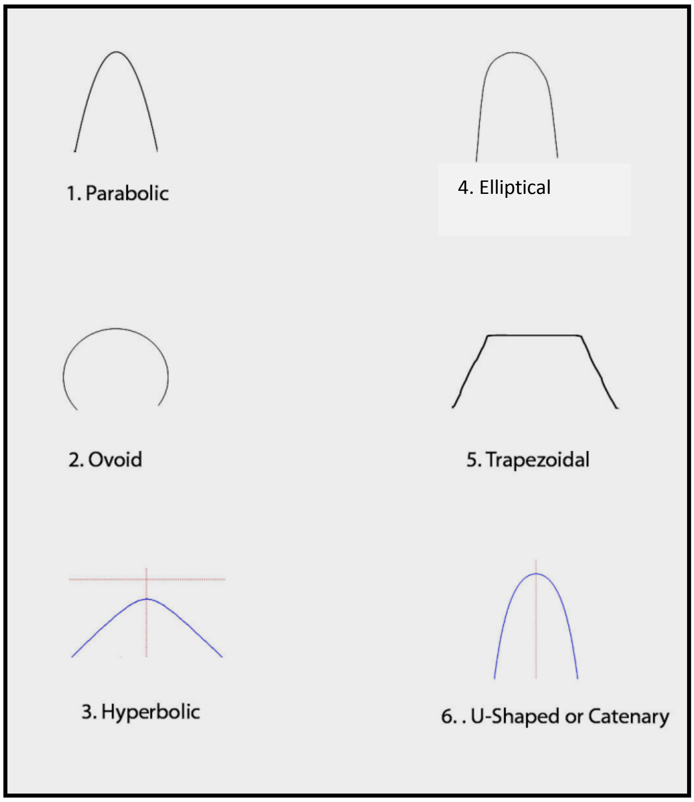


Figure 2.7: McCohnail and Scher classification of arch shape (derived from McCohnail and Scher (1949))

Apart from subjective evaluation of dental arch shape, other methods to quantify the shape have also been explored. A conventional metrical approach was one of the methods used to quantify shape by measuring linear distances and angles. However, one would argue that this approach is essentially measuring dental arch size rather than shape. It could, however, contribute in cases where a dental arch presents with simple rather than irregular morphology (Lestrel, 1989). Lestrel (2000) further categorised quantitative methods of analyzing dental shape into those dependent on landmarks representation and those that are based on boundary outline methods.

2.5.2.1 Geometric Morphometric Analysis (GMA)

One of the methods to study form that has gained a reputation within various fields is an approach to analysis referred to as 'Geometric Morphometric Analysis' (GMA). This refers to the interpretation of shape, based on landmark location. This technique has been widely applied in zoological studies. However, in recent years, its application has been widened to cover many research areas including the study of tooth morphology.

Many of the ideas that underlie the approaches currently used go back to the foundations of biometry in the late 19th century. This concept was introduced by people such as Galton, Pearson and others (Bookstein, 1998). Morphometric approaches were in broad use particularly during the 1960s and 1970s (Sneath and Sokal, 1973). The goal was to utilise objective methods to identify and classify organisms. This has led to the development of advanced statistical methods specifically designed for the analysis of morphological form. These new approaches and the wide availability of computers and statistical software made multivariate analyses of distance data a standard tool of evolutionary biologists during the 1980s. Most of these studies were based on measurements of various lengths and have become established to be what is now often called traditional morphometrics (Pimentel, 1979; Reyment et al., 1984; Bookstein et al., 1985).

The way an object is described can vary depending on a person's background. The description can range from the size, colour or shape of an object based on individual preferences. However, the most meaningful description will allow another person to understand a particular object to which that person has been referring; therefore, it will rely on how much information was described. For example, to describe a person, a layman may describe the type of clothes he wore, the colour of the skin, the shape of the face, lips or maybe the eyes. The most obvious shape description will usually referred to the overall shape of the face. Often, shape description is carried out based on a generally known shape, usually a geometrical shape. The reason behind it is mostly to familiarise the other person with a more technically understandable reference. A more analytical individual, for example, someone involved in the scientific aspect of an investigation, might describe the above person in different levels of detail. This may involve measuring distances between various landmarks present on the face or a series of stable points for face recognition. A more robust description will be an amalgamation of shape and measurements so that an object is represented in its entirety.

In the second half of the 1980s and 1990s there was a reinvention of morphometrics, including various geometric frameworks for analysing configurations of landmark points in two or three dimensions (Rohlf and Bookstein, 1990; Zelditch et al., 2004). Moreover, different approaches to shape analysis with direct relevance to biology also came from computer science and image analysis (Costa and Cesar, 2001). Morphometrics is a dynamic discipline and much unexplored territory remains. This is particularly true for the application of morphometric methods in fields that concern themselves with morphology, but where research traditions have not emphasised quantitative analysis such as dental arch shape.

GMA is basically characterising organismal form in a quantitative manner and it has several advantages. Quantitative characterisation tends to be more objective than qualitative description, making results more easily reproducible. Quantitative methods usually have better ability to detect small differences than qualitative inspection. In the study of dental arch variation, for example, subtle differences can be biologically relevant, and having methods that can reliably find and report those differences are therefore important.

Living organisms, even ‘simple’ ones, have highly complex body plans. Many different ways could be found to describe their morphological structure or even the arrangement of just a few parts. Morphometrics utilises an abstraction that reduces organismal form to a series of measurements, the arrangement of a set of landmark points that can be located on every specimen, or an outline contour.

Whilst the use of GMA has been widely use in the study of evolutionary biology, in recent years, the use of GMA in craniofacial research has gained in popularity. Studies on facial morphology (Popat et al., 2013), tooth morphology (Al-Shahrani et al., 2014, Polychronis et al., 2013) and dental arch morphology (Kieser et al., 2007, Sheets et al., 2011, Sheets et al., 2013) are some examples where GMA has been used to study variation within the craniofacial area.

The dental arch is part of the highly complex plan of the human body. As mentioned briefly earlier, many different ways could be found to describe arch morphology based on the arrangement of the teeth. Morphometrics simplifies this task by using a series of measurements based on a set of landmark points that can be located repeatedly across all populations being studied. A more robust description would be an amalgamation of shape and measurements so that an object can be characterised in a rigorous quantitative manner. Subtle differences can be biologically relevant, and having methods that can reliably find and report those differences is therefore important.

2.6 Forensic science and Individuality

The science of forensic identification, which comprises both human or product identification, may involve forensic experts from many disciplines, including pathologists, odontologists, anthropologists, biologists (DNA), and fingerprint, questioned document, and tool mark comparison personnel (Dale and Becker, 2007).

The ability to isolate a potential individual as the sole source of evidence or ‘the one’ is crucial; hence, the term ‘individuality’ or the more widely used term ‘unique’. This issue might be the most concerning problem to prove in a Court of Law. The urgency to make a major paradigm shift on the importance of this matter has been voiced widely (Saks and Koehler, 2005; Saks, 2010). Both authors challenged forensic experts in providing a designated research protocol to support the probability of having a match between two comparable evidence sources. What most experts are questioning nowadays is the ability to positively say that ‘this is it’ and ‘no other’ rather than just stopping at saying ‘it is a match’.

Through the lens of the electronic media, the two most prominent ways of identifying individuals are DNA and fingerprint comparisons. DNA experts for example have pointed out that DNA evidence is based on *'a set of genetic markers that is expected to occur less than once per five billion people'* (Balding, 1999). Furthermore, fingerprint experts are positive that no two individuals have the same fingerprints (Champod and Evett, 2001). The advantage that DNA and fingerprint experts have over other forensic experts is that these two sciences have the availability of large reference databases created over the course of their development.

Other areas of forensic science have also started moving towards probabilistic approaches. Christensen (2005) responded to the suggestion by proposing quantitative analysis of the frontal sinus to assist the identification process. The author focussed on ascertaining a standardised measurement of the frontal sinus that could help in objective comparison of this anatomical landmark. Other authors, such as Srihari (2002), endorsed the view of establishing objective validation in questioned document analysis.

Whilst different forensic fields might resort to different techniques of providing evidence of individuality of human phenotypes, the approach is likely to be the same. By using the application of mathematics and appropriate computer software, this question may well be answered.

Use of the human dentition as a way to identify a person has been well documented. This is evident from the majority of identification work in disaster situations being led by the teams within the field of forensic odontology. Whilst the notion that “teeth are highly variable” has formed the basis of work by forensic odontologists, is it possible for odontology experts to take a step further to use statistical reasoning to prove this? The bar should now be raised to address this question: “What’s the probability that it is so?” rather than limiting the idea to “It is so”.

2.6.1 Legal requirements

The requirement of proving individuality in forensic identification is perceived to be a consequence of Court rulings that supersede assumption and demand statistical consideration. Court rulings such as *Frye*, *Kumho* and *Daubert* have guided forensic experts in providing evidence in Court. They have also driven a different research approaches in forensic science to improve the issue of evidence handling and decision making.

Frye (1923) has served as a guideline in the United States courts for many years. According to *Frye*, any forensic expert wishing to provide opinion based on a scientific technique must ensure that the technique is well accepted by the relevant scientific community. Following the establishment of the Daubert principles in the result of *Daubert v Dow Pharmaceutical Inc. (1993)*, United State judges are required to consider the following guidelines for the admissibility of evidence in Court:

1. Is the evidence based on a testable theory or technique?

2. Has the theory or technique been peer reviewed?
3. In the case of a particular technique, does it have a known error rate and standards controlling the techniques operation?
4. Is the underlying science generally accepted by a relevant scientific community?

The first important rule according to the *Dauber*t judgement is that the theory and technique used must be refutable and testable. One could argue that this statement would overwrite any measures to prove 'uniqueness' in the identification process. The two most prominent authors against the ability or necessity to prove 'uniqueness' by research are Saks and Koehler (2005). Unless researchers manage to incorporate everyone in the world, these authors would suggest it is not something that can be proved. However, one crucial thing raised in any courtroom in the world is the ability to identify a particular person or object. Thus, where does that leave us? Would it be wise to therefore modify the use of the term 'unique' to something else?

2.6.2 Individuality versus uniqueness

The term 'unique' has been used, generally, to describe a subject, event or behaviour as being special or one-of-a-kind. Unique is defined as the state of being very remarkable and the only type within its group (Collins, 1990). Keiser-Nielsen (1977) highlighted the importance of avoiding the term unique in describing physical features. This was based on the view that the word 'unique' should be used exclusively for the existence of only one of its kind. Variations of different dental traits observed within the human dentition lead to the likelihood of individualising a person by using their teeth. In forensic identification, unique has been used loosely (some would say carelessly) by experts to add to the weight of a positive decision.

Individuality on the other hand refers to the characteristics that differentiate a subject from its group by describing unusual and striking qualities (Collins, 1990). Literally, it is not possible to prove ‘uniqueness’ as it is could require a research project involving each and every single human being in the world. Therefore, research in forensic identification is often directed at providing resounding evidence to support the statement of individuality, rather than providing a mere assumption, by the application of mathematics to provide probabilistic statement.

Lucas and Henneberg (2014) also highlighted the use of the term ‘singularity’ to replace unique. They proposed the idea should be to search for non-duplicates within a defined population rather than being interested in finding unique features within the whole world population.

The ability to determine individuality of the human dentition, using a sound statistical basis would carry significant weight whenever identification is to be concluded. According to the American Board of Forensic Odontology (ABFO) guidelines, positive identification is defined as “*The ante-mortem and post-mortem data match in sufficient detail to establish that they are from the same individual. In addition, there are no* *irreconcilable discrepancies"* (American Board of Forensic Odontology, 2013) Therefore, to withstand legal scrutiny, a high level of confidence is required.

A question still to be addressed is "*how high is high"* i.e. what confidence level is acceptable to the Courts. The burden of proof in Criminal Courts is "beyond reasonable doubt" whereas in Civil Courts it is "balance of probability" (Annas, 1999). Whilst the probability applied in the Civil Court level could be construed as being 51% or more, there is no defined percentage for "beyond reasonable doubt".

Acharya and Taylor (2003) addressed the issue of arriving at a positive identification by questioning the number of concordant points required to do so. The findings from their research stressed the importance of treating each case as a separate entity. It was also concluded that positive identification could be determined with as little as one concordant point. This article provides evidence of the suitability of human teeth to identify a deceased body. However, true statistical evidence is not provided.

The use of likelihood ratios in supporting the evidence of individuality has been reported by Christensen (2005) who studied the value of frontal sinus for identification purposes. By using Elliptic Fourier Analysis (EFA) to assess outlines of frontal sinuses, an estimated probability of a correct identification of 96% was found.

Another use of likelihood ratios can be seen as applied by experts in handwriting examination. Although this technique is usually used in situations where prior information is available, its use in investigative situations has also been explored by Taroni et al., (2011). This suggests the value of this technique and its growing potential in supporting evidence of individuality for forensic identification purposes.

Summary of literature review

Human dental variation occurs due to interactions between epithelial and mesenchymal cells which are influenced by genetic, epigenetic and environmental factors. The presence of this variation makes forensic dental identification possible. For a long time, positive dental identification has been achieved through comparison of ante-mortem and post-mortem images of teeth, particularly with the presence of some form of dental treatment. Where the dentition is sound (i.e. unrestored), the confidence level of the opinion diminishes. The belief that no two dentitions are the same resulted in the initiative to shift the focus to the existing variation and patterning of tooth morphology. Whilst achieving a definite uniqueness is impossible, providing characteristics of individuality using variability and patterning in dental crown size and dental arch size and shape should assist in the task of individualising people.

Chapter 3: Aims and objectives

3.1 Aims

The view that no two human dentitions are exactly alike is well accepted within the dental fraternity. At the same time, through extensive reading of the literature, it is apparent that one of the gaps in our knowledge is proof of this concept. It is a rigorous task to be undertaken; however, in order to identify individualising features that could best discriminate one individual from another, research looking at variation and patterning within populations is required. Therefore, the general aims of this current research were to address the following research questions.

1. Are there characteristics of the human dentition that will show variation and patterning between population groups?
2. Are there characteristics of the human dentition that will enable discrimination between population groups?
3. Are there characteristics of the human dentition that will enable assignment of an individual within a population?

3.2 Objectives

In order to achieve the aims, the following specific objectives were formulated.

1. To develop accurate and precise methods of measuring dental features. This aim was achieved by using two different methods, two-dimensional and three-dimensional imaging, to accommodate researchers or practitioners who may have access to only one of these methods or who are looking at alternative

methods. The aim was to have an image for each subject that is standardised in order to ensure repeatability and to reduce subjective assessment by the operator.

2. To quantify patterning and variation of dental features in a number of population groups. This was achieved by examination of dental crown size and dental arch size across different populations to determine significant findings that might affect the future development of a probabilistic model.
3. To establish population-specific variation (ethnicity, age, sex, etc.). This was done through multivariate analysis of a combination of variables. Using Principal Component Analysis (PCA), in which all variables are standardised into similar weighting, and discriminant Function Analysis, with particular emphasis on certain variables, to assist in separation of ethnic groups.

3.3 Hypotheses

There are several elements to be tested in this study. The first null hypothesis to be tested is that, for dental crown size, there is no significant difference between crown sizes among different ethnic groups, both using two dimensional and three dimensional methodologies. The alternative hypothesis is that dental crown size among ethnic groups can be distinguished.

The second null hypothesis to be tested is that for dental arch size there is no significant difference in size between the arch of different ethnic groups, both using two dimensional and three dimensional methodologies. The alternative hypothesis is that dental arch size among ethnic groups can be distinguished.

The third null hypothesis to be tested is that for dental arch shape there is no significant difference between arch shapes of different ethnic groups using two dimensional methodology. The alternative hypothesis is that dental arch size among ethnic groups can be distinguished.

Based on previous literature, it is anticipated that all null hypotheses will be rejected, and that there is a good indication that variation in tooth size, arch size and arch shape exists between ethnic groups from different geographical locations. Recommendations could, therefore, be made that routine observation and recording of tooth and arch morphology, in addition to pathological conditions, by dental practitioners would be a good adjunct for forensic purposes.

If expectations are correct, this research will provide additional methods to differentiate dental crown and dental arch size and shape, to quantify dental variation and patterning and to allow population distinctions among modern humans.

Chapter 4: Materials and methods

There is a great diversity of research equipment currently available to allow dental morphology to be measured. This chapter will discuss the types of equipment in general followed by specific description of the materials and methods utilised for the current research.

4.1 Equipment for data acquisition

4.1.1 Callipers

Callipers, dividers or other similar devices have been traditionally used as a standard for various metric measurements. This method had been refined by the progression from manual calliper to an electronic calliper that can be linked directly to a computer. The advantage of these devices is that they are fairly cheap, relatively small and therefore flexible for use in the field or other situations outside the laboratory. They are ideal for collecting relatively few measurements on each specimen. The accuracy of these methods has well been researched and has often been used as a gold standard to compare with new methods.

Callipers and similar devices are still in use in some contexts, but tend to now be replaced by 2D imaging equipment or 3D coordinate-measuring devices, which have become much cheaper in the past decade or two.

For this current research, a calliper was only used during the initial phase to assess the reliability of determining reference points between trained operators and was not utilised for the main findings of this research.

4.1.2 Imaging, two-dimensional

The availability of inexpensive equipment to capture two-dimensional (2D) images, such as digital cameras and flatbed scanners, allows this method to be widely used in dentistry. Whilst mainly used to assist in documentation of patient records, dental photography can also be an aid to communicate between dental practitioners and their patients when discussing treatment plans and giving oral education. Dental photography has also increased the potential for conducting dental research.

High quality single lens reflex (SLR) cameras at a reasonable price allow researchers to capture quality images of teeth. Cameras are often bundled with readily available software packages designed for general image analysis, including measurement and digitisation of landmarks and outline contours. This software can be freely available for any users or it may come at a price. Due to this ease of availability, digital imaging has become the method of choice for image acquisition in many areas of research.

Even consumer cameras now have high resolution of two million pixels or more and quite good optics (although there inevitably are distortions when extreme zoom positions are used). Image resolution of 2000 x 1500 pixels is usually adequate for locating landmarks or measuring distances precisely. A resolution in the order of one to three million pixels is a reasonable compromise between the resolution of fine detail and the requirements for image storage. Because many good and affordable digital cameras are now available, resolution is no longer a limit for the use of these cameras in morphometric studies. Resolution can be an issue, however, if video cameras, with a resolution in the order of 640 x 480 pixels, are used.

The quality of the optics should be tested before measurements are obtained, because many consumer cameras introduce distortions (particularly zoom cameras set to 'wide angle' mode). There are also digital cameras specially constructed for use with microscopes. These use the high-quality optics of the microscope and are therefore less prone to distortions, but they also are considerably more expensive than consumer cameras.

Another option is the use of flatbed scanners, which are inexpensive and have a high resolution and surprisingly good geometric properties. Therefore, using flatbed scanners is a viable option for relatively flat objects such as plant leaves or mouse mandibles.

4.1.2.1 Photography settings (2D imaging)

Unlike compact cameras, SLR cameras have the ability to help users gain total control over various camera settings at the highest quality, thus assisting in standardisation of the photographs taken (Ahmad, 2009). There is a variety of digital cameras available in the market. The numerous options of cameras available can be observed in dental articles published in a variety of different journals. For example, Bister et al., (2006) compared ten different digital SLR cameras used in the field of orthodontics and found that there were several issues to consider when deciding which camera to use. Digital SLR cameras have been shown to produce adequate images for dental photography; however, other issues such as user-friendliness, price and brand really depend on the preference of the end user.

A fundamental principle is to ensure that the camera being used is well standardised to the desired image. This standardisation also aids comparison of images between different users. The choice of camera presented in journal articles might change from one year to the next due to the rapid technology development in the camera world. Therefore, as long as basic camera principles and similar standard protocols are applied, one should be able to control the outcome of the photographs. The quality of the image obtained depends on the settings of the camera for each image. Table 4.1 shows basic photography principles that will influence the quality of images.

Table 4.1: Camera properties

Aperture	Aperture refers to the opening of the camera lens which controls the amount of light entering the camera. This component helps to determine the end exposure time and affects the depth of field of the image.
Depth of field	Depth of field determines the sharpness of different areas from the same object or sharpness of multiple objects.
Exposure	Exposure affects the appearance of the image in terms of the amount of light that reaches the sensor. A correctly exposed image requires a good balance of the control of light entering the camera.
F/number	F/number specified the size of the lens opening, which may range from 1 to 32. As the f-number increases, the opening of the lens aperture decreases, and the amount of light transmitted towards the lens is doubled.
Focusing system	Steady hands and the ability of the operator to focus accurately to the desired object ensure the sharpness of the image. The use of a copier stand, which holds the camera in place, eliminates the possible effect of 'shaky hands'. The lens may also be set to manual focus, so that the operator is able to focus on the area of interest.
Shutter speed	Shutter speed refers to the length of time that the camera sensor is exposed to light. The higher the number i.e. the faster shutter speed used means less light entering the camera. This affects the sharpness of the image.
ISO	ISO determines film sensitivity to light, colloquially known as the *speed* of the film. Unlike traditional film, ISO in digital cameras is determined electronically by the sensor. As a rule, the lowest ISO for the camera should be chosen to eliminate grain or 'noise'.
Focal length	The focal length of a lens determines its angle of view. This largely depends on the type of camera. Whilst this is not crucial as the use for current research does not require for large magnification of image.
Temperature	Temperature of camera light can be expressed as a Kelvin temperature. The white balance setting in the camera will determine the colour of the image. For the image shooting under a white fluorescent lamp, mostly in the office (which is the set-up for this current research) a temperature of 4200K was used.

The 2D imaging system used in this study was adapted from the system described by Brook et al., (1999).

The system, shown in Figure 4.1, was comprised of:

1. Canon EOS D50 digital camera with a 55 mm lens *(Canon Inc, Tokyo, Japan)*
2. Computer (*Lenovo)* or laptop (*Fujitsu)* directly attached to the camera
3. Copy stand attached with adjustable lighting *(Kaiser, Odenwald, Germany)*
4. *Model clamp with a universal joint*
5. Vertically adjustable table.
6. Levelling apparatus
7. ABFO ruler (*Powder Lightning Powder Company, Inc., Jacksonville USA)*

All images were captured remotely from the computer using Canon EOS digital utility software and stored in RAW and JPEG format. RAW format images were stored in their original form in external storage to ensure preservation of the original data. Image analyses were performed in the JPEG format, using ImageJ software (NIH, 2009).

Several photos, utilising different camera settings, were taken to determine the final format. Criteria to ensure good quality images included:

1. Ruler and dental cast were in focus.
2. All three circles on the ruler were visible.
3. No signs of over or underexposure.

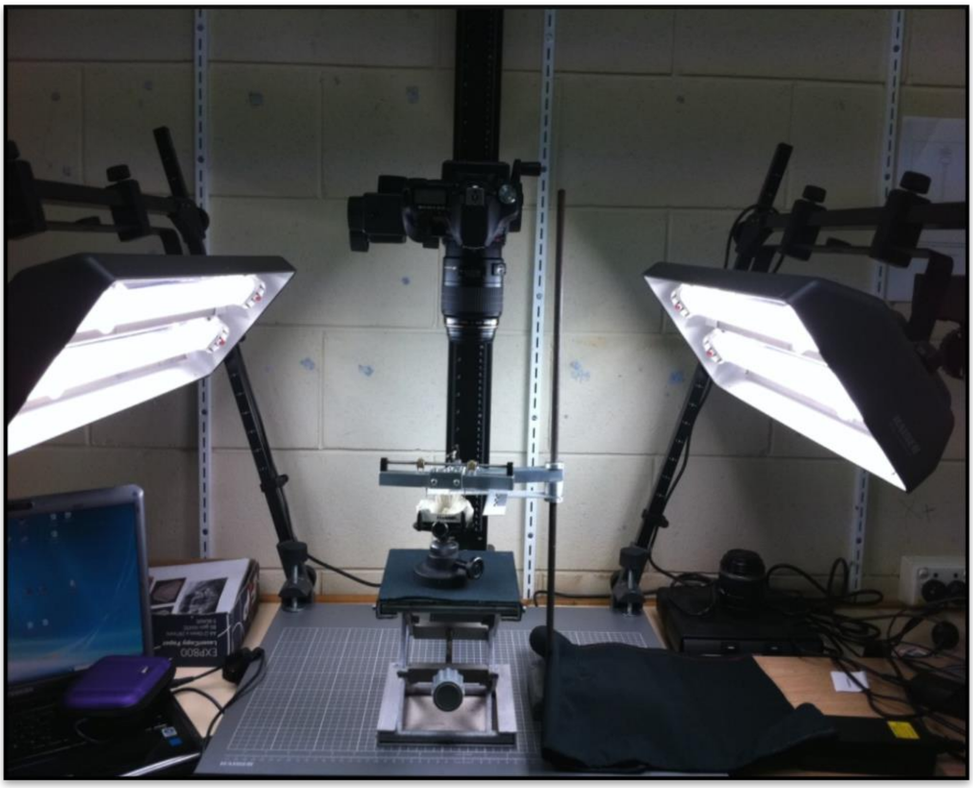


Figure 4.1: Photographic set up

Table 4.2 shows the camera settings used for this study.

Table 4.2: Camera settings employed for this research

F-stop	F22
Exposure time	1/20
ISO speed	100
Focal length	55
Temperature	4200K

4.1.2.2 Calibration

In order to avoid systematic errors related to the use of the equipment, a series of calibrations was performed. Optical distortion in any of the equipment is a source of error. Depending on the particular type of distortion, the resulting errors will be more or less variable. Measurements of calibration grids can show such distortions. Measurement of the same specimen in different orientations (e.g. rotated in the field of view) also should produce identical results. Figure 4.2 shows the United States Air Force (USAF) calibration grid used to evaluate camera resolution for measurements.

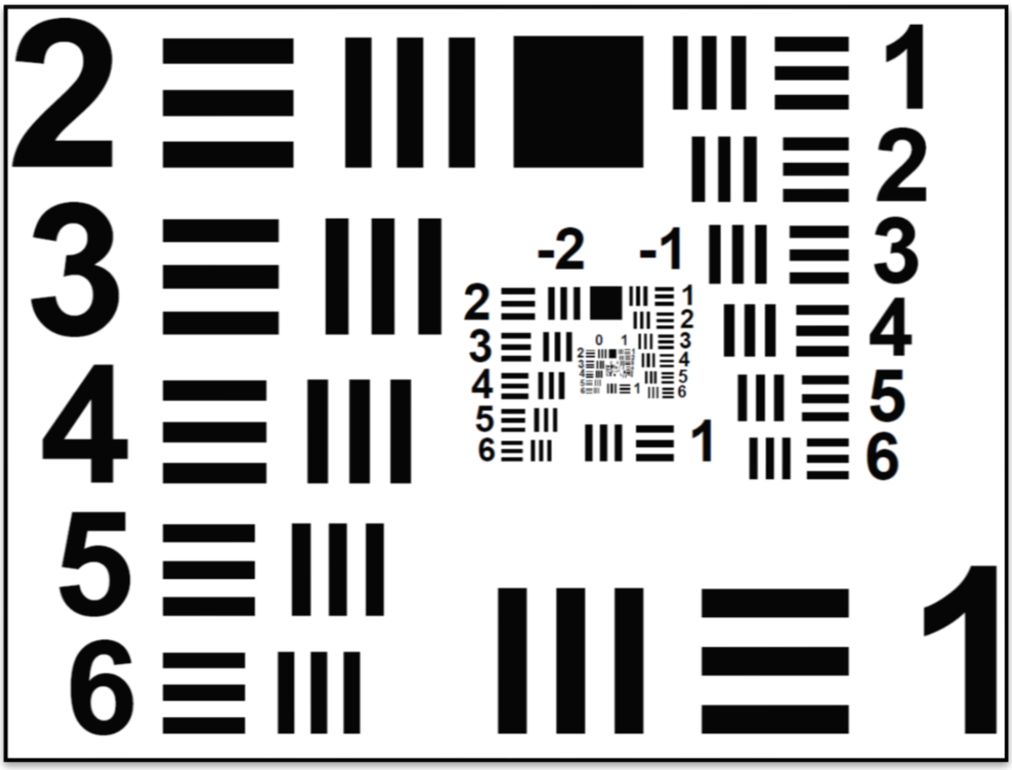


Figure 4.2: USAF calibration grid

Because specimens are usually measured in a consistent position (e.g. images of dental casts are obtained from the occlusal perspective), this effect will normally result in a consistent deviation of the measurements from the true values. This distortion may be compounded by difficulties with the positioning of specimens. Great care should be taken to align the dental casts with the focal plane of camera.

For this research, initial calibration was done using the grid shown in Figure 4.2 to determine the optimal distance between the camera and the dental cast.

4.1.2.3 Reference point selection for photographs standardisation

The choice of appropriate landmarks is an important consideration in any quantitative analysis. Amongst the many issues to consider are accuracy, reproducibility, efficacy and effectiveness. Quimby et al., (2004) defined the last two attributes (efficacy and effectiveness) as the ability of a procedure to give a favourable outcome under ideal conditions and normal condition for the latter. Therefore, to ensure that captured images of the dental casts possessed the above attributes, landmarks were chosen to ensure that all dental casts were orientated to the same reference plane by utilising a levelling apparatus. By doing this, all photographs of the dental casts were standardised. The landmarks that were chosen were the central fossae of the left and right first molars and the incisal edge of right or left central incisors.

4.1.2.4 Standardising photographs of dental cast

To ensure consistent alignment of all dental casts used in the project, a joint collaboration with the Faculty of Engineering at the University of Adelaide resulted in development of a levelling apparatus. This allowed standardisation of the 2D images by eliminating subjective orientation of the dental casts. This was achieved by developing an apparatus that could assist in positioning reference points on the dental casts (to create a fixed reference plane). The scale used as a reference for measurement was positioned at the same plane as the reference plane created on the dental cast. The distance from the scale to the camera lens was fixed at all times. The apparatus is shown in Figure 4.3. It consisted of a T-shaped aluminium frame with three adjustable tips. These tips were placed on the central fossa of upper left and right first molars and the midpoint of the right or left upper central incisor edge. These adjustable points allowed fine movement of the tip to permit the operator to place the tip in the designated position. The apparatus was orientated so that it was always parallel to the camera lens and checked by means of a spirit level placed on the apparatus stand.

Each dental cast was placed on a cast surveyor model clamp and adjusted by using its universal joint mechanism until all three tips contacted the reference points. The clamp was placed on an adjustable table so that it could be moved vertically, as required.

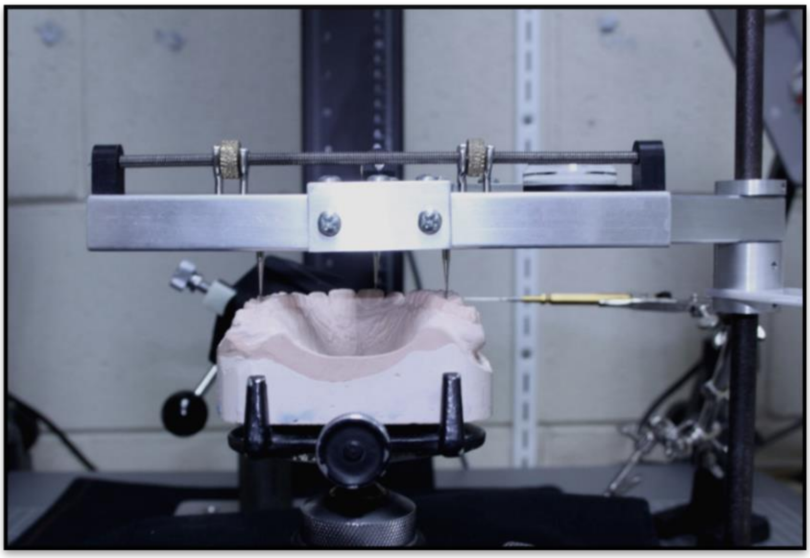


Figure 4.3: Levelling apparatus

Once each cast was correctly aligned the positioning apparatus was swung away so that only the cast and the scale were captured in the photograph. Each dental cast was subjected to one occlusal view photograph for analysis.

An ABFO No. 2 ruler, commonly used in forensic photography, was utilised as the reference scale. This ruler incorporates three circles (indicated as red circles in Figure 4.4) which are useful in helping to identify and compensate for distortion resulting from oblique camera angles. Measurements within the image are then made relative to the inscribed 1cm grid lines to compensate for distortion resulting from non-parallelism between the film and object planes. This ruler is constructed from "L" shaped laminated plastic 1mm thick. The mm markings are accurate to 0.1mm on the inner edges. The ruler was positioned parallel to camera lens and at the same level as the designated reference plane on the dental casts.

Figure 4.4: Example of a dental cast photo taken with ABFO No 2 ruler

4.1.3 Imaging, three-dimensional

The reliability of using three-dimensional (3D) imaging as an alternative to direct measurement of dental casts or 2D imaging has been studied extensively by many researchers (Nouri et al., 2009; Smith et al., 2009b). The focus in this area of research has been mainly in the orthodontic discipline as it is vital in this branch of dentistry to perform correct measurements for diagnosis and treatment planning.

As a powerful tool to visualise many objects, 3D imaging gives researchers involved in studying human phenotypes the opportunity to increase their understanding of variation. It allows researchers to perform various observations and measurements of a virtual dental cast as if it was real and at the same time preserve the information obtained in a quantitative format.

In forensic dentistry the use of 3D images allows preservation and association of evidence, as well as the opportunity to improve the presentation of evidence in Courts of Law. Members of the Court will be able to appreciate the detail of objects compared to two-dimensional photographs.

Many types of devices for measuring coordinates in 3D are available. Most of these are substantially more expensive than 2D imaging equipment, and will therefore be more restricted in their use than 2D imaging. Moreover, 3D analyses are inherently more difficult, particularly in terms of the graphical presentation of results.

Generally, 3D scanners can be divided into contact and non-contact scanners. A non-contact 3D scanner is usually preferable as it will reduce the risk of damaging the object that needs to be scanned (Bachrach et al., 2010). There is a range of 3D technology in each of these groups of scanners.

The most widely-used type of devices for 3D measurements uses a stylus with which the observer points to the landmarks on the specimen. The device then records the location of the tip of the stylus. This principle is used for digitising arms, where the stylus is at the tip of a movable arm, and the position is computed from the angles at the various joints of the arm (e.g. the Microscribe). Other types of digitisers have a stylus that is not attached to a solid structure such as an arm, and can be moved more freely. For these devices, the location of the stylus is recorded by electromagnetic or acoustic means. This type of device is particularly useful for specimens of medium or large size.

Another class of devices use optical scans of the entire surface of an object. This is done by projecting a laser beam (laser scanners) or a series of grid patterns (interferometry) on to the specimen and recording the image with a digital camera. The positions of a great number of points on the surface are then used to reconstruct the object (Hennessy et al., 2002). These devices are available for scanning objects from the size of a single tooth to entire buildings. For instance, specialised scanners for human faces can take a 3D image of a face in less than a second, so that the experience for the subject is similar to having a passport picture taken; accordingly, these devices are more and more frequently used in medical research.

In dentistry, two widely recognised scanners utilise either laser or white light technology. Each technology has its own advantages and limitations. Laser has wider application potential in terms of its flexibility in scanning a wide range of objects. White light technology, on the other hand, has the ability to scan an object faster when compared to a laser scanner.

Together with the hardware, various software used for image analysis is available in the market. It depends largely on the interest of the end user as to choice of the software that may be of most benefit to them.

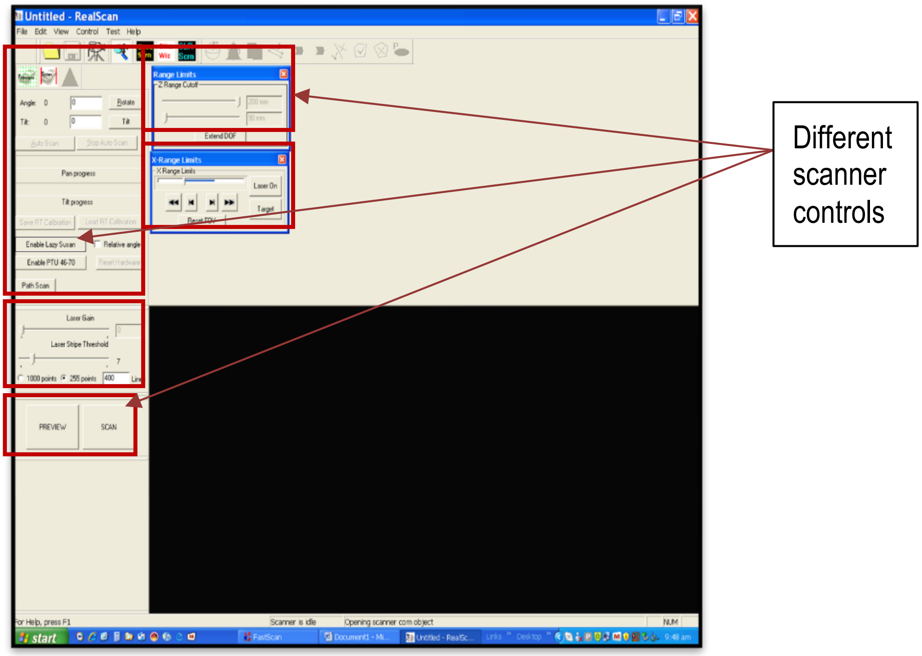
Finally, computed tomography, based either on X-ray or magnetic resonance, reconstructs not only the surface of a specimen, but its full volume including internal structures (Spoor et al., 2000). It therefore provides substantially more information than the other approaches, but is also the most expensive technology of those discussed here. This approach has been routinely used in medicine for many years, and is becoming more widely available in other research areas as well. Objects of any size, from insects to dinosaur skulls, can be scanned at high resolution and analysed in their full three-dimensional structure. Moreover, as the sensitivity of the sensors increases and scanning times reduced, it has become more feasible to use this technology even for live organisms, so that longitudinal studies of growth in 3D are feasible.

Technology is making rapid advances in this area, and it is likely to become still more powerful and also more affordable in the next few years. Therefore, it is to be expected that the proportion of morphometric studies using 3D data will increase further in the near future.

The 3D scanner utilised in this research was an Optix 400S laser scanner (*3D Digital, Connecticut, USA)*, shown in Figure 4.5. The scanner allows 3D image acquisition with a high accuracy (up to 50 µm). The scanner was controlled using a Microsoft™

Windows® XP based personal computer. Dedicated software, Slim 3D (*3D Digital, Connecticut, USA)*, provided with the 3D scanner was used to control the scanning process, cleaning and registration, aligning and merging. Different scanner settings were controlled to ensure the best quality 3D images were produced for the research project. Multiple series of scans were conducted to choose a standard setting for all scanned images.

Figure 4.5: Optix 400S laser scanner



Angle: 0
Tilt: 0
Z Range Cutoff: 200 mm, 90 mm
Laser Stripe Threshold: 7
○ 1000 points ● 255 points 400 Lines

Figure 4.6: Scanner controls for optimum 3D images

Figure 4.6 shows the scanner control settings. Arrows indicate the different features of the scanner that can be adjusted to produce a high quality 3D image. Optimum depth of field (DOF) of Optix 400S is between 100-200 mm and point density 1000 points per stripe, up to 1000 lines. Standard deviation of the measurement is ± 15 microns @100 mm. DOF is a range or distance between the object and the scanner which the 3D laser scanner can obtain an accurate image. Therefore, any scanning carried out beyond the DOF will result in a less accurate image. Field of view adjusted through limiting the 'X-range limit' will determine the starting point of the laser and the end point of that laser. A reference point 'marked' with Blu Tac was placed on the rotary table to determine the placement of the study cast once this range limit has been set. Point density is distance between neighbouring range measurement points that confirmed by the number of scan lines. 'Path scan' referred to the angle on X and Y axis that the rotary table will turn to position the study cast. A pre-determined path scan was loaded onto the software for automatic movement of the rotary cast (eg: X = 30° Y = 20° means the rotary table will turn 30° clockwise and tilted 20° up.

The high-resolution setting can be selected to capture detailed area of the objects but requires more time (up to two hours, depends on selected objects), while low-resolution setting allowed scanning process to be completed faster (up to 10 minutes for the whole process). For this study, high-resolution setting was used by choosing the point density setting of the scanner to maximum points (1000) with maximum lines (1000).

Table 4.3: Scanner settings

Laser gain	**0**
Laser striped threshold	10
Resolution	1000 points , 1000 lines
Path scan	Pre-loaded with 12 movement angles

Table 4.3 shows the scanner settings used for this research. All measurements for dental crown and arch size were performed in both 2D and 3D images and comparisons between these two techniques were undertaken.

4.2 Analysis of images

The characteristic of a laser scanner is that it can only capture the surface of the object that had been positioned within its field of view. Therefore, a number of scans taken from different angles were needed to acquire a complete image of the object.

The Slim 3D (*3D-Shape, GmbH, Erlangen, Germany*) software which was supplied with the scanner controlled the scanning process and can be used according to operators needs. All separate scan files were processed by the scanner software through three main steps of aligning and merging including cleaning and registration. Depending on the need of the scanning, different resolution setting can be chosen. In order to produce high quality images, the high-resolution setting was selected (by choosing the point density setting of the scanner to maximum points (1000) with maximum lines (1000)) to capture the dental casts with very high detail. However, this requirement subjected to a more post scanning process time (aligning, merging, cleaning and registration). The timing can be up to two hours.

The resulting combined images can be stored as pmh, stl and obj files. These files are triangulated point clouds where three points are lined together to create a face or surface. The pmh files are specific to merging and aligning software.

All scanned images were exported in three file types (STL, pmh, obj). The reasoning behind producing three different output file types was to accommodate future needs of storing and image processing. STL is a universal 3D file type that can be imported to most of 3D software platform.

Images were analysed using Rapidform Explorer (*INUS technology Inc and Rapidform Inc, Seoul, Korea*). Measurements that were performed on the 3D images were also compared to the measurement made using the corresponding 2D images. For 3D images, the dental cast images were positioned on-screen to mimic the standardisation process used in 2D imaging. All measurements obtained from the 3D images were recorded as direct linear distances between landmarks rather than following the contours of the crown shapes. Whilst this approach limits the potential of 3D imaging, it was used to enable comparable analyses between methodologies.

4.3 Samples

4.3.1 Ethical approval

This research was part of longitudinal studies of dental development in Australian twins and different ethnic groups. The study has been approved by the Human Research Ethics Committee, University of Adelaide (Project No: H-07-1984A) 'Dentofacial variation in twins: genetic and environmental determinants' and (Project No: H-09-2-2002) 'Dental variation in Malaysian populations with application to human identification' and for Australian Aboriginal materials as an extension of a previous project for which ethics approval was obtained from the University of Adelaide Human Research Ethics Committee (H/079/06).

4.3.2 Study design and location

This research project is a retrospective cross-sectional study designed to compare the dental crown size, dental arch size and dental arch shape of the permanent dentition from six population groups to understand variations between these groups.

The study was conducted in the Murray J. Barrett Laboratory, School of Dentistry at the University of Adelaide. This laboratory houses a wide collection of dental casts of twins and singletons from the Australian population, and of other ethnic groups, which has been collected for ongoing research projects conducted by the Craniofacial Biology Research Group. For the present research project dental casts of Australian twins, Australian Aborigines and Malay (Jahai) were utilised. Analyses of the dental casts were performed using both 2D and 3D imaging methodologies.

4.3.3 Population classification

It is important to remember that any classification will never be perfect as there is no such thing as a pure race and the biological characteristics used are continuous in nature and subject to evolutionary forces (Relethford 2008). There is evidence of overlap between ethnic groups in terms of continuous traits and overlap of frequencies for discontinuous traits (Relethford and Harding, 2001). The classification used as a means of grouping people with similarities in physical traits, cultures and geographical areas is ‘ethnicity’ rather than ‘race’ (Montagu, 1960).

Populations can be defined by geographical, demographic, economic, and social characteristics, as well as by the content of the survey (Ilvento et al., 1986). These characteristics include country of residence, age, sex, race, marital status, etc. At the same time, defining a population too narrowly can make it difficult, if not impossible, to obtain a list of the individual elements (Sudman, 1976).

4.3.3.1 European

History and Background

The planned arrival of Europeans to Australia began around 1788 when British colonists and convicts arrived to establish the first European settlements (Lee, 1906). According to the Australian Bureau of Statistics census (2011), apart from the leading reported ancestries as being English or Australian, most Australians declared themselves as being of European ancestry.

Background of recruitment of the group

The study sample consisted of monozygotic (MZ) and dizygotic (DZ) twin pairs enrolled in an ongoing study of dentofacial development of Australian twins and their families being undertaken in the School of Dentistry, the University of Adelaide. The group of twins utilised in this current study were selected from the second cohort, of three available cohorts. Zygosity had been previously determined by comparison of a number of genetic markers and analysis of up to six highly variable gene loci (FES, vWA31, F13A1, THO1, D21S11, FGA) on six different chromosomes by using DNA extracted from buccal cells. The probability of dizygosity, given concordance for all systems, is less than 1% (Townsend et al., 1995; Townsend et al., 2005).

Data collected for the twin study include serial dental casts of primary, mixed and permanent dentition (constructed in yellow stone from alginate impressions of upper and lower arches), oral examinations, intra-oral photographs, mono and stereo photographs (Figure 4.7), palm-finger prints, blood and cheek cells for zygosity determination, medical history and laterality tests as well as other information such as a questionnaire of families and family environment. The lists of twins were arranged according to their ID and random numbers were generated to select a pre-determined required sample size. For this current research, only permanent dental casts of one of the member of each twin pairs were used for this study to represent the European group.

Figure 4.7: Example of individuals of European ancestry

4.3.3.2 Australian Aboriginal group

History and Background

The second population group included in this study consisted of an Australian Aboriginal group named Warlpiri from the Yuendumu settlement in Central Australia. The Aboriginal living at the settlement, located around 185 miles north-west of Alice Springs, were known to be of pure Aboriginal ancestry (Brown et al., 2011). Figure 4.8 shows the location relative to the town of Alice Springs. In 1946, the Native Affairs

Branch of the Commonwealth Government established this isolated place for Warlpiri Aboriginal people (Brown et al., 2011).

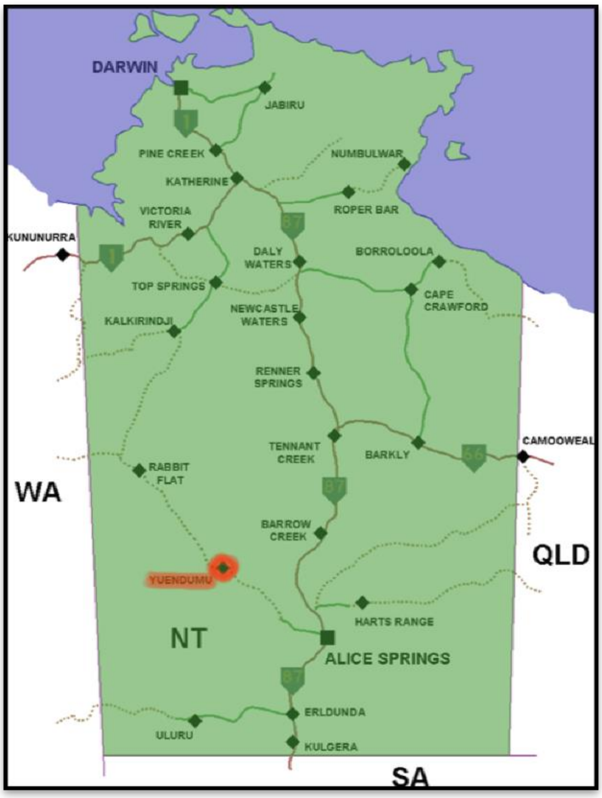


Figure 4.8: Location of Yuendumu (Source: hhhp://wiimedia.org)

Australian Aboriginal people have distinct features, including prominent mid-facial regions, which tend to differentiate them from other ethnic groups. Whilst, in general, they physically might resemble the ‘Negroid’ group, there are other features that cause anthropologists to separate them from the ‘Negroids’ and classify them as ‘Australoids’ (Townsend et al., 1990). Facial features can be seen in Figures 4.9 and 4.10.

Data for this group, including a large pool of dental casts and radiographs, were collected as part of a longitudinal study between the years 1960-1970. This collection has been the source of many research projects conducted over the ensuing decades (Brown et al., 2011). For the purpose of this current research, the selected dental casts were those with complete sets of permanent teeth (e.g. if an individual was represented by a series of dental casts from the age of 8-18, only the dental cast at the age of 18 was utilised in this research).

The lists of samples were arranged according to their ID number. Random numbers were generated to select a pre-determined number of subjects consisting of equal numbers of males and females.

Figure 4.9: Example of male Australian Aboriginal

Figure 4.10: Example of female Australian Aboriginal

4.3.3.3 Malaysian group

Malaysia is known for an array of ethnicities (Salleh, 2007). This population diversity has led to many research studies looking at diverse phenotypic variation, whether between individuals specifically or between different ethnicities generally.

History and background

Ethnic diversity in Malaysia

The multi-ethnic society of present day Malaysia largely resulted from the era of British colonisation, particularly in the late 19th and early 20th centuries. There are approximately 23 million people living in Malaysia (World Bank, 2009) of whom 55% are Malays, 26% are Chinese, 7.7% are Indians and less than 1% are Orang Asli. The native people of Malaysia, called Orang Asli in the Malay language, live in a new settlement area developed by the Malaysian Government through the department of Orang Asli affairs. The term Orang Asli is used to refer to 18 tribes from three larger groups totalling 92, 523 people (Pusat perkembangan kurikulum, 1998). The three groups are Negritos, Senoi and Proto-Malays (Carey, 1976). Each of these groups has its own language and culture and is distributed in different geographical areas of the Malaysian Peninsula.

Figure 4.11: Map of Malaysia showing 14 states
(Source: http://www.dromoz.com)

Malays

The term Malay was initially a self-reference used by the people inhabiting the Malay archipelago. Subsequently traders from South Asia and China used it as a social label. By the 16th and 17th centuries, Malay and 'being Malay' were associated with three major elements: a line of kingship, Islam as a religion and use of the Malay language (spoken and written), as well as practising Malay customs such as type of clothing and culinary practice (Salleh, 2007).

Chinese

The geographic, economic and and social patterns of Chinese immigration and settlement have been shaped by common geographic and linguistic origins in China. Chinese immigration to the Malaysian Peninsula peaked between the 1860s and 1930s. Chinese immigrants came from South-East China, Kwangsi Gukien and

Kwangtung Provinces. According to Salleh (2007), Chinese constitutes the second largest ethnic group in the country, making up over 24% of the population.

Indians

Indian merchants traded in the Malay Archiepilago as early as the first century. However, it was only in the 19th and 20th centuries that large numbers of Indian migrants, mainly from South India, arrived on the Malaysian Peninsular. Many were brought in as indentured labour, primarily to work in the rubber plantations (Salleh, 2007).

Orang Asli

Orang Asli are indigenous to Malaysian Peninsula and are believed to have occupied the land as early as 25,000 years ago. The early Orang Asli mostly lived in remote communities within specific geographical areas. They identified themselves by their ecological niche. Much of their culture and and spirituality was derived from their close association with the environment. With a total population of 133,775 in 2000, the Orang Asli comprise at least 18 subgroups distinguished into three categories: Negritos, Senoi and Proto-Malays; based on physical characteristics, linguistic affinities and cultural practices. There are several opinions regarding the origins and history of Negritos on the Malaysian Peninsula. It has been proposed (Salleh, 2007) that these people are the descendants of Australo-melanesoid population in Malaya and Indonesia, who were later replaced by Malays from Indonesia. The period of replacement was estimated to have occurred before the late Neolithic era.

Figure 4.12: Examples of Malaysian Malay, Chinese and Indian

Nagata (1979) reported that difficulties arose as there was a sex-ratio imbalance within the immigrants (more males than females), and there was pressure for inter-racial marriages with locals to take place. Even in today's Malaysian society, inter-racial marriages still occur between ethnic groups. The various Malaysian groups show differences in facial features, as seen in Figure 4.12.

This study utilised dental records previously collected for the purpose of other research (Khamis, 2005). Dental casts and other records of Malays, Chinese and Tamils were collected from secondary school children in Kelantan State (Kota Bharu, Kuala Krai and Tanah Merah) and Perak State (Ipoh). Records for the Orang Asli were collected from the new resettlement plan air banun, Banding Perak. The Orang Asli who participated in this study belong to the Jahai Tribe (subgroup of Negritos) who are only found in the northern part of the Malaysian Peninsula.

4.3.4 Selection criteria

Inclusion criteria used for all the samples were as follows:

1. Children that are healthy with no history of congenital craniofacial anomalies
2. No history of craniofacial treatment
3. No history of mixed marriages for the past three generations
4. Intact dental casts with no evidence of flaws in the cast that could obscure the features observed or measured.

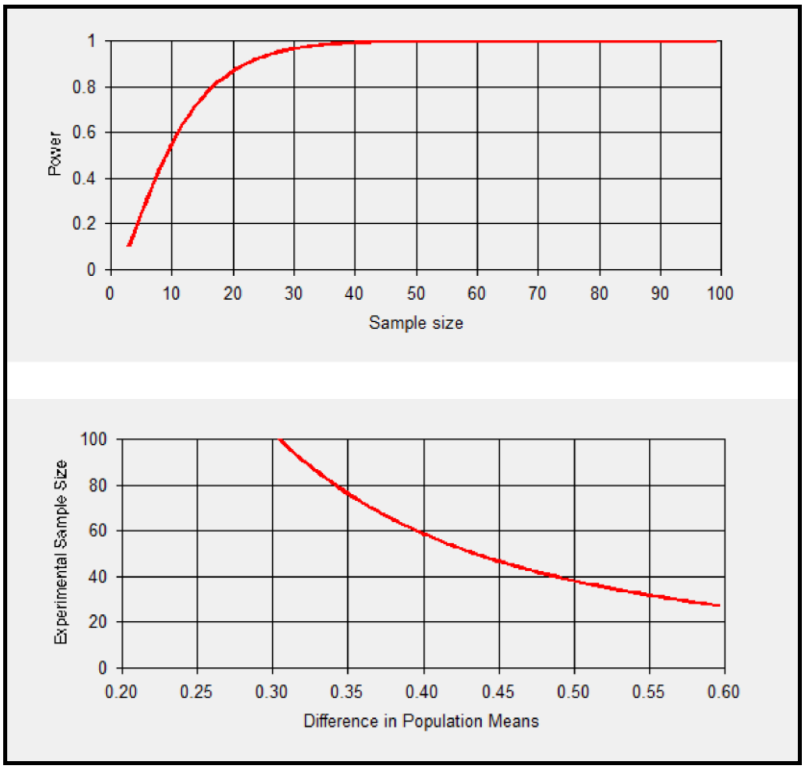
Subjects were selected primarily based on the quality of their study models. These study models were chosen from the various collections based on the criteria shown in Table 4.4.

Table 4.4: Inclusion and exclusion criteria

Ethnicity:	Selection of subjects was based on labeled study model collected for previous research. Based on a sample size calculation, study models of Europeans, Australian aboriginals and Malaysian samples were included.
Sex:	For each group, both male and female subjects were equally selected.
Age:	Study models taken during the age of permanent dentition (12 – 18 years old) were included.
Orthodontic treatment:	Subjects without prior history of orthodontic treatment were included.
Occlusion type:	No selection of particular dental occlusion/malocclusion or a particular skeletal pattern was made.
Study models:	Good quality study models were included for all subjects; thus, any defective study models were excluded.

4.3.5 Sample size

According to Israel (2009) there are several factors, which may be useful in determining the sample size required for a particular study. He highlighted the factors as follows: the purpose of the study, the size of the population, the risk of selecting a bad sample and the possibility of sampling errors. In addition, Miaoulis and Michener (1976) added others to help determine the sample size, including: level of precision, level of confidence risk, and degree of variability in the attributes being studied. Figure 14.13 shows the calculation of sample size for comparison of dental crown measurements between males and females based on an independent t-test for this study.



Alpha = 0.05, sigma = 0.50, design = independent, power = 0.99

Figure 4.13: Sample size estimations

In a previous study (utilising 100 subjects) with similar variables, the measurement values within each subject group were normally distributed with a standard deviation of approximately 0.5. If the true differences between two groups were 0.5, then the ability to reject the null hypothesis that the population means of one group to the other are equal with a probability (power) of close to 1.0. The Type I error probability associated with testing of this null hypothesis was 0.05.

The size of the sample used in the present study was similar to a previous study looking at similar variables but utilising calipers for measurement (Khamis, 2009). Previous studies comparing control and experimental groups which employed linear measurements utilised around 100 subjects (Brook et al., 2002, Ai-Shahrani et al., 2012). Brook and his colleagues (2002), for example, suggest that a comparison between two groups of 20 will give an 80% power to detect a size difference of 0.90 mm. They found that it is reasonable to expect size differences of this magnitude.

Table 4.5 shows demographic data of the study population. Six population groups were analysed: Europeans, Australian Aboriginals, Malaysian Malays, Chinese, Indians and Orang Asli. In total, around 600 study models were utilised in the study. The subjects were distributed almost equally among the groups, each group representing 15% (~100 subjects) of the total sample. The proportion of female to male subjects in each group was also equal: 50% (~50 subjects) of each sex.

Table 4.5 Demographic data of study sample

Population group	n	Age
European	134	14.8 ± 2.0
Australian Aboriginal	103	17.4 ± 3.7
Malay	110	16.4 ± 0.8
Chinese	101	14.8 ± 1.5
Indian	113	15.8 ± 1.4
Orang Asli	51	26.5 ± 8.5

The age range of the subjects was between 12 – 18 years. This age group was selected as only permanent dentitions were utilised (from central incisors to first molars). The ages were recorded based on the time of the impression. The average age for the whole sample was 15.8 years, with a standard deviation of 1.88 years. The Orang Asli group has a greater age due to limitations in selection of subjects during sample collection. The homogeneity of age range should help in the comparison process as progression of age may affect the normal morphological features of teeth.

4.4 Dental variables

Dental variables that have been frequently used in similar research were reviewed and findings from a pilot study conducted during the initial research phase noted, to determine which dental features seemed to discriminate best between individuals. It was also important to ensure that the dental variables chosen for the research were biologically meaningful.

These dental features were generally categorised into two groups:

1. Features related to individual teeth, i.e. size and shape
2. Features related to dental arches, i.e. inter-canine and inter-molar width

In the initial phase, several metric traits were observed and recorded. The main purpose during this stage was to detect any issues associated with locating different reference points for measurement to prevent those problems from arising in the next phase of the study (which was measurement through means of photographs).

4.4.1 Metric measurement

Linear measurements, based on defined landmarks, are commonly used in anthropological research (Hanihara and Ishida, 2005; Hanihara, 2010). For this study both tooth size and arch size were considered.

4.4.1.1 Tooth size

The tooth-size variables that were measured were maximum mesiodistal (MD) and buccolingual (BL) crown diameters.

The mesiodistal (MD) diameter from the occlusal view was defined as the maximum distance between the approximate surfaces of the crown, taken parallel to the occlusal plane for posterior teeth and incisal edge for anterior teeth. In cases where a tooth was rotated or positioned out of the general curvature of the dental arch, the measurement was obtained at the point where it would normally occur. For molars, these measurements were guided by following the central fissures of the tooth (Moores, 1957). Figures 4.14 and 4.15 illustrate the measurements described above.

Figure 4.14: Example of MD and BL measurements on 2D image

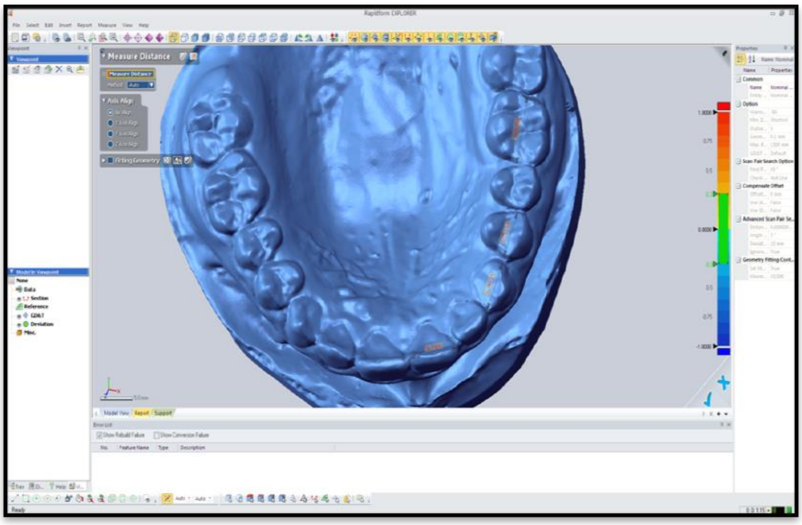


Figure 4.15: Example of MD and BL measurements on 3D image

Buccolingual (BL) diameter was recorded as the maximum diameter of the crown at right angles to the mesiodistal diameter (Moorrees 1957).

The method of measuring dental crown size was utilised for both 2D and 3D images. However, due to the time required to obtain the 3D images, the size of samples used for 3D data was smaller than the samples used for 2D data. Only 35 dental casts from each population group were scanned for 3D images.

4.4.1.2 Dental arch size - arch width

Arch width refers to the distance between two corresponding teeth in the left and right quadrants. In this study, all distances between every tooth from central incisors to first molars were measured (inter central incisors, inter lateral incisors, inter-canine, inter-first premolar, inter second premolar, inter-molar). For incisors, a point on the middle of the incisal edge was used as the reference point. For canine and premolars, the cusp tip on the canine and cusp tips on the buccal cusp of premolars were used as the reference point. For inter-molar distance, the mesiobuccal cusp tips were used as the reference points (Corruccini and Potter, 1980). Where there was evidence of wear facets on the cusp tips, a point was selected at the centre of that wear facet (Moorrees, 1959).

4.4.1.3 Arch shape

The reference points use to measure arch breadth were also utilised to document landmarks to measure arch shape. Details on the methods to quantify arch shape will be discussed in the following section.

4.4.2 Geometric Morphometric Analysis

4.4.2.1 Documenting coordinates

The majority of morphometric studies use configurations of landmarks that can be located precisely on each specimen and correspond between specimens. For Geometric Morphometric Analysis, ideally sample size should be at least twice as large as the number of landmarks for configuration (Zielditch et al., 2004, Klingenberg, 2011). The number of samples utilised for this study was large enough to fulfil this criterion (Klingenberg, 2011).

4.4.2.2 Landmarks descriptions:

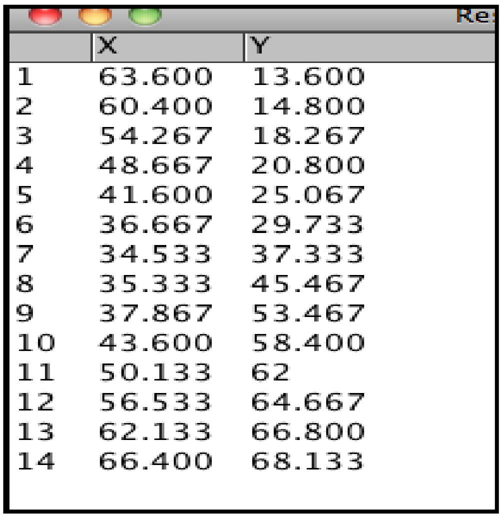
For the purpose of studying dental arch, a total of 14 landmarks were recorded using ImageJ software. These landmarks are shown in Figure 14.16 and described in Table 4.6. In cases where there was evidence of wear on the cusp tip, the landmarks were placed centrally within the wear facet.

Figure 4.16: Coordinates selection

Table 4.6: Landmarks for Geometric Morphometric Analysis

Tooth (FDI notation)	Reference Point
16	Distobuccal cusp tip
16	Mesiobuccal cusp tip
15	Buccal cusp tip
14	Buccal cusp tip
13	Buccal cusp tip
12	Central point on incisal edge
11	Central point on incisal edge
21	Central point on incisal edge
22	Central point on incisal edge
23	Buccal cusp tip
24	Buccal cusp tip
25	Buccal cusp tip
26	Mesiobuccal cusp tip
26	Distobuccal cusp tip

ImageJ recorded these landmarks as x and y cartesian coordinates (Figure 4.17). These values were then transferred to a Microsoft™ Office Excel® spreadsheet and arranged in the following format, x1,y1,x2,y2,…………x14,y14. Figure 14.16 illustrates the coordinate format.



```
      X        Y
1     63.600   13.600
2     60.400   14.800
3     54.267   18.267
4     48.667   20.800
5     41.600   25.067
6     36.667   29.733
7     34.533   37.333
8     35.333   45.467
9     37.867   53.467
10    43.600   58.400
11    50.133   62
12    56.533   64.667
13    62.133   66.800
14    66.400   68.133
```

Figure 4.17: Example of coordinates of landmarks used for dental arch shape analysis

The Excel® spreadsheets were then converted into a Tab delimited file and used to create the data sets for subsequent analysis by MorphoJ software (*The Apache Software Foundation, USA)*.

4.5 Statistical analysis

All statistical analyses were carried out using SPSS Version 19.0 (*SPSS Inc., 2011*).

4.5.1 Normality testing

Normal distribution, which is usually referred to as a bell curve or Gaussian distribution, is one descriptor of the distribution of data. This distribution, which is essentially a symmetrical bell shaped distribution, is displayed by many biological variables. If data follow such a distribution, they can be represented using common statistics such as the arithmetic mean and standard deviation. All variables measured and scored in this study were examined for normality.

4.5.2 Outliers

The presence of outliers can affect the final outcome of a test. However, in certain situations, a few individuals that could present with a value that is distant from the majority in the distribution could also be a subject of interest for identification purposes, suggesting that they possess a peculiar feature. For example, a person with peg-shaped lateral incisors would significantly affect the mean of mesiodistal and buccolingual dimensions relative to the group. For forensic identification purposes, this particular person will be considered to have features that may discriminate him or her from the rest of the group. However, in order to get a result that is a normal representation of a population, these outliers were excluded from the analysis.

Cleaning the data allows for detection of certain frank errors of measurement. This was done by measuring z-scores with the following formula:

$$\text{z-score} = \frac{x - \bar{x}}{SD}$$

x = individual measurement, $\bar{x}$ = sample mean, SD = standard deviation

Cases where the z-score was larger or smaller than three were checked for frank errors that may have occurred during measurement acquisition or data management.

4.5.3 Measurement error

In this study, several levels of assessment were carried out in order to minimise and quantify error. There are two important aspects of error measurement that should be considered, validity and reproducibility. Measurement also needs to be precise or accurate. Validity is influenced by the methods employed. In this study, the methods employed for both two- and three-dimensional measurements were assessed to ensure both image capture and landmark locations were valid.

4.5.4 Reliability and reproducibility

For measurements undertaken using dental casts, in order to ensure the measurements could be reliability measured at different times by different operators, a standard protocol was planned. This included choosing stable reference points to measure all variables in all samples. Therefore, any issues (e.g. dental caries) that prevented standard measurement were avoided. Inclusion and exclusion criteria were highlighted previously in the section describing the samples.

Reproducibility factors were assessed by comparing inter- and intra-observer measurement. All dental casts that were selected were measured twice two weeks apart by the same operator to assess intra-observer error. Another trained operator was employed to measure the same variables on 50 dental casts to assess inter-observer error.

Systematic errors or bias may arise from the limitations in the materials or methods employed. If particular measurements are persistently over- or under- measured, systematic error is predicted to occur. This type of error could be introduced by a number of sources, and one of them could be caused when the examiner unintentionally changes the measurement approach due to fatigue. Random errors are accidental errors that may result from difficulty in locating landmarks or random issues that occur during image acquisition. This may be caused by the quality of the images obtained, or the condition of the dental cast, where landmarks may not be clear in photographs. Both of these errors were reduced by ensuring that the photographs and 3D images were obtained using a standardised technique.

4.5.5 Statistical tests

Paired t-tests

Paired t-tests were utilised in order to compare means of repeated samples.

$$t = \frac{\bar{d}}{SE\bar{d}}$$

$\bar{d}$= mean difference between repeated measurements, SE $\bar{d}$ = standard error of the mean difference between repeated measurements

Dahlberg's statistic

Dahlberg's statistic (Dahlberg, 1940) or the technical error of measurement (Cameron, 1984) was used to determine the magnitude of random error in the recorded measurements.

$$S_e = \sqrt{\frac{\sum d^2}{2n}}$$

d = difference between repeated measurement, n = number of double determinations.

Descriptive statistics

Descriptive statistics, including mean values ($\bar{x}$), standard deviations (SD) and coefficients of variation (CV) for all metric measurements were computed.

The arithmetic mean of n observations was calculated as follows:

$$\bar{x} = \frac{\sum x}{n}$$

$\bar{x}$ = mean, n = sample size, $\sum x$= sum of all data points

The standard deviation was used to describe how the data were distributed around their mean.

$$\text{SD} = \sqrt{(\frac{1}{n-1}) \sum(x - x)^2}$$

Coefficients of variation

The coefficient of variation (CV) was used to quantify relative variability and enable comparisons of variation between different variables with different mean values or underlying scales.

$$\text{CV} = \frac{SD}{\bar{x}}(100)$$

Levene's Test and F-test

Prior to performing t-tests, Levene's test or test of variance ratio was carried out to compare variances between groups. An F-test was carried out in the absence of any departures from normality.

Independent t-test

A Student's t-test was used to compare means between independent groups. The level of significance was set at $p<0.05$. When comparisons of all six groups were made, analysis of variance (ANOVA) was applied.

Geometric Morphometric Analysis (GMA)

The data were processed using Geometric Morphometric Analysis (GMA). These methods provide some advantages over traditional morphometric analyses. They preserve the geometry of the object studied better than traditional measurements, and thus allow for a better analysis of shape; readily account for size correction; enable the identification of landmarks where shape differences occur and the relative levels of difference at each landmark; enable visualisation of the shape changes between specimens within the space; and, perhaps most importantly, enable the quantification of some traits that are difficult to measure with conventional measurements (Rohlf and Marcus, 1993; O'Higgins, 2000). Because of these qualities, GMA has gained widespread and increasing use in the recent literature on human variation (Harvati, 2003; Stynder et al., 2007 González-José et al., 2008).

In order to perform Geometric Morphometric Analysis, all recorded coordinates were transferred to a MorphoJ program (Klingenberg, 2011). This is the preferred and recommended software for this type of analysis because all statistical analysis can be done using one software program (Klingenberg, 2011).

Software

Geometric Morphometrics Analysis can be carried out using a number of software programs. Each software has a particular objective and can perform specific functions; data collections or multivariate analyses. These programs are freely accessible through the State University of New York. In this current study, MorphoJ (Klingenberg, 2011) and Morphologika were used to perform Geometric Morphometric Analyses (O'Higgins and Jones, 2006).

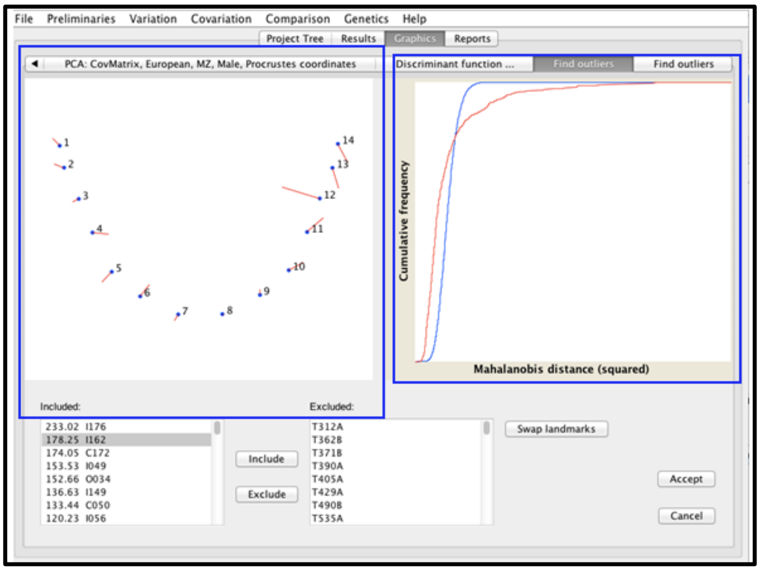
Procrustes analysis

Before coordinate data can be analysed, they must first undergo superimposition of the entire sample onto its Generalised Procustes Analysis (GPA) transformed mean configuration which brings all specimens to a common coordinate system. All specimens were scaled to unit centroid size (cs) because it is the only size measure that is uncorrelated with shape variation for small, random spherical variation at the landmarks.

Finding Outliers

Before further analyses were undertaken, datasets were checked for outliers by examining PCA scatter plots. This was done for both the total sample and within each population sample. The presence of outliers was investigated also by inspecting the vector of the Procrustes shape distances between the data of two dental arch shape and the mean shape. Outliers might represent extreme biological variation or be related to errors in data collection; if present, careful checking were undertaken as they can critically affect analytical results.

Figure 4.18 shows an interface within the MorphoJ software that dealt with finding outliers within the dataset.



Included:

233.02 I176
178.25 I162
174.05 C172
153.53 I049
152.66 O034
136.63 I149
133.44 C050
120.23 I056

Excluded:

T312A
T362B
T371B
T390A
T405A
T429A
T490B
T535A

Figure 4.18: An interface showing extreme outliers have been excluded from the analysis

The top left box contained the average shape of the dental arch represented by landmarks (marked as blue dots) and red lines that indicates the deviation of the specimen selected in the list "Included:" from the average.

The top right box contained a diagram with the cumulative distribution of the distances of individual specimens from the average shape of the entire sample. The blue curve is the curve expected for a multivariate normal distribution fitted to the data, whereas the red curve is the distribution of distances in the dataset. Depending on the relationship between the dimensionality of the data and the number of specimens in the dataset, either the Procrustes distance or the squared Mahalanobis distance is used (e.g. Klingenberg & Monteiro 2005). Procrustes distance is a measure of the absolute magnitude of the shape deviation, whereas Mahalanobis distance provides an indication of how unusual an individual is relative to the others in the sample (in larger samples).

It is accepted that many morphometric datasets do not fit well to a multivariate normal distribution. However, the pattern displayed as the red line that is stretched out to the right at the top of the diagram is a useful indicator to assess that the datasets is ‘clean’, indicating that there are one or a few specimens that deviate very strongly from the others.

Generation of covariance matrix

A covariance matrix was generated. Superimposed coordinates were analyzed statistically using principal components analysis (PCA), Procrustes distances, and Mahalanobis squared distances. The pattern of variation in the sample was evaluated through the PCA, and the similarities among specimens were assessed using inter-individual Procrustes distances (defined as the square root of the sum of squared distances between two superimposed landmark configurations).

Similarities among groups were evaluated using Mahalanobis D^2 and mean Procrustes distances between groups. The Mahalanobis statistic represents the morphological difference among groups, scaled by the inverse of the pooled withing-group covariance matrix. The larger the values of Mahalanobis distance the farther the group centroids are from each other.

Geometric morphometric methodology has the ability to describe the diversity between different shapes. Two methods are usually used to do this: principal component analysis (PCA) and Canonical Variate Analysis (CVA). PCA was used to display variation within groups while CVA was used to display differences between the groups.

Principal component analysis

PC scores are typically the shape coordinates that are used to investigate shape and allometric variation when tested by multivariate statistics (Zelditch et al., 2004). A PCA using the variance covariance matrix of the shape coordinates was performed to summarise shape variables in a small number of principal components that explain most of the total sample variance in this research. PCs can also be used to explore patterns of variation regardless of groups. If groups separate well on the first few PCs, this is a strong indication that the specimens occupy different regions of the shape space. If these differences are statistically significant, the significance value will need to be tested using multivariate tests for group differences.

In this research, a PCA was used to reduce the dimensionality in the data. The number of PCs to be retained for the statistical shape analysis was selected by measuring the correlation between the matrix of Procrustes shape distances in the full shape space and pairwise Euclidean distances in the reduced shape space (3, 6, 9 principal components, and so on). The 'elbow' in the plot suggests the minimum number of PCs that should be retained before the loss of information in the higher order PCs (which are excluded) becomes so large that it appreciably changes the relationships between specimens in the reduced shape space compared to the relationships between them in the full Procrustes shape space.

Comparison analysis

Whilst PCA is used to explore the data, other functions are used to compare data between two or more groups. For this analysis, two forms of analysis were carried out. Canonical Variate Analysis (CVA) was used to separate known groups in the data and provided an ordination that maximises the separation of the group means relative to the variation within groups. This is especially useful if the groups to be compared consist of more than two groups.

Another analysis that was carried out was Discriminant Function Analysis (DFA). This method was used to decide rules for distinguishing groups. The difference between CVA and DFA is that DFA allows the degree of separation between the groups to be quantified. The probability of correctly classifying the groups was also possible.

Multivariate analysis of dental features

One of the aims of this research was to identify population-specific variation (ethnicity, age, sex, etc.). This was done through multivariate analysis of a combination of variables. Principal Component Analysis (PCA) was used in which all variables are standardised into similar weighting, and discriminant Function Analysis, with particular emphasis on certain variables, to assist in separation of ethnic groups.

The dimensionality of a large number of variables can be reduced using a mathematical algorithm called Principal Component Analysis (PCA) (Joliffe, 2002). PCA was run to examine patterns of diversity within the groups. Due to the various parameters used to assess dental crown size and dental arch size variation, PCA was used to reduce this large number of variables to a smaller number of summary variables called principal components. Not only can the variations be visualised through this reduced principal components, samples can also be grouped according to the weighting of these principal componens (Ringnér, 2008).

Discriminant Function Analysis (DFA) was also carried out to attempt to discriminate between different groups. Discriminant Function Analysis is used to determine which continuous variables discriminate between two or more naturally occurring groups. In DFA, the independent variables are the predictors, this includes the entire dental crown and dental arch variables and the dependent variables are the population groups. This method is used to address the following question: can a combination of variables be used to predict population group membership? Several variables are included in a study to see which ones contribute to the discrimination between groups.

Discriminant Function Analysis was carried out into a 2-step process: (1) testing the significance of a set of discriminant functions, and; (2) classifying the groups.

Once group means are found to be statistically significant, classification of variables is undertaken. DFA automatically determines some optimal combination of variables. The first function provides the most overall discrimination between groups, the second provides second most, and so on. Moreover, the functions will be independent or orthogonal, that is, their contributions to the discrimination between groups will not overlap. The first function picks up the most variation; the second function picks up the greatest part of the unexplained variation. Computationally, a canonical correlation analysis is performed that will determine the successive functions and canonical roots. Classification is then possible from the canonical functions. Subjects are classified in the groups in which they had the highest classification scores. The maximum number of discriminant functions will be equal to the degrees of freedom, or the number of variables in the analysis, whichever is smaller.

Each of the allocations for the dependent categories in the initial classification were correctly classified. The attributes used to separate the groups should discriminate quite clearly between the groups so that group or category overlap is non-existent or minimal.

Chapter 5: Dental Crown Size

5.1 Measurement of validity

This section presents the findings of studies that were performed to assess measurement error. There were two assessments carried out to assess these potential errors; intra-observer comparisons and inter-observer comparisons. In order to measure intra- and inter- operator errors, paired t-tests were used to compare two sets of data and assess systematic error. Dahlberg statistics (Se) which measure the technical errors of measurement were used to assess random errors of measurement (Harris and Smith, 2009) as follows:

$$S_e = \sqrt{\frac{\sum d^2}{2n}}$$

d = difference between the first and the second measures, n = number of pairs

5.1.1 Intra-observer error

Intra-observer error was determined by a replication study. Fifty sets of dental casts were selected in order to perform this task. The data acquisition method that was highlighted in the Materials and Methods chapter was repeated twice by the same operator. The errors arising from these repeated measurements were tested using paired t-tests and also quantified using Dahlberg statistics (technical error of measurement).

In order to achieve these objectives, measurements were carried out using a small number of samples. Data were based on repeated measurements of 50 photographic images of maxillary and mandibular dental models, obtained by the same operator on two separate occasions (2 weeks apart) using the same software package (ImageJ). Table 5.1 shows that there were no systematic differences between measurements (P>0.05), and the Se values were small, ranging from 0.03 to 0.17 mm, indicating that random errors were small and unlikely to bias the results.

Table 5.1: Results of double determinations with 2D system

Tooth	n	Mean differences (mm)	Dahlberg	t-value	P –value
Mesiodistal (MD)					
11	50	0.04	0.05	1.56	0.19
12	50	0.02	0.06	0.40	0.71
13	50	0.03	0.07	0.55	0.61
14	50	0.00	0.07	0.12	0.90
15	50	0.06	0.07	1.67	0.17
16	50	0.04	0.11	0.53	0.62
Buccolingual (BL)					
11	50	0.10	0.03	2.02	0.11
12	50	0.13	0.17	0.45	0.68
13	50	0.05	0.16	1.81	0.14
14	50	0.08	0.14	1.99	0.12
15	50	0.05	0.10	0.78	0.48
16	50	0.09	0.13	1.19	0.30

**Tooth is described in FDI notation*

The same method of measurement was carried out using the same samples but using three dimensional imaging and Rapidform software. Data were based on repeated measurements of 50 3D images of maxillary and mandibular dental models, obtained by the same operator on two separate occasions (2 weeks apart). Table 5.2 shows that there were no systematic differences between measurements (P>0.05), and the Se values were small, ranging from 0.05 to 0.09 mm, indicating that random errors were small and unlikely to bias the results. The percentage of the total variation due to error variance was found to be about 10%, suggesting that measurement error was small.

Table 5.2: Results of double determination with 3D system

Tooth	n	Mean differences (mm)	Dahlberg (Se)	t-value	P –value
Mesiodistal (MD)					
11	50	0.04	0.08	0.94	0.38
12	50	0.00	0.08	0.18	0.86
13	50	0.13	0.06	0.40	0.70
14	50	0.03	0.06	0.86	0.42
15	50	0.03	0.05	1.22	0.27
16	50	0.04	0.06	1.20	0.27
Buccolingual (BL)					
11	50	0.03	0.08	0.66	0.53
12	50	0.05	0.07	1.61	0.15
13	50	0.04	0.06	1.22	0.26
14	50	0.01	0.08	0.13	0.90
15	50	0.02	0.06	0.45	0.67
16	50	0.03	0.09	0.61	0.56

**Tooth is described in FDI notation*

Measurements obtained using the ImageJ package were compared to measurements obtained using the Rapidform software package. This was done to ensure adequacy of both software packages used in this study. Data were compiled from 50 images measured initially using the ImageJ software and re-measured on a different occasion using the Rapidform software package (Table 5.3). Both measurements involved the same steps, including selection of landmarks as described earlier in Chapter 4. Table 5.3 shows that there were no significant differences in the measurements obtained from the two different software packages ($P>0.05$), with Se values ranging from 0.03 to 0.20 mm, except for measurement of buccolingual of 13 ($p<0.05$), however the average value of differences between measurements for this tooth was -0.11 which can still be considered within an acceptable clinical range. These results show that the software packages are highly comparable; and validate our use of both types of equipment and software.

Table 5.3: Intra-operator measurements obtained using ImageJ (2D images) and measurements obtained using Rapidform (3D images)

Tooth	n	Mean differences (mm)	Dahlberg	t-value	P –value
Mesiodistal (MD)					
11	50	0.03	0.11	0.34	0.75
12	50	0.04	0.15	0.36	0.74
13	50	0.01	0.12	0.09	0.93
14	50	-0.08	0.07	2.85	0.05
15	50	-0.07	0.07	2.06	0.10
16	50	-0.06	0.06	2.17	0.10
Buccolingual (BL)					
11	50	0.03	0.17	0.28	0.79
12	50	0.00	0.19	0.02	0.99
13	50	-0.11	0.09	3.94	0.02
14	50	-0.09	0.03	2.05	0.11
15	50	-0.04	0.10	0.56	0.60
16	50	0.06	0.20	0.43	0.69

**Tooth is described in FDI notation*

5.1.2 Inter-observer error

In order to assess errors between observers, another PhD student was asked to perform the measurement task. The methods used by the first operator were repeated by the other operator on a sub- sample of photographic images (n= 50). Initially, a 'practice' run was held in order to familiarise the second operator with computer software and reference points. Then, using instructions given by the author, the second operator carried out the task in her own time. Data were based on 50 images measured initially by one operator using ImageJ and compared to measurements obtained by the other operator using the same software package. The measurements conducted by both operators followed the same criteria, including the selection of landmarks, as described earlier. Table 5.4 shows that there were no significant differences between measurements obtained from the two different operators (P>0.05). Se values ranged from 0.06 to 0.12 mm, indicating that random errors were small and unlikely to bias the results. No evidence of systematic errors was found, and random errors were less than 10% of observed variance.

Table 5.4: Interobserver reproducibility for selected dental crown size measurements using ImageJ

Tooth	n	Mean differences (mm)	Dahlberg	t-value	P –value
Mesiodistal (MD)					
11	50	0.03	0.11	0.34	0.75
12	50	0.04	0.15	0.36	0.74
13	50	0.01	0.12	0.09	0.93
14	50	-0.08	0.07	2.85	0.05
15	50	-0.07	0.07	2.06	0.10
16	50	-0.06	0.06	2.17	0.10
Buccolingual (BL)					
11	50	0.03	0.17	0.28	0.79
12	50	0.00	0.19	0.02	0.99
13	50	-0.11	0.09	3.94	0.02
14	50	-0.09	0.03	2.05	0.11
15	50	-0.04	0.10	0.56	0.60
16	50	0.06	0.20	0.43	0.69

**Tooth is described in FDI notation*

5.1.3 Validation of the 3D laser scanner for odontometric measurements

The accuracy of the 3D laser scanner used to obtain 3-dimensional measurements was tested against that of the 2-dimensional measurement method by:

1. Investigating intra-observer repeatability
2. Investigating inter-observer reproducibility

Validation of the technique is estimated by making repeat measurements on a sample using specified criteria of measurement. Repeatability conditions are when replicate measurements are made by a single observer using the same equipment on two separate occasions. Reproducibility is when replicate measurements were made by a different observer.

The researcher and another operator from the research team scanned 20 randomly selected study models. Three selected teeth (the upper right central incisor, upper right canine and the upper right first molar) were used to carry out the measurements; namely the maximum mesiodistal (MD) and buccolingual (BL) dimensions of dental crowns.

The criteria for all measurements were standardised between the two operators. Details about the definitions of both measurements have been explained in the Materials and Methods chapter. All the measurements using the 3D laser scanner were obtained on two separate occasions at an interval of two weeks.

The difference between the measurements made by the investigator on the first and second occasions indicated intra-observer repeatability (Table 5.2), and the differences between the first occasion measurements obtained by the investigator and by a second operator indicated inter-observer reproducibility (Table 5.5).

Intra- and inter-operator reliability was assessed using the intra-class correlation coefficient (ICC). The results showed that inter-operator reliability for all variables ranged from 0.77-0.90 and 0.75-0.94 for the manual and 3D methods respectively (Table 5.5). Intra-operator reliability for 3D method and for all variables ranged from 0.69-0.88 for operator 1 and 0.68-86 for operator 2 (Table 5.5). The intra- and inter-operator reliability was substantial or excellent for all.

Table 5.5: Inter-observer reproducibility for selected dental crown size measurements using 3D imaging and Rapidform software

Tooth	n	Mean differences (mm)	Dahlberg (Se)	t-value	P –value	Correlation
Mesiodistal (MD)						
11	20	0.06	0.10	0.92	0.41	0.975 ($p<0.05$)
13	20	0.04	0.04	1.69	0.17	0.959 ($p<0.05$)
16	20	0.04	0.05	1.19	0.30	0.960 ($p<0.05$)
Buccolingual (BL)						
11	20	0.07	0.06	2.61	0.06	0.960 ($p<0.05$)
13	20	-0.03	0.07	0.59	0.58	0.874 ($p<0.05$)
16	20	0.00	0.11	0.00	0.99	0.973 ($p<0.05$)

**Tooth is described in FDI notation*

5.1.4 Discussion

The tests of repeatability and reproducibility of the methodology that were utilised throughout the study served to support the validity of the measurement methods. It is important to ensure that the methods produced minimal error (if any) in order to make further inferences in the later chapters. Systematic errors were measured using paired t- tests, and random errors were measured using Dahlberg's statistics for all methods used in this study. The findings from intra-operator measurement (Tables 5.1 and 5.2) and inter-operator measurements (Tables 5.3 and 5.4) showed no systematic significant differences.

Repeated measurement of mesiodistal dental crown dimensions conducted by the two different methods, using ImageJ for two dimensional imaging and by Rapidform for three-dimensional imaging, showed no systematic significant differences between measurements obtained at different occasions (Tables 5.2 and 5.4). These findings are comparable to other published studies that have utilized measurements of mesiodistal dental crown size (Brook et al., 2009). The use of Dahlberg statistics revealed that the random errors resulting from the methods used to measure the parameters were minimal and within accepted ranges, similar to results reported by Ribeiro et al., (2013).

In conclusion, the methods utilized throughout this study showed a high level of precision. There was no evidence of significant systematic error due to the methods of data acquisition and measurement used in this study. The random errors were shown to be small when compared to the extent of variation observed in the study variables and were, therefore, considered to be unlikely to bias the results.

5.2 Comparison of permanent dental crown size between population groups

5.2.1 Introduction

When analysing normal morphological features of teeth, dental crown size is the most commonly measured parameter, both clinically and for research purposes. Six population groups, i.e. Europeans, Australian Aboriginals, Malaysian (Malay, Chinese, Indian, and Orang Asli) were used to assess dental crown size in the permanent teeth. These observations, along with the findings described in the next chapters, contribute to the understanding of dental variation within and between human populations. It is well understood that genetic makeup and exposure to different environmental conditions contributes to this variation. It is important to maximise our knowledge of this variation before moving further into utilising it to develop a model for forensic identification.

5.2.2 Aims

1. To assess the differences of dental crown size between male and female subjects within several population groups.
2. To assess the differences in dental crown size across all of the populations.

5.2.3 Null Hypotheses

Two null hypotheses were formulated. The first null hypothesis to be tested was that the dental crown size of males is similar to that of females. The second null hypothesis to be tested was that, for dental crown size, there is no significant difference between crown sizes among different ethnic groups.

5.2.4 Materials and methods

5.2.4.1 Ethical approval

University of Adelaide Human Ethics Committee approval was obtained (Appendix 11.1).

5.2.4.2 Sample selection and measurement

To obtain adequate samples for this research, analyses were carried out using dental casts of Europeans, Australian Aboriginals, Malaysian Malays, Malaysian Chinese, Malaysian Indians and Malaysian Orang Asli. Details about the method of sampling and acquisition of data have been given in Chapter 4. Analyses were done using both two-dimensional and three-dimensional imaging. The sample selection criteria are shown in Table 5.6.

Table 5.6: Sample selection criteria

Inclusion Criteria	**Exclusion Criteria**
Subjects with permanent dentitions	Subjects with deciduous or mixed dentition
Good quality study models	Poor quality study models
All the permanent teeth were fully erupted and present, from permanent right first molar to the permanent left first molar	Restorative work or carious teeth that might hamper mesiodistal or buccolingual measurement
No obvious interproximal or occlusal wear of teeth	Wear or defects that affect dental measurements

For measurement purposes, landmarks were selected as below:

1. Mesiodistal dental crown size was defined as the distance between the most mesial point on the crown to the most distal point. This distance is usually midway between the buccal and lingual surfaces.
2. Buccolingual dental crown size was defined as the distance between the most buccal point on the buccal surface of the crown to the most lingual point on the lingual surface. The line is perpendicular to the mesiodistal line.

To ensure similar approaches, 3D images were aligned according to the same 2D view and measured using a similar approach.

5.2.5 Results

This section will present descriptive statistics of dental crown size measured in all population groups.

Table 5.7: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Europeans (in mm)

		N	Mean	SD	CV	N	Mean	SD	CV
Mesiodistal			**Male**				**Female**		
Right	16	71	10.4*	0.53	5.1	63	10.1	0.50	5.0
	15	64	6.7	0.32	4.9	57	6.6	0.42	6.3
	14	71	6.9*	0.37	5.3	60	6.7	0.40	6.0
	13	66	7.8*	0.39	4.9	58	7.4	0.45	6.0
	12	70	7.0*	0.67	9.6	63	6.7	0.62	9.3
	11	71	8.7*	0.55	6.2	63	8.4	0.55	6.6
Left	21	71	8.7*	0.55	6.3	63	8.4	0.54	6.5
	22	71	6.8	0.69	9.0	63	6.6	0.57	8.5
	23	67	7.9*	0.37	4.8	54	7.4	0.42	5.7
	24	70	6.9*	0.38	5.5	61	6.7	0.37	5.6
	25	64	6.8	0.53	7.8	56	6.6	0.40	6.1
	26	71	10.3*	0.56	5.4	63	10.0	0.50	5.0
Buccolingual									
Right	16	71	11.7*	0.46	4.0	63	11.2	0.55	5.0
	15	64	9.6*	0.49	5.1	57	9.3	0.48	5.2
	14	71	9.4*	0.47	5.0	60	9.1	0.47	5.2
	13	66	8.0*	0.80	9.2	58	7.5	0.77	9.0
	12	70	7.1*	0.86	9.4	63	6.7	0.83	9.2
Left	11	71	8.4*	0.95	8.9	63	7.8	0.82	9.1
	21	71	8.4*	0.98	9.4	63	7.7	0.94	8.8
	22	71	7.2*	0.93	9.8	63	6.7	0.83	9.9
	23	67	8.0*	0.94	9.8	54	7.4	0.90	9.0
	24	70	9.4*	0.48	5.1	61	9.1	0.48	5.3
	25	63	9.6*	0.52	5.4	56	9.3	0.49	5.3
	26	71	11.7*	0.52	4.4	63	11.2	0.63	4.6

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.7 shows descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary teeth in the European population. All average dental crown dimensions in males were greater than those in females (with differences ranging from 0.2 to 0.4 mm), for both mesiodistal and buccolingual dimensions. All differences between the sexes were statistically significant, except for the mesiodistal crown size of tooth 15 and 25. Values of the coefficient of variation (CV) for the anterior teeth for both mesiodistal and buccolingual dimensions were high. A possible reason for this is that the measurements were performed on standardised photographs compared with direct measurement using callipers. Small variations in tooth angulation could have then led to increased variation in the range of measurements obtained, thereby leading to large CV values.

Table 5.8: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Europeans (in mm)

		N	Mean	SD	CV	N	Mean	SD	CV
			Male				**Female**		
	Mesiodistal								
Left	36	71	10.9*	0.63	5.8	63	10.5	0.58	5.5
	35	67	7.2*	0.45	6.3	58	7.0	0.43	5.7
	34	69	7.1*	0.41	5.7	62	6.9	0.37	5.5
	33	71	7.1*	0.43	6.1	62	6.6	0.33	5.1
	32	71	6.1	0.36	5.9	63	5.9	0.53	8.9
	31	71	5.4	0.37	6.8	63	5.3	0.35	6.6
Right	41	71	5.5*	0.31	5.7	63	5.3	0.32	6.0
	42	71	6.1	0.42	6.9	63	5.9	0.42	7.2
	43	71	7.1*	0.44	6.3	63	6.7	0.40	5.9
	44	68	7.2	0.44	6.1	61	7.0	0.38	5.5
	45	66	7.3*	0.41	5.6	59	7.0	0.42	6.0
	46	71	11.0*	0.68	6.2	62	10.6	0.64	6.1
	Buccolingual								
Left	36	71	10.7*	0.53	4.9	63	10.3	0.50	4.9
	35	67	8.6*	0.51	6.0	58	8.3	0.46	5.5
	34	69	7.9*	0.44	5.6	62	7.7	0.40	5.2
	33	71	7.4*	0.72	9.7	62	7.1	0.69	9.8
	32	71	7.1*	0..69	9.7	63	6.7	0.65	9.7
	31	71	7.1*	0.63	8.9	63	6.7	0.62	9.3
Right	41	71	7.1*	0.64	9.0	63	6.7	0.66	9.9
	42	71	7.1*	0.65	9.2	63	6.8	0.64	9.4
	43	71	7.2	0.70	9.7	63	6.8	0.63	9.3
	44	68	7.9*	0.45	5.7	60	7.6	0.41	5.4
	45	66	8.5	0.52	6.1	59	8.4	0.48	5.7
	46	71	10.6*	0.49	4.6	62	10.3	0.46	4.5

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.8 shows descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular teeth in the Europeans sample. All dental crown size mean values in males exceeded those in females for both mesiodistal and buccolingual dimensions (ranging from 0.1 to 0.5 mm). Mesiodistal dimensions of teeth 36, 35, 33, 31, 41, 43, 45 and 46 showed statistically significant differences between males and females. For buccolingual dimensions, only the first molar showed a significant difference between the sexes. Higher CV values for most anterior teeth and especially for buccolingual dimensions of anterior teeth were noted. The nature of the measurement (where all measurements were obtained on one standardized photograph) may have contributed to these higher CV values. However, the pattern of values of CV was consistent with Field theory where, for each tooth class, the distal tooth in the class tended to show more variations except for mandibular incisors where the mesial tooth shows more variation than the distal tooth. This pattern was consistent throughout all populations (Table 5.9 to Table 5.13). Further discussion of this finding will be provided in a later section of this chapter.

Table 5.9: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Australian Aboriginals (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					**Female**		
	Mesiodistal									
Right	16	52	11.0*	0.49	4.5	16	51	10.7	0.53	5.0
	15	52	6.9	0.50	7.2	15	51	6.8	0.44	6.5
	14	52	7.4	0.46	6.2	14	51	7.2	0.47	6.5
	13	52	8.1*	0.54	6.7	13	51	7.8	0.50	6.4
	12	52	7.5*	0.60	8.1	12	51	7.1	0.62	8.7
	11	48	9.1*	0.55	6.0	11	50	8.8	0.54	6.1
Left	21	46	9.1*	0.60	6.6	21	50	8.8	0.52	6.0
	22	51	7.5*	0.64	8.6	22	51	7.1	0.66	9.4
	23	52	8.1*	0.51	6.2	23	50	7.8	0.54	7.0
	24	52	7.4*	0.56	7.5	24	51	7.2	0.45	6.6
	25	52	7.0	0.51	7.3	25	51	6.9	0.45	6.6
	26	52	10.8	0.62	5.8	26	51	10.6	0.64	6.01
	Buccolingual									
Right	16	52	12.4*	0.60	4.8	16	51	11.8	0.56	4.7
	15	52	10.3*	0.68	6.6	15	51	9.9	0.57	5.7
	14	52	10.1*	0.60	5.9	14	51	9.8	0.54	5.5
	13	52	9.0*	0.66	7.3	13	51	8.3	0.63	7.6
	12	52	7.6	0.73	9.6	12	51	7.3	0.70	9.6
	11	48	9.0*	0.70	7.9	11	50	8.5	0.73	8.6
Left	21	46	9.1*	0.82	9.0	21	50	8.5	0.74	8.7
	22	51	7.7*	0.75	9.7	22	51	7.3	0.72	9.9
	23	52	8.9*	0.63	7.1	23	51	8.3	0.68	8.2
	24	52	10.1*	0.52	5.2	24	51	9.8	0.55	5.6
	25	52	10.2*	0.52	5.1	25	50	9.9	0.59	6.0
	26	52	12.3*	0.60	4.8	26	51	11.9	0.61	5.1

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.9 shows descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary teeth in the Australian Aboriginal population. All dental crown size mean values in males were greater than those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.2 to 0.5 mm). Mesiodistal dimensions of teeth 16, 11, 23 and 26 showed statistically significant differences between males and females. For buccolingual dimensions, all teeth showed significant differences except for 12.

Table 5.10: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Australian Aboriginals (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					**Female**		
	Mesiodistal									
Left	36	51	11.7*	0.49	4.2	36	49	11.2	0.56	5.0
	35	51	7.4	0.46	6.3	35	51	7.2	0.51	7.0
	34	52	7.3	0.54	7.4	34	50	7.1	0.45	6.3
	33	52	7.3*	0.40	5.5	33	51	6.9	0.44	6.4
	32	52	6.5*	0.38	5.9	32	51	6.3	0.42	6.6
	31	51	5.8*	0.32	5.5	31	51	5.6	0.45	8.1
Right	41	52	5.7	0.34	6.0	41	51	5.6	0.45	8.1
	42	52	6.5*	0.35	5.4	42	51	6.3	0.44	7.1
	43	52	7.4*	0.47	6.3	43	51	6.9	0.40	5.8
	44	51	7.2	0.54	7.5	44	51	7.1	0.45	6.3
	45	52	7.4	0.43	5.7	45	51	7.3	0.54	7.4
	46	50	11.7*	0.50	4.3	46	49	11.3	0.57	5.0
	Buccolingual									
Left	36	51	11.2*	0.53	4.7	36	50	10.9	0.50	4.6
	35	51	9.0*	0.57	6.4	35	51	8.7	0.55	6.7
	34	52	8.3	0.48	5.8	34	50	8.1	0.55	6.7
	33	52	8.3*	0.82	9.9	33	51	7.7	0.55	7.1
	32	52	7.9*	0.78	9.9	32	51	7.5	0.72	9.6
	31	51	7.9*	0.78	9.9	41	51	7.6	0.69	9.1
Right	41	52	7.9*	0.76	9.6	41	51	7.6	0.65	8.6
	42	52	7.8	0.72	9.3	42	51	7.6	0.69	9.1
	43	52	8.4*	0.76	9.1	43	51	7.7	0.72	9.4
	44	51	8.3	0.47	5.6	44	51	8.2	0.51	6.2
	45	52	9.0*	0.56	6.3	45	51	8.6	0.62	7.2
	46	50	11.2*	0.52	4.7	46	49	10.8	0.53	4.9

*$p<0.05$, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.10 shows descriptive statistics for mandibular teeth in the Australian Aboriginal sample. All dental crown size measures in males exceeded those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.5mm). There were similar average values for mesiodistal dental crown dimension of tooth 34, 35 and 44. Mesiodistal dimensions of teeth 36, 33, 43 and 46 showed significant differences between males and females and the same pattern was observed for buccolingual dimensions.

Table 5.11: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Malays (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					**Female**		
		Mesiodistal								
Right	16	57	10.6	0.55	5.2	16	52	10.5	0.57	5.4
	15	57	7.2	0.65	9.0	15	51	7.1	0.64	9.0
	14	58	7.3	0.50	6.9	14	52	7.2	0.47	6.5
	13	56	8.0*	0.52	6.5	13	52	7.7	0.56	7.3
	12	57	7.1	0.63	8.9	12	52	7.0	0.68	9.7
	11	58	8.4	0.61	7.3	11	52	8.3	0.62	7.5
Left	21	58	8.5	0.53	6.2	21	52	8.4	0.59	7.1
	22	58	7.2	0.60	8.3	22	52	7.1	0.60	8.4
	23	56	7.9	0.60	7.6	23	52	7.7	0.65	8.5
	24	57	7.3	0.55	7.5	24	52	7.2	0.56	7.7
	25	55	7.0	0.64	9.1	25	49	7.0	0.45	6.5
	26	54	10.5	0.56	5.3	26	49	10.4	0.60	5.8
		Buccolingual								
Right	16	54	11.6*	0.62	5.4	16	49	11.3	0.55	4.8
	15	53	9.6	0.63	6.5	15	49	9.4	0.53	5.6
	14	54	9.8*	0.55	5.6	14	49	9.5	0.70	7.3
	13	52	8.1*	0.72	8.9	13	49	7.8	0.67	8.7
	12	53	7.7	0.81	9.3	12	49	7.4	0.67	9.0
	11	54	9.0	0.89	9.9	11	49	8.7	0.79	9.1
Left	21	54	9.0	0.89	9.9	21	49	8.7	0.82	9.4
	22	54	7.5	0.64	8.6	22	49	7.5	0.69	9.2
	23	53	8.1	0.76	9.4	23	49	7.9	0.69	8.8
	24	53	9.8	0.58	5.9	24	49	9.6	0.48	5.0
	25	52	9.7	0.67	6.9	25	48	9.5	0.48	5.1
	26	54	11.6*	0.59	5.1	26	49	11.0	0.51	4.7

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.11 shows descriptive statistics of maxillary teeth for the Malay sample. All measurements in males were generally greater than those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.5 mm). A few dental crown dimensions showed similar mean values between males and females (mesiodistal of 16, 24 and 26). Some of the dental crown sizes were greater in females than males (mesiodistal of 11, 12, 21 and 22). The mesiodistal dimension of canine teeth showed significant differences between males and females while, for buccolingual dimensions, teeth 16, 13 and 23 showed significant differences.

Table 5.12: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Malays (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					**Female**		
	Mesiodistal									
Left	36	54	11.3*	0.53	4.7	36	49	11.0	0.51	4.7
	35	53	7.3	0.48	6.6	35	49	7.3	0.45	6.1
	34	56	7.3	0.42	5.7	34	50	7.2	0.42	5.9
	33	56	7.2*	0.50	7.0	33	51	6.8	0.44	6.4
	32	56	6.1	0.38	6.2	32	51	6.2	0.36	5.8
	31	56	5.5	0.31	5.6	31	51	5.5	0.31	5.6
Right	41	56	5.5	0.37	6.9	41	51	5.5	0.33	6.1
	42	56	6.1	0.38	6.3	42	49	6.2	0.40	6.5
	43	56	7.2*	0.55	7.7	43	51	6.8	0.40	5.9
	44	56	7.3	0.48	6.7	44	51	7.1	0.42	6.0
	45	55	7.3	0.48	6.7	45	48	7.2	0.49	6.8
	46	56	11.2	0.56	5.0	46	49	11.1	0.54	4.9
	Buccolingual									
Left	36	54	10.7	0.48	4.5	36	49	10.6	0.56	5.3
	35	53	8.5	0.53	6.2	35	49	8.4	0.54	6.4
	34	56	8.0	0.51	6.4	34	50	7.9	0.56	7.2
	33	56	7.5	0.63	8.4	33	51	7.3	0.53	7.3
	32	56	7.3	0.71	9.7	32	51	7.2	0.64	9.0
	31	56	7.3	0.70	9.7	31	51	7.1	0.61	8.7
Right	41	56	7.2	0.70	9.7	41	51	7.0	0.61	8.7
	42	56	7.3	0.70	9.6	42	49	7.2	0.69	9.6
	43	56	7.5	0.72	9.6	43	51	7.2	0.61	8.5
	44	56	8.0	0.60	7.5	44	51	7.8	0.50	6.4
	45	55	8.6	0.56	6.5	45	50	8.4	0.51	6.1
	46	56	10.7	0.52	4.8	46	49	10.5	0.50	4.8

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.12 shows descriptive statistics for dental crown size of mandibular teeth in the Malay sample. Measurements in males were generally greater than those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.4 mm). There were a few dental crown dimensions with similar average values between males and females (mesiodistal of 31 and 45). Some of the dental crown sizes were greater in females than males (mesiodistal of 32, 35, 41 and 42). The mesiodistal dimensions of canine and molar teeth showed significant differences between males and females while, for buccolingual dimensions, canine teeth showed significant differences.

Table 5.13: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Chinese (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					**Female**		
		Mesiodistal								
Right	16	50	10.7*	0.54	5.0	16	51	10.4	0.46	4.4
	15	47	7.2*	0.42	5.8	15	49	7.0	0.44	6.2
	14	50	7.5*	0.38	5.1	14	50	7.2	0.45	6.3
	13	50	8.3*	0.47	5.7	13	51	7.9	0.45	6.3
	12	50	7.5*	0.57	7.6	12	51	7.2	0.53	7.5
	11	50	8.8*	0.46	5.2	11	51	8.5	0.44	5.1
Left	21	50	8.8*	0.43	4.9	21	51	8.5	0.38	4.5
	22	50	7.5*	0.59	7.8	22	51	7.2	0.59	8.3
	23	50	8.1*	0.51	6.3	23	51	7.9	0.44	5.5
	24	50	7.5*	0.34	4.6	24	50	7.2	0.45	4.3
	25	49	7.2*	0.38	5.2	25	49	7.0	0.39	5.5
	26	49	10.7*	0.47	4.5	26	51	10.3	0.45	4.3
		Buccolingual								
Right	16	50	11.8*	0.47	4.3	16	51	11.3	0.50	4.0
	15	47	9.8*	0.53	5.4	15	49	9.4	0.61	6.5
	14	50	10.0*	0.50	5.0	14	50	9.6	0.57	6.0
	13	50	8.0	0.79	9.9	13	51	7.8	0.68	9.6
	12	50	7.7	0.73	9.5	12	51	7.4	0.71	9.7
	11	50	8.9	0.82	9.2	11	51	8.7	0.82	9.4
Left	21	50	9.0	0.80	8.9	21	51	8.8	0.87	9.9
	22	50	7.7	0.72	9.4	22	51	7.6	0.74	9.8
	23	50	8.1	0.76	9.4	23	51	7.9	0.57	7.3
	24	50	10.1*	0.50	5.0	24	50	9.7	0.58	6.0
	25	49	9.9*	0.53	5.4	25	49	9.5	0.60	6.3
	26	49	11.8*	0.44	3.7	26	51	11.3	0.55	4.9

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.13 shows descriptive statistics of maxillary teeth in the Chinese sample. All dental crown dimension in males exceeded those for females in both mesiodistal and buccolingual dimensions. Mesiodistal dimensions of teeth 14, 13, 23, 24, 25 and 26 showed significant differences between males and females. For buccolingual dimensions, all posterior teeth showed significant differences between the sexes.

Table 5.14: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Chinese (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					Female		
		Mesiodistal								
Left	36	47	11.3*	0.46	4.1	36	49	10.9	0.54	5.0
	35	48	7.4	0.46	6.2	35	46	7.3	0.37	5.1
	34	50	7.4*	0.37	5.1	34	50	7.1	0.33	4.6
	33	50	7.3*	0.41	5.6	33	50	6.9	0.45	6.6
	32	50	6.3	0.37	5.9	32	48	6.1	0.40	6.5
	31	50	5.7	0.31	5.5	31	49	5.5	0.33	5.9
Right	41	50	5.7	0.31	5.5	41	50	5.5	0.34	6.1
	42	49	6.3*	0.38	6.1	42	48	6.0	0.36	5.9
	43	50	7.3*	0.41	5.6	43	50	6.9	0.43	6.2
	44	50	7.5*	0.37	5.0	44	50	7.2	0.37	5.1
	45	49	7.5*	0.42	5.6	45	49	7.2	0.60	8.3
	46	47	11.4*	0.57	5.0	46	49	11.0	0.52	4.9
	Buccolingual									
Left	36	47	10.8	0.45	4.2	36	49	10.6	0.52	4.9
	35	48	8.7	0.55	6.4	35	46	8.4	0.45	5.3
	34	50	8.2	0.40	4.8	34	50	7.9	0.49	6.3
	33	50	7.7*	0.71	9.3	33	50	7.3	0.59	8.1
	32	50	7.3	0.71	9.6	32	48	7.1	0.69	9.7
	31	50	7.3	0.70	9.6	31	49	7.0	0.68	9.7
Right	41	50	7.3	0.72	9.9	41	50	6.9	0.68	9.9
	42	49	7.3	0.73	9.9	42	48	7.1	0.69	9.7
	43	50	7.4	0.45	6.1	43	50	7.3	0.53	7.2
	44	50	8.3*	0.42	5.1	44	50	7.9	0.51	6.5
	45	49	8.7	0.63	7.2	45	49	8.5	0.53	6.3
	46	47	10.9*	0.48	4.4	46	49	10.5	0.46	4.3

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.14 shows descriptive statistics of mandibular teeth in the Chinese sample. All dental crown size variables in males were larger than those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.4 mm). Mesiodistal dimensions of all posterior teeth showed statistically significant differences between males and females, and the same pattern was also observed for buccolingual dimensions.

Table 5.15: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Indians (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					Female		
	Mesiodistal									
Right	16	53	10.5	0.52	4.9	16	60	10.3	0.56	5.5
	15	53	6.9	0.37	5.4	15	60	6.7	0.37	5.5
	14	53	7.1	0.37	5.3	14	60	6.9	0.37	5.3
	13	51	7.9*	0.46	5.8	13	58	7.5	0.44	5.9
	12	53	7.2*	0.57	7.9	12	60	6.9	0.65	9.4
	11	53	8.7*	0.36	4.2	11	59	8.4	0.55	6.5
Left	21	53	8.7*	0.43	5.0	21	59	8.4	0.52	6.2
	22	53	7.2*	0.51	7.1	22	60	6.9	0.55	8.1
	23	53	7.8*	0.45	5.7	23	59	7.5	0.38	5.1
	24	53	7.1	0.41	5.7	24	60	6.9	0.43	6.2
	25	52	7.0*	0.37	5.3	25	56	6.7	0.42	6.3
	26	53	10.6*	0.50	4.7	26	59	10.2	0.57	5.6
	Buccolingual									
Right	16	53	11.6*	0.48	4.2	16	60	11.2	0.55	4.9
	15	53	9.6	0.52	5.4	15	60	9.2	0.51	5.5
	14	53	9.6	0.49	5.1	14	60	9.3	0.51	5.5
	13	51	7.7	0.72	9.4	13	58	7.6	0.73	9.7
	12	53	7.4	0.73	9.9	12	60	7.1	0.95	13.4
	11	53	8.5	0.83	9.8	11	59	8.4	0.79	9.4
Left	21	53	8.6	0.84	9.8	21	59	8.5	0.79	9.3
	22	53	7.3	0.71	9.7	22	60	7.3	0.72	9.9
	23	53	7.7	0.69	9.0	23	59	7.6	0.71	9.4
	24	53	9.6	0.46	4.8	24	60	9.3	0.50	5.4
	25	52	9.6	0.58	6.0	25	56	9.3	0.57	6.2
	26	53	11.6*	0.49	4.3	26	59	11.2	0.56	5.0

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.15 shows descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary teeth in the Indian sample. All dental crown sizes measured in males were greater than those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.2 to 0.4 mm). Mesiodistal dimension of all posterior teeth, canine and central incisors showed significant differences between males and females. For buccolingual dimensions, all posterior teeth and canine showed significant differences.

Table 5.16: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Indians (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					Female		
		Mesiodistal								
Left	36	51	11.0	0.61	5.5	36	60	10.8	0.54	5.1
	35	52	7.4	0.45	6.1	35	59	7.2	0.42	5.8
	34	53	7.2	0.38	5.2	34	59	7.1	0.43	6.0
	33	53	7.0*	0.39	5.6	33	60	6.7	0.40	6.0
	32	53	6.1	0.39	6.4	32	60	5.9	0.40	6.8
	31	53	5.5	0.33	5.9	31	60	5.4	0.48	8.9
Right	41	53	5.5	0.29	5.2	41	60	5.4	0.44	8.1
	42	53	6.1	0.36	5.9	42	60	5.9	0.39	6.6
	43	53	7.0	0.41	5.9	43	58	6.8	0.45	6.6
	44	53	7.2	0.37	5.1	44	59	7.1	0.42	6.0
	45	51	7.4	0.41	5.5	45	60	7.3	0.43	5.9
	46	51	11.1*	0.57	5.1	46	58	10.8	0.74	6.9
		Buccolingual								
Left	36	51	10.8	0.44	4.1	36	60	10.6	0.57	5.5
	35	52	8.6	0.54	6.3	35	59	8.5	0.57	6.7
	34	53	7.9	0.55	6.9	34	59	7.8	0.50	6.4
	33	53	7.3	0.72	9.9	33	60	7.0	0.61	8.6
	32	53	7.4*	0.70	9.5	32	60	7.0	0.68	9.7
	31	53	7.6*	0.74	9.6	31	60	7.1	0.69	9.7
Right	41	53	7.5*	0.72	9.5	41	60	7.0	0.68	9.7
	42	53	7.4*	0.73	9.9	42	60	7.0	0.69	9.9
	43	53	7.2	0.68	9.4	43	58	6.9	0.64	9.3
	44	53	7.9	0.49	6.2	44	59	7.7	0.52	6.8
	45	51	8.6	0.45	5.3	45	60	8.4	0.51	6.0
	46	51	10.8*	0.45	4.2	46	58	10.5	0.52	5.0

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.16 shows descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular teeth in the Indian sample. All dental crown sizes in males showed greater dimensions for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.4 mm). Mesiodistal dimensions of teeth 36, 35, 34, 33, 43 and 46 showed significant differences between males and females. For buccolingual dimensions, teeth 36, 34, 33 and 46 showed significant differences.

Table 5.17: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Orang Asli (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					Female		
		Mesiodistal								
Right	16	23	10.7	0.52	4.9	16	23	10.3	0.61	5.9
	15	25	6.8	0.42	6.2	15	25	6.7	0.45	6.7
	14	25	7.1	0.42	5.9	14	25	7.0	0.50	7.1
	13	26	7.9*	0.42	5.4	13	25	7.5	0.43	5.8
	12	25	6.9	0.54	7.8	12	24	6.5	0.62	9.6
	11	25	8.6	0.59	6.8	11	25	8.2	0.55	6.7
Left	21	26	8.6	0.62	7.2	21	23	8.2	0.61	7.4
	22	25	7.0	0.56	8.1	22	24	6.5	0.55	8.5
	23	26	7.9	0.48	6.1	23	24	7.7	0.41	5.4
	24	25	7.1	0.44	6.3	24	25	7.1	0.50	7.2
	25	25	6.9	0.41	6.0	25	25	6.7	0.45	6.7
	26	24	10.6	0.55	5.2	26	23	10.3	0.59	5.7
		Buccolingual								
Right	16	23	12.1*	0.55	4.6	16	23	11.4	0.41	3.6
	15	25	9.6	0.48	5.0	15	25	9.4	0.50	5.4
	14	25	9.6	0.62	6.5	14	25	9.4	0.53	5.6
	13	26	8.5	0.78	9.2	13	25	8.2	0.48	5.9
	12	25	7.6	0.76	9.3	12	24	7.2	0.66	8.7
	11	25	9.2	0.75	8.2	11	25	8.7	0.82	9.4
Left	21	26	9.2	0.90	9.7	21	23	8.6	0.78	9.1
	22	25	7.4	0.72	9.7	22	24	7.3	0.73	9.7
	23	26	8.5	0.61	7.3	23	24	8.1	0.60	7.4
	24	25	9.6	0.59	6.1	24	25	9.4	0.58	6.2
	25	25	9.5	0.51	5.3	25	25	9.4	0.50	5.3
	26	24	12.1	0.51	4.2	26	23	11.4	0.39	3.4

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.17 shows descriptive statistics of maxillary teeth in the Orang Asli sample. Dental crown sizes in males generally exceeded those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.5 mm). There were a few dental crown dimensions that showed similar average values between males and females (mesiodistal of 14 and 24) and (buccolingual of 15 and 25). Some of the dental crown sizes were greater in females than males (buccolingual of 12,14, 22 and 24). The mesiodistal dimension of tooth 13 showed a significant difference between males and females. For buccolingual dimensions, only the first molars showed a significant difference.

Table 5.18: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Orang Asli (in mm)

		N	Mean	SD	CV		N	Mean	SD	CV
			Male					Female		
		Mesiodistal								
Left	36	22	11.0	0.48	4.4	36	18	10.7	0.56	5.3
	35	25	7.1	0.40	5.6	35	25	7.1	0.36	5.0
	34	26	7.1	0.44	6.3	34	25	6.9	0.47	6.8
	33	26	7.3*	0.41	5.7	33	24	6.9	0.45	6.6
	32	26	6.3	0.48	7.6	32	24	6.0	0.45	7.5
	31	26	5.5	0.41	7.3	31	25	5.3	0.45	8.5
Right	41	25	5.5	0.37	6.8	41	25	5.3	0.47	8.8
	42	26	6.3	0.35	5.5	42	24	6.0	0.45	7.5
	43	26	7.2*	0.37	5.2	43	25	6.8	0.45	6.5
	44	25	7.0	0.37	5.2	44	25	6.9	0.60	8.7
	45	25	7.1	0.37	5.2	45	25	7.1	0.32	4.6
	46	22	11.1*	0.51	4.6	46	18	10.6	0.54	5.2
		Buccolingual								
Left	36	22	10.7	0.45	4.2	36	18	10.4	0.48	4.7
	35	25	8.5	0.53	6.3	35	25	8.3	0.40	4.8
	34	26	8.0	0.63	7.9	34	25	7.8	0.63	8.1
	33	26	8.2*	0.75	9.1	33	24	7.8	0.67	8.7
	32	26	8.1	0.68	8.5	32	24	8.0	0.71	8.9
	31	26	8.0	0.65	8.1	31	25	7.8	0.76	9.8
Right	41	25	8.1	0.79	9.7	41	25	7.7	0.75	9.7
	42	26	8.1	0.80	9.9	42	24	7.9	0.75	9.5
	43	26	8.1*	0.68	8.4	43	25	7.6	0.66	8.7
	44	25	8.0	0.60	7.5	44	25	7.6	0.56	7.4
	45	25	8.4	0.49	5.9	45	25	8.2	0.50	6.1
	46	22	10.8*	0.48	4.5	46	18	10.4	0.50	4.8

*p<0.05, N = sample size, SD = Standard deviation, CV = Coefficient of variation, all teeth in FDI notation

Table 5.18 shows descriptive statistics of mandibular teeth in the Oran Asli sample. Dental crown sizes in males were generally exceeded those in females for both mesiodistal and buccolingual dimensions (with differences ranging from 0.1 to 0.3 mm). There were a few dental crown dimension that showed similar average value between males and females (mesiodistal of 35 and 45) and (buccolingual of 32, 34 and 45). Some of the dental crown sizes were greater in females than males (buccolingual of 35, 41 and 42). None of the mesiodistal and buccolingual dimensions showed significant differences.

Table 5.19: Percentage of dimorphism according to ethnic group (maxillary teeth)

		% dimorphism					
		European	Australian Aboriginal	Malay	Chinese	Indian	Orang Asli
Mesiodistal							
Right	16	3.46	2.58	0.02	1.75	2.81	2.11
	15	1.28	0.77	1.31	2.75	4.23	0.71
	14	2.03	1.23	0.99	4.58	3.72	0.51
	13	3.89	2.56	4.50	4.98	5.66	5.31
	12	1.87	3.56	-0.90	2.05	3.48	2.29
	11	3.59	2.94	1.59	2.01	3.24	4.86
Left	21	2.91	2.03	1.07	1.87	3.65	4.48
	22	2.44	3.61	1.74	3.23	5.63	2.21
	23	4.88	4.66	4.00	4.35	5.33	1.75
	24	2.31	1.74	0.54	3.80	3.23	0.98
	25	0.89	1.26	1.35	2.47	5.09	0.70
	26	2.65	2.48	0.09	2.86	3.99	0.96
Buccolingual							
Right	16	3.73	5.08	2.29	3.71	3.52	4.29
	15	1.76	3.38	2.13	3.82	4.58	0.28
	14	2.52	2.13	2.78	4.54	3.91	1.38
	13	5.41	6.07	5.89	4.82	3.26	1.62
	12	5.10	1.02	1.95	3.91	4.12	0.86
Left	11	4.81	4.53	3.46	2.24	4.24	3.86
	21	5.80	3.00	3.18	2.29	3.23	4.49
	22	6.01	2.15	2.65	1.20	2.68	1.45
	23	5.91	6.94	6.68	7.35	3.49	1.95
	24	2.71	1.91	2.57	3.59	3.58	1.29
	25	1.86	3.09	2.09	3.88	4.41	0.01
	26	3.77	3.37	2.11	4.00	3.60	3.84

Table 5.19 shows percentages of dimorphism according to different ethnic groups for maxillary teeth. The percentage dimorphism was calculated by subtracting the mean for females from that for males, and then dividing by the value for females. From the table,

the pattern of dimorphism was similar across populations. For mesiodistal dental crown size, the highest percentage recorded was 5.66% in the Indian group. All population groups showed that canine teeth tended to be more dimorphic than other teeth. For buccolingual dental crown size, the canine was the most dimorphic tooth in most groups, with the highest score of 6.94% in Australian Aboriginals. Exceptions were noted for the Indian and Orang Asli groups, where the right second premolar and left lateral incisor showed the greatest dimorphism. Highlighted values in yellow indicate the highest percentages of dimorphism for each population sample.

Table 5.20: Percentage of dimorphism according to ethnic group (mandibular teeth)

		% dimorphism					
		European	Australian Aboriginal	Malay	Chinese	Indian	Orang Asli
Mesiodistal							
Right	36	2.91	4.61	2.85	2.87	2.51	2.46
	35	3.18	1.40	-1.38	2.76	3.02	-0.17
	34	2.00	0.16	0.68	3.81	2.52	1.18
	33	5.90	5.57	5.42	6.45	5.12	3.80
	32	0.74	3.10	-0.83	2.93	3.33	3.20
	31	1.83	3.38	-0.78	1.60	2.05	2.69
Left	41	3.22	1.50	-2.07	0.90	1.51	2.03
	42	1.74	3.20	-1.12	3.10	3.07	2.70
	43	4.90	5.61	4.60	6.15	4.69	2.85
	44	1.56	-0.53	1.43	3.86	3.02	0.48
	45	2.20	1.59	-0.17	3.30	2.38	0.23
	46	3.57	3.47	1.10	2.95	3.27	2.94
Buccolingual							
Right	36	2.83	2.14	0.46	2.04	2.31	1.43
	35	3.18	1.58	1.93	2.63	1.87	1.37
	34	2.74	1.60	2.22	4.94	2.78	0.29
	33	4.54	7.05	4.37	5.42	5.64	4.41
	32	6.94	3.63	2.38	4.00	5.28	0.80
Left	31	6.97	3.46	2.67	4.58	8.16	1.29
	41	7.59	3.09	2.13	5.83	7.14	3.30
	42	6.26	2.17	1.99	2.28	7.12	2.36
	43	4.80	7.05	5.24	3.56	3.07	2.97
	44	2.98	1.49	2.06	4.44	2.54	2.90
	45	2.43	2.91	2.27	2.35	2.27	0.30
	46	2.52	2.73	1.18	2.95	2.86	2.19

Table 5.20 shows percentages of dimorphism according to different ethnic groups for mandibular teeth. The pattern of dimorphism was also similar across populations. For mesiodistal crown dimensions, all groups showed tooth 33 as the most dimorphic tooth, except for Australian Aboriginals who showed 43 as the most dimorphic. For buccolingual dental crown dimensions, across all populations, teeth with the highest dimorphic scores tended to be the anterior ones, with 31 for Indians, 41 for Europeans and Chinese, 43 for Australian Aboriginals and Malays and 33 for Orang Asli.

Highlighted values in yellow indicate the highest percentages of dimorphism for each population sample.

5.2.6 Correlations

There is evidence of correlation between mesiodistal and buccolingual dental crown size of antimeric teeth (Dempsey et al., 1995) and between the mesiodistal and buccolingual dimension (Scott and Turner, 2000, Sharma et al., 2014). Values of correlation between these two parameters suggest the theoretical correlations of polygenic inheritance (Townsend et al., 1978). Polygenic inheritance describes the effect of multiple genes on phenotypes, which may explain some of the correlations of variables within the dentition.

In general, the pattern of correlation between mesiodistal and buccolingual dimension were highly correlated ($p<0.05$) across all population groups. Similar pattern were observed for the correlation of mesiodistal and buccolingual dimension for antimeric teeth ($p<0.05$). For this section, only example of one of the population groups (Europeans) will be displayed to show the pattern (Figure 5.21).

Table 5.21: Correlation between mesiodistal dental crown dimensions of antimeric maxillary teeth in European males

Variables	MD21	MD22	MD23	MD24	MD25	MD26
MD16	.522	.266	.368	.292	.333	.851*
MD15	.381	.478	.352	.509	.819*	.328
MD14	.306	.414	.423	.832*	.579	.343
MD13	.164	.253	.775*	.420	.376	.362
MD12	.477	.774*	.225	.383	.383	.299
MD11	.846*	.600	.195	.362	.225	.538

*correlation is significant at $p<0.05$

Table 5.21 shows correlations of mesiodistal crown dimension of maxillary teeth. There is a moderate to high correlation of the mesiodistal dimension. Correlation of dental crown dimensions between isomers and antimeres might be affected from specific intrauterine events during odontogenesis and less from genetic effect (Garn et al.,1979).

Table 5.22: Correlation between mesiodistal and buccolingual dental crown dimensions of right maxillary teeth in European males

Variables	BL16	BL15	BL14	BL13	BL12	BL11
MD16	.512*	.078	.256	.267	.229	.411
MD15	.085	.535*	.523*	.109	.251	.368
MD14	.317	.548*	.691*	-.029	.288	.440
MD13	.278	.074	.326	.244	.184	.391
MD12	.229	.333	.384	-.013	.340	.382
MD11	.382	.149	.304	.274	.266	.495*

*correlation is significant at $p<0.05$

Table 5.22 shows correlations of mesiodistal and buccolingual dental crown dimensions of maxillary teeth. There is a moderate correlation of the mesiodistal and buccolingual dimension.

Table 5.23: Correlation between mesiodistal dental crown dimensions of antimeric maxillary teeth in European females

Variables	MD21	MD22	MD23	MD24	MD25	MD26
MD16	.479	.353	.323	.356	.505*	.882*
MD15	.418	.406	.386	.636	.834*	.428
MD14	.307	.424	.467	.787*	.637	.539
MD13	.422	.428	.773*	.458	.473	.201
MD12	.521*	.773*	.544	.340	.477	.357
MD11	.848*	.640	.521	.257	.539	.607

* correlation is significant at $p<0.05$

As observed in males, there is also a moderate to high correlation of mesiodistal dimensions of maxillary teeth (shown in Table 5.23)

Table 5.24 Correlation between mesiodistal dental crown dimensions of maxillary teeth in males across all population groups.

	11	12	13	14	15	16
11	1.00	0.49*	0.39*	0.37*	-0.03	0.49*
12		1.00	0.49*	0.52*	0.30*	0.43*
13			1.00	0.56*	0.07	0.37*
14				1.00	0.37*	0.47*
15					1.00	0.34*
16						1.00

*p<0.05, all teeth in FDI notation

For males, right maxillary teeth from tooth 11 to tooth 16 showed weak to moderate significant correlations in terms of mesiodistal crown size (p<0.05), except for tooth 11 and 15 and 13 and 15 (Table 5.24). The highest correlation for mesiodistal dental crown size was found between teeth 14 and 13. A scatter plot is shown below to display this correlation (Figure 5.1)

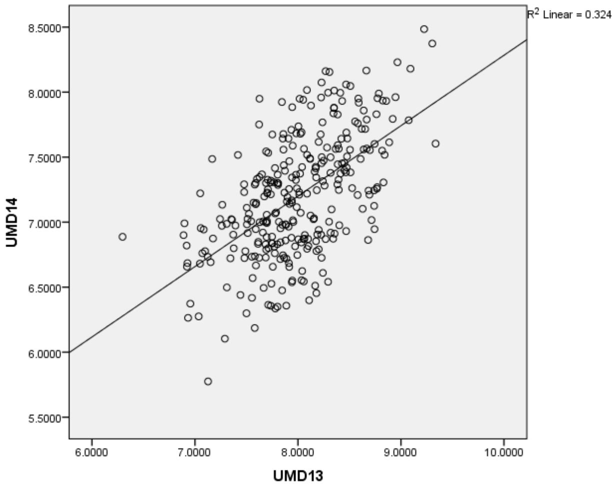


Figure 5.1 Scatter plot showing correlation between mesiodistal dental crown size of tooth 13 to 14 in males

Figure 5.1 shows the correlation between tooth 14 and 13 With N = 438, there was a significant positive correlation of 0.56 ($p < 0.05$) between the mesiodistal crown size of 14 and 13.

Table 5.25: Correlation between mesiodistal crown dimensions of maxillary teeth in females across all population groups

	11	12	13	14	15	16
11	1.00	0.56*	0.54*	0.53*	0.17*	0.55*
12		1.00	0.51*	0.47*	0.32*	0.34*
13			1.00	0.64*	0.31*	0.48*
14				1.00	0.48*	0.60*
15					1.00	0.39*
16						1.00

*p<0.05, all teeth in FDI notation

Table 5.25 shows that for the females the right maxillary teeth from tooth 11 to tooth 16 showed weak to moderate significant correlations in terms of mesiodistal crown size (p<0.05). The highest correlation was between 14 and 13 as displayed in males.

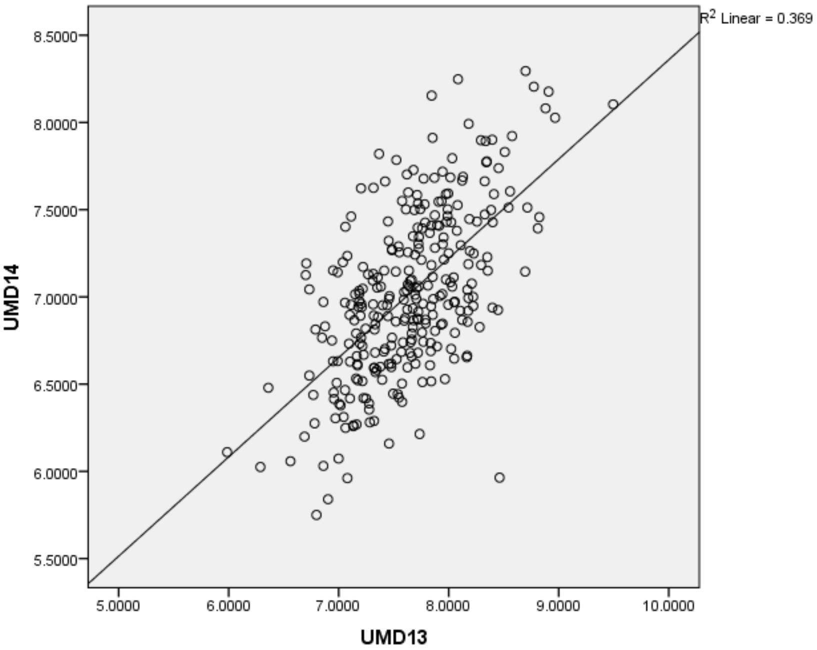


Figure 5.2: Scatter plot showing correlation between mesiodistal dental crown size of tooth 13 to 14 in females

Figure 5.2 shows the scatter plot for the mesiodistal crown size of teeth 14 and 13 in females.

Table 5.26: Correlation between maximum buccolingual crown dimensions of maxillary teeth in males across all population groups

	11	12	13	14	15	16
11	1.00	0.53*	0.41*	0.45*	0.27*	0.33*
12		1.00	0.45*	0.38*	0.33*	0.17*
13			1.00	0.40*	0.36*	0.30*
14				1.00	0.78*	0.54*
15					1.00	0.54*
16						1.00

*p<0.05, all teeth in FDI notation

Table 5.26 shows that for males the right maxillary teeth from tooth 11 to tooth 16, there were weak to moderate positive correlations in terms of buccolingual dental crown size (p<0.05).

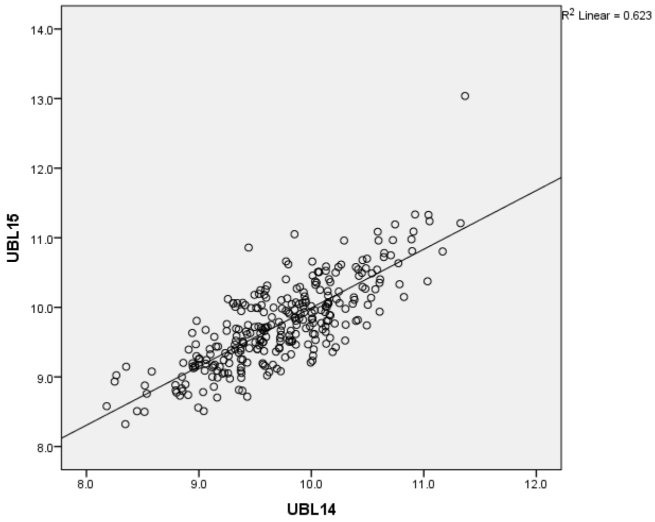


Figure 5.3: Scatter plot showing correlation between buccolingual dental crown size of tooth 14 and 15 in males

Figure 5.3 shows the association between buccolingual dental crown size of 14 and 15 in males. With N = 438, there was a significant positive correlation of 0.76 ($p < 0.05$) between the buccolingual dental crown size of 15 and 14.

Table 5.27: Correlation between buccolingual crown dimensions of maxillary teeth in females across all population groups

	11	12	13	14	15	16
11	1.00	0.58*	0.40*	0.40*	0.36*	0.42*
12		1.00	0.44*	0.44*	0.43*	0.38*
13			1.00	0.47*	0.41*	0.47*
14				1.00	0.76*	0.64*
15					1.00	0.67*
16						1.00

*p<0.05, all teeth in FDI notation

Table 5.27 shows that for females the right maxillary teeth from tooth 11 to tooth 16 there were moderate positive significant correlations in terms of buccolingual dental crown size (p<0.05).

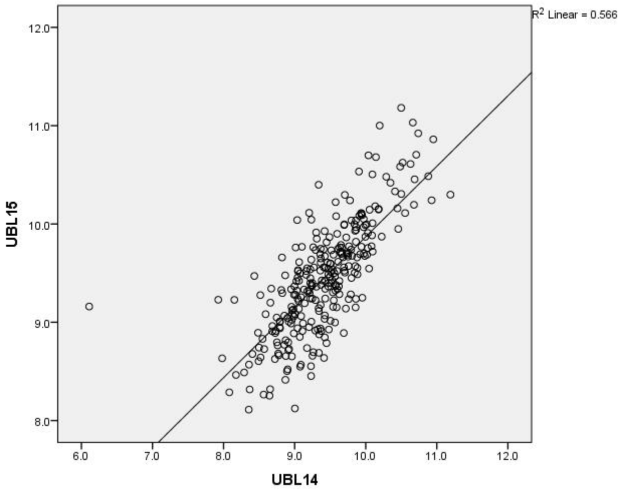


Figure 5.4: Scatter plot showing correlation between buccolingual dental crown size of tooth 14 and 15 in females

Figure 5.4 shows the association between buccolingual dental crown size of 14 and 15 in females. With N = 300, there was a positive significant correlation of 0.76 ($p < 0.05$) between the buccolingual dental crown size of 15 and 14.

Table 5.28: Correlation between mesiodistal crown dimensions of mandibular teeth in males across all population groups

	41	42	43	44	45	46
41	1.00	0.67*	0.57*	0.47*	0.42*	0.53*
42		1.00	0.67*	0.49*	0.37*	0.51*
43			1.00	0.51*	0.40*	0.48*
44				1.00	0.64*	0.43*
45					1.00	0.47*
46						1.00

*p<0.05, all teeth in FDI notation

Table 5.28 shows that for males the right mandibular teeth from tooth 41 to tooth 46 there were moderate positive significant correlations in terms of mesiodistal dental crown size (p<0.05).

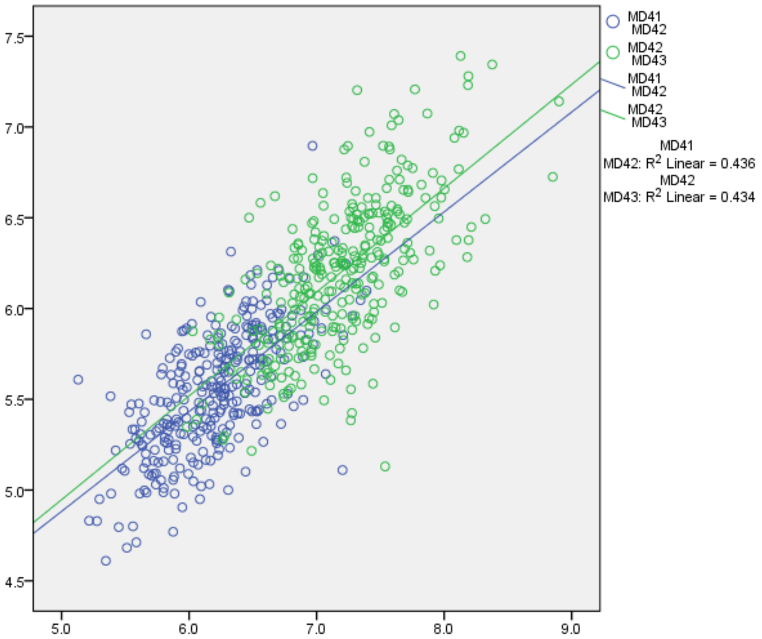


Figure 5.5: Scatter plot showing correlation between mesiodistal dental crown size of tooth 41 and 42 and 42 and 43 in males

Figure 5.5 shows the association between mesiodistal dental crown size of 42 and 41 and 42 and 43 in males. With N= 438, there was a positive significant correlation of

0.67 between 41 and 42 and between 42 and 43 respectively ($p < 0.05$). This was the highest correlation value for males.

Table 5.29: Correlation between maximum mesiodistal crown dimensions of mandibular teeth in females across all population groups

	41	42	43	44	45	46
41	1.00	0.66*	0.54*	0.42*	0.40*	0.48*
42		1.00	0.61*	0.57*	0.39*	0.48*
43			1.00	0.55*	0.43*	0.50*
44				1.00	0.56*	0.46*
45					1.00	0.46*
46						1.00

*p<0.05, all teeth in FDI notation

Table 5.29 shows that for females the right mandibular teeth from tooth 41 to tooth 46 there were moderate positive correlations in terms of mesiodistal dental crown size ($p<0.05$).

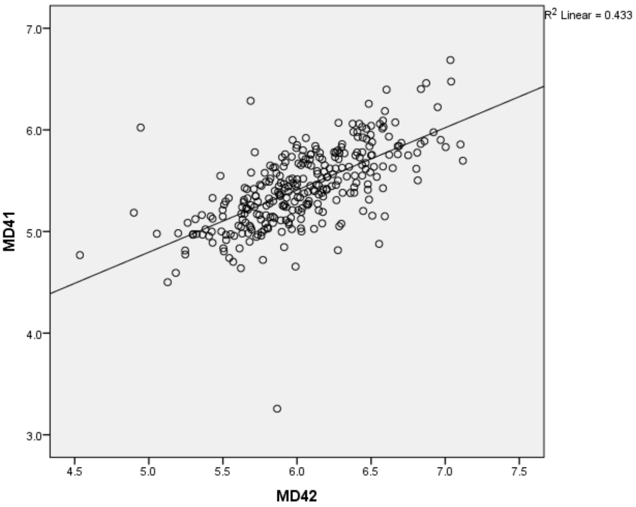


Figure 5.6: Scatter plot showing correlation between mesiodistal dental crown size between tooth 41 and 42

Figure 5.6 shows the association between mesiodistal dental crown size of 42 and 41 in females. With N = 438, the highest correlation for mesiodistal dental crown size in female was between tooth 41 and 42. There was a positive significant correlation of 0.66 ($p < 0.05$).

Table 5.30: Correlation between maximum buccolingual crown dimensions of mandibular teeth in males across all population groups

	41	42	43	44	45	46
41	1.00	0.85*	0.63*	0.41*	0.27*	0.36*
42		1.00	0.65*	0.35*	0.27*	0.29*
43			1.00	0.38*	0.30*	0.30*
44				1.00	0.56*	0.50*
45					1.00	0.51*
46						1.00

*p<0.05, all teeth in FDI notation

Table 5.30 shows that for males the right mandibular teeth from tooth 41 to tooth 46 there were weak to strong positive significant correlations in terms of buccolingual dental crown size ($p<0.05$).

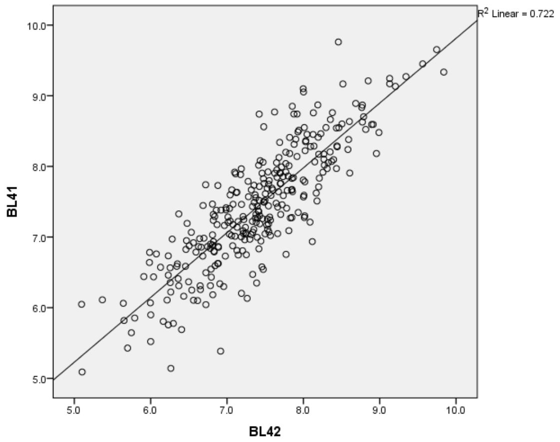


Figure 5.7: Scatter plot showing correlation between buccolingual dental crown size between tooth 41 and 42

Figure 5.7 shows the association between buccolingual dental crown size of 41 and 42 in males. With N = 438, the highest correlation for buccolingual dental crown size in males was between tooth 41 and 42. There was a strong positive significant correlation of 0.85 ($p < 0.05$).

Table 5.31: Correlation between maximum buccolingual crown dimensions of mandibular teeth in females across all population groups

	41	42	43	44	45	46
41	1.00	0.85*	0.50*	0.32*	0.28*	0.42*
42		1.00	0.53*	0.31*	0.26*	0.39*
43			1.00	0.40*	0.24*	0.31*
44				1.00	0.62*	0.57*
45					1.00	0.62*
46						1.00

*$p<0.05$, all teeth in FDI notation

For the females, a similar pattern of correlations was displayed by the right mandibular teeth from tooth 41 to tooth 46. Table 5.31 shows that all teeth had a weak to strong positive significant correlation in terms of buccolingual dental crown size ($p<0.05$).

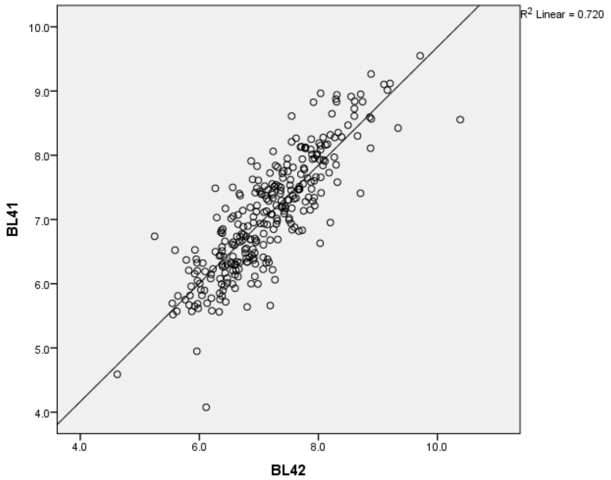


Figure 5.8: Scatter plot showing correlation between buccolingual dental crown size between tooth 41 and 42

Figure 5.9 shows the association between buccolingual dental crown size of 41 and 42 in females. With N = 438, the highest correlation for buccolingual dental crown size in females was between tooth 41 and 42. There was a strong positive significant correlation of 0.85 ($p < 0.05$).

5.2.7 Three dimensional imaging

The following Tables 5.31 to 5.40 summarise the descriptive statistics for dental crown size based on three-dimensional imaging in all the samples, except for the Orang Asli who were excluded because of their relatively low sample size. The trends in tooth size, as well as the patterns in differences between the sexes, were similar to those obtained using 2D data. The use of three dimensional imaging to produce image of dental casts is a more sophisticated technique in not only preserving the study model but also in archiving the study model for future usage and for future advancement in research purposes. Whilst it is acknowledged that not all practitioners will have a 3D scanner available at their own practice, the evidence provided in this study will give insight into how common measurements can be carried out using 2D or 3D methods, provided that the 2D images are taken using standardised methodology.

It is important to highlight the value of analysing what is available (intact structure). In this research, the advantage of measuring mesiodistal and buccolingual crown dimensions is highlighted and it is shown that these measurements can be made precisely provided all criteria are followed. The pattern of sexual dimorphism and ethnic variation that has been displayed shows that it is possible to gain considerable information based on normal features of teeth, a fact that has been highlighted by other researchers.

With 3D imaging, future research can be directed at novel features (phenotypes) that cannot be carried out using 2D imaging. Further discussion on this matter will be provided in the final chapter of this thesis.

Table 5.32: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Europeans (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Right	16	35	10.2	0.49	4.8
	15	35	6.6	0.38	5.8
	14	35	6.8	0.34	5.0
	13	35	7.6	0.43	5.6
	12	35	6.8	0.54	7.8
	11	35	8.5	0.51	6.0
Left	21	35	8.5	0.51	6.0
	22	35	6.7	0.59	8.7
	23	35	7.7	0.40	5.2
	24	35	6.9	0.36	5.2
	25	35	6.7	0.39	5.8
	26	35	10.2	0.50	4.9
Buccolingual					
Right	16	35	11.4	0.49	4.3
	15	35	9.5	0.48	5.1
	14	35	9.3	0.45	4.8
	13	35	7.9	0.59	7.5
	12	35	7.1	0.53	7.5
	11	35	8.2	0.57	6.9
Left	21	35	8.2	0.52	6.4
	22	35	7.1	0.60	8.4
	23	35	8.0	0.62	7.8
	24	35	9.3	0.45	4.9
	25	35	9.5	0.51	5.4
	26	35	11.4	0.53	4.6

*All teeth are described in FDI notation

Table 5.32 shows 3D measurements of mesiodistal and buccolingual crown size in Europeans. Values of CVs tended to conform to Field theory (i.e. 12 is more variable than 11, 15 is more varied than 14). The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 16 using 2D images is 10.4 mm (in males) and 10.1 mm (in females) while it is 10.2 mm using 3D method.

Table 5.33: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Europeans (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Left	36	35	10.6	0.58	5.5
	35	35	7.1	0.39	5.5
	34	35	7.0	0.36	5.2
	33	35	6.8	0.42	6.1
	32	35	5.9	0.34	5.8
	31	35	5.4	0.33	6.1
Right	41	35	5.4	0.31	5.9
	42	35	6.0	0.34	5.8
	43	35	6.9	0.42	6.0
	44	35	7.1	0.37	5.2
	45	35	7.2	0.37	5.2
	46	35	10.7	0.62	5.8
Buccolingual					
Left	36	35	10.5	0.49	4.7
	35	35	8.5	0.45	5.2
	34	35	7.8	0.40	5.2
	33	35	7.4	0.43	5.8
	32	35	7.0	0.45	6.4
	31	35	7.0	0.36	5.2
Right	41	35	7.0	0.44	6.3
	42	35	7.1	0.47	6.7
	43	35	7.3	0.39	5.4
	44	35	7.7	0.39	5.0
	45	35	8.5	0.43	5.1
	46	35	10.5	0.44	4.2

*All teeth are described in FDI notation

Table 5.33 shows 3D measurements of mesiodistal and buccolingual crown size in Europeans. Values of CVs tended to conform to Field theory (i.e. 35 is more variable than 34). CV of buccolingual dimensions of lower incisors did not seem to follow this theory. The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 36 using 2D images is 10.9 mm (in males) and 10.5 mm (in females) while it is 10.6 mm using 3D method.

Table 5.34: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Australian Aboriginals (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Right	16	35	10.7	0.40	3.8
	15	35	6.8	0.33	4.8
	14	35	7.1	0.37	5.2
	13	35	7.9	0.51	6.5
	12	35	7.2	0.62	8.6
	11	35	8.9	0.48	5.4
Left	21	35	8.8	0.49	5.6
	22	35	7.2	0.58	8.0
	23	35	7.8	0.54	6.9
	24	35	7.2	0.38	5.2
	25	35	6.8	0.34	5.0
	26	35	10.6	0.44	4.2
Buccolingual					
Right	16	35	12.0	0.46	3.8
	15	35	9.9	0.46	4.6
	14	35	9.8	0.45	4.6
	13	35	8.5	0.65	7.7
	12	35	7.4	0.62	8.4
	11	35	8.6	0.64	7.4
Left	21	35	8.7	0.64	7.4
	22	35	7.4	0.62	8.4
	23	35	8.4	0.70	8.3
	24	35	9.8	0.44	4.5
	25	35	9.9	0.47	4.7
	26	35	12.0	0.43	3.6

*All teeth are described in FDI notation

Table 5.34 shows 3D measurements of mesiodistal and buccolingual crown size in Australian Aboriginals. Conformed to the field theory CV within each tooth classes is observed (i.e. 12 is more varied than 11, 15 is more varied than 14). The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 16 using 2D images is 11.0 mm (in males) and 10.7 mm (in females) while it is 10.7 mm using 3D method.

Table 5.35: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Australian Aboriginals (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Left	36	35	11.3	0.52	4.6
	35	35	7.2	0.42	5.8
	34	35	7.1	0.38	5.4
	33	35	7.0	0.42	6.0
	32	35	6.3	0.37	5.8
	31	35	5.6	0.42	7.5
Right	41	35	5.6	0.40	7.0
	42	35	6.3	0.37	5.9
	43	35	7.1	0.43	6.0
	44	35	7.1	0.38	5.3
	45	35	7.3	0.39	5.4
	46	35	11.4	0.51	4.5
Buccolingual					
Left	36	35	10.9	0.41	3.7
	35	35	8.7	0.39	4.5
	34	35	8.1	0.45	5.5
	33	35	7.9	0.57	7.2
	32	35	7.6	0.76	9.9
	31	35	7.6	0.77	9.0
Right	41	35	7.7	0.80	9.5
	42	35	7.6	0.72	9.5
	43	35	7.9	0.60	7.6
	44	35	8.1	0.42	5.1
	45	35	8.7	0.47	5.4
	46	35	10.9	0.45	4.1

*All teeth are described in FDI notation

Table 5.35 shows 3D measurements of mesiodistal and buccolingual crown size in Australian Aboriginals. Most values of CVs tended to follow Field theory. The mean value of each dental crown size are comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 36 using 2D images is 11.7 mm (in males) and 11.2 mm (in females) while it is 11.3 mm using 3D method.

Table 5.36: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Malay (3D method)(in mm)

		N	Mean	SD	CV
Mesiodistal					
Right	16	35	10.5	0.48	4.6
	15	35	6.9	0.40	5.8
	14	35	7.3	0.46	6.3
	13	35	7.9	0.51	6.4
	12	35	7.0	0.49	6.9
	11	35	8.5	0.48	5.6
Left	21	35	8.5	0.47	5.5
	22	35	7.1	0.50	7.1
	23	35	7.9	0.52	6.6
	24	35	7.4	0.43	5.9
	25	35	7.0	0.44	6.4
	26	35	10.4	0.47	4.5
Buccolingual					
Right	16	35	11.5	0.48	4.2
	15	35	9.5	0.53	5.5
	14	35	9.7	0.51	5.3
	13	35	8.0	0.58	7.3
	12	35	7.5	0.34	4.5
	11	35	8.9	0.47	5.3
Left	21	35	9.0	0.38	4.2
	22	35	7.6	0.43	5.7
	23	35	8.1	0.45	5.6
	24	35	9.8	0.42	4.3
	25	35	9.6	0.42	4.4
	26	35	11.6	0.50	4.3

*All teeth are described in FDI notation

Table 5.36 shows 3D measurements of mesiodistal and buccolingual crown size in Malays. Most values of CVs followed Field theory (i.e. 22 is more variable than 21, 25 is more variable than 24) except for the buccolingual crown dimensions of 11 and 12. The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 16 using 2D images is 10.6 mm (in males) and 10.5 mm (in females) while it is 10.5 mm using 3D method.

Table 5.37: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Malays (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Left	36	35	11.1	0.50	4.5
	35	35	7.3	0.43	5.9
	34	35	7.3	0.40	5.5
	33	35	7.0	0.47	6.6
	32	35	6.2	0.35	5.6
	31	35	5.5	0.31	5.6
Right	41	35	5.5	0.37	6.7
	42	35	6.2	0.37	5.9
	43	35	7.0	0.45	6.4
	44	35	7.2	0.42	5.8
	45	35	7.3	0.46	6.3
	46	35	11.1	0.50	4.4
Buccolingual					
Left	36	35	10.5	0.41	3.9
	35	35	8.5	0.52	6.1
	34	35	7.9	0.56	7.1
	33	35	7.5	0.57	7.6
	32	35	7.3	0.54	7.4
	31	35	7.3	0.50	6.9
Right	41	35	7.2	0.55	7.6
	42	35	7.4	0.70	9.5
	43	35	7.5	0.54	7.3
	44	35	7.9	0.42	5.4
	45	35	8.5	0.41	4.8
	46	35	10.5	0.40	3.8

*All teeth are described in FDI notation

Table 5.37 shows 3D measurements of mesiodistal and buccolingual crown size in Malays. Most values of CVs followed Field theory, although the pattern was reversed for the buccolingual crown dimensions of the premolars. The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 36 using 2D images is 11.3 mm (in males) and 11.0 mm (in females) while it is 11.1 mm using 3D method.

Table 5.38: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Chinese (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Right	16	35	10.5	0.46	4.4
	15	35	7.1	0.39	5.4
	14	35	7.3	0.37	5.1
	13	35	8.1	0.49	6.1
	12	35	7.2	0.52	7.3
	11	35	8.6	0.43	5.0
Left	21	35	8.5	0.38	4.4
	22	35	7.2	0.48	6.7
	23	35	7.9	0.45	5.7
	24	35	7.3	0.38	5.3
	25	35	7.0	0.32	4.6
	26	35	10.4	0.46	4.5
Buccolingual					
Right	16	35	11.4	0.49	4.3
	15	35	9.5	0.55	5.8
	14	35	9.7	0.52	5.4
	13	35	8.1	0.58	7.2
	12	35	7.5	0.48	6.4
	11	35	8.7	0.46	5.3
Left	21	35	8.9	0.50	5.6
	22	35	7.6	0.55	7.3
	23	35	8.0	0.45	5.6
	24	35	9.8	0.41	4.2
	25	35	9.6	0.52	5.4
	26	35	11.5	0.49	4.3

*All teeth are described in FDI notation

Table 5.38 shows 3D measurements of mesiodistal and buccolingual crown size in Chinese. CV values generally followed Field theory (i.e. 22 is more variable than 21, 25 is more variable than 24). The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 16 using 2D images is 10.7 mm (in males) and 10.4 mm (in females) while it is 10.5 mm using 3D method.

Table 5.39: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Chinese (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Left	36	35	11.0	0.52	4.7
	35	35	7.3	0.43	5.8
	34	35	7.2	0.32	4.5
	33	35	7.0	0.38	5.5
	32	35	6.1	0.37	6.1
	31	35	5.5	0.30	5.4
Right	41	35	5.5	0.32	5.8
	42	35	6.1	0.32	5.3
	43	35	7.0	0.40	5.7
	44	35	7.3	0.33	4.5
	45	35	7.4	0.38	5.1
	46	35	11.1	0.57	5.1
Buccolingual					
Left	36	35	10.7	0.45	4.2
	35	35	8.5	0.43	5.1
	34	35	8.0	0.43	5.4
	33	35	7.6	0.43	5.7
	32	35	7.2	0.43	5.9
	31	35	7.1	0.48	6.7
Right	41	35	7.1	0.51	7.2
	42	35	7.1	0.41	5.8
	43	35	7.5	0.46	6.2
	44	35	8.0	0.41	5.1
	45	35	8.5	0.45	5.2
	46	35	10.7	0.49	4.6

*All teeth are described in FDI notation

Table 5.39 shows 3D measurements of mesiodistal and buccolingual crown size in Malays. Values of CV generally followed Field theory except for the buccolingual crown dimensions of 34 and 35. The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 36 using 2D images is 11.3 mm (in males) and 10.9 mm (in females) while it is 11.0 mm using 3D method.

Table 5.40: Descriptive statistics for mesiodistal and buccolingual dental crown size of maxillary right and left teeth in Indians (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Right	16	35	10.4	0.49	4.7
	15	35	6.8	0.38	5.6
	14	35	7.0	0.38	5.4
	13	35	7.7	0.48	6.2
	12	35	7.0	0.57	8.2
	11	35	8.5	0.45	5.2
Left	21	35	8.5	0.48	5.6
	22	35	7.0	0.56	8.0
	23	35	7.6	0.42	5.5
	24	35	7.0	0.40	5.7
	25	35	6.8	0.38	5.6
	26	35	10.4	0.52	5.0
Buccolingual					
Right	16	35	11.4	0.52	4.6
	15	35	9.4	0.51	5.4
	14	35	9.4	0.50	5.3
	13	35	7.8	0.54	6.9
	12	35	7.2	0.55	7.6
	11	35	8.6	0.50	5.9
Left	21	35	8.6	0.55	6.4
	22	35	7.3	0.50	6.8
	23	35	7.8	0.53	6.8
	24	35	9.5	0.49	5.2
	25	35	9.5	0.54	5.7
	26	35	11.4	0.54	4.8

*All teeth are described in FDI notation

Table 5.40 shows 3D measurements of mesiodistal and buccolingual crown size in Chinese. Values of CV generally followed Field theory (i.e. 22 is more variable than 21, 25 is more variable than 24). The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 16 using 2D images is 10.5 mm (in males) and 10.3 mm (in females) while it is 10.4 mm using 3D method.

Table 5.41: Descriptive statistics for mesiodistal and buccolingual dental crown size of mandibular right and left teeth in Indians (3D method) (in mm)

		N	Mean	SD	CV
Mesiodistal					
Left	36	35	10.9	0.53	4.9
	35	35	7.3	0.42	5.8
	34	35	7.1	0.40	5.6
	33	35	6.9	0.42	6.1
	32	35	6.0	0.40	6.7
	31	35	5.5	0.36	6.6
Right	41	35	5.4	0.31	5.7
	42	35	6.0	0.35	5.9
	43	35	6.8	0.43	6.2
	44	35	7.1	0.38	5.4
	45	35	7.3	0.39	5.4
	46	35	11.0	0.60	5.5
Buccolingual					
Left	36	35	10.7	0.52	4.9
	35	35	8.6	0.54	6.3
	34	35	7.9	0.55	7.0
	33	35	7.2	0.58	8.0
	32	35	7.3	0.56	7.7
	31	35	7.4	0.52	7.0
Right	41	35	7.4	0.54	7.3
	42	35	7.3	0.52	7.2
	43	35	7.2	0.46	6.4
	44	35	7.8	0.49	6.3
	45	35	8.6	0.46	5.4
	46	35	10.6	0.48	4.5

*All teeth are described in FDI notation

Table 5.41 shows 3D measurements of mesiodistal and buccolingual crown size in Malays. Values of CV generally followed Field theory with a few exceptions. The mean value of each dental crown size is comparable to measurements carried out on the 2D images. (i.e. mean value of mesiodistal of 36 using 2D images is 11.0 mm (in males) and 10.8 mm (in females) while it is 10.9 mm using 3D method.

5.3 Comparison of techniques: two dimensional versus three dimensional

One of the aims of this study was to explore different methodologies for measuring variation of dental crown size. This aim was achieved by performing this task using a standardised two-dimensional system as a source for two-dimensional data, as well as an Optix 400S 3D laser scanner for three-dimensional data. More information about both of these methods was detailed in the Materials and Methods chapter of this thesis.

Table 5.42 highlights differences in measurement of dental crown size using both of these techniques, for three of the study samples. Malaysian samples were categorized, as one population group. Two different methods are reported, 2D and 3D, to show comparisons between them. The issue of cost will weigh one against the other. Without 3D imaging, it is still possible to record dental crown size by means of 2D imaging, provided that the system is standardised and also measurements are carefully defined and recorded.

The values of CV tended to be less variable when measurement was carried out using the 3D method. This may suggest that measurements obtained using the 3D method have greater validity and are less affected by tooth rotations. However, in terms of reproducibility of the measurements when similar reference points were used, measurements using both of these methods were comparable. This has been highlighted earlier in this section in terms of measurement reliability.

Table 5.42: Descriptive statistics for dental crown size in three populations using 2D and 3D systems – mesiodistal crown diameters (in mm)

Tooth	2D									3D								
	Europeans			Australian Aboriginals			Malaysians			Europeans			Australian Aboriginals			Malaysians		
Males	n	Mean	SD	n	Mean	SD	n	Mean	SD	N	Mean	SD	n	Mean	SD	n	Mean	SD
11	35	8.7	0.47	35	**9.1**	0.55	35	8.4	0.61	35	8.5	0.61	35	**9.3**	0.41	35	8.2	0.67
12	35	7.0	0.67	35	**7.5**	0.6	35	7.1	0.63	35	7.2	0.72	35	**7.7**	0.51	35	7.4	0.44
13	35	7.8	0.39	35	**8.1**	0.54	35	8.0	0.52	35	7.8	0.57	35	**8.1**	0.63	35	**8.1**	0.35
14	35	6.9	0.37	35	**7.4**	0.46	35	7.3	0.50	35	6.7	0.38	35	**7.4**	0.47	35	6.9	0.47
15	35	6.7	0.33	35	6.9	0.50	35	**7.2**	0.06	35	6.6	0.30	35	**7.0**	0.40	35	6.8	0.27
16	35	10.4	0.53	35	**11.0***	0.49	35	10.6	0.55	35	10.3	0.67	35	**11.1***	0.55	35	10.6	0.2
Females	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
11	35	8.4	0.55	35	**8.8**	0.54	35	8.5	0.62	35	8.5	0.61	35	**9.0**	0.65	35	8.7	0.47
12	35	6.7	0.62	35	7.0	0.76	35	**7.4**	0.68	35	6.9	0.53	35	7.1	0.72	35	**7.6**	0.62
13	35	7.4	0.45	35	**7.8**	0.50	35	7.7	0.56	35	7.5	0.38	35	**8.0**	0.61	35	7.5	0.50
14	35	6.7	0.40	35	**7.2***	0.47	35	**7.2**	0.47	35	6.8	0.33	35	**7.4***	0.55	35	6.8	0.1
15	35	6.6	0.42	35	6.8	0.44	35	**7.1**	0.89	35	6.7	0.42	35	**7.0**	0.41	35	6.8	0.95
16	35	10.1	0.50	35	**10.7***	0.53	35	10.5	0.57	35	10.0	0.64	35	**10.9***	0.56	35	10.5	0.3

**All teeth are described in FDI notation*

**shaded values indicate the largest mesiodistal crown diameters in comparison to other groups*

5.4 Discussion

Dental crown dimensions have been used by several researchers to understand more about variation in sexual dimorphism within and between human populations (Garn et al., 1977; Ditch et al., 1972; Brown and Townsend, 1979; Acharya and Mainali, 2008). The differences between dental crown dimensions of males and females are reported to be only around 3–4% in magnitude (Kieser, 1990). However, by recognizing the most striking features that contribute to differences between males and females, profiling of individuals could become feasible.

Whilst the sexing of teeth using dental crown dimensions could not exclusively point to a particular individual, the information obtained from quantification of dental crown variables rather than subjective observation can help narrow down possible choices. Acharya and Mainali (2008) highlighted the value of both mesiodistal and buccolingual dental crown size as a better odontometric method of determining sex rather than using only one dental crown dimension. This has been confirmed generally in this study where, in specific populations, findings from average values of mesiodistal dental crown dimensions gave different outcomes compared to the use of buccolingual dental crown size.

The analyses revealed that canines were the most sexually dimorphic teeth across all populations. This is comparable to research carried out by Angadi et al., (2013) who highlighted that the canine is the most sexually dimorphic tooth followed by molar teeth. In general, dental crown dimension variables were significantly larger in males. These findings support those by Angadi et al., (2013) and Zorba et al., (2011). There is some evidence of the opposite trend in sexual dimorphism, with female tooth dimensions being larger than those of males for some of the dental crown dimensions, especially in Orang Asli but this result is rare.

Traditionally, measurement of dental crown size directly from study models has been carried out to explore sexual dimorphism within human populations. With regards to the analysis of dental features for the study of variation (in general) and for specific use of profiling the sex of an individual, one can extend from the traditional method to various alternatives. With the development of sophisticated imaging systems and statistical methods to quantify shapes, it is now becoming feasible to objectively compare the shapes of dental crowns between males and females and between individuals from different ethnic groups (Al-Shahrani et al., 2014).

A number of variations in dental crown size have been widely reported and this has given rise to important findings and conclusions. These variations could be related to many factors, such as differences between different population groups as well as sexual dimorphism. However, all variations are influenced by the interaction of genetic, epigenetic and environmental factors (Brook et al., 2014b). This interaction may have a direct or indirect impact on the development of the dentition. Garn et al., (1980) reported that the size of the dentition could be affected by a number of genes, not just a single gene. Small tooth dimensions could also be linked to poor maternal conditions during pregnancy and small birth size.

The dimensions of dental crowns differ among different populations. While smaller tooth dimensions can be seen in European populations than in Chinese, larger tooth dimensions are observed in Australian Aboriginals and Africans (Bailit, 1975; Perzigian, 1976; Yuen et al., 1997). The influence of population variation, racial or ethnic variation has also been shown in dental crown size (Brook et al., 2009). It was noted that Europeans have narrower anterior teeth and broader posterior teeth. Conversely, Africans and Australian Aboriginals have shorter and broader anterior teeth in conjunction with longer and narrower posterior teeth (Harris and Rathbun, 1991).

In this study, dental crown size was found to be largest in the Australian Aboriginal sample, putting these people in the megadontic group of dentitions (Hanihara and Ishida, 2005). Europeans had the smallest dental crown size compared to the other populations. This is also consistent with other research (Hanihara and Ishida, 2005; Brook et al., 2009).

The Malaysian sample tended to fall in between the Australian Aboriginal and European groups in terms of their tooth size, with Malays tending to have larger tooth size compared with the other populations. The findings of the present study are comparable to those of previous research carried out on the same Malays population group but where the measurements were carried out using digital callipers (Khamis et al., 2007).

Sexual dimorphism is considered as an important factor in dental crown dimension variation. Females were found to have narrower recorded crown dimensions than males (Moorrees et al., 1957). Other researchers obtained the same finding for both tooth size and shape (Garn et al., 1967; Garn and Lewis, 1970). There were sex differences in the mesiodistal and buccolingual dimensions, with the latter being bigger than the former. Lavelle (1975) reported that males generally had larger tooth sizes than females. Kondo and Townsend (2006) measured the overall crown size and areas of individual cusps and their finding also demonstrated sexual dimorphism, with values in males exceeding those in females. On the other hand, other studies have not found any sexual dimorphism in their samples (Mirabella et al., 2011; Yaqoob et al., 2011). The results show that for all of the samples, dental crown size in males was greater generally than in females. This is consistent with previous studies that have confirmed the occurrence of sexual dimorphism within the human dentition (Alvesalo, 1971).

Mesiodistal dimensions of first molars, both upper and lower, tended to show the most dimorphism across all populations. These findings are similar to those of Khamis et al., (2007) who compared dental crown size within and between Malaysian populations. The canine teeth showed the strongest evidence of high levels of sexual dimorphism. Evidence of sexual dimorphism in humans has been observed since the 1960s by Garn et al., (1967). More recently, Zorba et al., (2011) and Khamis et al., (2007) have highlighted that canines tend to be the most dimorphic teeth followed by first premolars, maxillary second premolars and mandibular second molars. Highly dimorphic teeth noted in this study were the upper canine, in both dimensions, in Malays, and the mesiodistal diameter of the lower first molars in Chinese. Buccolingual dimensions of first molars, both upper and lower, also showed high levels of dimorphism across all populations.

Garn et al., (1967) proposed the presence of a ‘canine field’. This field suggested the likelihood of the lateral incisor and first premolar for sexual dimorphism being affected by the adjacent sexually dimorphic canine. This evidence was displayed in all samples except for the Orang Asli group.

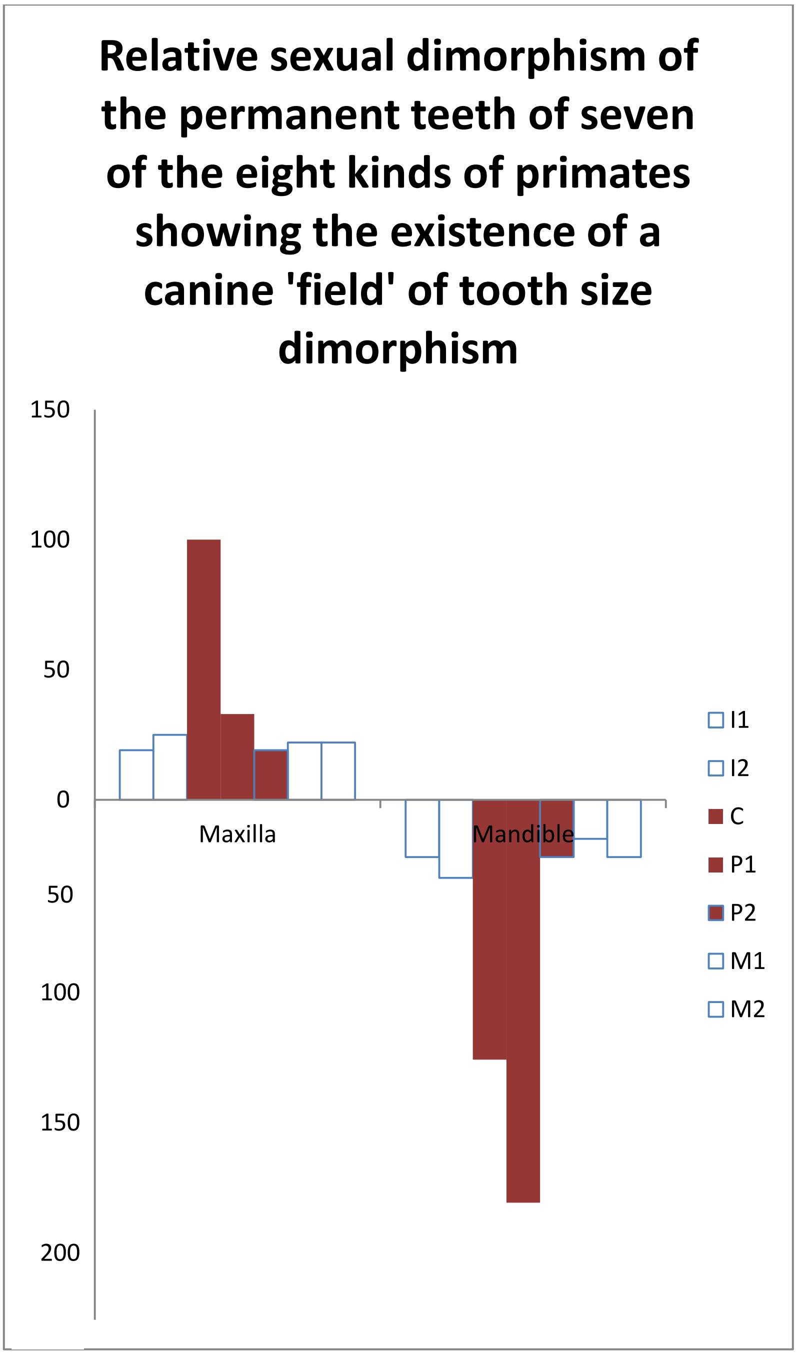


Figure 5.9: Canine field of sexual dimorphism (adapted from Garn et al., (1967))

The percentage value of sexual dimorphism for tooth size was calculated as follows: 100 x ([male mean- female mean]/female mean), where mean values of tooth size for a specific tooth were entered into the formula. The average percentage of sexual dimorphism observed in dental crown size ranged from 5.65% (for mesiodistal dental crown size) to 6.73% (for buccolingual dental crown size). The values tended to be greater for buccolingual dimensions, with the highest percentage recorded for the buccolingual dimension of the upper central incisor of the European group, with a value of 8.57%. When comparisons were made between the different ethnic groups for the degree of sexual dimorphism, the Australian Aboriginal group and the European group both showed high values.

Correlations between dimensions

There were strong correlations between teeth of the same class, for example between the mesiodistal dimensions of central and lateral incisors or between the mesiodistal dimensions of first and second premolars. There was also evidence of strong correlations between canines and first premolars in females. The premolars are usually considered to be the ‘middle’ teeth separating anterior teeth (consisting of incisors and canines) from the posterior molars. They are also considered to be teeth that are characteristic of modern humans, providing evidence of evolutionary trends in tooth development over time. It is possible that the maximum mesiodistal crown size of the canine and first premolar may in some way be correlated to one another during the developmental process.

Two-dimensional versus three-dimensional imaging

Using a 2D approach, where all the measurements were obtained using standardised photographs, measurements of the labiolingual dimensions of anterior teeth (e.g. central and lateral incisors) were more difficult to record accurately and this was reflected in the higher values of the coefficients of variation of these dimensions compared to other teeth. It is difficult to determine the maximum labiolingual crown dimensions of anterior teeth using 2D images as their maximum diameters are near to the cervical region and minor variations in the location of the gingival margins or the alignment of these teeth can lead to variation in measurement.

Evidence from this study supports the potential value of using 3D imaging to measure dental crown size. Using 3D imaging, it is possible to measure other variables (such as surface areas or volumes) rather than traditional linear dimensions. It has been shown in this research that acceptable levels of reliability can be reached using 3D systems.

The dimensions were generally not significantly different whether measured by 2D or 3D approaches, which indicate that three dimensional imaging now comes close to the ‘gold standard’ of measuring directly on a study model. This has been highlighted by other researchers who have also looked at the potential use of 3D imaging to measure dental variables (Smith et al., 2009a). 3D equipment can be costly but this method provides a realistic alternative and a more valid representation of a dental cast than 2D images that do not allow the entire crown of the tooth to be visualised with the high level of accuracy required for research purposes.

5.5 Multivariate analysis

The use of normal morphological features of the dentition has the potential to be more widely used in identification cases. Whilst the current practice of identifying features of dental treatments is often useful in obtaining a positive identification, this will serve its purpose in situations where no dental treatment has been carried out.

This section looks at comparing dental crown measurements to investigate whether or not there is enough information within the dentition to be used for identification.

In order to identify a combination of features that may be useful in discriminating groups, a principal component analysis was conducted. Principal component analysis (PCA) is a method of reducing the data. In this section, all linear measurements of dental crown size were put together to ascertain the relationships between dental variables. With a large number of variables measured, the dispersion matrix was too large to study and interpret properly. The aim is to display the value of each dental variable to be used for variation and identification purposes. Therefore, to interpret all the data in a more meaningful form, it was necessary to reduce the number of variables to a few, interpretable linear combinations of the data. Each linear combination corresponds to a principal component.

The 'Rotated Component Matrix' of dental crown size shows factor variance after rotation (Varimax) which was used to transform the initial matrix into one that is easier to interpret.

The aim of this part of analysis is to display the value of having a large number of information on dental variables to display group separation. The analysis was carried out using progressive addition of information beginning from only mesiodistal and buccolingual of teeth on the maxillary arch, to only those of mandibular arch and combination of both and then combination of dental crown size with dental arch size.

PCA of dental crown variables of the maxillary arch.

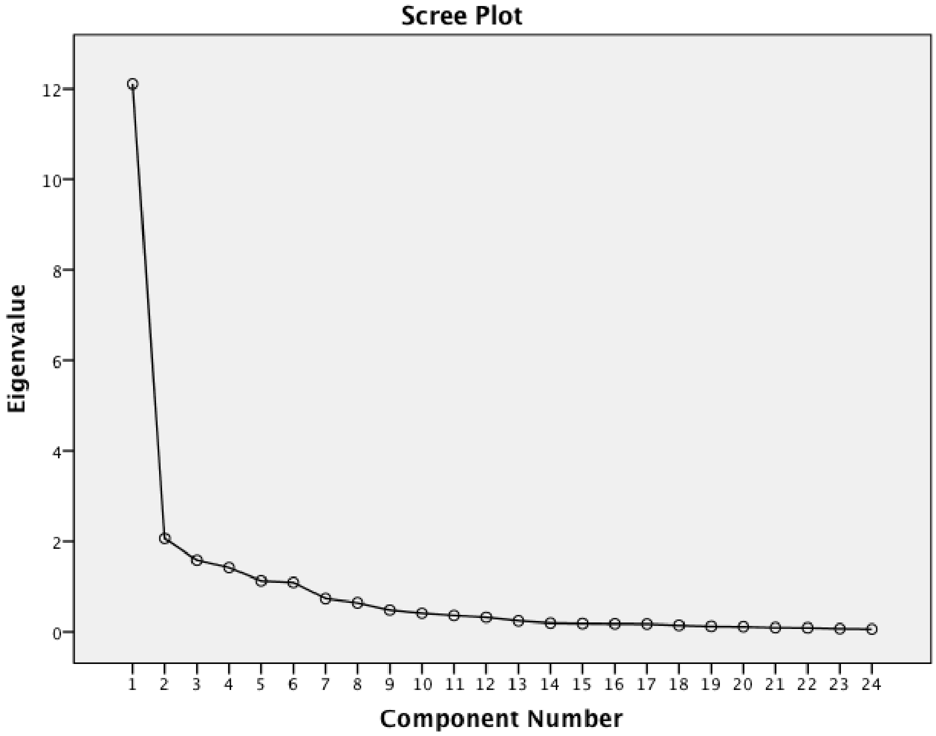


Figure 5.10: Scree plot showing variance of each component in the dataset

Based on figure 5.9, a scree plot was used to visualize the number of components to be retained to explain a high percentage of variation. Based on the 'elbow point' in the scree plot, a total of 4 components were retained to explain 71.6 % variation.

Rotated Component Matrix[a]

	Component			
	1	2	3	4
UMD16	.327	.738	.111	.256
UMD15	.616	.175	.067	.511
UMD14	.647	.241	.209	.453
UMD13	.425	.296	.290	.417
UMD12	.249	.269	.166	.743
UMD11	.118	.711	.128	.475
UMD21	.168	.662	.128	.505
UMD22	.264	.208	.244	.733
UMD23	.433	.285	.344	.350
UMD24	.674	.227	.233	.396
UMD25	.631	.215	.048	.513
UMD26	.270	.755	.135	.227
UBL16	.421	.763	.274	-.030
UBL15	.788	.318	.228	.113
UBL14	.779	.285	.345	.161
UBL13	.243	.226	.721	-.162
UBL12	.195	.033	.659	.419
UBL11	.109	.210	.742	.257
UBL21	.135	.194	.753	.294
UBL22	.204	.009	.679	.452
UBL23	.304	.131	.742	-.062
UBL24	.769	.244	.334	.176
UBL25	.805	.303	.212	.109
UBL26	.481	.731	.274	-.013

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 7 iterations.

Figure 5.11: Rotated component matrix of 4 components

In the correlation matrix (not showing in this section), the variables are highly correlated. All values are greater than 0.3.

Table 5.43 Group assignment based on the rotated component matrix of maxillary dental crown dimension variables

Classification Results[a]

Ethnicity			Predicted Group Membership						Total
			Europeans	Australian Aboriginals	Malaysian Malay	Malaysian Chinese	Malaysian Indians	Malaysian Orang Asli	
Original	Count	Europeans	74	8	4	0	18	5	109
		Australian Aboriginals	13	57	6	6	7	1	90
		Malaysian Malay	4	7	35	26	25	1	98
		Malaysian Chinese	3	3	18	51	17	1	93
		Malaysian Indians	24	10	13	12	44	2	105
		Malaysian Orang Asli	7	8	7	5	3	9	39
	%	Europeans	67.9	7.3	3.7	.0	16.5	4.6	100.0
		Australian Aboriginals	14.4	63.3	6.7	6.7	7.8	1.1	100.0
		Malaysian Malay	4.1	7.1	35.7	26.5	25.5	1.0	100.0
		Malaysian Chinese	3.2	3.2	19.4	54.8	18.3	1.1	100.0
		Malaysian Indians	22.9	9.5	12.4	11.4	41.9	1.9	100.0
		Malaysian Orang Asli	17.9	20.5	17.9	12.8	7.7	23.1	100.0

a. 50.6% of original grouped cases correctly classified.

Discriminant Function Analysis of dental crown variables of the maxillary arch allowed only about 50% of correctly classified individuals between the six population groups (Table 5.43). Canonical discriminant functions using weighted dental variables that were weighted using the first four components of PCAs (MD of 16,26,14,24,15,25,11,21,12,22 and BL of 16,26,14,15,24,25,13,23) shows separation was obvious between Australian aboriginals and the European and Malaysian groups. However Malaysian groups were pooled within close space.

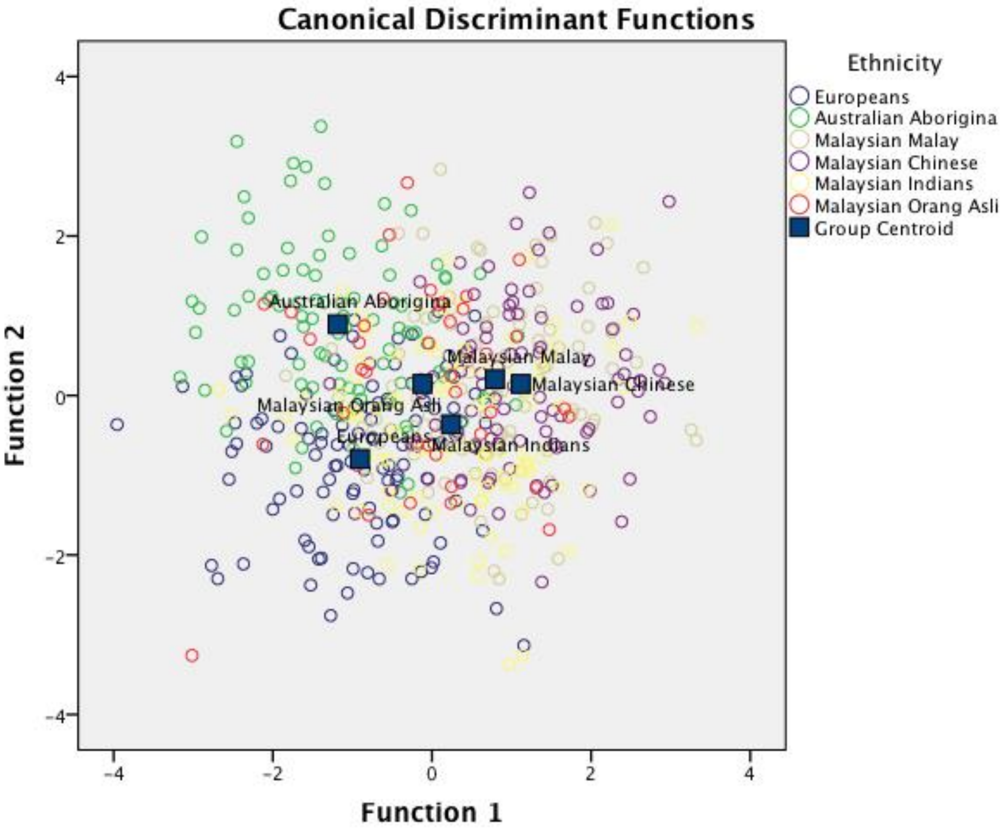


Figure 5.12: Canonical discriminant functions of maxillary dental crown dimensions

PCA of dental crown variables of the mandibular arch.

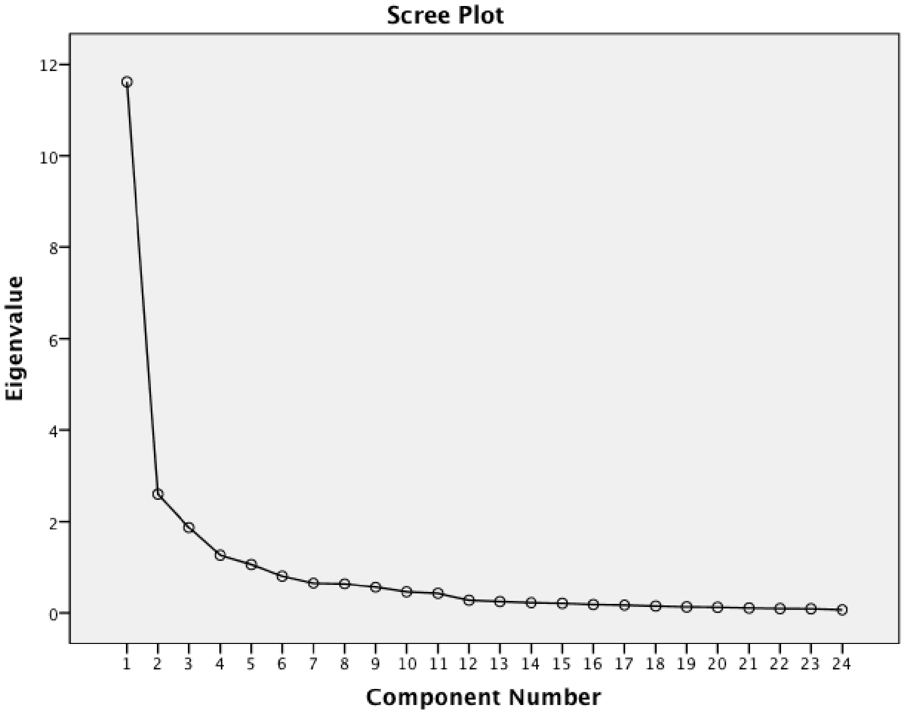
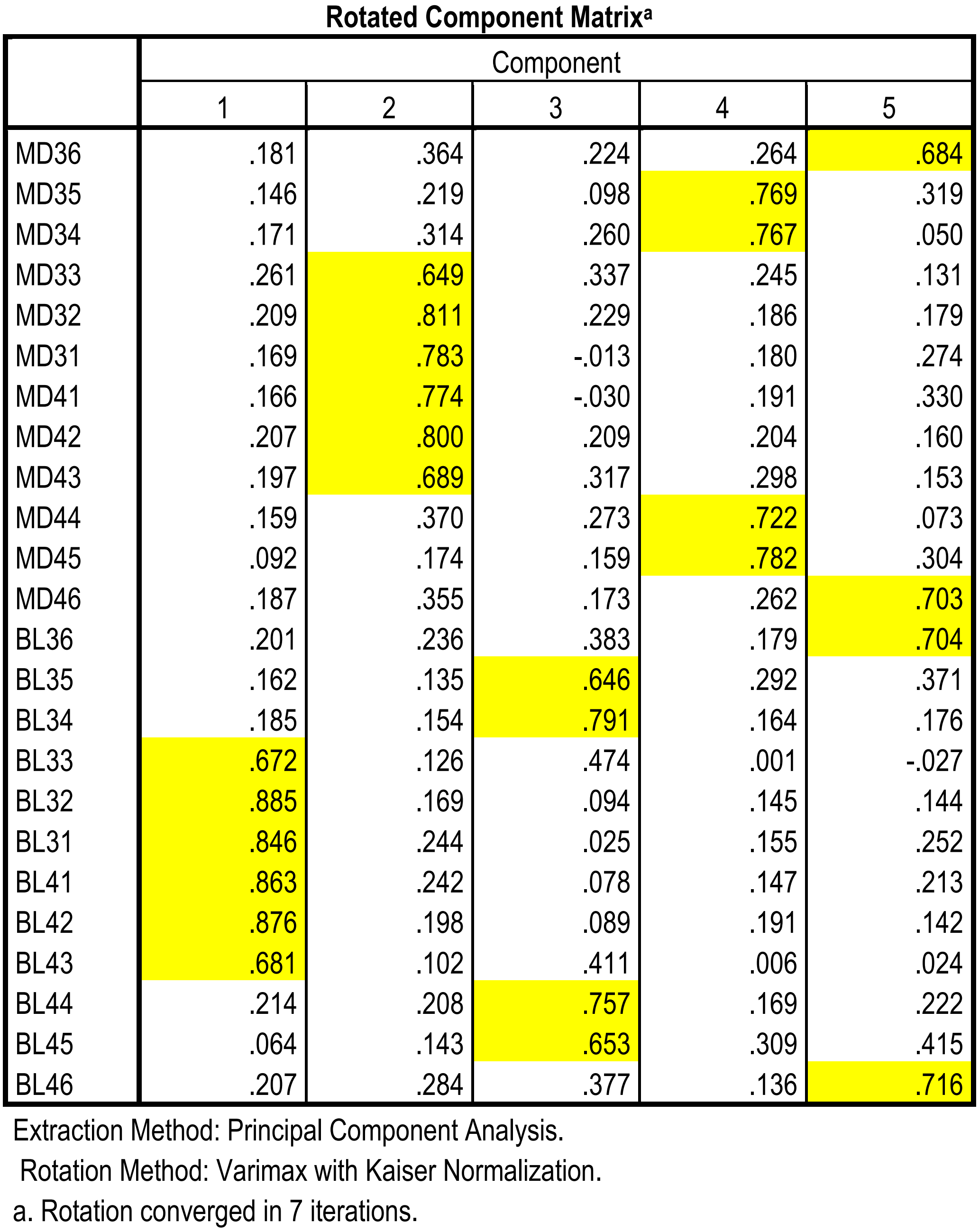


Figure 5.13: Scree plot of component numbers after PCA

Based on figure 5.13, a scree plot was used to visualize the number of components to be retained to explain high percentage of variation. Based on the ‘elbow point’ in the scree plot, a total of 5 components were retained to explain 76.7 % variation.



Rotated Component Matrix[a]

	Component				
	1	2	3	4	5
MD36	.181	.364	.224	.264	.684
MD35	.146	.219	.098	.769	.319
MD34	.171	.314	.260	.767	.050
MD33	.261	.649	.337	.245	.131
MD32	.209	.811	.229	.186	.179
MD31	.169	.783	-.013	.180	.274
MD41	.166	.774	-.030	.191	.330
MD42	.207	.800	.209	.204	.160
MD43	.197	.689	.317	.298	.153
MD44	.159	.370	.273	.722	.073
MD45	.092	.174	.159	.782	.304
MD46	.187	.355	.173	.262	.703
BL36	.201	.236	.383	.179	.704
BL35	.162	.135	.646	.292	.371
BL34	.185	.154	.791	.164	.176
BL33	.672	.126	.474	.001	-.027
BL32	.885	.169	.094	.145	.144
BL31	.846	.244	.025	.155	.252
BL41	.863	.242	.078	.147	.213
BL42	.876	.198	.089	.191	.142
BL43	.681	.102	.411	.006	.024
BL44	.214	.208	.757	.169	.222
BL45	.064	.143	.653	.309	.415
BL46	.207	.284	.377	.136	.716

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 7 iterations.

Figure 5.14: Rotated component matrix of 5 components of mandibular dental arch

In the Correlation Matrix (not showing in this section), the variables are highly correlated. All values are greater than 0.3. Different weightage of PCs were observed between maxillary dental crown variables to the mandibular dental crown variables.

Discriminant Function Analysis of dental crown variables of the mandibular arch still allowed only about 50% of correctly classified individuals between the six population groups (Table 5.44). Canonical functions analysis using dental variables weighted in the first five components of PCA shows separation was still obvious between Australian Aboriginals and the Europeans and Malaysian groups. Malaysian groups were more closely pooled within the same space in function 1. There is an overlap between the European and Indian group averages.

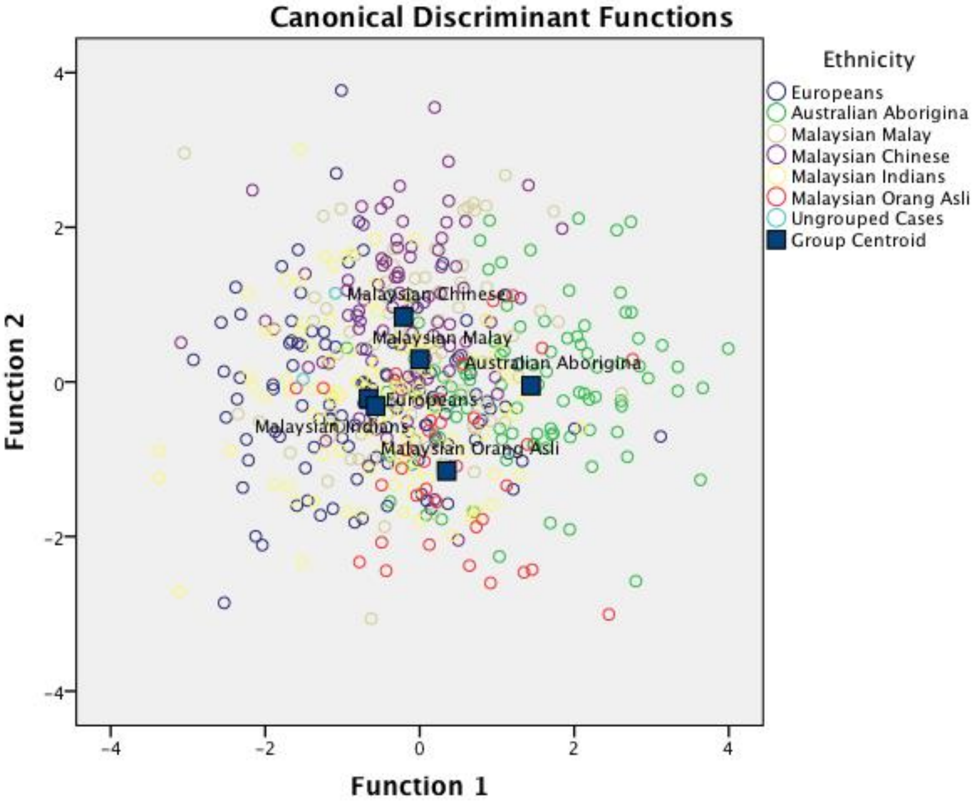


Figure 5.15: Canonical discriminant functions of mandibular dental crown dimensions

Table 5.44 Group assignment based on the rotated component matrix of mandibular dental crown dimension variables

Classification Results[a]

		Ethnicity	Predicted Group Membership						Total
			Europeans	Australian Aboriginals	Malaysian Malay	Malaysian Chinese	Malaysian Indians	Malaysian Orang Asli	
Original	Count	Europeans	55	9	13	11	27	3	118
		Australian Aboriginals	7	66	8	5	9	3	98
		Malaysian Malay	16	11	36	14	16	3	96
		Malaysian Chinese	8	6	9	50	12	2	87
		Malaysian Indians	22	12	6	16	48	4	108
		Malaysian Orang Asli	6	5	4	1	4	14	34
		Ungrouped cases	1	0	1	0	0	0	2
	%	Europeans	46.6	7.6	11.0	9.3	22.9	2.5	100.0
		Australian Aboriginals	7.1	67.3	8.2	5.1	9.2	3.1	100.0
		Malaysian Malay	16.7	11.5	37.5	14.6	16.7	3.1	100.0
		Malaysian Chinese	9.2	6.9	10.3	57.5	13.8	2.3	100.0
		Malaysian Indians	20.4	11.1	5.6	14.8	44.4	3.7	100.0
		Malaysian Orang Asli	17.6	14.7	11.8	2.9	11.8	41.2	100.0
		Ungrouped cases	50.0	.0	50.0	.0	.0	.0	100.0

a. 49.7% of original grouped cases correctly classified.

PCA of dental crown variables of the maxillary and mandibular dental arch.

The next section is looking at utilizing both variables of the maxillary and mandibular teeth.

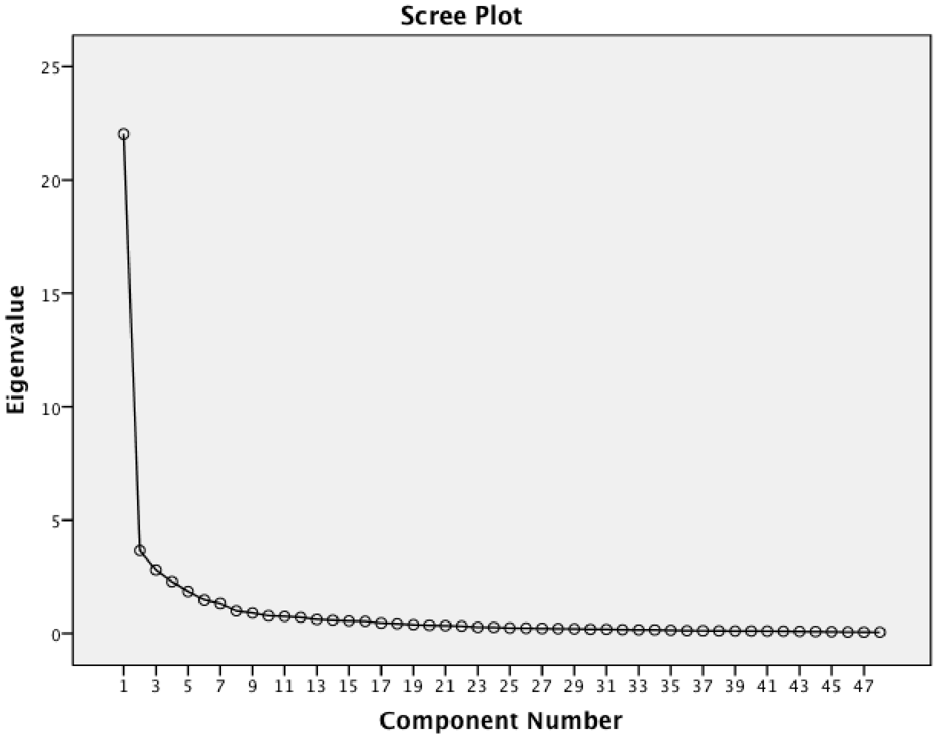


Figure 5.16: Scree plot of component numbers after PCA

If all dental crown dimensions (maxillary and mandibular) were put together and PCA was carried out, about 5 components were selected to explain variation as shown in Figure 5.16.

Rotated Component Matrix[a]

	Component				
	1	2	3	4	5
UMD16	.252	.361	.124	.753	.122
UMD15	.239	.711	.168	.246	.015
UMD14	.266	.681	.226	.204	.086
UMD13	.366	.352	.123	.184	.040
UMD12	.694	.294	.163	.078	.052
UMD11	.699	.140	.104	.374	.116
UMD21	.714	.193	.139	.341	.094
UMD22	.677	.292	.199	.060	.051
UMD23	.334	.302	.141	.171	.056
UMD24	.271	.628	.283	.178	.084
UMD25	.268	.729	.205	.253	.054
UMD26	.229	.332	.067	.749	.153
UBL16	.275	.056	.470	.626	.231
UBL15	.261	.351	.681	.180	.159
UBL14	.243	.390	.627	.134	.141
UBL13	.016	-.085	.209	.179	.301
UBL12	.213	.175	.132	.064	.211
UBL11	.148	.196	.077	.161	.341
UBL21	.149	.238	.070	.176	.336
UBL22	.203	.202	.156	.077	.207
UBL23	.016	-.010	.219	.155	.286
UBL24	.230	.362	.601	.106	.100
UBL25	.236	.368	.678	.180	.142
UBL26	.281	.112	.466	.626	.234
MD36	.309	.364	.214	.643	.148
MD35	.208	.714	.186	.263	.145
MD34	.235	.696	.245	.079	.181
MD33	.475	.318	.215	.182	.257
MD32	.709	.241	.187	.213	.196
MD31	.784	.187	.113	.194	.181
MD41	.793	.190	.074	.239	.164
MD42	.713	.229	.209	.198	.201
MD43	.521	.346	.210	.211	.170
MD44	.295	.645	.282	.114	.171
MD45	.199	.666	.255	.252	.078
MD46	.312	.339	.179	.663	.168
BL36	.240	.148	.445	.648	.140
BL35	.152	.254	.741	.240	.146
BL34	.050	.152	.714	.153	.147
BL33	.030	-.044	.308	.084	.640
BL32	.142	.150	.081	.130	.861
BL31	.264	.127	.066	.217	.821
BL41	.257	.135	.106	.181	.835
BL42	.158	.203	.089	.122	.862
BL43	.036	-.010	.309	.071	.634
BL44	.112	.158	.702	.212	.169
BL45	.162	.291	.731	.267	.062
BL46	.268	.112	.418	.679	.155

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 7 iterations.

Figure 5.17: Rotated component matrix of 5 components of all dental crown variables

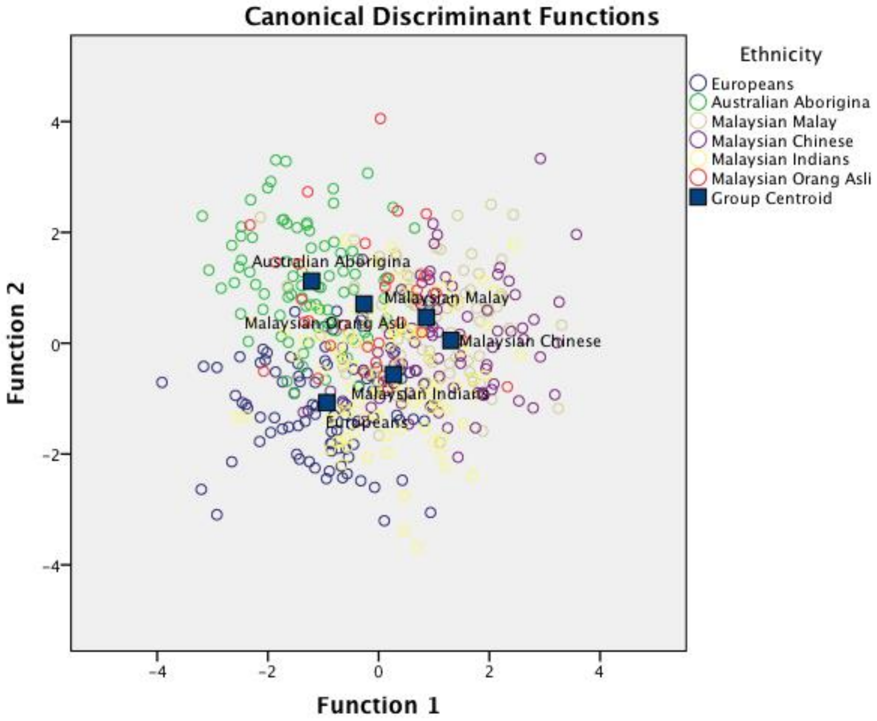


Figure 5.18: Canonical discriminant functions of all dental crown variables

As displayed on Figure 5.13, 5.15 and 5.18, canonical functions analysis indicated that the more combination of dental crown variables, the better potential of separating population samples. This suggests the value of having full information on the dental crown dimensions of possibly all teeth. The blue squares indicate the group centroids. For Malays, Chinese, Indians and Orang Asli, there was a general tendency of overlapping between the groups. This is predicted as all of these groups, despite differences in the original biological make, have assimilated to varying degrees, making it difficult to separate them. On the other hand, European and Australian Aboriginal groups displayed clear separation between the two.

Table 5.45: Group assignment based on the rotated component matrix of mandibular dental crown dimension variables

Classification Results[a]

Ethnicity			Predicted Group Membership						Total
			Europeans	Australian Aboriginals	Malaysian Malay	Malaysian Chinese	Malaysian Indians	Malaysian Orang Asli	
Original	Count	Europeans	78	6	3	3	11	0	101
		Australian Aboriginals	4	64	9	2	6	1	86
		Malaysian Malay	5	5	44	15	19	0	88
		Malaysian Chinese	8	1	15	47	10	2	83
		Malaysian Indians	19	9	8	10	51	2	99
		Malaysian Orang Asli	1	2	9	1	2	16	31
	%	Europeans	77.2	5.9	3.0	3.0	10.9	.0	100.0
		Australian Aboriginals	4.7	74.4	10.5	2.3	7.0	1.2	100.0
		Malaysian Malay	5.7	5.7	50.0	17.0	21.6	.0	100.0
		Malaysian Chinese	9.6	1.2	18.1	56.6	12.0	2.4	100.0
		Malaysian Indians	19.2	9.1	8.1	10.1	51.5	2.0	100.0
		Malaysian Orang Asli	3.2	6.5	29.0	3.2	6.5	51.6	100.0

a. 61.5% of original grouped cases correctly classified.

Table 5.46 Group assignment based on the value of dental crown measurement according to sex

European

Classification Results[a,b]

		Sex	Predicted Group Membership			Total
			Male	Female		
Original	Count	Male	59	12		71
		Female	16	47		63
	%	Male	83.1	16.9		100.0
		Female	25.4		74.6	100.0

[a] Ethnicity = Europeans

[b] 79.1% of original grouped cases correctly classified.

Australian Aboriginal

Classification Results[a,b]

		Sex	Predicted Group Membership		Total
			Male	Female	
Original	Count	Male	41	11	52
		Female	5	46	51
	%	Male	78.8	21.2	100.0
		Female	9.8	90.2	100.0

[a] Ethnicity = Australian Aboriginals

[b] 84.5% of original grouped cases correctly classified.

Malay

Classification Results[a,b]

		Sex	Predicted Group Membership		Total
			Male	Female	
Original	Count	Male	49	9	58
		Female	12	40	52
	%	Male	84.5	15.5	100.0
		Female	23.1	76.9	100.0

[a] Ethnicity = Malaysian Malay

[b] 80.9% of original grouped cases correctly classified.

Chinese

Classification Results[a,b]

		Sex	Predicted Group Membership		Total
			Male	Female	
Original	Count	Male	34	16	50
		Female	15	36	51
	%	Male	68.0	32.0	100.0
		Female	29.4	70.6	100.0

[a] Ethnicity = Malaysian Chinese

[b] 69.3% of original grouped cases correctly classified.

Indian

Classification Results[a,b]

		Sex	Predicted Group Membership		Total
			Male	Female	
Original	Count	Male	40	13	53
		Female	9	51	60
	%	Male	75.5	24.5	100.0
		Female	15.0	85.0	100.0

[a] Ethnicity = Malaysian Indians

[b] 80.5% of original grouped cases correctly classified.

Orang Asli

Classification Results[a,b]

		Sex	Predicted Group Membership			Total
			Male	Female		
Original	Count	Male	21	5		26
		Female	8	17		25
	%	Male		80.8	19.2	100.0
		Female	32.0	68.0		100.0

[a] Ethnicity = Malaysian Orang Asli

[b] 74.5% of original grouped cases correctly classified.

Discussion

Multivariate analysis of dental crown variables allows for further data exploration when multiple statistical outcomes are required and multiple variables are involved. In order to achieve the first aim of this research, "*Are there characteristics of the human dentition that will show variation between population groups?"*, descriptive analysis and univariate analyses of dental crown variables were performed as described in the earlier part of this chapter.

In order to achieve the next two aims of this research, *"Are there characteristics of the human dentition that will enable discrimination between population groups?"* and *"Are there characteristics of the human dentition that will enable assignment of individual within a population?" ,* multivariate analyses of the dental crown variables were carried out. Kieser et al., (1985a), Kieser et al., (1985b) and Potter (1972) performed multivariate analyses on odontometric data to investigate patterns of dental variation and their effect to population assignment. A similar approach was used for this current research by means of Principal Component Analysis. Principal Component Analysis is a method that can reduce a large number of variables into a smaller number of principal components that explain most of the variance observed. Through this approach, multidimensional scaling was done to reduce a large number of variables into a smaller number of potentially meaningful clusters (Tabachnick and Fidell, 1983). This can then emphasize patterns of intercorrelation among the variables and also suggest the source(s) of the variation in a group of variables (Tabachnick and Fidell, 1983).

Results consistently showed that a combination of dental crown measurements could provide assignment of groups and separation between population groups. When dental variables were plotted, several patterns emerged in regard to the six populations. The first pattern was that the Australian Aboriginal populations separated from the European populations based on size. The Australian Aboriginal populations generally exhibited larger dental crown size than those of the European populations. This is not surprising, as it has previously been shown that Australian populations tend to have larger overall tooth size than Europeans (Kondo et al., 2005; Brown and Townsend, 2001).

Group assignment was also improved when more combinations of dental crown variables was utilized. The likelihood of obtaining a correct group assignment of an individual was higher when more information on size was available as shown in Table 5.39 which indicates 61.5% of the original group was classified compared to 49.7% of original group correctly classified when only mandibular dental crown size information was used as shown in Table 5.38 and 50.6% when only maxillary dental crown size was used.

In the cases of the Malaysian groups, they tended to group closely to each other. This is expected due to genetic admixture associated with geographical and cultural assimilation among Malaysians. The mean size fell between Australian Aboriginals and the Europeans, with Indians having a closer relationship to Europeans. The reduced size of the dentition in the Indian group caused a skew towards the Europeans relative to the Australian Aboriginals.

The value of correctly assigned individual to respective group increases as the number of variables increases. Whilst the percentage range from only around 50 – 60%, its potential to discriminate geographical populations is promising. Future attempt may involve combination of dental crown dimension and shape.

Chapter 6: Dental arch size and shape

6.1 Introduction

This chapter focuses on the analysis of dental arch size and shape in the study samples. Like dental crown size, variation in dental arch size can be observed within and between different human populations. A combination of dental crown size and arch size serves to highlight the extent of variation observed between the dentitions of individuals. The growth and development of alveolar bone is influenced by the presence of developing teeth. Therefore, it is logical to look at both of these features, i.e. tooth size and dental arch size and shape, when attempting to distinguish between individuals within and between populations. Data on the size and shape of the dental arches can be useful for the purposes of both research, for example understanding human variation and evolution, as well as clinical diagnosis and treatment planning (Burris and Harris, 2000).

6.2 Aims

The purpose of this chapter is to investigate variations in dental arch size and shape within and between different population groups.

6.3 Null Hypotheses

Two null hypotheses are put forward in this chapter:

1. Dental arch size in males is similar to that in females.

2. There are no systematic differences in dental arch shape within and between different human populations.

6.4 Materials and Methods

6.4.1 Ethical approval

University of Adelaide Human Ethics Committee approval was obtained (Appendix 12.1).

6.4.2 Measurements

To obtain an adequate sample size for this research, analyses were performed using all available dental casts of Europeans, Australian Aboriginals, Malaysian Malays, Malaysian Chinese, Malaysian Indians and Malaysian Orang Asli. Details about the method of sampling and acquisition of data have been explained in Chapter 4 (Materials and Methods). Analyses were done using both two-dimensional and three-dimensional imaging.

The sample selection criteria were as follows:

Table 6.1: Sample selection criteria

Inclusion Criteria	**Exclusion Criteria**
Subjects with permanent dentitions	Subjects with deciduous or mixed dentition
Good quality study models	Poor quality study models
Pairs of corresponding teeth on left and right sides are present	One of the corresponding teeth on left or right side are missing

For measurement purposes, dental arch size refers to the distance between two corresponding teeth in the left and right quadrants. In this study, the distances between all tooth pairs from central incisors to first molars were measured (inter-central incisor, inter-lateral incisor, inter-canine, inter-first premolar, inter-second premolar, inter-molar). For incisors, a point on the middle of the incisal edge was used as the reference point. For canines and premolars, the cusp tips on the canines and cusp tips on the buccal cusps of premolars were used as the reference points. For inter-molar distance, the mesiobuccal cusp tips were used as the reference points (Corruccini and Potter, 1980). When there was evidence of some wear on the cusp tips, a point was selected at the centre of the wear facet (Moorrees, 1959).

In terms of reliability of the chosen landmarks for measurement, intra-examiner and inter-examiner reproducibility and measurement errors were evaluated based on locating the landmarks and calculating linear measurements for 50 randomly selected dental casts on two separate occasions, and by two different examiners. In order to measure intra- and inter- operator errors, paired t-tests were used to compare the two sets of data and assess systematic error. Dahlberg statistics (Se), which measure the technical errors of measurement, were used to assess random errors of measurement (Harris and Smith, 2009). The formula for the Dahlberg statistic, Se, is as follows:

$$S_e = \sqrt{\frac{\sum d^2}{2n}}$$

d = between the first and the second measures, n = number of pairs

In order to compare 2D and 3D approaches, similar methods were applied for both. Even though 3D images can be manoeuvred and visualized from every angle, the measurements were carried out from the same viewpoint as the 2D images. The focus was on the measurement of linear dimensions and on assessing the comparability of the two methodologies. This section will present descriptive statistics for dental arch size measured in all study samples.

6.5 Measurement validity

Two assessments were carried out to assess potential sources of error; intra-observer comparisons and inter-observer comparisons.

6.5.1 Intra-observer error

Intra-observer error was determined by a replication study. Fifty sets of dental casts were randomly selected in order to perform this task. The same operator repeated the data acquisition method that was highlighted in the Materials and Methods chapter after a period of one month. The errors arising from these repeated measurements were tested using paired t-tests and also quantified using the Dahlberg statistic (technical error of measurement).

In order to achieve these objectives, measurements were carried out using a small number of samples. Data were based on repeated measurements of 50 photographic images of maxillary and mandibular dental models, obtained by the same operator on two separate occasions using the same software package, ImageJ. Table 6.2 shows that there were no significant differences between measurements ($P>0.05$), and the Se values were small, ranging from 0.09 to 0.24 mm, indicating that random errors were small and unlikely to bias the results.

Table 6.2: Results of double determinations with 2D system

Parameters	n	Mean differences (mm)	Dahlberg	t-value	p – value
Maxillary					
Inter- first molar	50	0.04	0.17	1.09	0.30
Inter- second premolar	48	0.07	0.20	1.86	0.07
Inter- first premolar	50	0.08	0.24	1.68	0.09
Inter- canine	47	0.06	0.23	1.35	0.18
Inter- lateral incisor	50	0.00	0.21	0.10	0.92
Inter- central incisor	50	0.06	0.16	1.87	0.07
Mandibular					
Inter- first molar	50	0.02	0.09	0.78	0.46
Inter- second premolar	49	0.04	0.12	0.30	0.77
Inter- first premolar	49	0.02	0.10	0.49	0.64
Inter- canine	50	0.01	0.09	0.64	0.54
Inter- lateral incisor	49	0.05	0.11	1.22	0.25
Inter- central incisor	50	0.04	0.08	0.92	0.38

**All teeth are described in FDI notation*

Table 6.3: Results of double determination with 3D system

Parameters	n	Mean differences (mm)	Dahlberg	t-value	p – value
Maxillary					
Inter- first molar	50	0.04	0.13	0.75	0.46
Inter- second premolar	48	0.10	0.16	1.65	0.11
Inter- first premolar	50	0.09	0.17	1.70	0.10
Inter- canine	47	0.03	0.17	0.36	0.72
Inter- lateral incisor	50	0.02	0.14	0.01	0.90
Inter- central incisor	50	0.04	0.13	1.19	0.24
Mandibular					
Inter- first molar	50	0.01	0.09	0.12	0.91
Inter- second premolar	49	0.07	0.12	0.88	0.43
Inter- first premolar	49	0.01	0.10	0.17	0.87
Inter- canine	50	0.02	0.10	0.11	0.91
Inter- lateral incisor	49	0.02	0.09	0.31	0.77
Inter- central incisor	50	0.04	0.07	0.77	0.48

**All teeth are described in FDI notation*

The same method of measurement was carried out with the same samples but using three-dimensional imaging and Rapidform software. Data were again based on repeated measurements of 50 3D images of maxillary and mandibular dental models, obtained by the same operator on two separate occasions. Table 6.3 shows that there were no significant differences between measurements (P>0.05), and the Se values were small, ranging from 0.01 to 0.10 mm, indicating that random errors were small and unlikely to bias the results.

The percentage of the total variation due to error variance for both 2D and 3D measures was found to be about 10%, suggesting that measurement error was unlikely to influence the results of the study.

Measurements obtained using the ImageJ package were compared to measurements obtained using the Rapidform software package. This was done to ensure adequacy of both software packages used in this study. Data were compiled from 50 images measured initially using the ImageJ software for two dimensional images and re-measured on a different occasion using the Rapidform software package for three dimensional images (Table 6.3). Both measurements involved the same steps, including selection of landmarks as described earlier in Chapter 4. Table 6.4 shows that there were no significant differences in the measurements obtained from the two different software packages (P>0.05), with Se values ranging from 0.08 to 0.24 mm. These results show that the software packages are highly comparable, and validate our use of both equipment and software (2D and 3D).

Table 6.4: Intra-operator measurements obtained using ImageJ (2D images) and measurements obtained using Rapidform (3D images)

Parameters	n	Mean differences (mm)	Dahlberg	t-value	p – value
Maxillary					
Inter- first molar	50	0.01	0.23	0.06	0.95
Inter- second premolar	48	0.06	0.14	0.20	0.84
Inter- first premolar	50	0.09	0.17	0.37	0.72
Inter- canine	47	0.03	0.20	0.33	0.76
Inter- lateral incisor	50	0.12	0.24	0.83	0.45
Inter- central incisor	50	0.14	0.19	0.87	0.42
Mandibular					
Inter- first molar	50	0.04	0.12	0.56	0.60
Inter- second premolar	49	0.09	0.09	1.96	0.11
Inter- first premolar	49	0.03	0.10	0.47	0.66
Inter- canine	50	0.11	0.18	1.13	0.31
Inter- lateral incisor	49	0.08	0.08	2.59	0.05
Inter- central incisor	50	0.06	0.18	0.53	0.62

**All teeth are described in FDI notation*

6.5.2 Inter-observer error

In order to assess errors in landmark location between observers, another PhD student was asked to perform the measurement task. The methods used by the first operator were repeated by the second operator on the same photographic images (n= 50). Initially, a 'practice' run was held in order to familiarise the second operator with computer software and reference points. Then, using instructions given by the author, the second operator carried out the task in their own time. Data were based on 50 images measured initially by one operator using ImageJ and compared to measurements obtained by the other operator using the same software package. The measurements conducted by both operators followed the same criteria, including the selection of landmarks, as described earlier. Table 6.4 shows that there were no significant differences between measurements obtained from the two different operators

(P>0.05). Se values ranged from 0.08 to 0.24 mm, indicating that random errors were small and unlikely to influence the results. No evidence of systematic errors was found.

Table 6.5: Interobserver reproducibility for dental arch size measurements using ImageJ

Parameters	n	Mean differences (mm)	Dahlberg	p – value	Correlation
Maxillary					
Inter- first molar	50	0.01	0.11	0.71	0.989
Inter- second premolar	48	0.02	0.07	0.24	0.973
Inter- first premolar	50	0.04	0.12	0.72	0.939
Inter- canine	47	0.10	0.23	0.31	0.924
Inter- lateral incisor	50	0.05	0.14	0.45	0.947
Inter- central incisor	50	0.06	0.19	0.42	0.925
Mandibular					
Inter- first molar	50	0.04	0.12	0.60	0.963
Inter- second premolar	49	0.05	0.10	0.10	0.933
Inter- first premolar	49	0.02	0.08	0.36	0.969
Inter- canine	50	0.09	0.24	0.31	0.919
Inter- lateral incisor	49	0.07	0.20	0.29	0.924
Inter- central incisor	50	0.04	0.13	0.52	0.969

6.5.3 Discussion

The tests of repeatability and reproducibility of the methodology that were utilized throughout the study served to support the validity of the measurement methods. It was important to ensure that the methods produced minimal error (if any) in order to make further inferences in the later chapters. Systematic errors were assessed using paired t-tests, and random errors were measured using Dahlberg's statistics for all methods used in this study. The findings from intra-operator measurement (Tables 6.2, Table 6.3 and Table 6.4) and inter-operator measurements (Tables 6.6) showed no systematic significant differences.

6.6 Dental arch size

6.6.1 Dental arch size analysis

Descriptive statistics were computed for size with the groups split according to sex (i.e. the two sexes were treated separately). In the female subjects, a decrease in mean size was found moving from the Australian Aboriginal group, Malaysian Chinese group, Malaysian Malays, Europeans, Malaysian Indians and Malaysian Orang Asli. The same pattern was observed for the male subjects. Unpaired t-tests indicated that the average arch size found for male subjects was greater than that found for females across all population groups ($p<0.05$) as shown in Table 6.6, Table 6.7, Table 6.8, Table 6.9, Table 6.10 and Table 6.11. Although there were some outliers within the group initially, these subjects were removed prior to comparison after careful checking of the cause of the outliers. Those that were not included were outliers due to data entry errors. The coefficients of variation ranged between 4 - 9%. The Malaysian Orang Asli group had a wider range of dental arch size as reflected in the values of the coefficients of variation, indicating that their arch size dimensions were more varied compared to others.

Table 6.6: Dental arch width in Europeans (mm)

	n	Mean	SD	CV		n	Mean	SD	CV
		Male					**Female**		
Maxillary									
Inter-molar	71	52.2*	3.02	5.8	Inter-molar	63	50.1	2.83	5.7
Inter-second premolar	62	46.7*	3.15	6.7	Inter-second premolar	55	44.9	2.89	6.4
Inter-first premolar	70	41.3	3.08	7.5	Inter-first premolar	60	39.9	2.77	6.9
Inter-canine	66	34.7*	1.79	5.2	Inter-canine	54	33.4	2.24	6.7
Inter-lateral incisor	70	23.7*	1.74	7.3	Inter-lateral incisor	63	22.8	1.73	7.6
Inter-central incisor	71	9.2	0.84	9.1	Inter-central incisor	63	9.0	0.82	9.1
Mandibular									
Inter-molar	71	45.4*	2.71	6.0	Inter-molar	62	43.5	2.61	6.0
Inter-second premolar	66	39.7*	2.83	7.1	Inter-second premolar	56	38.4	2.32	6.1
Inter-first premolar	68	34.3*	2.24	6.5	Inter-first premolar	61	33.1	2.26	6.8
Inter-canine	71	26.4*	1.82	6.9	Inter-canine	62	25.6	2.28	8.9
Inter-lateral incisor	71	16.5*	1.39	8.5	Inter-lateral incisor	62	16.1	1.29	8.0
Inter-central incisor	71	5.5	0.53	9.7	Inter-central incisor	63	5.4	0.43	8.0

* p<0.05

Dental arch size measurements in the European group showed that arch size was consistently greater in males compared to females. All comparisons were significantly different (p<0.05), except for the inter-central incisor distances for both maxillary and mandibular arches and also inter-first premolar in maxillary arch (Table 6.6).

Table 6.7: Dental arch width in Australian Aboriginals (in mm)

	N	Mean	SD	CV		N	Mean	SD	CV
		Male					Female		
Maxillary									
Inter-molar	37	57.5*	1.86	3.2	Inter-molar	47	54.5	2.27	4.2
Inter-second premolar	37	51.9*	1.97	3.8	Inter-second premolar	47	49.5	2.23	4.5
Inter-first premolar	37	47.0*	2.11	4.5	Inter-first premolar	47	45.4	2.08	4.6
Inter-canine	37	38.9*	2.17	5.6	Inter-canine	47	37.5	2.10	5.6
Inter-lateral incisor	37	26.4*	1.61	6.1	Inter-lateral incisor	47	25.3	1.86	7.3
Inter-central incisor	37	9.2	0.80	8.7	Inter-central incisor	47	9.1	0.86	9.5
Mandibular									
Inter-molar	37	50.0*	2.20	4.4	Inter-molar	47	48.2	2.47	5.1
Inter-second premolar	37	43.5*	2.17	5.0	Inter-second premolar	47	41.8	2.50	6.0
Inter-first premolar	37	38.7*	2.14	5.5	Inter-first premolar	47	37.4	2.16	5.8
Inter-canine	37	29.8*	1.55	5.2	Inter-canine	47	29.0	2.14	7.4
Inter-lateral incisor	37	17.8	1.14	6.4	Inter-lateral incisor	47	17.3	1.41	8.1
Inter-central incisor	38	5.8	0.45	7.9	Inter-central incisor	47	5.6	0.42	7.5

*$p<0.05$

Dental arch size measurements in the Australian Aboriginal group were consistently greater in males compared to females. Table 6.7 illustrates that all dimensions showed significant differences ($p<0.05$), except for the inter-central incisors in the maxilla and the inter-lateral incisor and inter-central incisor in the mandible.

Table 6.8: Dental arch width in Malays (in mm)

	N	Mean	SD	CV		N	Mean	SD	CV
		Male					Female		
Maxillary									
Inter-molar	49	55.1*	2.79	5.1	Inter-molar	41	53.0	3.26	6.2
Inter-second premolar	49	49.7*	3.35	6.7	Inter-second premolar	41	47.6	3.69	7.8
Inter-first premolar	49	44.2*	2.50	5.7	Inter-first premolar	41	42.5	3.14	7.4
Inter-canine	49	36.3*	2.07	5.7	Inter-canine	41	35.1	2.37	6.8
Inter-lateral incisor	49	24.0	1.56	6.5	Inter-lateral incisor	41	23.7	2.00	8.5
Inter-central incisor	49	8.5	0.63	7.4	Inter-central incisor	41	8.7	0.56	6.5
Mandibular									
Inter-molar	49	46.5	3.01	6.5	Inter-molar	41	45.4	3.16	7.0
Inter-second premolar	49	40.1	3.06	7.6	Inter-second premolar	41	40.1	3.48	8.7
Inter-first premolar	49	35.7	2.68	7.5	Inter-first premolar	41	34.9	2.36	6.8
Inter-canine	49	27.5	2.41	8.8	Inter-canine	41	27.4	2.51	9.2
Inter-lateral incisor	49	17.0	1.43	8.4	Inter-lateral incisor	41	16.7	1.29	7.7
Inter-central incisor	49	5.5	0.52	9.4	Inter-central incisor	41	5.5	0.46	8.4

*$p<0.05$

Descriptive statistics for dental arch width in the Malay group showed that arch width was consistently higher in males compared to females (Table 6.8). Arch width variables that showed significant differences ($p<0.05$) were inter-molar, inter-premolar and inter-canine in the maxillary arch. Arch widths in the mandibular arch were not significantly different between males and females.

Table 6.9: Dental arch width in Chinese (in mm)

	N	Mean	SD	CV		N	Mean	SD	CV
	Male					Female			
Maxillary									
Inter-molar	41	55.3*	3.11	5.6	Inter-molar	37	53.5	3.42	6.4
Inter-second premolar	41	50.1*	3.47	6.9	Inter-second premolar	37	48.2	3.30	6.9
Inter-first premolar	41	44.5*	2.95	6.6	Inter-first premolar	37	42.6	2.54	6.0
Inter-canine	41	36.1	2.47	6.9	Inter-canine	37	35.3	2.19	6.2
Inter-lateral incisor	41	24.1	2.15	8.9	Inter-lateral incisor	37	23.8	1.18	5.0
Inter-central incisor	41	8.9	0.79	8.9	Inter-central incisor	37	8.7	0.67	7.7
Mandibular									
Inter-molar	41	46.8*	3.66	7.8	Inter-molar	37	44.9	2.56	5.7
Inter-second premolar	41	41.5	2.38	5.7	Inter-second premolar	37	40.0	2.94	7.4
Inter-first premolar	41	35.6	3.02	8.5	Inter-first premolar	37	34.6	2.25	6.5
Inter-canine	41	27.8	2.23	8.0	Inter-canine	37	27.2	2.01	7.4
Inter-lateral incisor	41	17.4	1.30	7.5	Inter-lateral incisor	37	16.9	1.36	8.1
Inter-central incisor	41	5.8	0.39	6.8	Inter-central incisor	37	5.5	0.37	6.8

*$p<0.05$

Descriptive statistics for dental arch width in the Chinese group showed that arch width was consistently higher in males compared to females displayed in Table 6.9. Dental arch width variables that showed significant differences ($p<0.05$) were intermolar and interpremolar for the maxillary arch, and only intermolar for the mandibular arch.

Table 6.10: Dental arch width in Indians (in mm)

	N	Mean	SD	CV		N	Mean	SD	CV
	Male					Female			
Maxillary									
Inter-molar	48	53.0*	3.11	5.9	Inter-molar	51	51.5	3.03	5.9
Inter-second premolar	48	46.7	3.40	7.3	Inter-second premolar	51	45.9	3.07	6.7
Inter-first premolar	48	41.7	2.55	6.1	Inter-first premolar	51	41.0	2.28	5.6
Inter-canine	48	34.8	2.47	7.1	Inter-canine	51	34.1	2.14	6.3
Inter-lateral incisor	48	23.8	2.24	9.4	Inter-lateral incisor	51	23.6	1.62	6.9
Inter-central incisor	48	8.8	0.46	5.3	Inter-central incisor	51	8.8	0.81	9.2
Mandibular									
Inter-molar	48	45.1*	2.62	5.8	Inter-molar	51	43.7	2.87	6.6
Inter-second premolar	48	39.2	3.02	7.7	Inter-second premolar	51	33.8	2.04	6.0
Inter-first premolar	48	33.8	2.04	6.0	Inter-first premolar	51	33.5	2.14	6.4
Inter-canine	48	26.5	1.65	6.2	Inter-canine	51	26.1	1.50	5.8
Inter-lateral incisor	48	16.5	1.04	6.3	Inter-lateral incisor	51	16.3	1.12	6.8
Inter-central incisor	48	5.5	0.41	7.5	Inter-central incisor	51	5.5	0.49	9.1

*$p < 0.05$

Descriptive statistics for dental arch width in the Indians group (Table 6.10) showed that arch width was consistently higher in males compared to females. Dental arch width variables that showed significant differences (p<0.05) were inter-molar width in both arches.

Table 6.11: Dental arch width in Orang Asli (in mm)

	n	Mean Male	SD	CV		n	Mean Female	SD	CV
Maxillary									
Inter-molar	18	54.2*	2.56	4.7	Inter-molar	18	52.1	3.49	6.7
Inter-second premolar	18	48.7*	3.12	6.4	Inter-second premolar	18	46.3	3.33	7.2
Inter-first premolar	18	43.7*	2.36	5.4	Inter-first premolar	18	40.7	2.78	6.8
Inter-canine	18	35.3*	2.07	5.9	Inter-canine	18	32.8	2.70	8.2
Inter-lateral incisor	18	24.1*	1.71	7.1	Inter-lateral incisor	18	22.4	2.19	9.8
Inter-central incisor	18	9.1*	0.39	4.3	Inter-central incisor	18	8.3	0.51	6.2
Mandibular									
Inter-molar	18	46.2	1.99	4.3	Inter-molar	18	46.1	3.41	7.4
Inter-second premolar	18	40.9	2.10	5.1	Inter-second premolar	18	39.7	2.82	7.1
Inter-first premolar	18	35.6	1.99	5.6	Inter-first premolar	18	34.3	2.17	6.3
Inter-canine	18	27.9*	2.27	8.1	Inter-canine	18	26.2	2.46	9.4
Inter-lateral incisor	18	16.9	0.73	4.3	Inter-lateral incisor	18	16.4	0.67	4.1
Inter-central incisor	18	5.6	0.50	8.9	Inter-central incisor	18	5.4	0.41	7.7

$^*p < 0.05$

Descriptive statistics for dental arch width in the Orang Asli group (Table 6.11) shows that arch width was consistently higher in males compared to females. All arch width variables showed significant differences ($p<0.05$) for the maxillary arch; only inter-canine showed a significant difference for the mandibular arch.

6.6.2 Summary of descriptive analysis of dental arch width

Across all groups, dental arch width was consistently larger in males than females. However, in general, unpaired t-tests indicated that the measurements that were significantly smaller in females than males ($p<0.05$) were those of the inter-molar and inter-canine distance for both arches, with an average value of 52.6 mm for the smallest inter-molar arch width (in Europeans) and 56.7 mm for the largest inter-molar arch width (in Australian Aboriginals). The larger groups (Australian Aboriginals, Malays and Chinese) tended to have the inter-canine widths of the mandibular arch that were not significantly larger in males than females. However, for the maxillary arch, all groups showed significant differences in terms of inter-molar and inter-canine arch widths between males and females, with the average value of 45.5 mm for the smallest inter-molar arch width (in the Indian group) and 49.3 mm for the largest (in Australian Aboriginals).

Table 6.12 shows combined data for males and females across populations with the Australian Aboriginals displaying the largest inter-arch width between all teeth (from central incisors to first molars). The yellow squares indicate those of highest value.

Table 6.12: Descriptive statistics for dental arch dimensions (mm) in males and females across populations

	Malay				Chinese				Indian				Orang Asli				European				Australian Aboriginal			
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV
Maxilla																								
Inter-molar	110	54.0	3.18	5.9	100	54.4	3.11	5.7	113	52.1	3.14	6.0	45	53.3	3.03	5.7	96	51.2	3.12	6.1	103	55.7	2.69	4.8
Inter-second premolar	106	48.6	3.56	7.3	96	49.2	3.45	7.0	108	46.2	3.22	6.9	51	47.6	3.05	6.4	85	46.0	3.18	6.9	103	50.4	2.63	5.2
Inter-first premolar	109	43.2	2.88	6.7	99	43.6	3.01	6.9	113	41.2	2.51	6.1	50	42.3	2.74	6.5	94	40.7	3.01	7.4	103	45.9	2.43	5.2
Inter-canine	108	35.5	2.36	6.7	101	36.0	2.45	6.8	108	34.3	2.34	6.8	51	33.9	2.58	7.6	90	34.1	2.09	6.1	102	38.0	2.28	6.0
Inter lateral incisor	109	23.7	1.8	7.6	101	24.0	1.88	7.8	113	23.4	1.99	8.5	50	23.2	1.97	8.5	96	23.3	2.08	8.9	102	25.6	1.87	7.3
Inter central incisor	110	8.6	0.64	7.5	101	8.9	0.74	8.3	111	8.8	0.66	7.5	51	8.6	1.02	10.9		9.1	0.84	9.2	92	9.1	0.82	9.0
Mandible																								
Inter-molar	103	45.9	3.14	6.9	93	45.9	3.22	7.0	112	44.3	2.77	6.3	43	46.2	2.85	6.2	133	44.5	2.81	6.3	101	48.9	2.64	5.0
Inter-second premolar	99	40.0	3.1	7.7	94	40.6	3.79	9.3	110	38.6	3.13	8.1	49	40.5	2.48	6.1	122	39.1	2.68	6.9	102	42.4	2.7	6.4
Inter-first premolar	106	35.2	2.66	7.6	100	35.0	3.05	8.7	112	33.7	2.1	6.2	51	35.1	2.14	6.1	129	33.8	2.51	7.4	101	38.0	2.31	6.1
Inter-canine	107	27.3	2.4	8.8	100	27.4	2.54	9.3	112	26.2	1.71	6.5	51	27.1	2.29	8.5	133	26.0	2.07	7.9	103	29.3	1.95	6.7
Inter lateral incisor	105	16.8	1.32	7.8	96	17.2	1.34	7.8	112	16.4	1.11	6.8	50	16.7	1.51	9.1	133	16.3	1.6	9.8	102	17.5	1.31	7.5
Inter central incisor	107	5.5	0.47	8.6	100	5.7	0.46	8.1	113	5.5	0.46	8.4	50	5.4	0.61	11.2	134	5.4	0.64	9.2	103	5.7	0.54	9.5

N = sample size, SD = standard deviation, CV = coefficient of variation

6.7 Correlations

Table 6.13: Correlations between maxillary inter arch width dimensions in European males

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1.00	0.88*	0.73*	0.59*	0.55*	0.23*
Inter-second premolar		1.00	0.87*	0.65*	0.64*	0.25*
Inter-first premolar			1.00	0.69*	0.72*	0.31*
Inter-canine				1.00	0.77*	0.42*
Inter-lateral incisor					1.00	0.51*
Inter-central incisor						1.00

*indicates significant difference of p<0.05

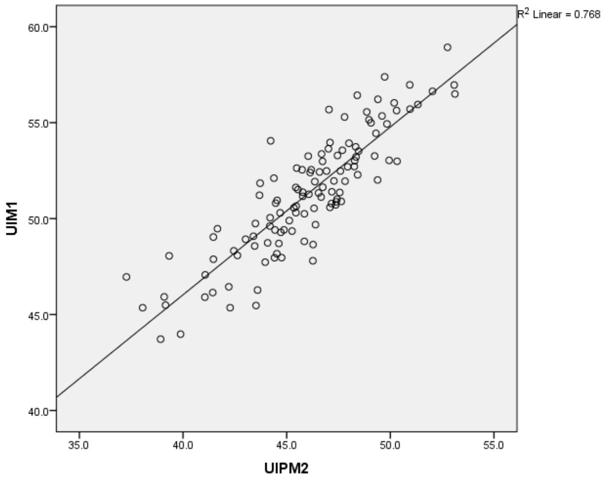


Figure 6.1: Scatter plot showing the correlation between inter- second premolar and inter-molar dimensions

Table 6.13 presents values of correlation coefficients in European males, showing that there were significant correlations between the different dental arch width measurements. For example, inter-molar arch size showed a strong correlation with inter-second premolar arch size, with an r value of 0.88 (p<0.05). Figure 6.1 provides a visual representation of the association between inter-molar and inter-second premolar arch size in the form of a scatter plot.

Table 6.14: Correlations between maxillary inter arch width measures in Australian Aboriginals

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1.00	0.90*	0.76*	0.62*	0.50*	0.20
Inter-second premolar		1.00	0.88*	0.65*	0.49*	0.21
Inter-first premolar			1.00	0.80*	0.57*	0.27*
Inter-canine				1.00	0.81*	0.46*
Inter-lateral incisor					1.00	0.60*
Inter-central incisor						1.00

*indicates significant difference of p<0.05

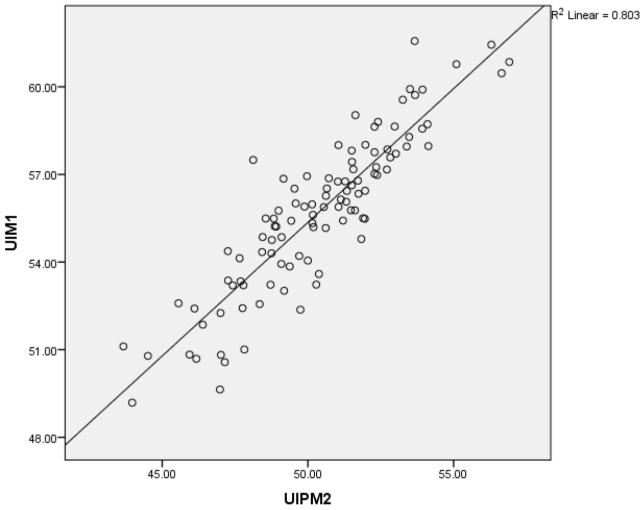


Figure 6.2: Scatter plot showing correlation between inter-second premolar and inter-molar dimensions

Table 6.14 displays correlation between all arch width variables in the Australian aboriginal group. All were significantly correlated, except for the association between inter-molar arch size and inter-central incisor distance. There was a strong correlation between the arch widths recorded for the first premolar and for the second premolar, with a value of 0.88 ($p<0.05$) (Figure 6.2)

Table 6.15: Correlations between mandibular inter arch widths in Australian Aboriginals

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1.00	0.85*	0.69*	0.53*	0.52*	0.34*
Inter-second premolar		1.00	0.72*	0.61*	0.55*	0.35*
Inter-first premolar			1.00	0.81*	0.69*	0.45*
Inter-canine				1.00	0.80*	0.55*
Inter-lateral incisor					1.00	0.77*
Inter-central incisor						1.00

*indicates significant difference of $p<0.05$

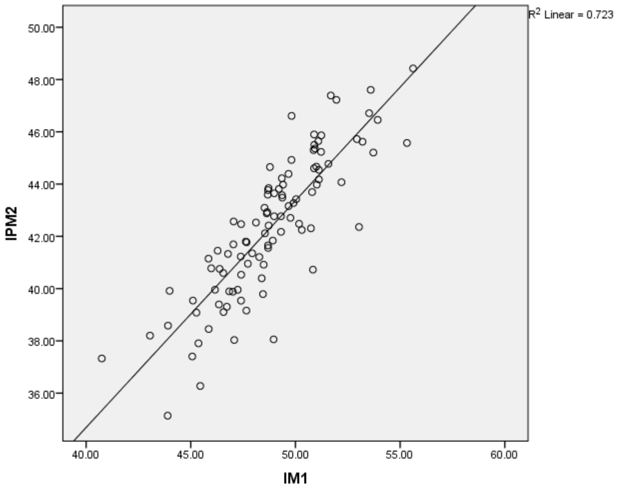


Figure 6.3: Scatter plots showing correlation between inter-second premolar and inter-molar

Inter-molar width showed the strongest correlation with inter-second premolar width, with a value of 0.88 (p<0.05).

Table 6.16: Correlations between maxillary arch width measures in Malays

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1.00	0.79*	0.77*	0.56*	0.43*	0.20*
Inter-second premolar		1.00	0.74*	0.58*	0.35*	0.12*
Inter-first premolar			1.00	0.65*	0.52*	0.26*
Inter-canine				1.00	0.64*	0.31*
Inter-lateral incisor					1.00	0.30*
Inter-central incisor						1.00

*indicates significant difference of p<0.05

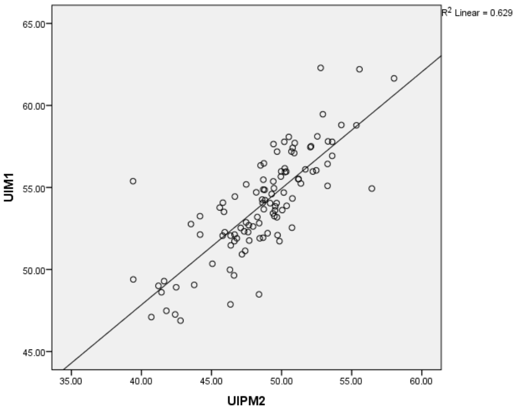


Figure 6.4: Scatter plot showing correlation between inter-second premolar and inter-molar distance

Table 6.17: Correlations between mandibular arch width measures in Malays

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.794**	.671**	.571**	.422**	.265**
Inter-second premolar		1	.591**	.575**	.453**	.238*
Inter-first premolar			1	.759**	.577**	.300**
Inter-canine				1	.736**	.420**
Inter-lateral incisor					1	.631**
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Table 6.18: Correlations between maxillary arch width measures in Chinese

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.722**	.727**	.468**	.334**	.078
Inter-second premolar		1	.673**	.407**	.306**	.038
Inter-first premolar			1	.562**	.551**	.069
Inter-canine				1	.571**	.215*
Inter-lateral incisor					1	.194
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed

Table 6.19: Correlations between mandibular arch width measures in Chinese

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.693**	.711**	.523**	.401**	.109
Inter-second premolar		1	.551**	.432**	.314**	.036
Inter-first premolar			1	.692**	.570**	.242*
Inter-canine				1	.676**	.207*
Inter-lateral incisor					1	.534**
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Table 6.20: Correlations between maxillary arch width measurement in Indians

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.793**	.710**	.506**	.353**	.029
Inter-second premolar		1	.685**	.304**	.335**	-.057
Inter-first premolar			1	.445**	.579**	.109
Inter-canine				1	.585**	.261**
Inter-lateral incisor					1	.348**
Inter-central incisor						1

**Correlation is significant at the 0.01 level (2-tailed)

Table 6.21: Correlations between mandibular arch width measurement in Indians

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.809**	.655**	.328**	.309**	.156
Inter-second premolar		1	.643**	.384**	.392**	.198*
Inter-first premolar			1	.480**	.393**	.236*
Inter-canine				1	.567**	.443**
Inter-lateral incisor					1	.684**
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Table 6.22: Correlations between maxillary arch width measurement in Orang Asli

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.789**	.755**	.606**	.484**	.259
Inter-second premolar		1	.767**	.583**	.457**	.195
Inter-first premolar			1	.828**	.618**	.301*
Inter-canine				1	.670**	.305*
Inter-lateral incisor					1	.434**
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Table 6.23: Correlations between mandibular arch width measurement in Orang Asli

	Inter-molar	Inter-second premolar	Inter-first premolar	Inter-canine	Inter-lateral incisor	Inter-central incisor
Inter-molar	1	.787**	.557**	.395**	.152	.106
Inter-second premolar		1	.693**	.575**	.283	.207
Inter-first premolar			1	.785**	.583**	.348*
Inter-canine				1	.713**	.484**
Inter-lateral incisor					1	.621**
Inter-central incisor						1

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

6.8 Further analysis of dental arch width

A one-way between subjects ANOVA was conducted to compare the effect of different population groups on dental arch width. There was a significant difference in arch width between population groups at the level of $p < 0.05$. Post hoc comparisons using Tukey HSD tests indicated that the mean values for maxillary inter-molar arch width of the Europeans and Australian Aboriginals were significantly different. The mean values of Malaysian Malays and Australian Aboriginals also showed a significant difference. Orang Asli and Australian Aboriginal groups also showed a significant difference. However, values for all other Malaysian groups (Indian, Chinese and Orang Asli) did not differ significantly from those of the Europeans and Malaysian Malays.

Post hoc comparisons using Tukey HSD test indicated that the mean value for maxillary inter-second premolar arch width of the Europeans and Australian Aboriginal groups and all Malaysian groups were significantly different, except for the Indians. There was no significant difference between the Malaysian groups.

For both inter-first premolar and inter-canine arch width, there was a significant difference between the Orang Asli group and the Australian Aboriginal group and between the Malays and the Europeans and Australian Aboriginal group. There was no significant difference between the Indians and Europeans groups.

These results suggest that different population groups do display significant differences in dental arch widths. Medium range groups between the microdontic and megadontic groups do not appear to be significantly different.

Figure 6.5 shows individuals from each population who represents a good approximation of the population averages.

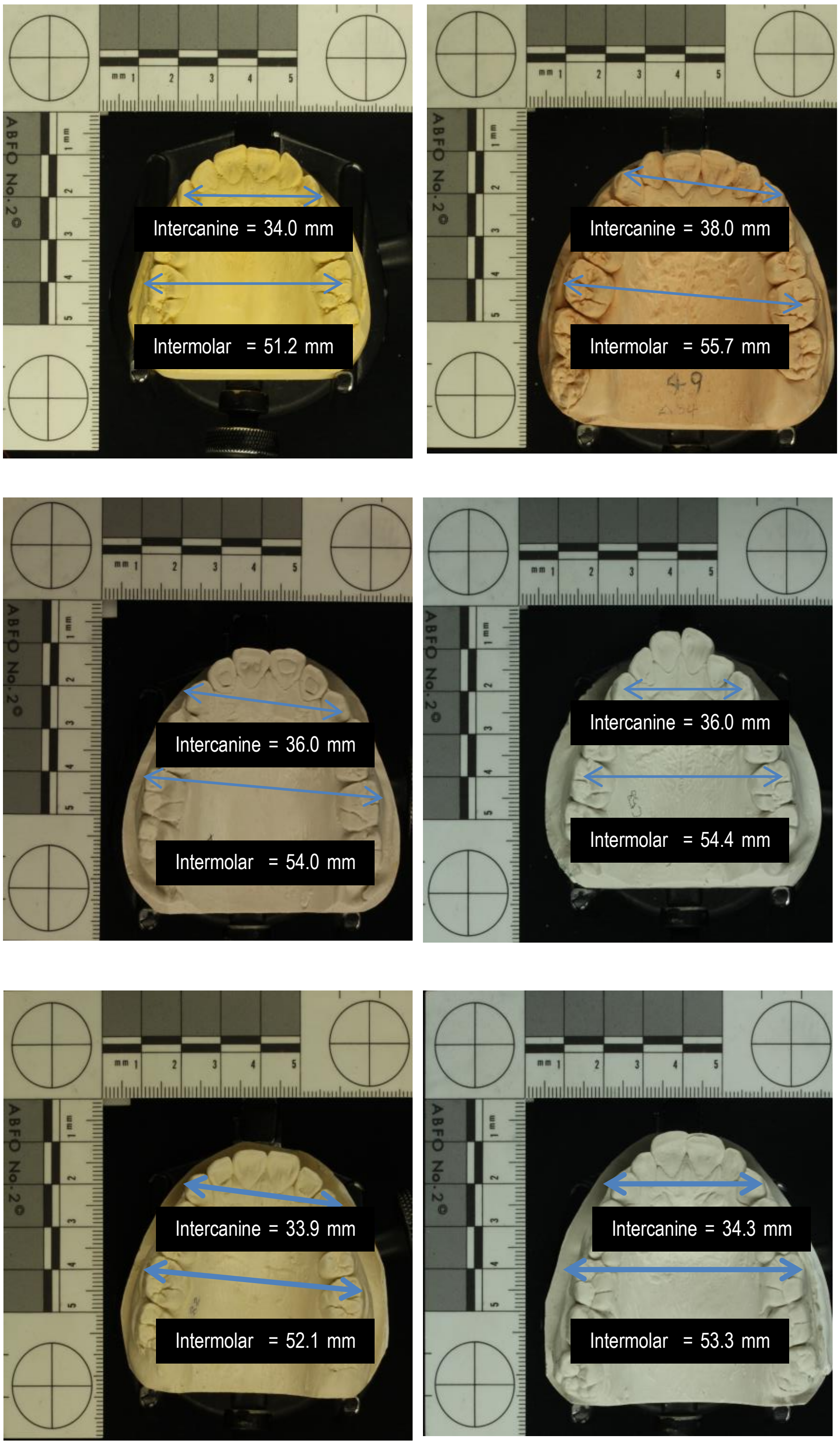


Figure 6.5: Comparison of Inter-arch dimensions between sample groups scaled to similar size (clockwise from top left: Europeans, Australian Aboriginals, Chinese, Orang Asli, Indians, Malays

6.8.1 Discussion

Data on dental arch width can give an insight into variation within and among populations. Such information is as valuable as studying data on dental crown size. Variation observed within dental arches gives a higher order of understanding of dental variation compared to data from single teeth.

Dental arch size measured between landmarks identified on homologous teeth in the opposite quadrants can provide a reliable representation of dental arch width. Similar techniques have been used by other researchers, including Rosetto et al., (2009). Some researchers may utilize different landmarks in measuring these inter-arch width parameters. It is important to note various approaches in these measurements in order to make comparisons between study results. Table 6.24 highlights the comparison between a few studies where the authors utilized similar approaches in measuring inter-arch width.

Table 6.24: Comparisons between Inter-first molar widths reported by different researchers in various populations

Inter-first molar arch width	Males			Females		
	N	Means	SD	N	Means	SD
Australian aboriginal (Dalidjan et al., 1995)	40	50.8	2.54	40	48.8	1.94
White subjects (Dalidjan et al., 1995)	30	47.9	2.88	30	46.7	2.81
Malay (Khatib et al., 2011)	126	54.3	2.10	126	51.9	2.30
Southern Chinese (Ling and Wong, 2009)	210	54.5	2.93	148	52.6	2.59
South Indian (Prasad et al., 2013)	90	49.5	1.10	90	48.2	1.20
Malaysian Malay (Othman et al., 2012)	30	55.6	2.29	30	53.3	2.28
Malaysian Orang Asli (Othman et al., 2012)	15	53.5	2.77	51	53.9	2.39
Indonesian (Dalidjan et al., 1995)	30	50.1	1.94	30	48.9	2.44

Evidence of ethnic differences in dental arch width has been shown by many researchers (Lavelle et al., 1970, Dalidjan et al., 1995). The Australian Aboriginal group, for example, is well known for their large dental arch size in comparison to other groups such as Caucasians and Egyptians. This research indicated that all inter-arch width parameters were consistently larger in Australian Aboriginal groups compared to other population. Europeans displayed the smallest dental arch size. The larger dental arch width can be related to the larger dental crown size highlighted in the previous chapter. Brown et al. (1987) discovered that intercuspation of maxillary and mandibular arch represents a successful adaptation to the demands of vigorous mastication. Therefore, diet habits practised within a population group will in turn affect the growth process of the underlying bone that will then affect the size of the dental arches. Figure 6.6 to Figure 6.11 shows scatter plot of average values and values at 25th and 75th percentile for dental arch width for each population.

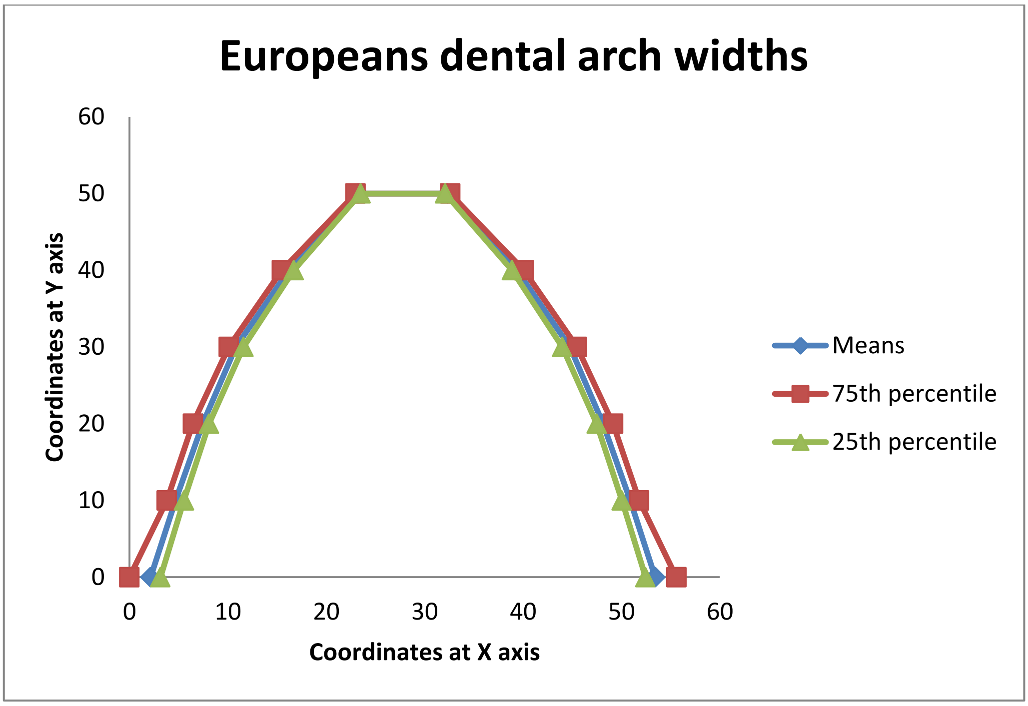


Figure 6.6: Scatter plot showing comparison of dental arch width in Europeans

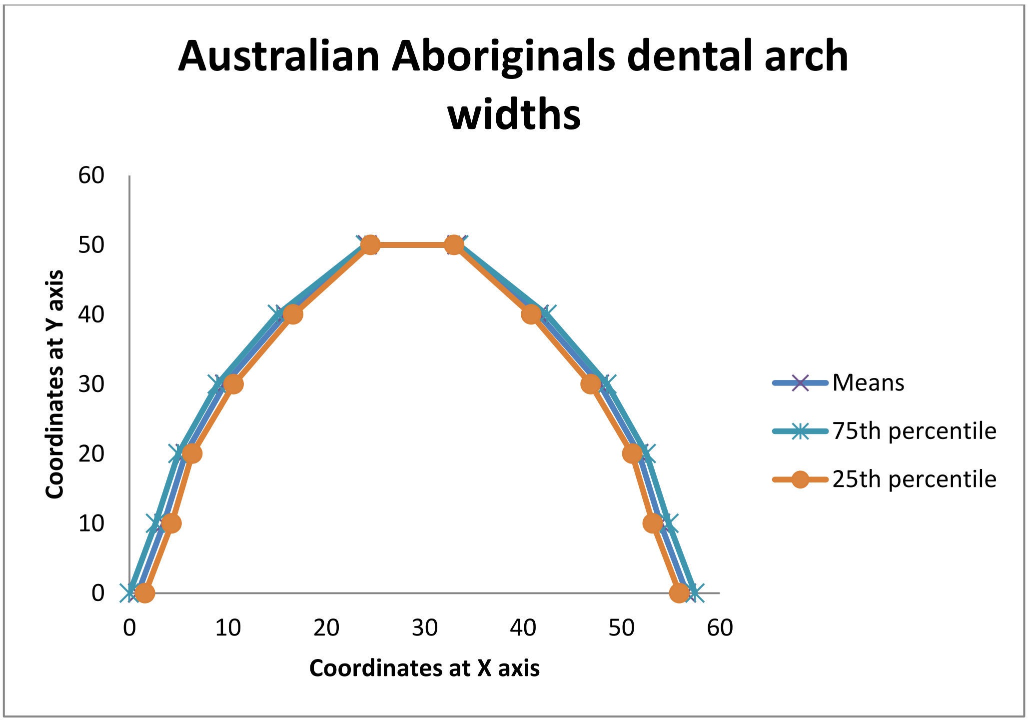


Figure 6.7: Scatter plot showing comparison of dental arch width in Australian Aboriginals

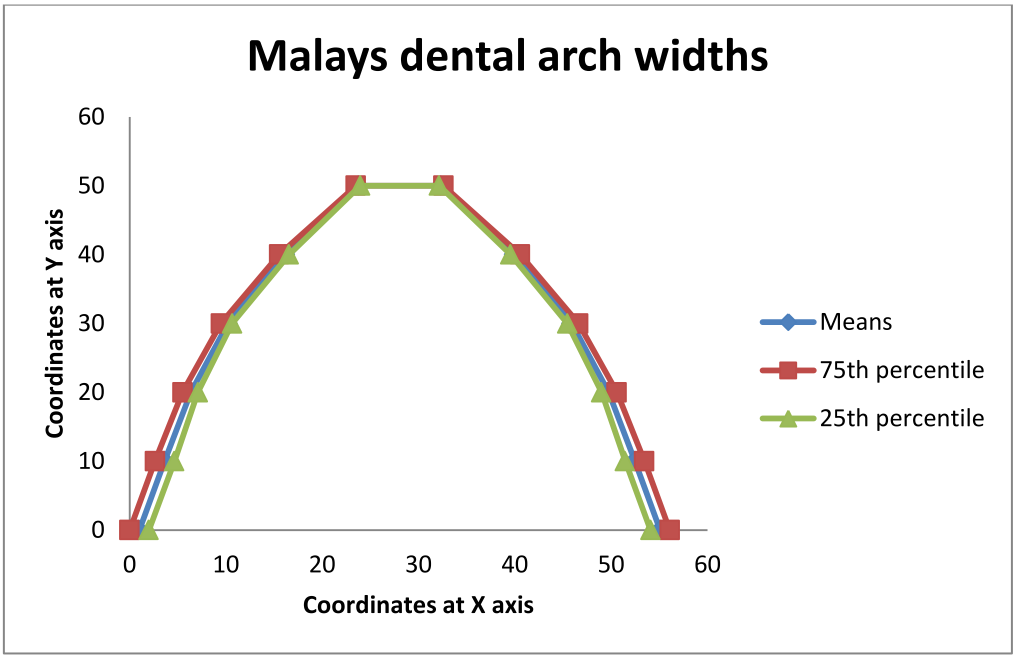


Figure 6.8: Scatter plot showing comparison of dental arch width in Malays

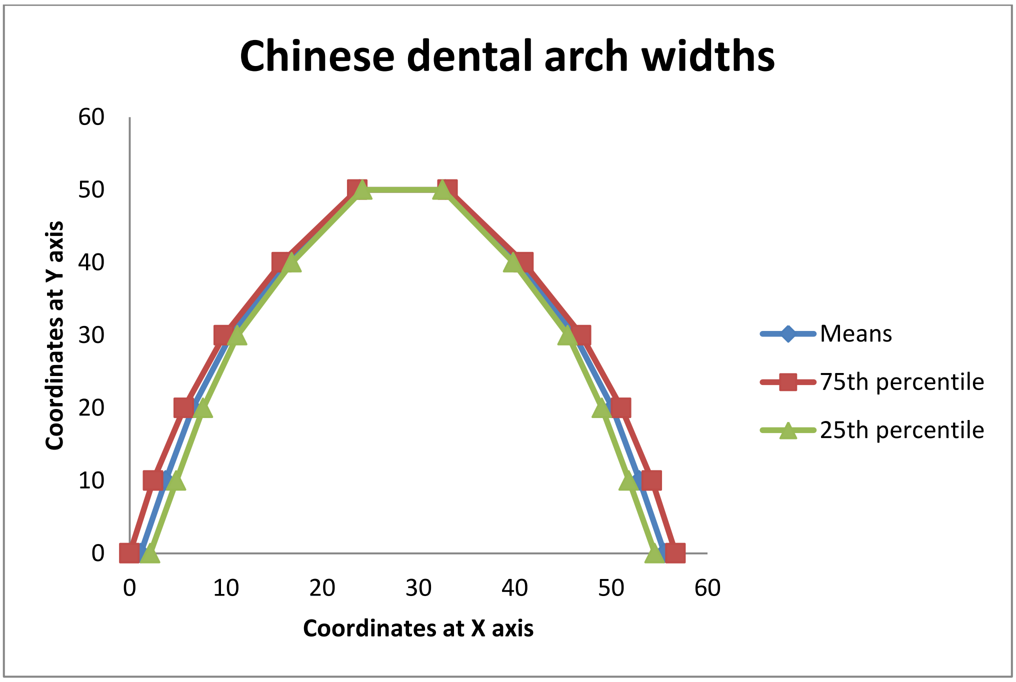


Figure 6.9: Scatter plot showing comparison of dental arch width in Chinese

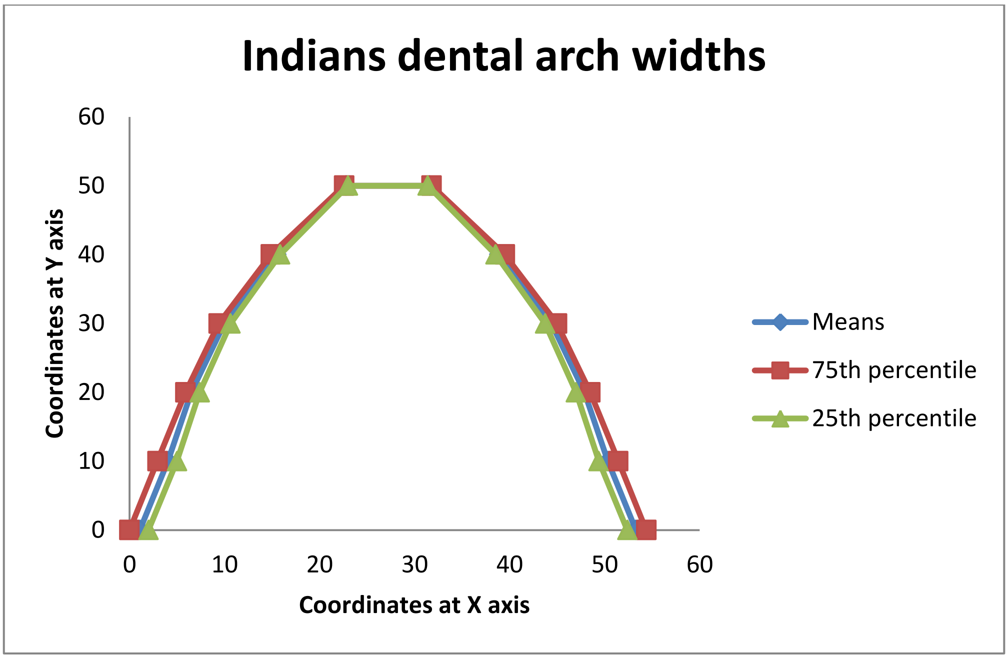


Figure 6.10: Scatter plot showing comparison of dental arch width in Indians

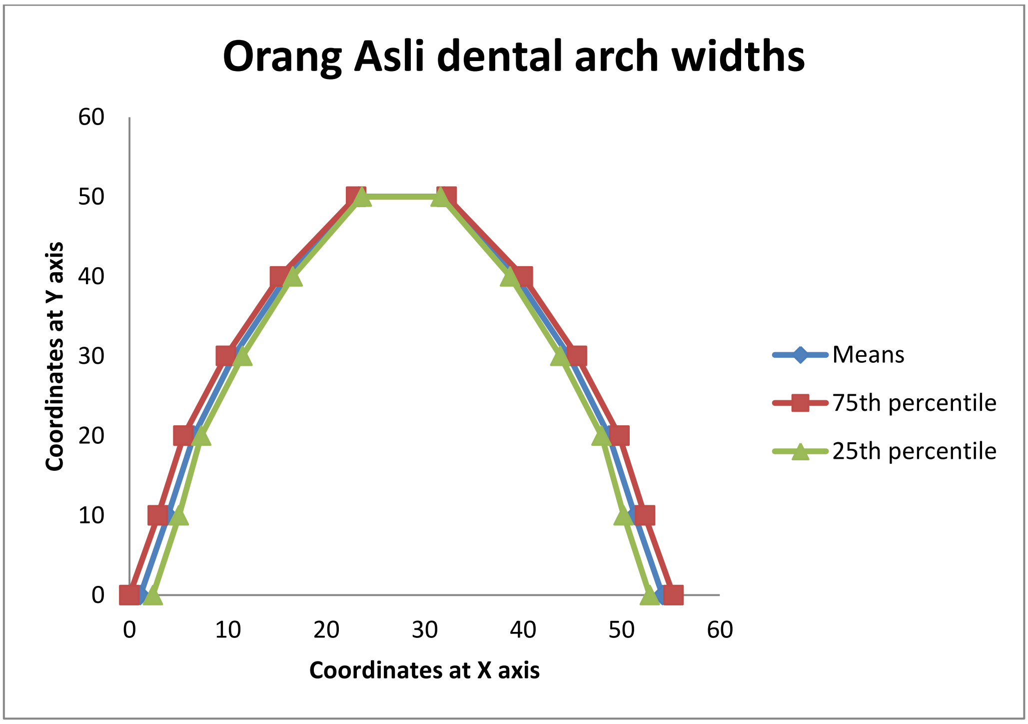


Figure 6.11: Scatter plot showing comparison of dental arch width in Orang Asli

Recording variation in dental arch width has been one means of studying dental variation between population groups. Apart from measuring dimensions directly on study models, some researchers have also attempted to use other methods, such as radiographic assessment (Akyalcin et al., 2013). Whilst the approach was quite difficult technically and different than previous other methods of measuring dental arch width, the study by Akyalcin and colleagues revealed that there was evidence of ethnic and sexual differences in the dental and mandibular arch widths and that these differences were statistically significant. The types of subjects included were different to those in the present study, however the findings indicated that the dental arches of white Americans were quite distinctive; their dental arches were narrower than those of other ethnic groups studied, i.e. Mexican Americans and black Americans. In the present study, Australian Aboriginal groups had the largest dental arch width and Europeans had the smallest arch width and they were significantly different.

The pattern of dental arch size data across populations was similar to that of dental crown size measurements, which suggests an association between dental arch size and dental crown size (Al-Khatib et al., 2011). In certain circumstances where tooth size and arch discrepancies exist, tooth crowding or spacing may result.

In general, arch width shows significant differences between males and females for all maxillary and mandibular arch dimensions except for the width measured between the incisors (Harris, 1997).

The use of two methods, two-dimensional imaging and three-dimensional imaging, has shown good outcomes. The use of three-dimensional imaging serves the purpose of performing linear measurements making it comparable to direct measurements on the dental casts. This has been supported by other research that uses 3D systems to measure dental arch width and dental crown size compared to direct measurement on dental casts with correlations between 0.80 to 0.99 with minimal error (Al Khatib et al., 2012).

6.9 Dental arch shape

This section will present analyses using fourth-order orthogonal polynomial analysis. The following formula representing an orthogonal polynomial is based on the work of Lu (1966):

$y= b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4$

b_2 = quadratic

b_4 = quartic

b_2 and b_4 represented the tendency for the arch shape to be tapered and square respectively

Hughes et al. (2002) clarified Lu's (1966) work on fitting orthogonal polynomials to arch shape data, highlighting a number of errors in the original application. The modified approach described by Hughes was utilized in the present study for the analysis of data displayed in Table 6.25

A series of four coefficients representing the various components of arch shape was developed from the resultant partitioning of variance. Arch symmetry was represented by the quadratic (b_2) and quartic (b_4) terms, reflecting parabolic and square arch shapes respectively. Arch asymmetry was described by linear asymmetry b_1 (lopsidedness) and cubic asymmetry b_3 (tiltedness).

Table 6.25 shows descriptive statistics for the fourth order polynomial coefficients for maxillary and mandibular arches across populations.

Table 6.25: Descriptive statistics for fourth order orthogonal polynomial coefficients for maxillary and mandibular arch across all populations

		b_1		b_2		b_3		b_4			b_1		b_2		b_3		b_4	
	Male									**Female**								
	N	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**N**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Maxilla																		
European	71	0.083**	0.017	-0.602	0.046	0.834**	0.053	0.825	0.055	63	0.081	0.017	-0.592	0.033	0.825	0.038	0.814	0.041
Australian Aboriginal	52	0.073	0.008	-0.566***	0.032	0.800***	0.041	0.775***	0.042	51	0.075	0.007	-0.566	0.034	0.777	0.044	0.772	0.046
Malay	58	0.077	0.014	-0.578*	0.028	0.803*	0.030	0.795*	0.033	52	0.077	0.010	-0.601	0.029	0.828	0.035	0.821	0.037
Chinese	50	0.078	0.010	-0.588	0.030	0.814	0.037	0.807	0.040	51	0.077	0.011	-0.593	0.032	0.818	0.038	0.811	0.039
Indian	53	0.079	0.016	-0.594	0.031	0.821	0.037	0.814	0.038	59	0.080	0.017	-0.595	0.043	0.821	0.047	0.814	0.050
Orang Asli	25	0.076	0.009	-0.595	0.037	0.824	0.040	0.817	0.042	25	0.077	0.015	-0.599	0.043	0.829	0.042	0.821	0.043
Mandible																		
European	71	0.242~	0.153	-0.524~	0.135	0.861	0.070	0.866	0.062	62	0.261	0.150	-0.508	0.134	0.853	0.066	0.861	0.056
Australian Aboriginal	51	0.089	0.011	-0.616	0.039	0.853	0.046	0.837ε	0.047	50	0.088	0.009	-0.620	0.035	0.856	0.038	0.841	0.041
Malay	54	0.088*	0.011	-0.613*	0.035	0.851*	0.042	0.835*	0.044	45	0.095	0.014	-0.637	0.038	0.882	0.046	0.867	0.048
Chinese	45	0.092	0.016	-0.631	0.047	0.868	0.061	0.854	0.065	48	0.088	0.013	-0.631	0.047	0.878	0.051	0.863	0.055
Indian	52	0.089	0.016	-0.639	0.038	0.885°	0.049	0.870	0.050	60	0.090	0.013	-0.645	0.051	0.891	0.056	0.877	0.060
Orang Asli	25	0.076	0.009	-0.595	0.037	0.824	0.040	0.817	0.042	21	0.097	0.012	-0.656	0.063	0.908	0.081	0.892	0.082

N = sample size, SD = standard deviation

* Significant difference between males and females

** Significant difference between Europeans and Australian Aboriginal

***Australian aboriginals significantly different from all groups

~ Europeans significantly different from all groups

° Indians significantly different from Europeans and Australian Aboriginals

ε Australian Aboriginals significantly different from Euroepans, Indians and Orang asli

The four coefficients represent the components of arch shape (b_1, b_2, b_3, b_4). Arch symmetry represented by b_2 and b_4, explains the taperedness or the squaredness of the arch shape. The largest magnitude of b_2 was observed in Europeans for the maxillary arch while it was in Indians for the mandibular arch. This suggests the tendency for the maxillary arch of the Europeans and mandibular arch of the Indians to be more tapered. Larger value of b_2 mean that arch shape tends to be more parabolic in form while greater values of b_4 indicate that arch shape is more square in form. Coefficients between sample groups were not significantly different.

Table 6.25 shows descriptive statistics for the fourth order orthogonal polynomial coefficients for maxillary and mandibular dental arches. The b_2 coefficient (taperedness) showed the lowest variability about its mean followed by the b_4 (squaredness). Negative or positive signs for b_2 and b_4 indicated that the curve was downward or upward in relation to its reference coordinates.

6.9.1 Discussion

Orthogonal polynomials provide a useful method for describing arch shape because the coefficients have a biological interpretation. The general pattern of the coefficients was similar across the groups. This method for assessing arch shape provides some advantage in giving a better interpretation of shape rather than a single common description of shape (i.e. rounded). This chapter shows progression from linear measurement of arch size through values of dental arch widths and then followed by description of arch shape with some biological interpretation through values of coefficient.

6.10 General discussion

The transition of information from individual dental crown size to the more generalized features of dental arch size can give insights into the relationship between the size of teeth and how they are arranged. This information illustrates a dynamic process of development of maxillary and mandibular bone together with individual tooth development, which leads to variation between individuals and population groups. Barrett et al. (1965) demonstrated the tendency for Australian Aboriginals to have larger mesiodistal and buccolingual crown size leading to the tendency for the dental arch size to be larger as well.

The comparisons of size and shape of dental arches between males and females showed that male arches generally tended to be larger than female dental arches. This finding is consistent with previous reports by Eguchi et al. (2004) and Barrett and Brown (1968). Barrett et al. (1965) has also looked at the size of dental arches of Australian Aboriginals and found that they are larger compared to other populations. In most studies, maxillary or mandibular (or both) widths have been found to be larger in male than in female subjects (Cassidy et al., 1998).

The results show that all maxillary arch widths were significantly larger than corresponding mandibular dimensions. The nature of an ideal occlusion where intercuspation between maxillary and mandibular teeth is classified among others by the area where maxillary first molar lies on the mesiobuccal groove of the mandibular first molar and that the incisal edge of the lower incisors occlude on the cingulum plateau of the maxillary central incisors. For both of these features to occur, a larger size of maxillary jaw needs to occlude on a smaller mandibular jaw.

The variations observed in size and shape of the dental arches could be due to the variation in the growth process of bones and due to the variation of individual dental crown size and position. There is some equilibrium within the masticatory system in which forces exerted around the teeth cause them to achieve a stable state (Proffitt, 1978).

6.11 Multivariate analysis of dental arch size and dental crown dimensions

In the previous chapter, multivariate analyses were carried out by performing principal component analysis of all dental crown variables. A combination of dental crown variables and dental arch variables improves our ability to discriminate between groups.

6.11.1 Combination of dental crown size (maxillary and mandibular) and dental arch size

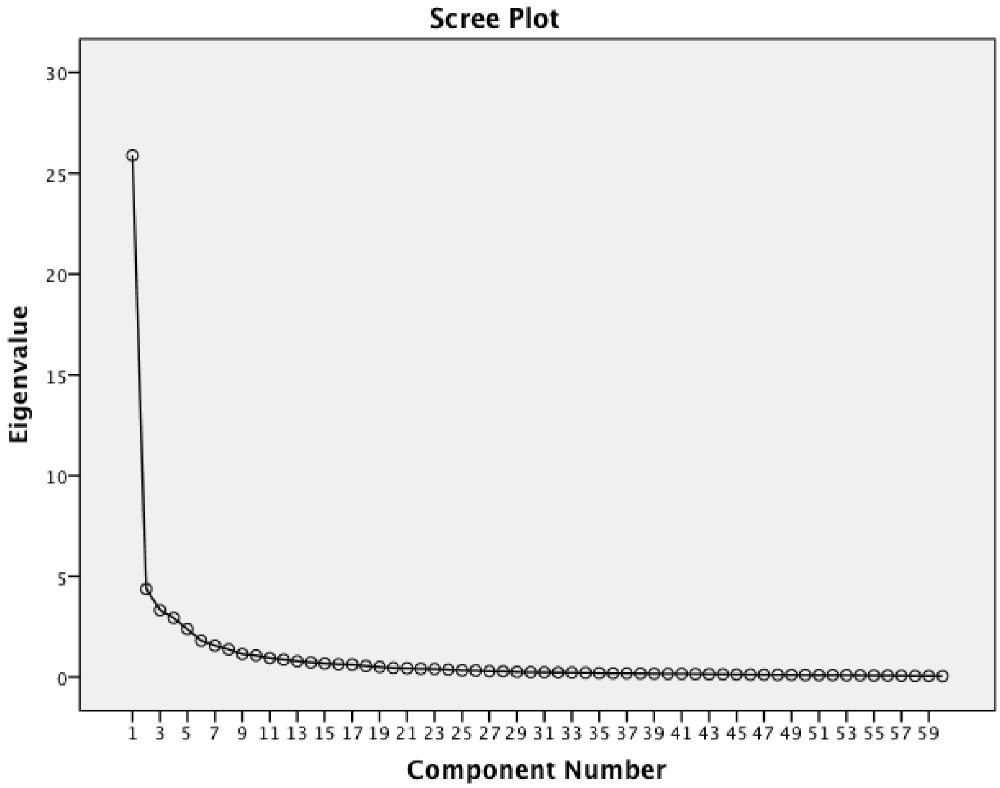


Figure 6.12: Scree plot showing variance of each component in the dataset

Rotated Component Matrix[a]

	Component			
	1	2	3	4
MD36	.556	.470	.222	.164
MD35	.549	.432	.070	.105
MD34	.539	.384	.195	.105
MD33	.482	.452	.253	.263
MD32	.389	.633	.256	.190
MD31	.200	.763	.196	.156
MD41	.182	.807	.155	.144
MD42	.381	.627	.248	.189
MD43	.511	.502	.228	.184
MD44	.557	.419	.143	.122
MD45	.555	.397	.078	.060
MD46	.516	.484	.195	.175
BL36	.602	.332	.077	.260
BL35	.728	.086	.010	.188
BL34	.673	-.031	.096	.274
BL33	.242	-.051	.302	.632
BL32	.103	.232	.199	.816
BL31	.091	.386	.091	.784
BL41	.119	.359	.112	.807
BL42	.116	.267	.181	.791
BL43	.243	-.034	.320	.669
BL44	.675	.044	.117	.298
BL45	.754	.125	-.023	.120
BL46	.558	.370	.114	.271
UIM1	.311	.182	.787	.153
UIPM2	.260	.144	.808	.096
UIPM1	.227	.208	.823	.217
UIC	.375	.394	.619	.168
UII2	.128	.364	.527	.264
UII1	.060	.508	.049	.108
UMD16	.534	.490	.116	.173
UMD15	.613	.410	.090	.025
UMD14	.633	.411	.266	.101
UMD13	.493	.386	.285	.132
UMD12	.372	.608	.112	.137
UMD11	.290	.694	.205	.150
UMD21	.336	.711	.167	.128
UMD22	.395	.581	.145	.168
UMD23	.489	.325	.307	.155
UMD24	.663	.362	.261	.124
UMD25	.635	.454	.053	.045
UMD26	.476	.478	.109	.199
UBL16	.605	.275	.232	.335
UBL15	.771	.155	.236	.215
UBL14	.777	.156	.292	.252
UBL13	.299	-.091	.347	.498
UBL12	.274	.198	.115	.510
UBL11	.251	.259	.110	.615
UBL21	.286	.277	.096	.616
UBL22	.334	.214	.049	.534
UBL23	.347	-.065	.377	.499
UBL24	.741	.133	.298	.225
UBL25	.777	.141	.243	.199
UBL26	.628	.298	.236	.325
IM1	.147	.136	.838	.155
IPM2	.023	.138	.824	.158
IPM1	.123	.242	.802	.265
IC	.182	.425	.647	.242
II2	.029	.535	.490	.295
II1	.070	.652	.224	.228

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.

Figure 6.13 Rotated component matrix for PCA of dental crown and dental arch variables

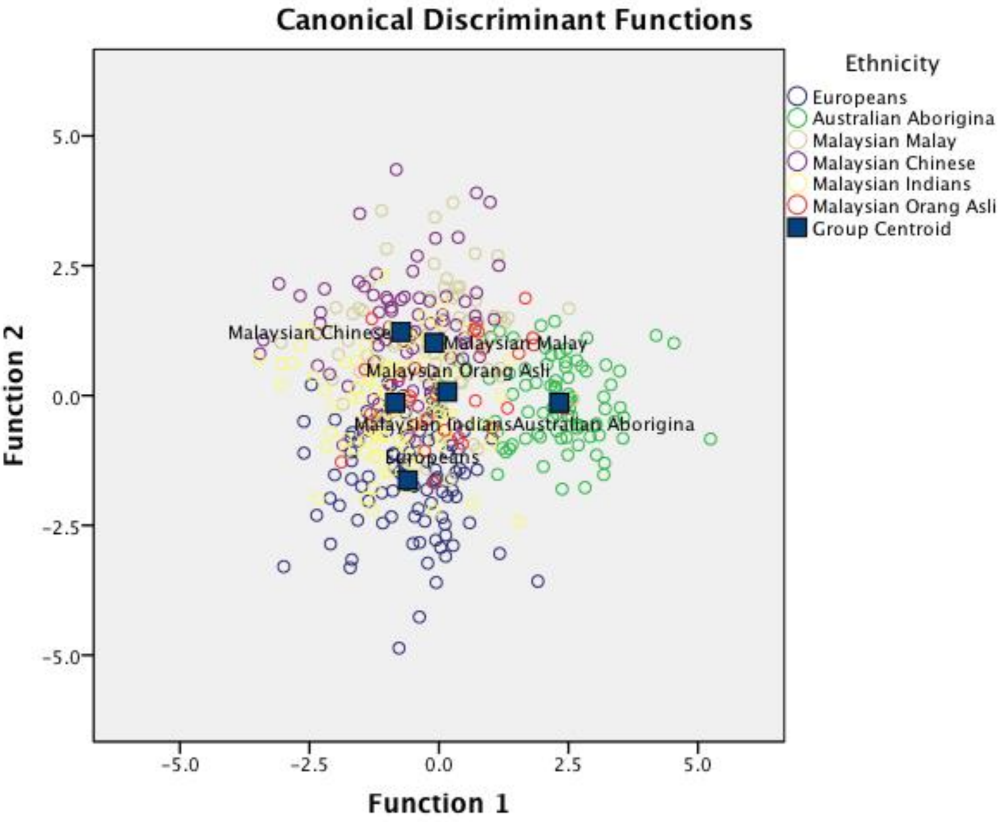


Figure 6.14 Canonical discriminant functions showing function 1 v function 2

Table 6.26: Group classification based on PCA

Classification Results[a]

Ethnicity			Predicted Group Membership						Total
			Europeans	Australian Aboriginals	Malaysian Malay	Malaysian Chinese	Malaysian Indians	Malaysian Orang Asli	
Original	Count	Europeans	75	1	2	2	14	0	94
		Australian Aboriginals	1	75	4	1	2	0	83
		Malaysian Malay	5	5	42	14	15	1	82
		Malaysian Chinese	7	0	12	52	7	1	79
		Malaysian Indians	20	4	9	7	58	4	102
		Malaysian Orang Asli	2	1	5	1	5	14	28
	%	Europeans	79.8	1.1	2.1	2.1	14.9	.0	100.0
		Australian Aboriginals	1.2	90.4	4.8	1.2	2.4	.0	100.0
		Malaysian Malay	6.1	6.1	51.2	17.1	18.3	1.2	100.0
		Malaysian Chinese	8.9	.0	15.2	65.8	8.9	1.3	100.0
		Malaysian Indians	19.6	3.9	8.8	6.9	56.9	3.9	100.0
		Malaysian Orang Asli	7.1	3.6	17.9	3.6	17.9	50.0	100.0

[a] 67.5% of original grouped cases correctly classified

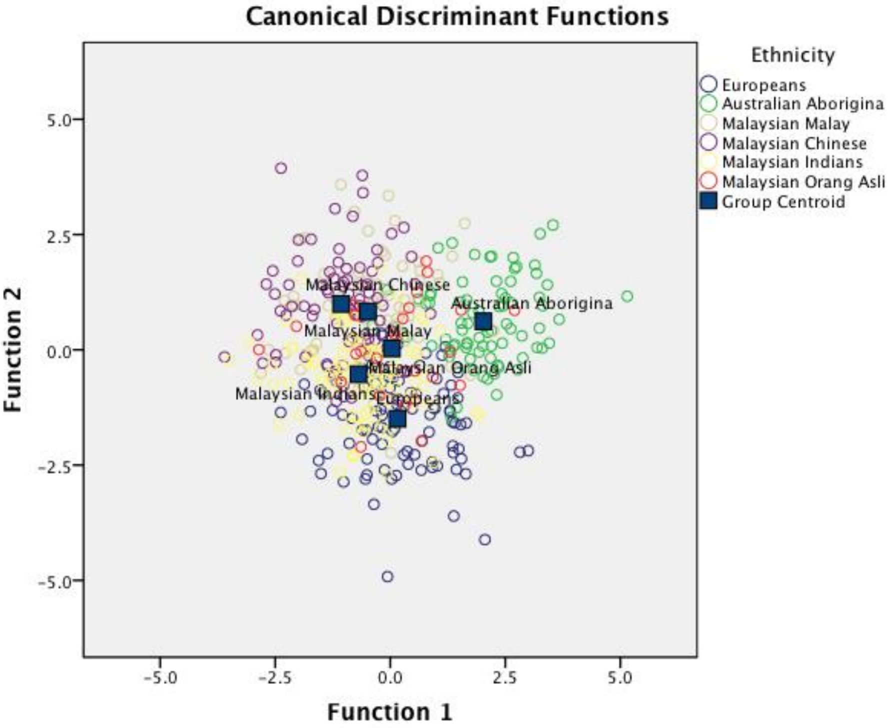


Figure 6.15: Canonical discriminant functions showing function 1 v function 2

From PCAs, the first four functions accounted for 62.8% of variation extracted from the mesiodistal and buccolingual dental crown size of upper and lower teeth, and dental arch size. The highest discriminating ability accounted for 43.1%, while the second function accounted for 7.5%.

Table 6.27: Wilks' Lambda

Test of Function(s)	Wilks' Lambda	Chi-square	Df	Sig.
1 through 5	.228	727.235	120	.000
2 through 5	.432	413.357	92	.000
3 through 5	.678	191.289	66	.000
4 through 5	.856	76.680	42	.001
5	.950	25.326	20	.189

The null hypothesis that the canonical correlations associated with the functions were equal to zero was rejected for the first four tests, with p-values less than the alpha level of 0.05. Test five, that tested the fifth canonical correlation analysis alone, had a p-value greater than 0.05, which did not give enough evidence to reject the null hypothesis.

The amount of separation between groups is displayed in Figure 6.15. Blue squares indicated distribution of the group centroids. While previous analysis displayed a general tendency for values in Malays, Chinese, Indians and Orang Asli to overlap, there was a better separation between the groups but they were still close together. On the other hand, Europeans and Australian Aboriginals displayed clear separation.

Chapter 7: Geometric Morphometric Analysis

7.1 Introduction

Studies of dental morphology include exploration of the variation of teeth between individuals within and between populations. There have been numerous studies that have focussed on quantifying these features in order to better explain the amount of variation. Chapter 5 has looked into that variation in terms of linear measurements of dental crown size. Chapter 6 further explored the size of the dental arches. Quantifying these features helped to supplement evidence of variation.

Over the last three decades, there has been an increase in studies of variation in dental arch shape. The study of dental arch shape has contributed to the application of clinical dental sciences, including orthodontic, prosthetic and maxillofacial surgery treatment planning. Quantifying dental arch shape is further useful to the study of craniofacial growth and human evolution and also to the application of forensic dental identification and forensic bite mark investigation. Due to the benefits of studying dental arch shape, many approaches have been used to model the dental arch and these have been continuously refined over the years.

Quantifying dental arch size and shape when combined with previous information on dental crown size may add more information to better identify individuals. There is a steady trend in quantifying dental arch shapes. This includes using simple geometrical form, measuring size, geometrical and mathematical models, fourth-order polynomials

(Lu et al., 1966, Hughes et al., 2001), and most recently Geometric Morphometric Analysis (Banabilh et al., 2009). The use of certain types of mathematical models should provide a more objective explanation of dental arch shape variation.

Geometric Morphometric Analysis

Morphometrics is useful to allow quantitative descriptions of organisms in order to better compare between subjects and to eliminate reliance on verbal descriptions. The shift from traditional to more quantitative descriptions has been enabled by advances in statistical analytical methods. Descriptions of shape or form can help to describe organisms. The limitations of traditional morphometrics is dealing with distances, areas, angles and they are all generally highly correlated and therefore do not provide independent pieces of information. In morphometrics, form is a composite of size and shape information; shape is form with the size variation removed. Both shape and form is a definition of an object within a defined space. Form is usually in three dimensional form while shape is in two dimensional form. In morphometrics, shape is used to describe the geometric properties of an object that are independent of the object's overall size, position, and orientation. Shape is form with the size variation removed whereas the form of an object comprises both its shape and size (Mitteroecker and Gunz, 2009).

A more sophisticated approach to describing variation in shape, called Geometric Morphometrics, has been developed over the last 20 years (Adams et al., 2004).

Geometric Morphometric Analysis (GMA) is a quantitative representation of shape using geometric coordinates (landmarks). Details on GMA were highlighted in Chapter 2 and Chapter 4. This method uses a set of landmarks to describe shape variation independent of differences in size.

This chapter examines arch shape using a GMA approach. Using this technique, dental arch shape was compared between populations and the distances, in shape space, between different populations were analysed to better understand segregation between one group's dental arch shape to the other.

Geometric morphometrics is a form of statistical analysis used widely to study biological form by utilizing a set of anatomical landmarks represented by Cartesian coordinates (O'Higgins and Jones, 1998; Adams et al., 2004; Sanfilippo et al., 2009). Previously, the use of this technique was limited to the study of animal biological form. Previously, was this approach was rarely being used in the field of dentistry. However, it has now gained popularity among dental researchers, including Al-Shahrani et al. (2013) who looked at differentiating tooth crown shape, and Bush et. al. (2013) who have applied this type of analysis to understand dental arch shape variation for forensic use.

7.2 Methods

Dental arch shapes were quantified by scaling sets of landmarks in relation to centroid size and minimizing translational and rotational differences across all individuals using a least squares method called Generalized Procrustes Analysis (GPA) (Rohlf and Slice, 1990). This step in GMA is quite similar to that used in chapter 5 for fitting fourth-order polynomials, where the arch coordinates were first aligned on a common axis through the mesiobuccal cusps of the permanent first molars, and the arch shapes were then transformed to unit centroid size. The advantage of GMA is that it does not rely on the initial alignment of specific landmarks, but uses a least-squares approach to align all landmarks, minimizing any rotational variation. The final measures of shape are relative rather than absolute, allowing (relatively) straightforward comparisons between individuals or groups that are invariant to rotation or translation.

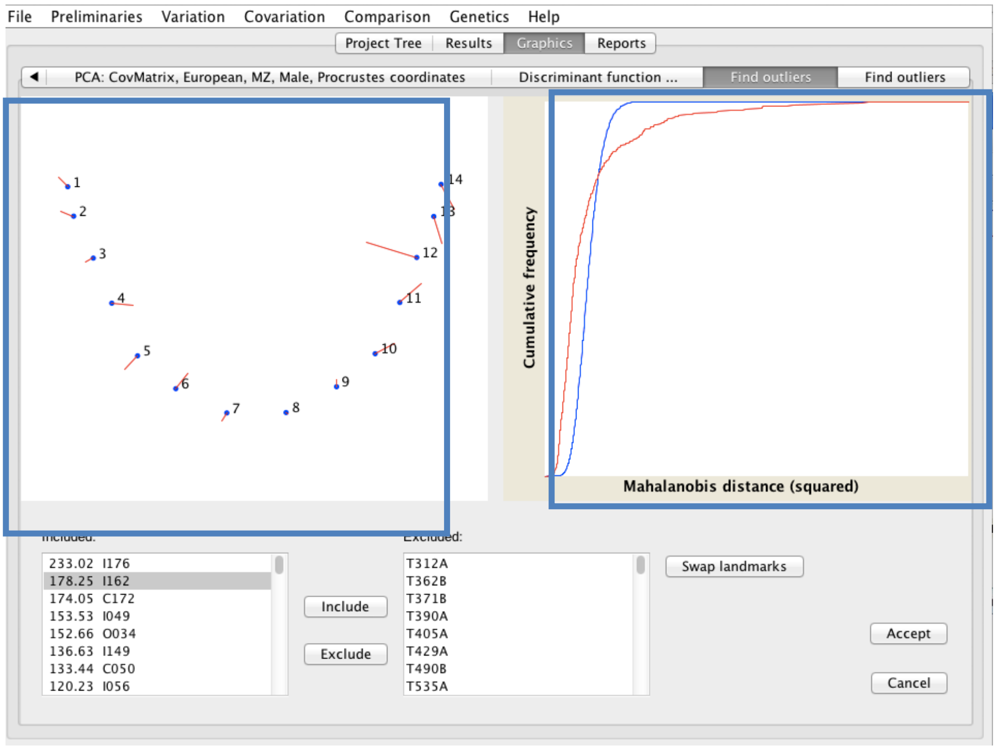
This approach is different from those adopted in traditional morphometrics, where each variable is treated separately. It may seem unclear to treat the entire shape as a single unit, but according to Zelditch (2004), the power of these methods and their ability to visualize shape variation graphically overcomes this problem. Again, for any shape, a number of dimensions are lost during GPA.

7.3 Procrustes superimposition

Geometric morphometrics analyses were performed using MorphoJ 1.02j. In the current research, the data for each dental arch shape (i.e. the raw x and y coordinates of the landmarks) were loaded into the software. The x and y coordinates of the recorded 12 landmarks on the dental arch size were subjected to a Procrustes analysis to be scaled, translated and rotated to best fit (Detailed description of the method can be referred to the chapter 4: Materials and method). The shape differences between the landmark configurations of two individual dental arch shape can be quantified by their Procrustes distance, which is approximately the square root of the sum of the squared distances between pairs of corresponding landmarks. Centroid size was saved as a separate variable for testing size differences. Statistical analyses are univariate for size but must be multivariate for shape, i.e. performed on all shape variables. This is because shape is inherently multivariate consisting of a combination of points represented by landmarks in which each of these landmarks carries information to create that shape. By taking into account all of these points, the shape can be quantified. The Procrustes distances between objects were then subjected to a Principal component analysis (PCA). Principal component analysis (PCA) is a multivariate approach to data reduction. It reduces the total number of variables into a smaller set of orthogonal (uncorrelated) variables that encapsulate the majority of the observed variation. It can be used to display the major features of shape variation and also as an ordination method.

7.3.1 Outliers

The data were checked for outliers by examining PCA scatter plots. This was done both on the total sample and within each population sample. The presence of outliers was investigated also by inspecting the vector of the Procrustes shape distances between the data of two dental arch shape and the mean shape. Outliers might represent extreme biological variation or be related to errors in data collection; either condition warranted careful checking as they can critically affect analytical results.



233.02 I176
178.25 I162
174.05 C172
153.53 I049
152.66 O034
136.63 I149
133.44 C050
120.23 I056

T312A
T362B
T371B
T390A
T405A
T429A
T490B
T535A

Figure 7.1: An interface showing extreme outliers have been excluded from analysis

In Figure 7.1, the top left box contains the average shape of the dental arch represented by landmarks (marked as blue dots) and red lines that indicate the deviation of the specimen selected in the list "Included:" from the average.

The top right box contains a diagram with the cumulative distribution of the distances of individual specimens from the average shape of the entire sample. The blue curve is the curve expected for a multivariate normal distribution fitted to the data, whereas the red curve is the distribution of distances in the dataset. Depending on the relationship between the dimensionality of the data and the number of specimens in the dataset, either the Procrustes distance or the squared Mahalanobis distance was used (e.g. Klingenberg & Monteiro 2005). Procrustes distance is a measure of the absolute magnitude of the shape deviation, whereas Mahalanobis distance provides an indication of how unusual an individual is relative to the others in the sample (in larger samples).

The aim was to achieve a pattern where the red line was stretched out to the right at the top of the diagram, indicating that there were one or a few specimens that deviated very strongly from the others (Figure 7.1). Therefore, from initial analysis of the data, outliers, which indicate certain individuals who deviate significantly from the average, in terms of certain coordinate points, were excluded.

7.4 Results

A principal component analysis (PCA) examined dental arch shape differences using the matrix of group means. The mean shape coordinates from the full set of sample shape variables was computed to obtain the mean. The analysis was performed for all samples in a two-dimensional analysis (n=541) using MorphoJ and Morphologika2 v2.5. Shape differences of the dental arches between the groups are described below. Additionally, the analysis was also carried out on both sexes as significant differences between them were noted.

A Procrustes fit was carried out and PCA was then performed. Twenty-four components were extracted. The first 5 principal components (PCs) explained approximately 80% of total shape variance. PC1 and PC2 alone accounted for about 36.9% and 11.5% of total shape variance. The multivariate analysis of variance (MANOVA) of sex by groups for shape showed that all factors including their interaction were highly significant.

7.4.1 Group differences

For each population group, the analyses of the samples were also carried out for male and female groups due to the evidence that sexual dimorphism was significant and the pattern of group shape differences was different between the sexes (significant interaction). The differences between means were significant ($p<0.05$). Procrustes distance between males and females was about 0.006 and the Mahalanobis distance between males and females was about 0.5379.

Table 7.1: Classification/misclassification tables

	Male	**Female**	**Total**
Male	165	105	270
Female	106	165	271

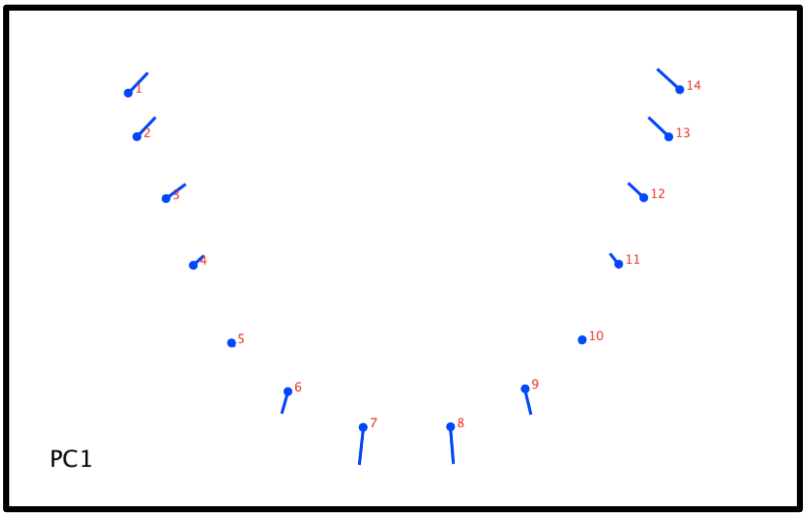


Figure 7.1: Lollipop graph showing PC1 of procrustus coordinates of shape changes of all group

Based on the lollipop graphs (Figure 7.1) on the point of displacement of each coordinates, population groups were compared using discriminant Function Analysis to assess the amount of difference and similarity between them. Similarity relationship among population groups were summarized using PCA on the average shape variables.

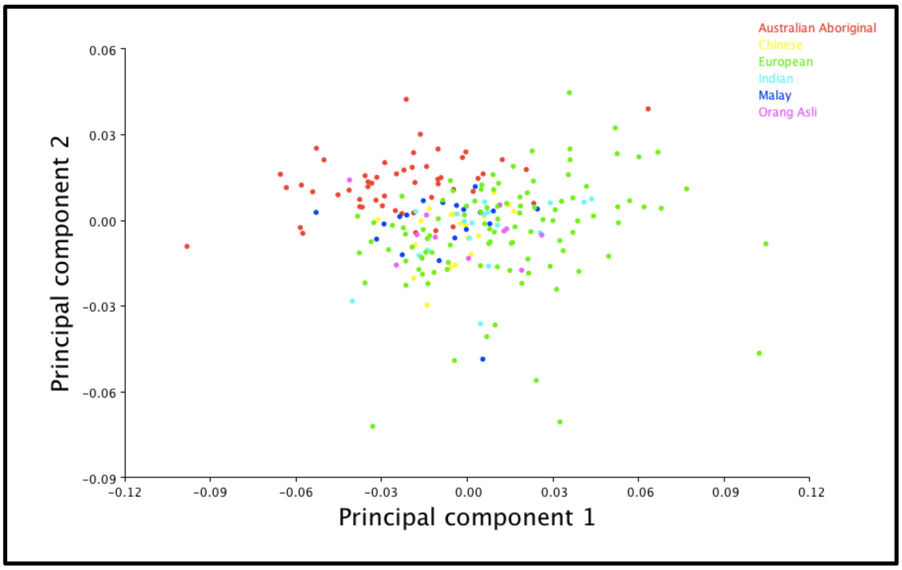


Figure 7.2: Scatter plot of the first principal components (PCs) of shape variables

Figure 7.2 shows a scatter plot where PC1 differentiated the population groups according to the megadontic to microdontic grouping, while PC2 separated the Australian Aboriginal group from the European group. Figure 7.3 shows a better representation of the group separation (average shape)

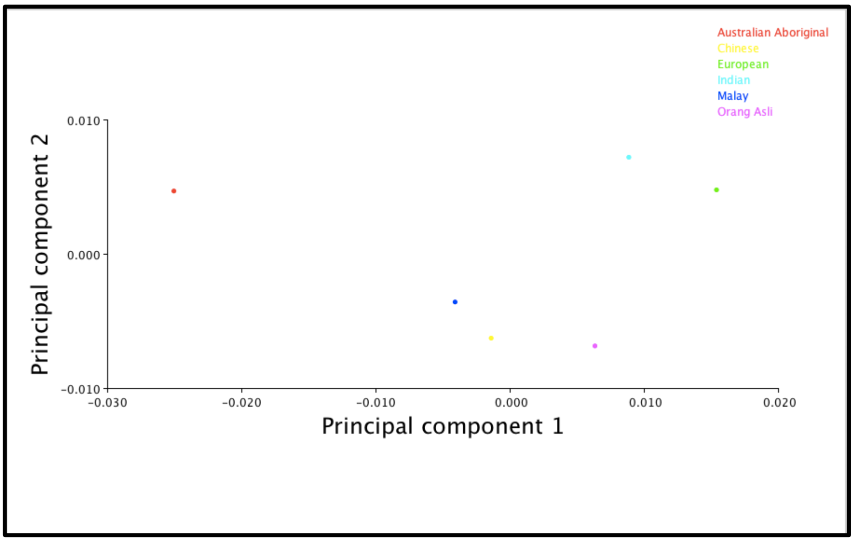


Figure 7.3: Scatter plot of the first two principal components (PCs) of mean dental arch shape variables

Figure 7.3 shows a scatter plot of the average of shape coordinates among population groups. The scatter plot of the first two PCs of shape showed a separation between the Australian Aboriginal group and the European group with the Malaysian sample grouped in the middle. PC1 shows that there is a large separation between the Australian Aboriginals and the other populations. The Europeans and the Indians showed a close relationship. PC2 shows separation between the Malaysian groups from the Australian Aboriginals and Europeans.

Table 7.2: Variation among groups, scaled by the inverse of the within-group variation

	Eigenvalues	% Variance	Cumulative %
1.	0.58541389	53.205	53.205
2.	0.22349305	20.312	73.516
3.	0.14741484	13.398	86.914
4.	0.07977532	7.250	94.164
5.	0.06421017	5.836	100.000

There is evidence of significant differences of dental arch shape between the populations.

Table 7.3: Mahalanobis distances among groups

	1 Australian Aboriginals	2 Chinese	3 Europeans	4 Malay	5 Indians
2. Chinese	1.9778				
3. European	2.3570	1.4169			
4. Indian	2.0051	1.3710	0.9973		
5. Malay	1.7389	0.9603	1.3021	1.1972	
6. Orang Asli	2.5972	1.6504	1.6354	1.6090	1.4996

P-values from permutation tests (10000 permutation rounds) for Mahalanobis distances among groups:

	1 Australian Aboriginals	2 Chinese	3 Europeans	4 Malay	5 Indians
2. Chinese	<.0001				
3. European	<.0001	<.0001			
4. Indian	<.0001	<.0001	0.0006		
5. Malay	<.0001	0.0073	<.0001	<.0001	
6. Orang Asli	<.0001	<.0001	<.0001	<.0001	<.0001

Table 7.4: Procrustes distances among groups

	1 Australian Aboriginals	2 Chinese	3 Europeans	4 Malay	5 Indians
2. Chinese	0.0274				
3. European	0.0408	0.0211			
4. Indian	0.0344	0.0188	0.0107		
5. Malay	0.0233	0.0076	0.0219	0.0179	
6. Orang Asli	0.0340	0.0160	0.0180	0.0162	0.0152

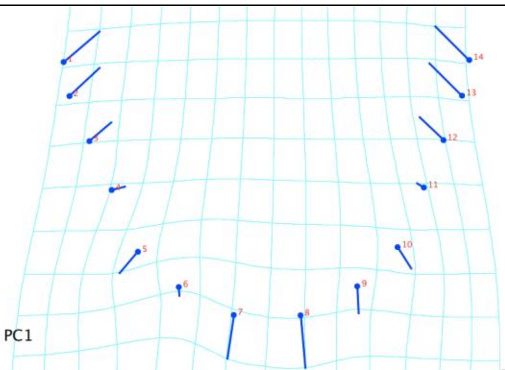
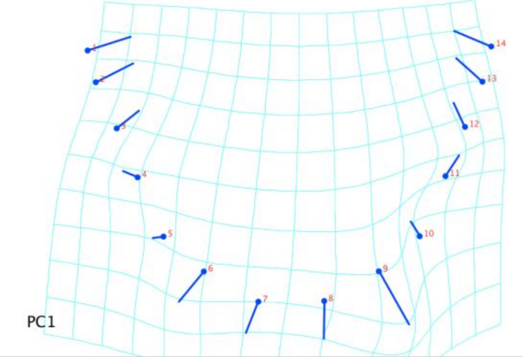
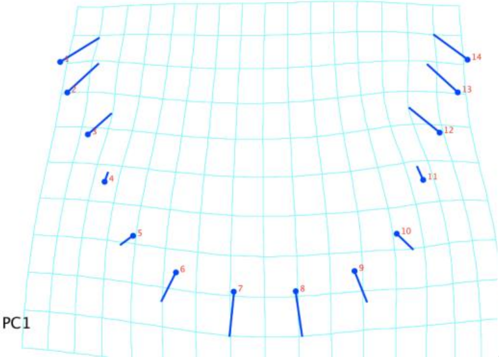
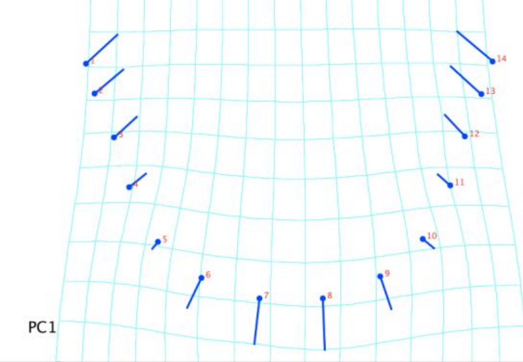
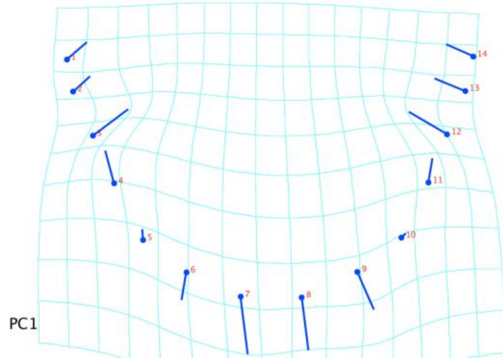
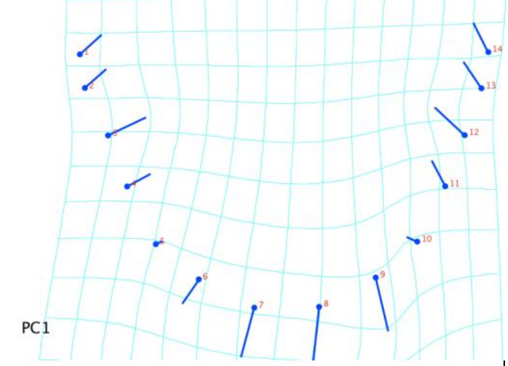
P-values from permutation tests (10000 permutation rounds) for Procrustes distances among groups:

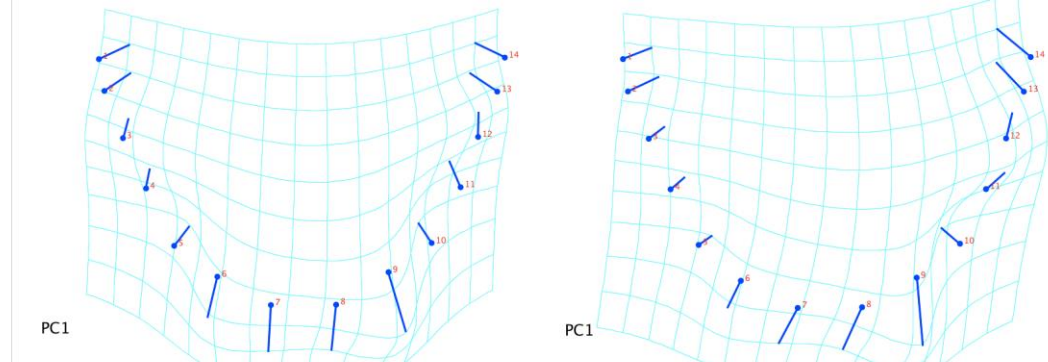
	1 Australian Aboriginals	2 Chinese	3 Europeans	4 Malay	5 Indians
2. Chinese	<.0001				
3. European	<.0001	<.0001			
4. Indian	<.0001	0.0008	0.0754		
5. Malay	<.0001	0.4906	<.0001	0.0004	
6. Orang Asli	<.0001	0.0272	0.0035	0.0332	0.0196

7.4.2 Analysis of transformation of shape according to each sample

Shape variation explained by the principal component analysis can be visualized through graphic representation (Hennessy and Stringer, 2002). Displacements of the coordinates can be represented using thin-plate splines (Bookstein, 1989; O'Higgins and Dryden, 1993), warping a wireframe (Penin et al., 2002), or by transformation grids (O'Higgins and Jones, 1998) which is the most popular method and the method that will be used in this chapter.

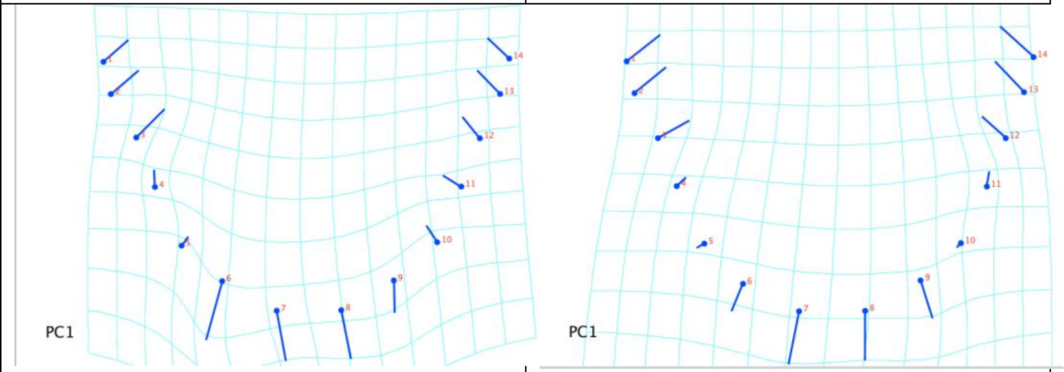
7.5 Geometric Morphometric Analysis for maxillary dental arch shape

Tranformation grid for arch shape (PC1)	
	
European (Male) PC1 (scale factor 0.2)	**European (Female) PC1 (scale factor 0.2)**
	
Australian Aboriginal (Male) PC1 (scale factor 0.2)	**Australian Aboriginal (Female) PC1(scale factor 0.2)**
	
Malay (Male) PC1 (scale factor 0.2)	**Malay (Female) PC1 (scale factor 0.2)**



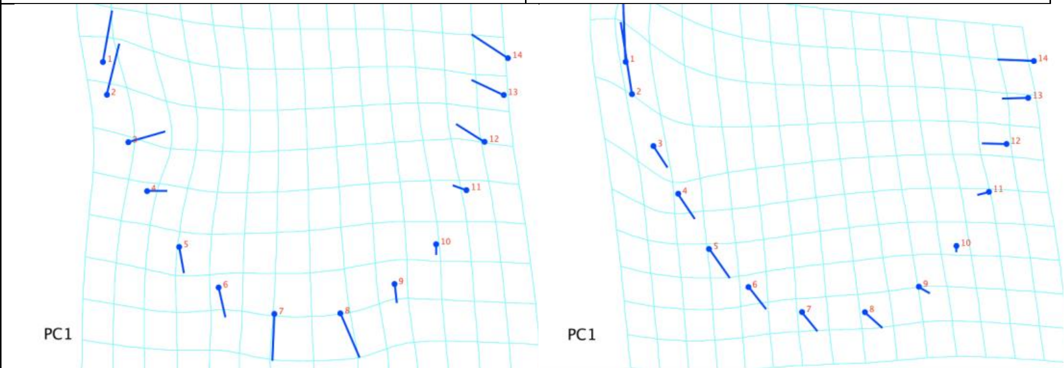
Chinese (Male) PC1 (scale factor 0.2)

Chinese (Female) PC1 (scale factor 0.2)



Indian (Male) PC1 (scale factor 0.2)

Indian (Female) PC1 (scale factor 0.2)

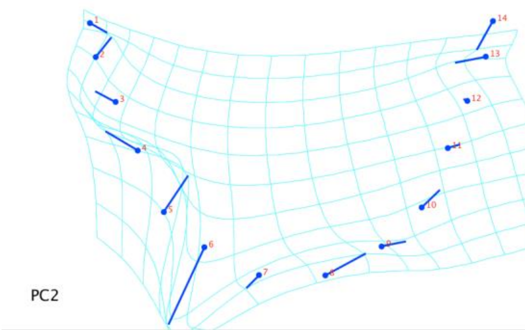
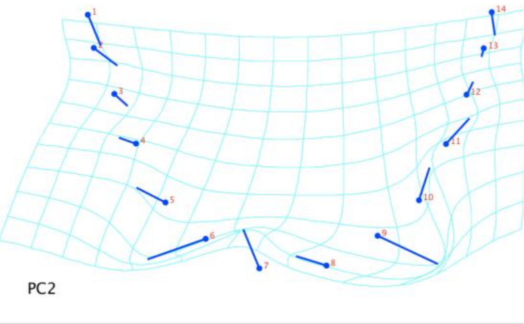
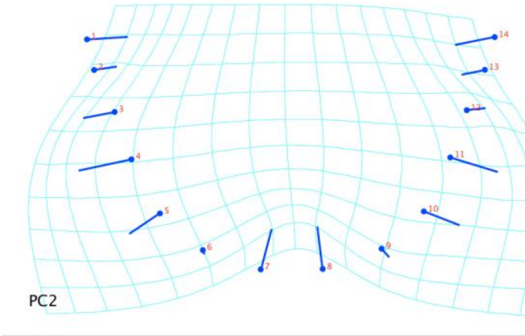
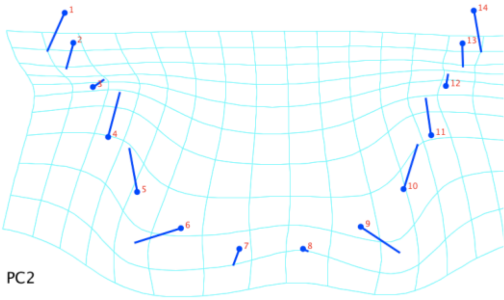
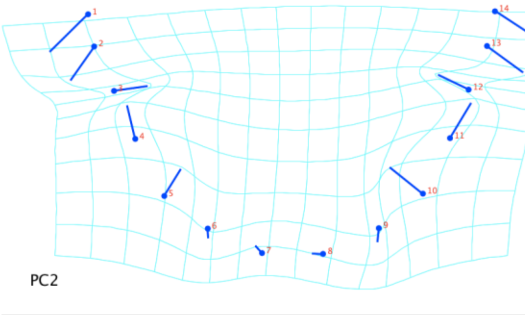
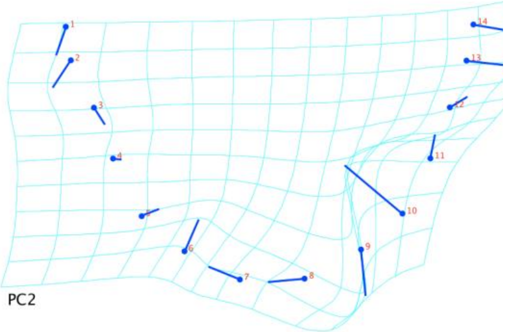


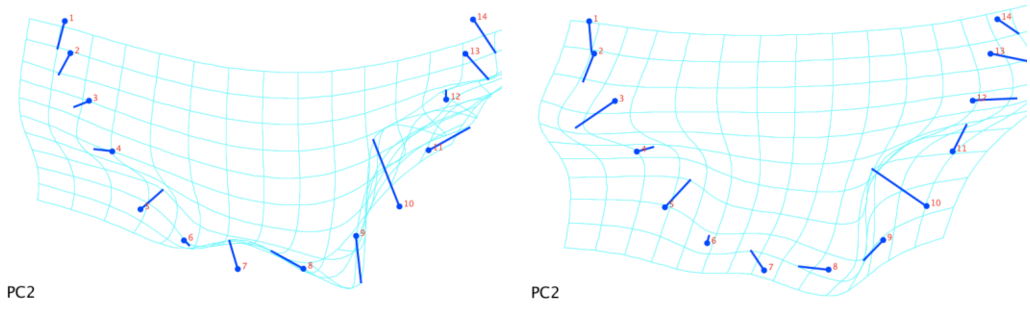
Orang Asli (Male) PC1 (scale factor 0.2)

Orang asli (Female) PC1 (scale factor 0.2)

Figure 7.4: Transformation grid of PC1 (scaled to factor 0.2) showing deformation of arch shape in the starting to target shape for all population groups

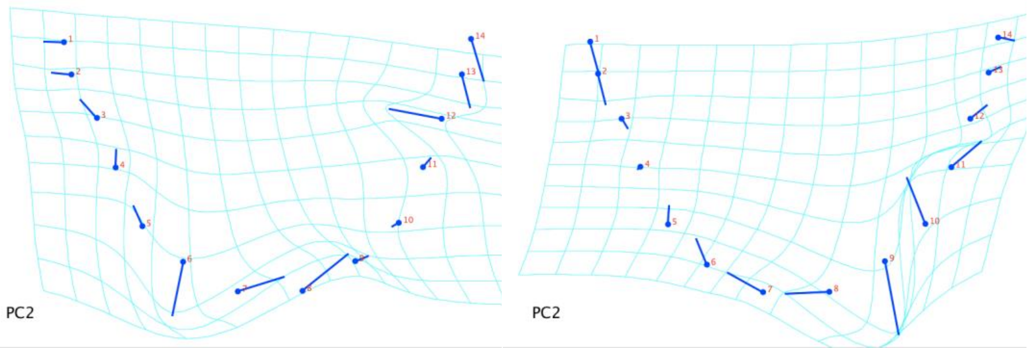
In general, the starting shape represented by the lines connected by the blue dots was the control mean shape and the target shape was the respective population groups mean shapes. Comparisons of arch shape were carried out between population groups. In general, significant differences were found between each group to the population mean. The pattern was less clear within the premolar area.

Tranformation grid for arch shape (PC2)	
	
European (Male) PC2 (scale factor 0.2)	European (Female) PC2 (scale factor 0.2)
	
Australian Aboriginal (Male) PC2 (scale factor 0.2)	Australian Aboriginal (Female) PC2 (scale factor 0.2)
	
Malay (Male) PC2 (scale factor 0.2)	Malay (Female) PC2 (scale factor 0.2)



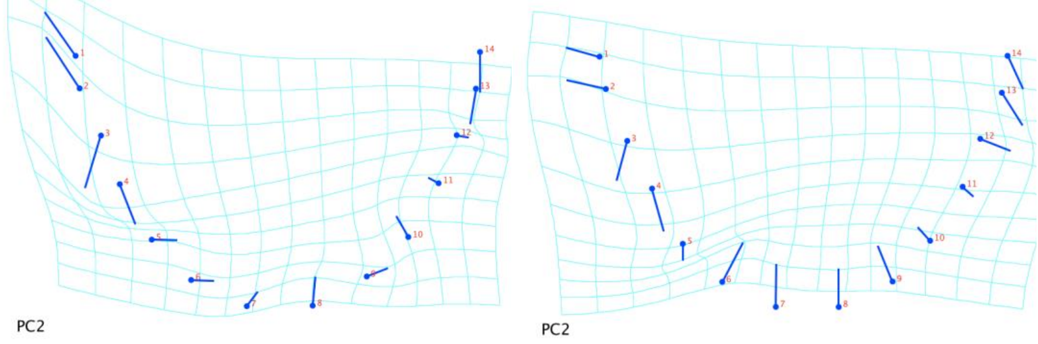
Chinese (Male) PC2 (scale factor 0.2)

Chinese (Female) PC2 (scale factor 0.2)



Indian (Male) PC2 (scale factor 0.2)

Indian (Female) PC2 (scale factor 0.2)



Orang Asli (Male) PC2 (scale factor 0.2)

Orang Asli (Female) PC2 (scale factor 0.2)

Figure 7.5: Transformation grid of PC2 (scaled to factor 0.2) showing deformation of arch shape in the starting to target shape for all population groups

7.5.1 Detailed analysis of GMA according to population

7.5.1.1 European

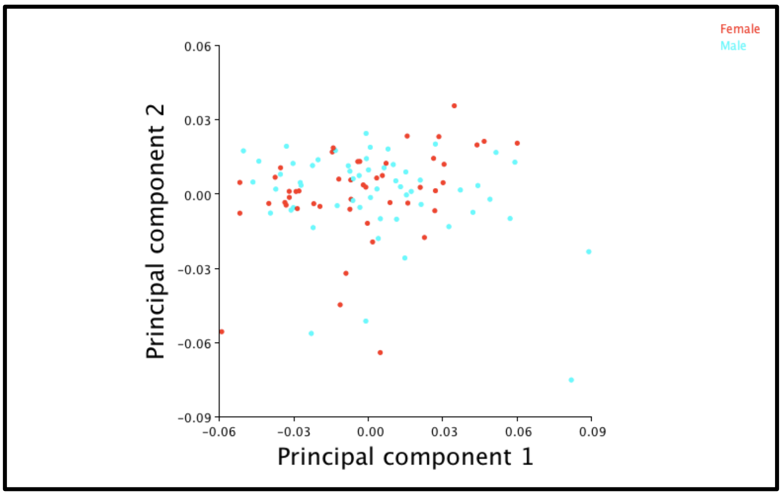


Figure 7.6: Europeans group overall shapes. Scatter plot of the first two principal components (PCs) of shape variables

A variance of 61.6% in the European group was explained by principal components 1 and 2 (Figure 7.6). The wireframe graph shown in Figure 7.7 shows directional differences from the average dental arch shape of the group (Procrustes transformation). From the graph it can be seen that there was anterior displacement of anterior segment of the dental arch, explaining the tendency of anterior teeth of this group to be displaced labially from the mean shape. The posterior segment shows a lingual displacement of the position of the teeth.

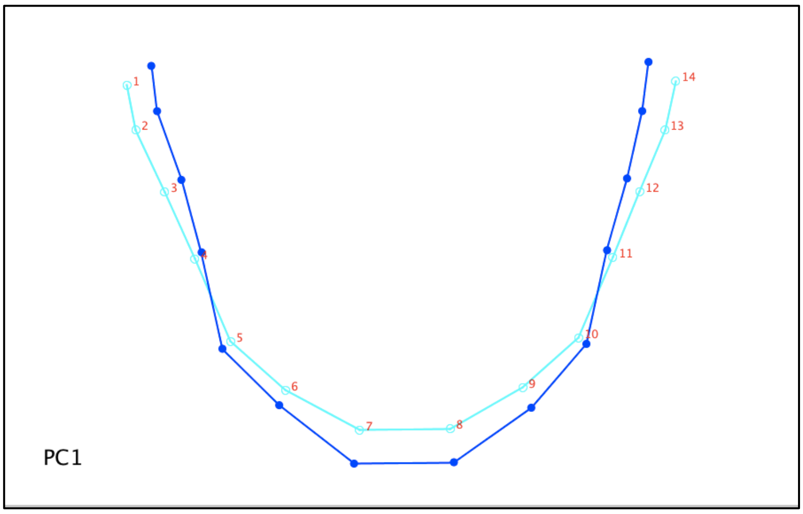


Figure 7.7: Wireframe graph shows PC shape changes (PC1) to the maxillary dental arch shape of the Europeans (dark blue) relative to the grand mean (light blue)

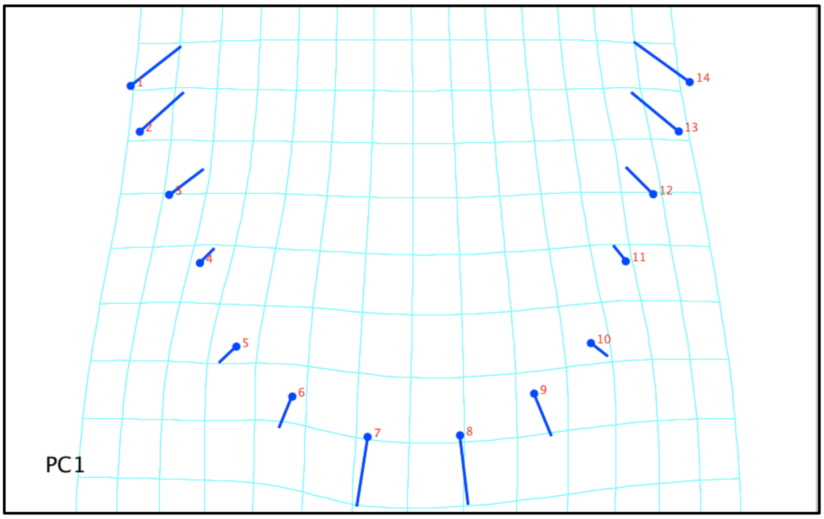


Figure 7.8: Lollipop graph on transformation grid shows the direction of change for each individual landmark of the Europeans to the general group

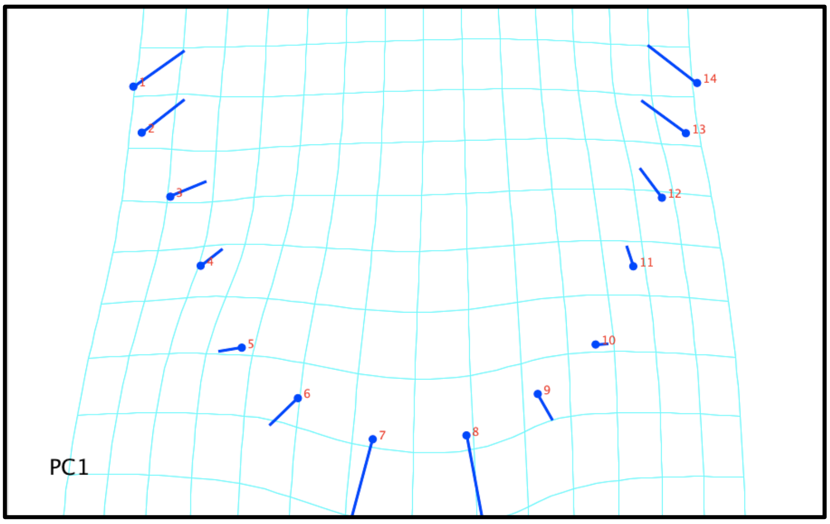


Figure 7.9: Lollipop graph shows the direction of change for each individual landmark of the maxillary dental arch between female and Europeans mean for principal component 1 (scale factor 0.2)

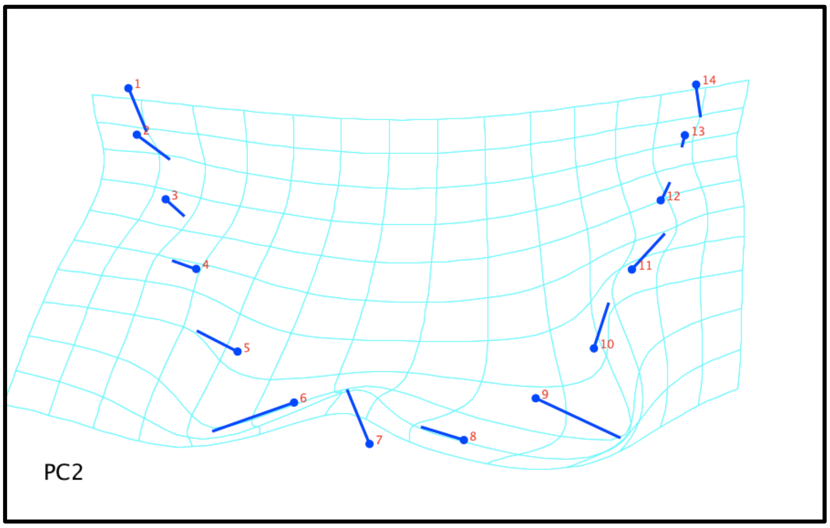


Figure 7.10 Lollipop graph shows the direction of change for each individual landmark of the maxillary dental arch between female and Europeans mean for principal component 2 (scale factor 0.2)

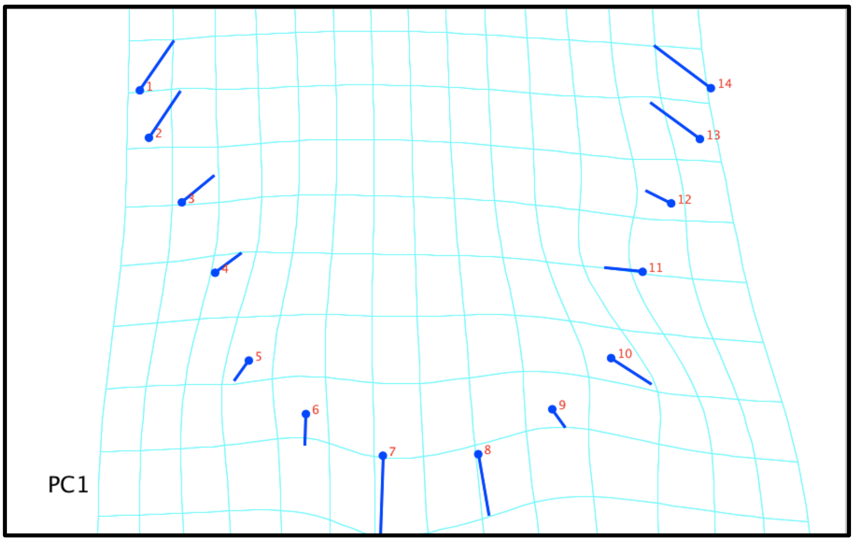


Figure 7.11: Lollipop graph shows the direction of change for each individual landmark of the maxillary dental arch between male and Europeans mean for principal component 1 (scale factor 0.2)

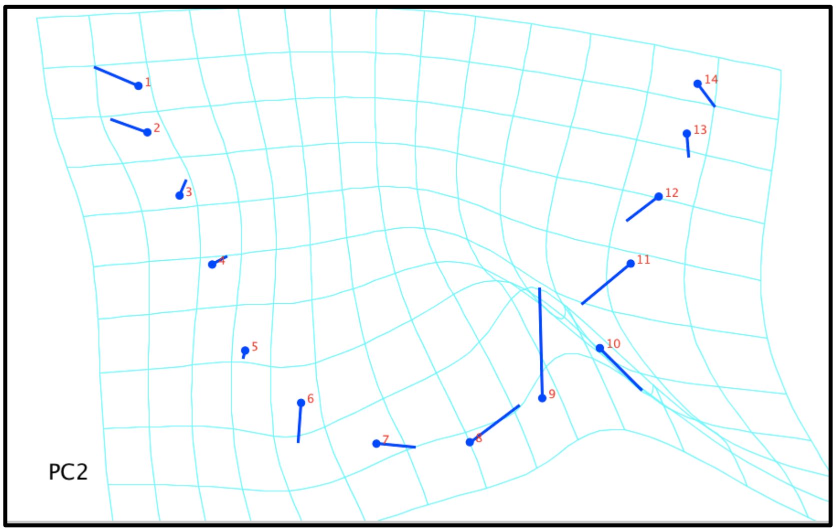


Figure 7.12: Lollipop graph shows the direction of change for each individual landmark of the maxillary dental arch between male and Europeans mean for principal component 2 (scale factor 0.2)

The variance for the European female group was 0.00182 in comparison to the variance of 0.00242 for the European group combined. There was less variation in dental shape among the female group compared to whole group (male and female combined).

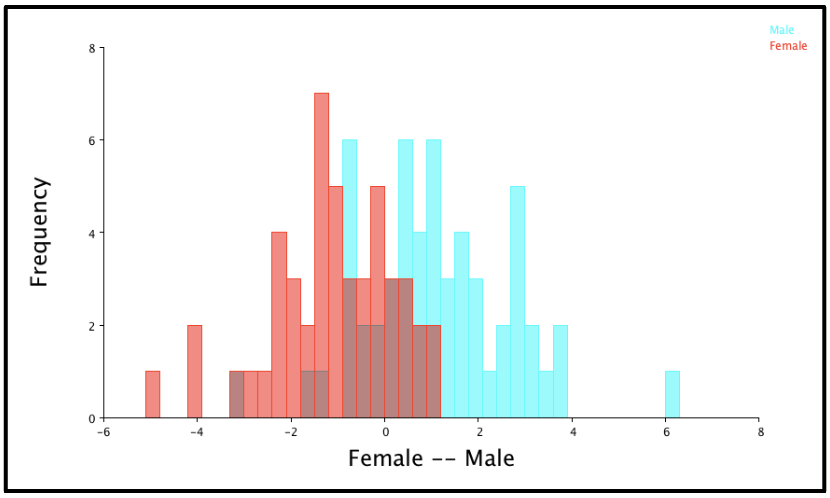


Figure 7.13 Discriminant analysis between arch shape of male and female of Europeans

The Mahalanobis distance between Europeans males and females was 1.49 ($p<0.05$). Procrustes distances among groups (between male and female) was 0.01 ($p<0.05$). To recall, Procrustes distance is a measure of the absolute magnitude of the shape deviation, whereas Mahalanobis distance provides an indication of how unusual an individual is relative to the others in the sample (in larger samples)).

7.5.1.2 Australian Aboriginal

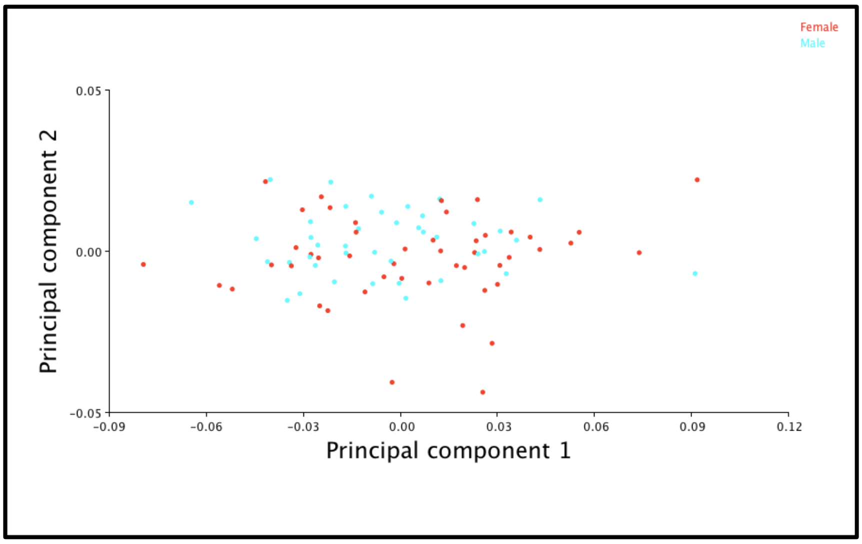


Figure 7.14: Scatter plot 58.5% of the first two principal components of shape variables variance in the Australian Aboriginals

The first and second PCs accounted for 58.5% and 8.5% of total variance. The wireframe graph in Figure 7.14 shows directional differences from the average dental arch shape of the group. From the graph it shows that there was the possibility of displacement of anterior segment of the dental arch, explaining the tendency of prognathism of anterior teeth of this group. The posterior segment shows a lingual displacement of the position of the teeth

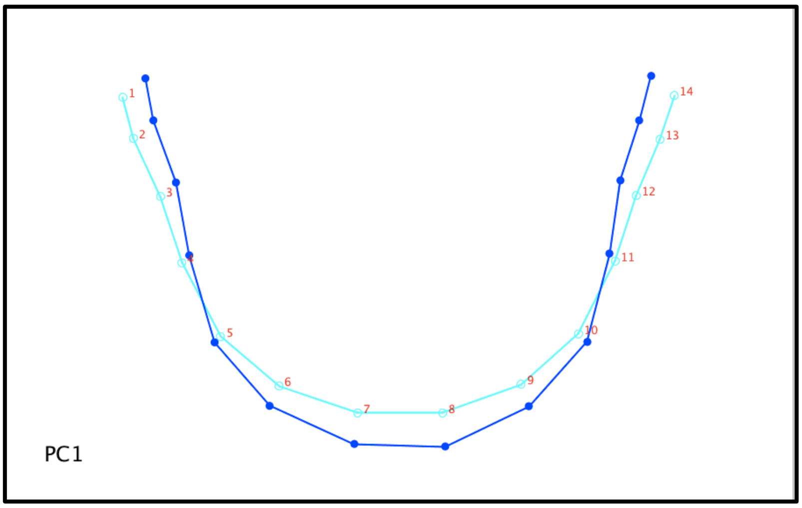


Figure 7.15: Wireframe graph of PC1 (scale to the factor of 0.2) shows shape changes between male and female of Australian Aboriginal

The Mahalanobis distances among groups between male and female was 1.4344, while Procrustes distances among groups (between male and female) was 0.0116 but these values were not statistically different.

7.5.1.3 Malays

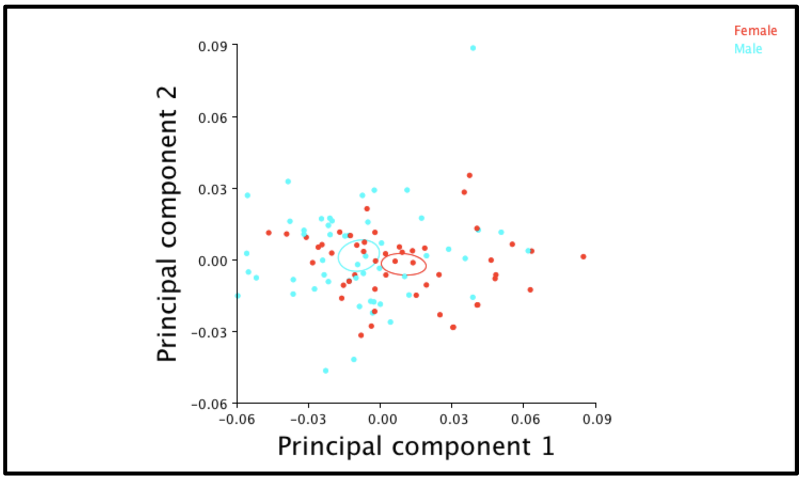


Figure 7.16: Scatter plot 58.5% of the first two principal components of shape variables variance in the Malays group.

Figure 7.16 showed the first 2 PCAs of Malay's arch shape. PC 1,2,3 and 4 explained about 66.6% of variance in the Malay group. The wireframe graph in Figure 7.16 shows directional differences from the average dental arch shape of the group. From the graph it shows that there was anterior displacement of anterior segment of the dental arch, explaining the tendency of prognathism of anterior teeth of this group. The posterior segment shows a lingual displacement of the position of the teeth.

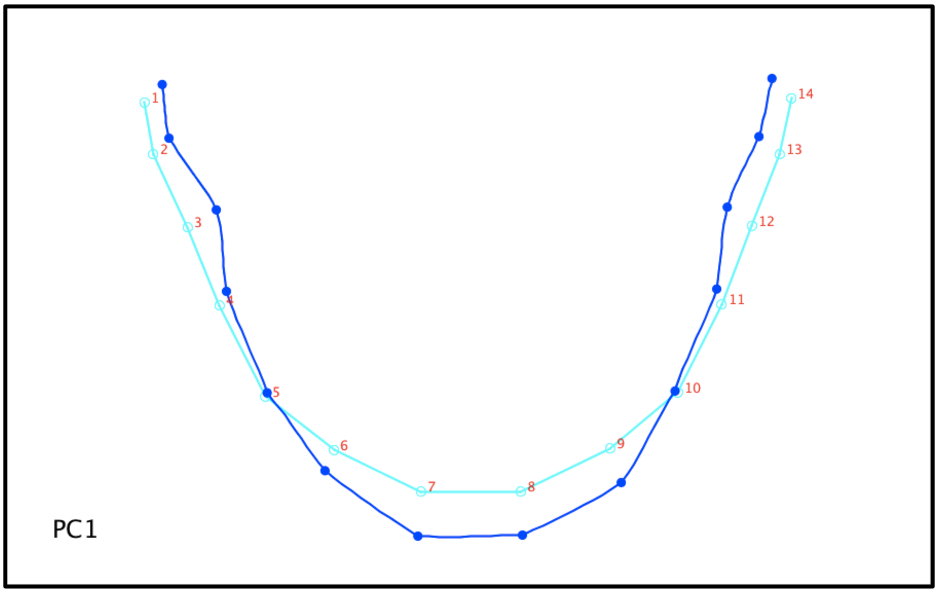


Figure 7.17: Wireframe graph of PC1 (scale to the factor of 0.2) shows shape changes between male and female of Malay group

7.5.1.4 Chinese

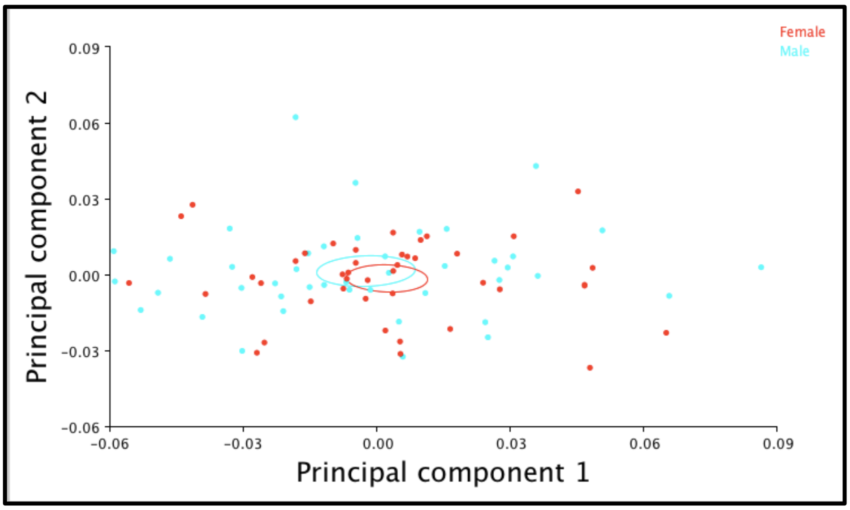


Figure 7.18: Scatter plot 58.5% of the first two principal components of shape variables variance in the Chinese group.

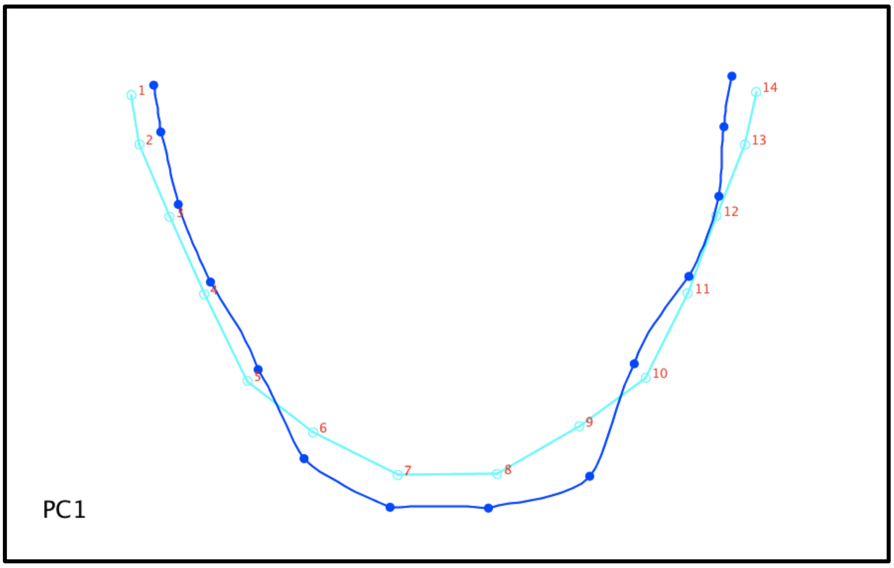


Figure 7.19: Wireframe graph of PC1 (scale to the factor of 0.2) shows shape changes between male and female of Chinese group

7.5.1.5 Indian

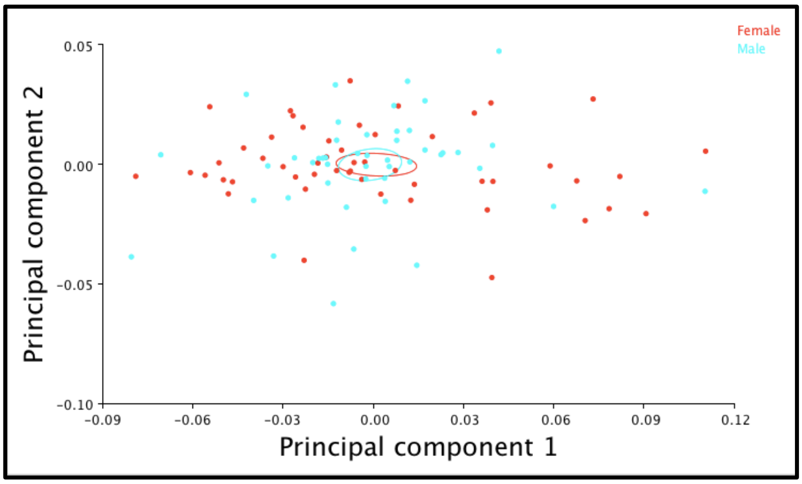


Figure 7.20: Scatter plot 58.5% of the first two principal components of shape variables variance in the Indians group

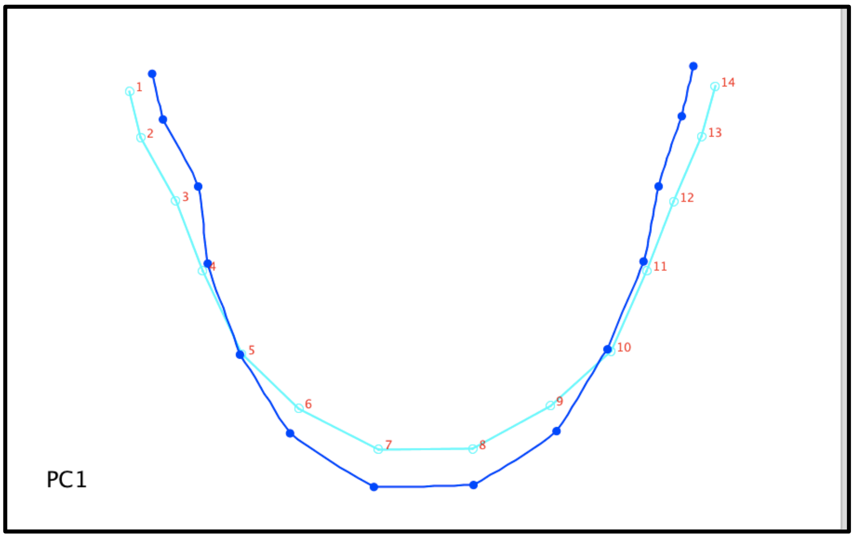


Figure 7.21: Wireframe graph of PC1 (scale to the factor of 0.2) shows shape changes between male and female of Indian group

7.5.1.6 Orang Asli

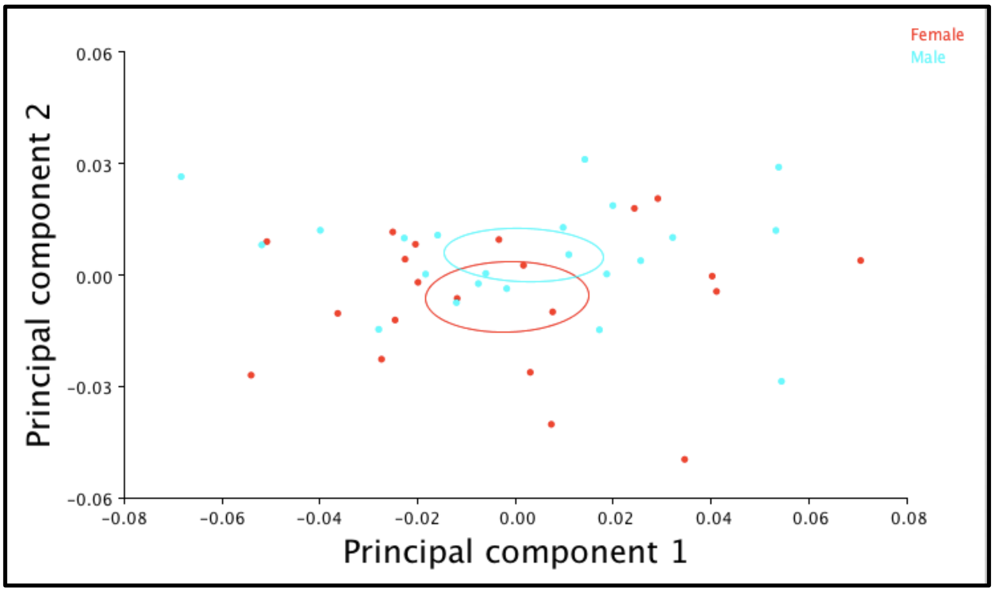


Figure 7.22: Scatter plot 58.5% of the first two principal components of shape variables variance in the Orang Asli group

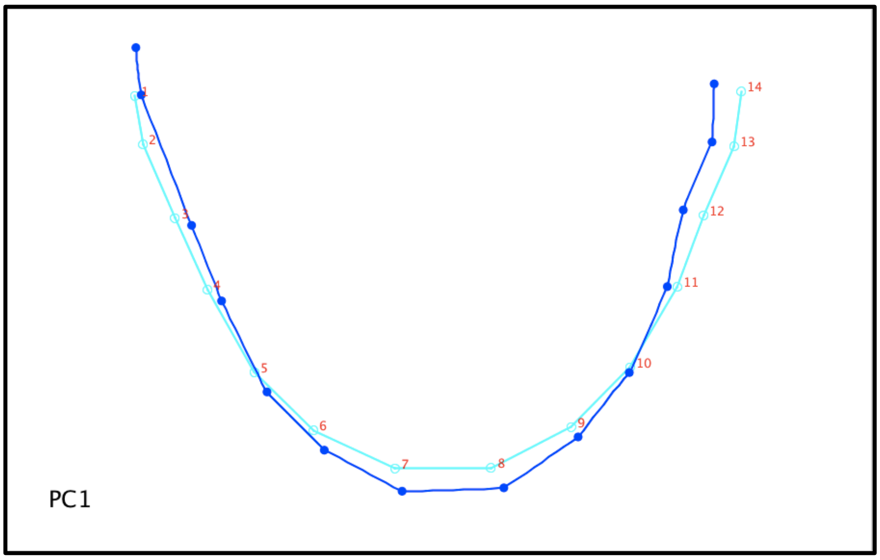


Figure 7.23: Wireframe graph of PC1 (scale to the factor of 0.2) shows shape changes between male and female of Orang Asli grou

7.5.2 Comparison between Europeans and Indians

Discriminant Function Scores indicated that Europeans and Indians had a close relationship of dental arch shapes. Discriminant Function Analysis of Europeans' and Indians' dental arch shape revealed a Mahalanobis distance of 0.99984 and a Procrustes distance of 0.01 (p<0.05). Cross validation showed a close relationship between the two population groups with classification/misclassification display below.

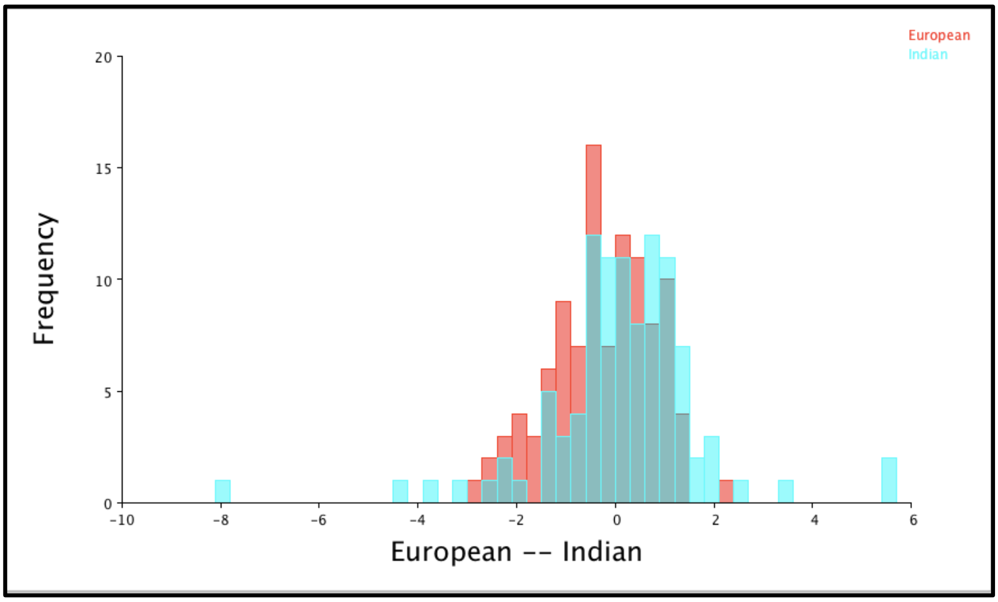
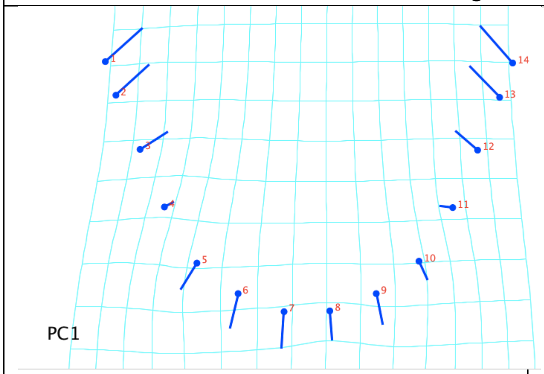


Figure 7.24: Cross validation of arch shape of Europeans and Indians

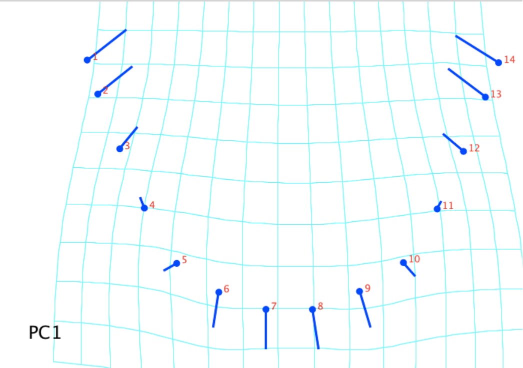
7.6 Geometric Morphometric Analysis for mandibular dental arch shape

7.6.1 Shape transformation of mandibular arch shape using Procrustes analysis

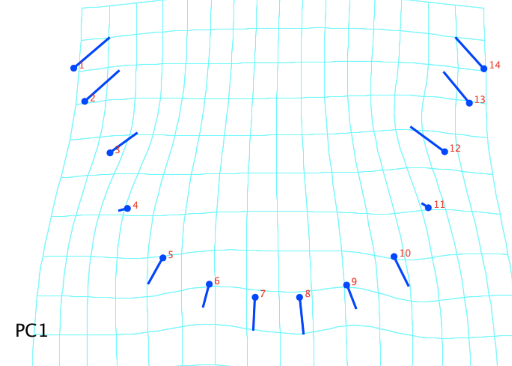
Tranformation grid for arch shape (PC1)



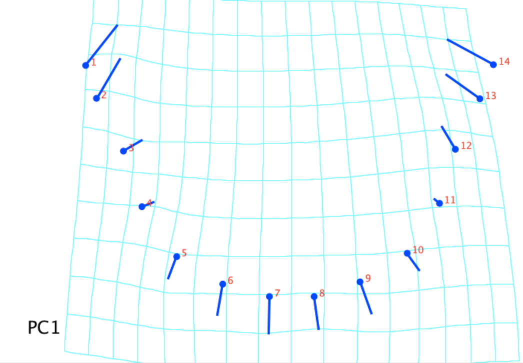
European (Male) PC1 (scale factor 0.2)



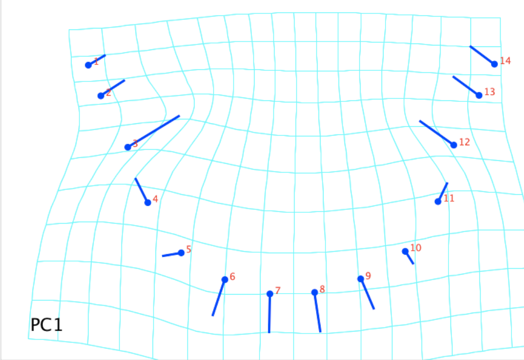
European (Female) PC1 (scale factor 0.2)



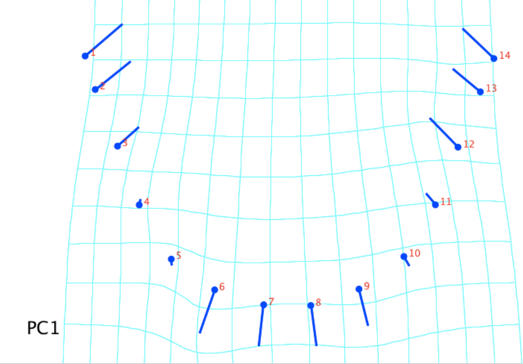
Australian Aboriginal (Male) PC1 (scale factor 0.2)



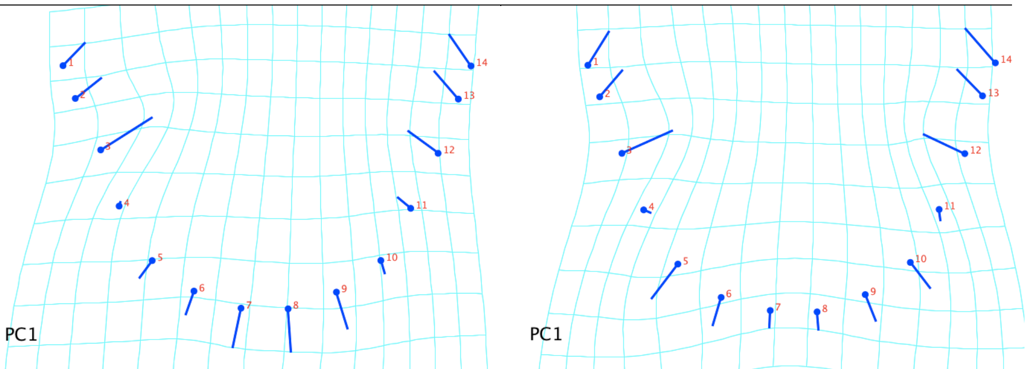
Australian Aboriginal (Female) PC1(scale factor 0.2)



Malay (Male) PC1 (scale factor 0.2)

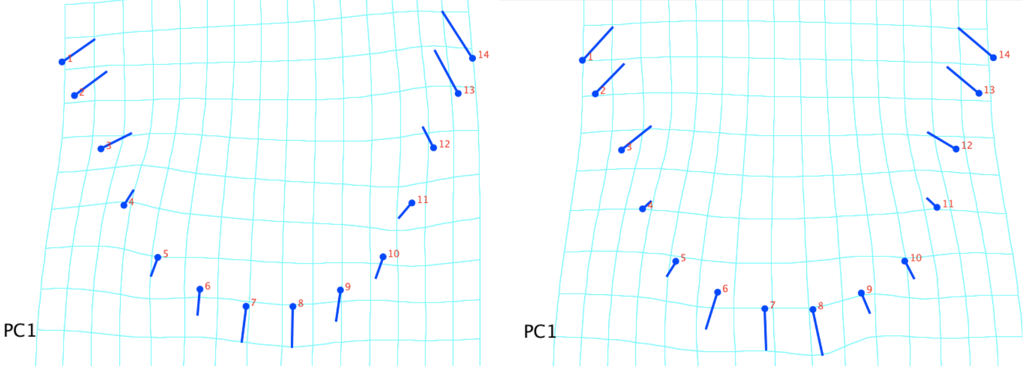


Malay (Female) PC1 (scale factor 0.2)



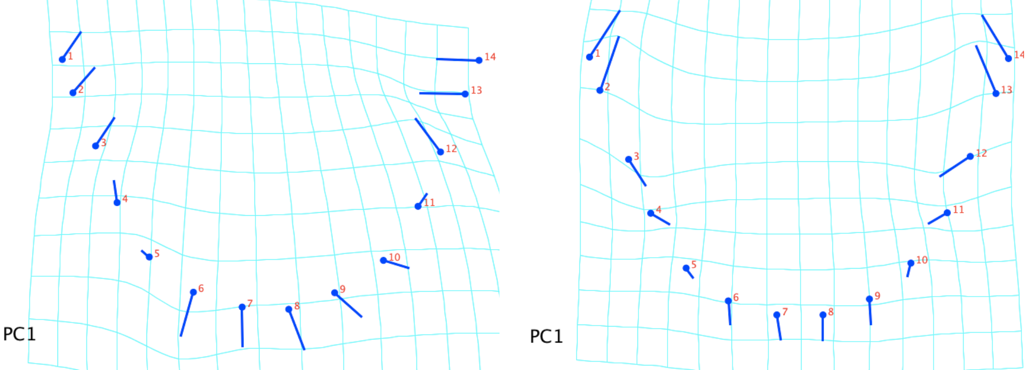
Chinese (Male) PC1 (scale factor 0.2)

Chinese (Female) PC1 (scale factor 0.2)



Indian (Male) PC1 (scale factor 0.2)

Indian (Female) PC1 (scale factor 0.2)

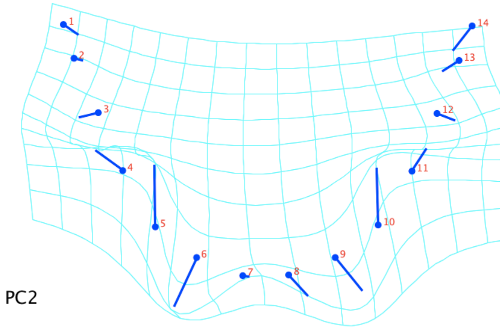


Orang Asli (Male) PC1 (scale factor 0.2)

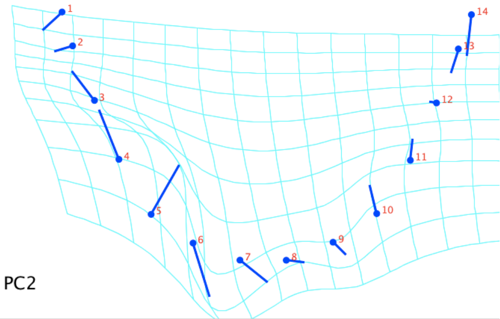
Orang Asli (Female) PC1 (scale factor 0.2)

Figure 7.25: Lollipop graph showing PC1 of Procrustes analysis of mandibular arch shape between population sample

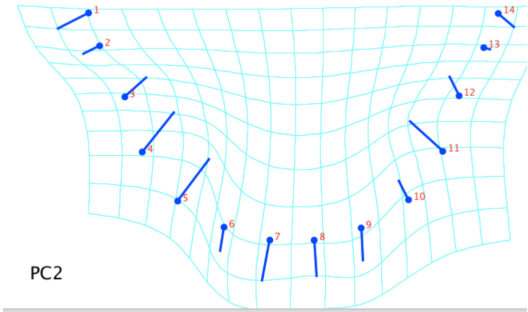
Tranformation grid for arch shape (PC2)



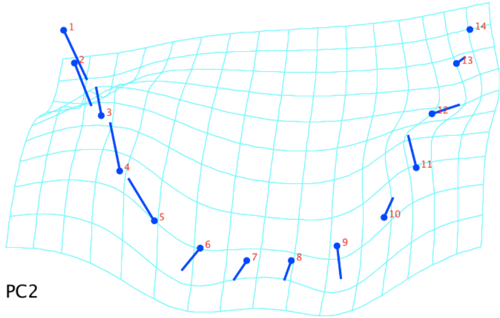
European (Male) PC2 (scale factor 0.2)



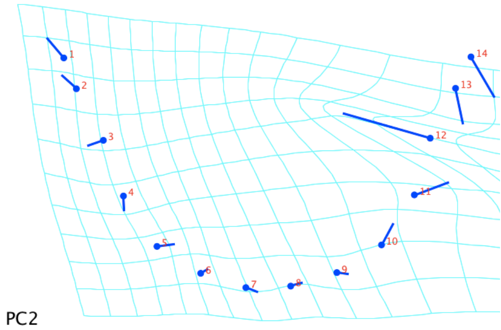
European (Female) PC2 (scale factor 0.2)



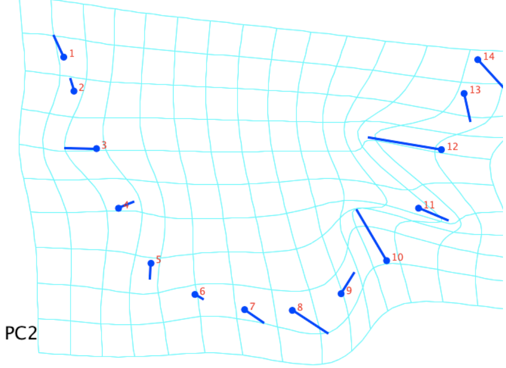
Australian Aboriginal (Male) PC2 (scale factor 0.2)



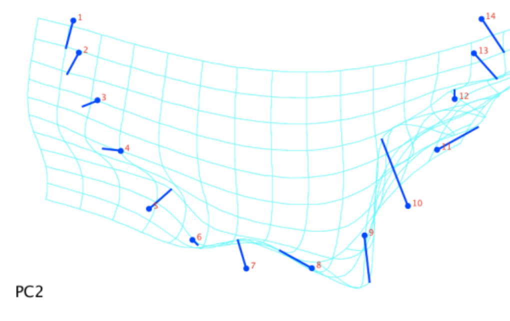
Australian Aboriginal (Female) PC2 (scale factor 0.2)



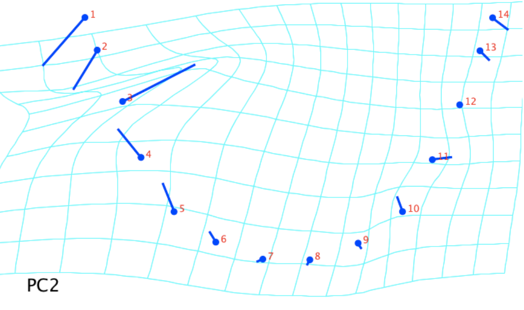
Malay (Male) PC2 (scale factor 0.2)



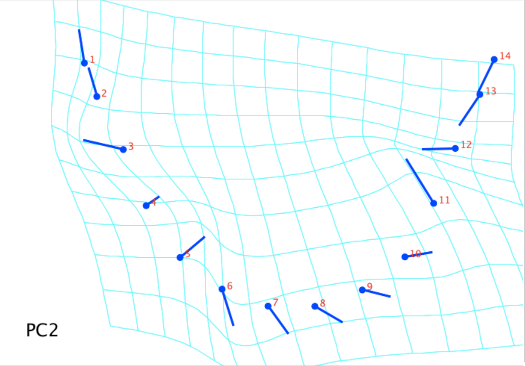
Malay (Female) PC2 (scale factor 0.2)



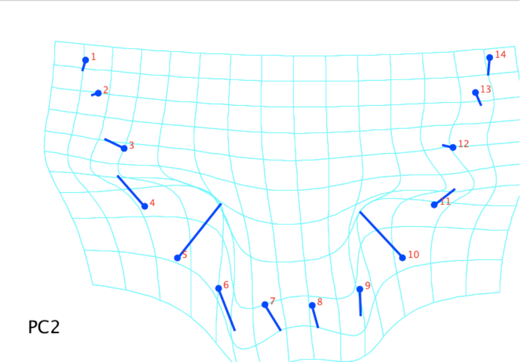
Chinese (Male) PC2 (scale factor 0.2)



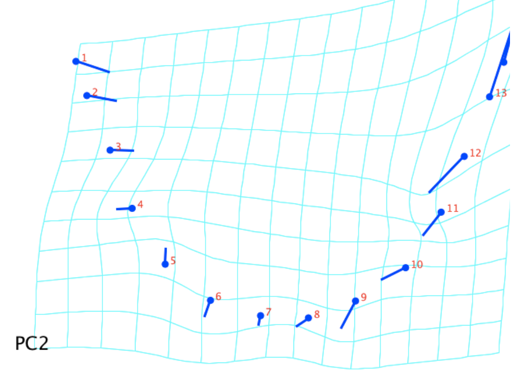
Chinese (Female) PC2 (scale factor 0.2)



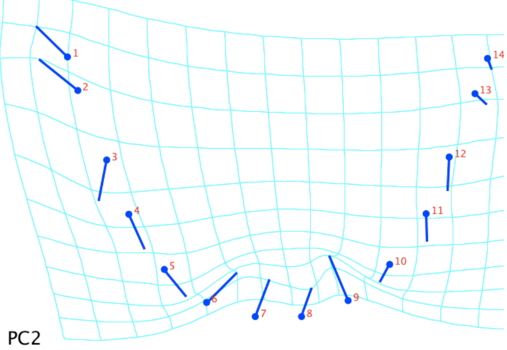
Indian (Male) PC2 (scale factor 0.2)



Indian (Female) PC2 (scale factor 0.2)



Orang Asli (Male) PC2 (scale factor 0.2)



Orang Asli (Female) PC2 (scale factor 0.2)

Figure 7.26: Lollipop graph showing PC1 of Procrustes analysis of mandibular arch shape between population sample

7.6.2 Detailed analysis of GMA according to population

7.6.2.1 Europeans

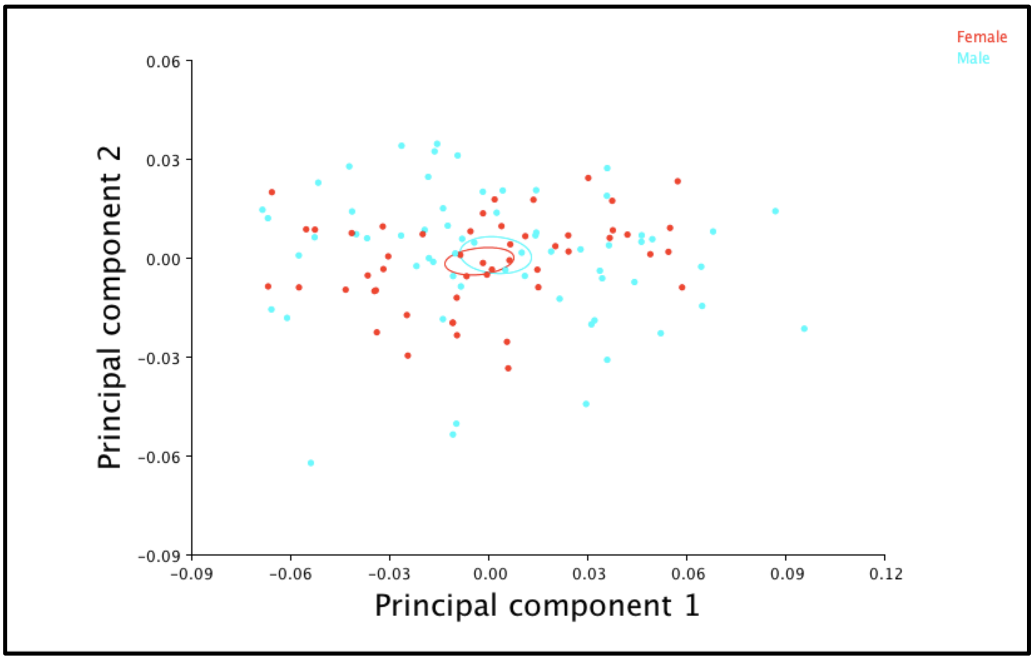


Figure 7.27: European group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

Figure 7.27 shows a scatter plot of overall shape of the Europeans group. PC1 and PC2 explain about 56.6% of variation between the males and females (PC1 42.8% while PC2 13.8%). Similarity in shape among European group per sex was summarized using a PCA on the matrix of mean shape variables. A mean shape is computed by taking the sample average of shape coordinates from the full set of shape variables (Figure 7.41).

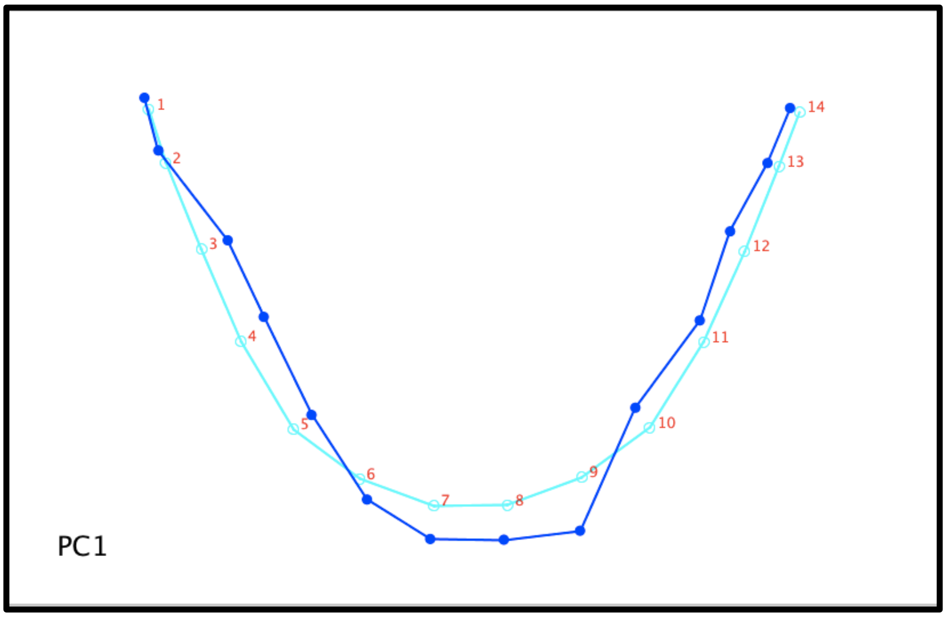


Figure 7.28: Wireframe graph for Europeans group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses were not significant between males and females with a p value > 0.05. According to the discriminant analysis of shape, only 23.9% of female Europeans were correctly classified while only 30.9% of male Europeans were correctly classified according to arch shape. When the results were cross-validated, the percentages of correctly classified individual dropped to just over 17.2% in females and 21.6% in males.

7.6.2.2 Australian Aboriginals

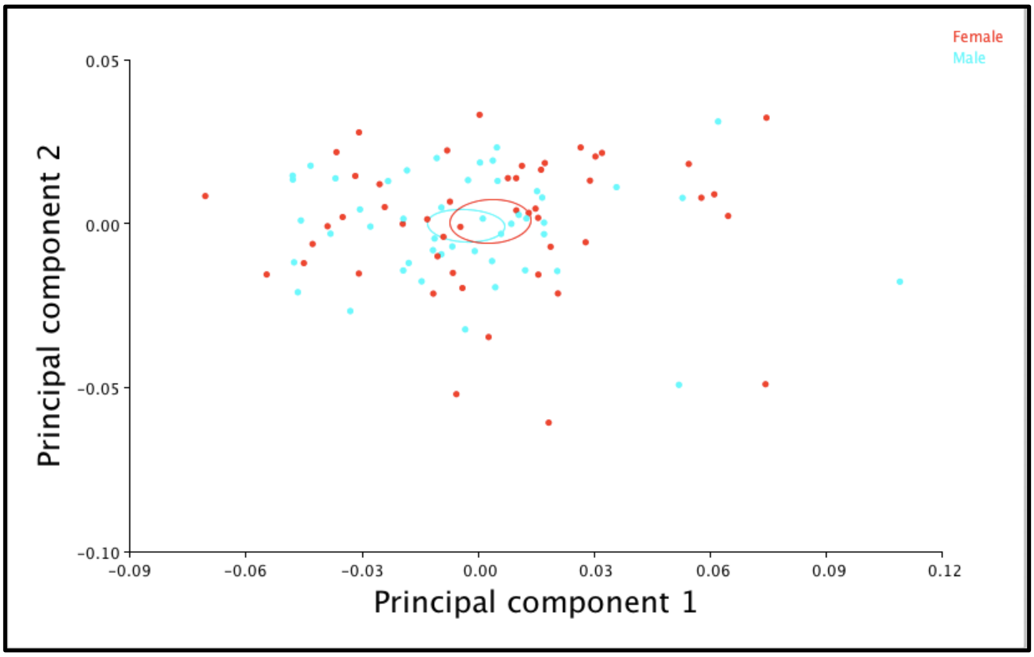


Figure 7.29: Australian Aboriginal group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

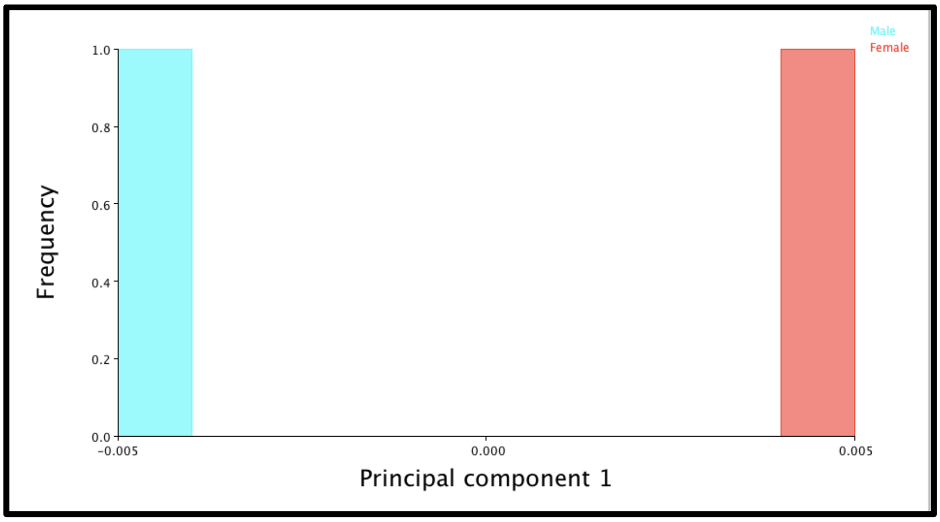


Figure 7.30: Australian Aboriginal average shape pooled by sex

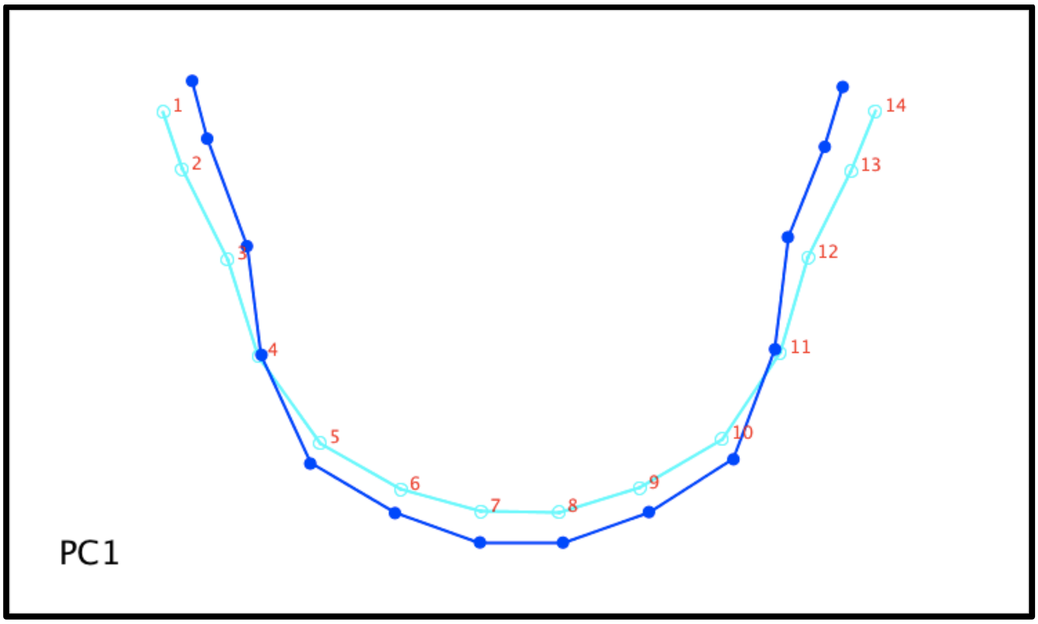


Figure 7.31: Wireframe graph for Australian Aboriginal group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses were not significant between males and females with a p value > 0.05. According to the discriminant analysis of shape, males and females in the Australian Aboriginal group could be better classified but the percentage was still low. Only 32.0% of female Australian Aboriginals were correctly classified while 37.9% of male Australian Aboriginals were correctly classified according to arch shape. When the results were cross-validated, the percentages of correctly classified individual dropped to just over 26.2% in females and 28.1% in males.

7.6.2.3 Malays

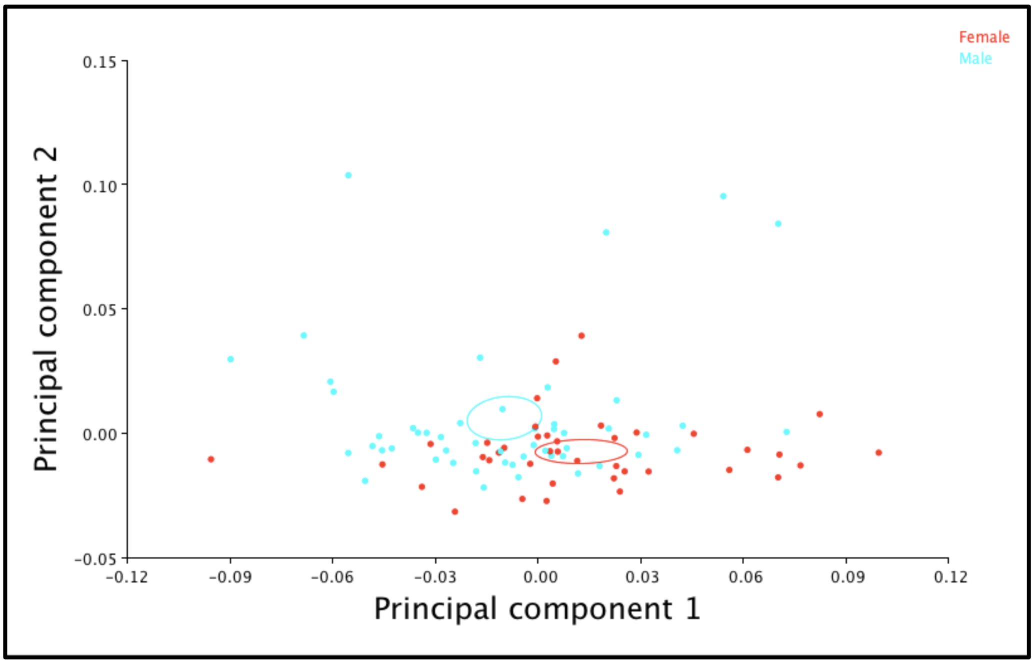


Figure 7.32: Malays group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

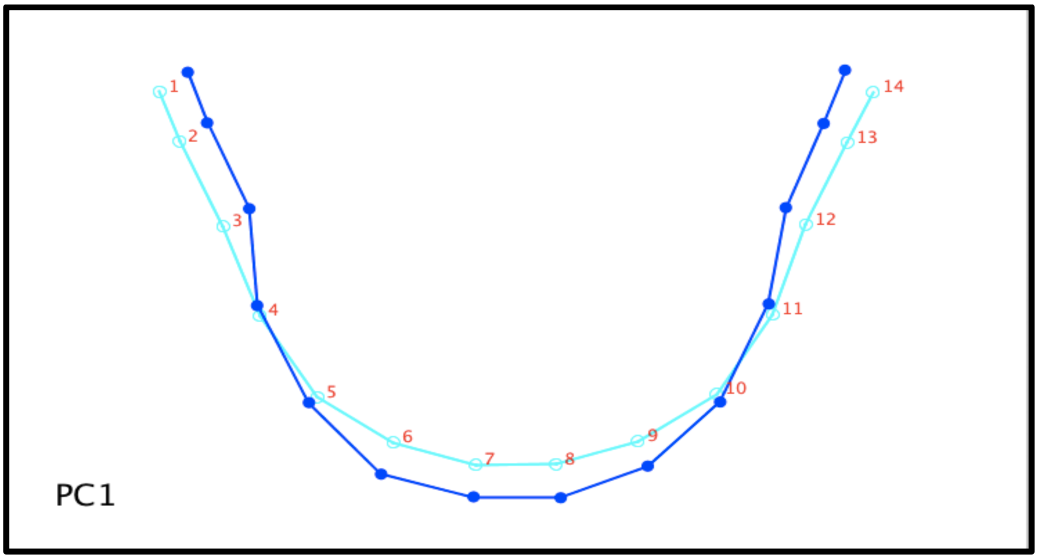


Figure 7.33: Wireframe graph for Malay group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses yielded significant difference between males and females with a p value < 0.05. According to the discriminant analysis of shape, male and female Malays could be better classified compared to the previous two groups. About 77.5% of female Malays were correctly classified while 80.0% of male Malays were correctly classified according to arch shape. When the results were cross-validated, the percentages of correctly classified individual dropped to just 60% in both females and males.

7.6.2.4 Chinese

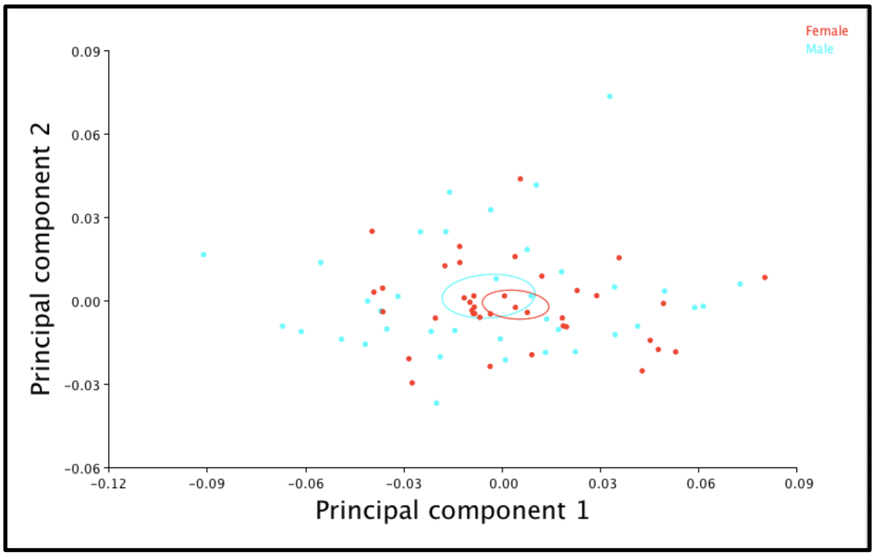


Figure 7.34: Chinese group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

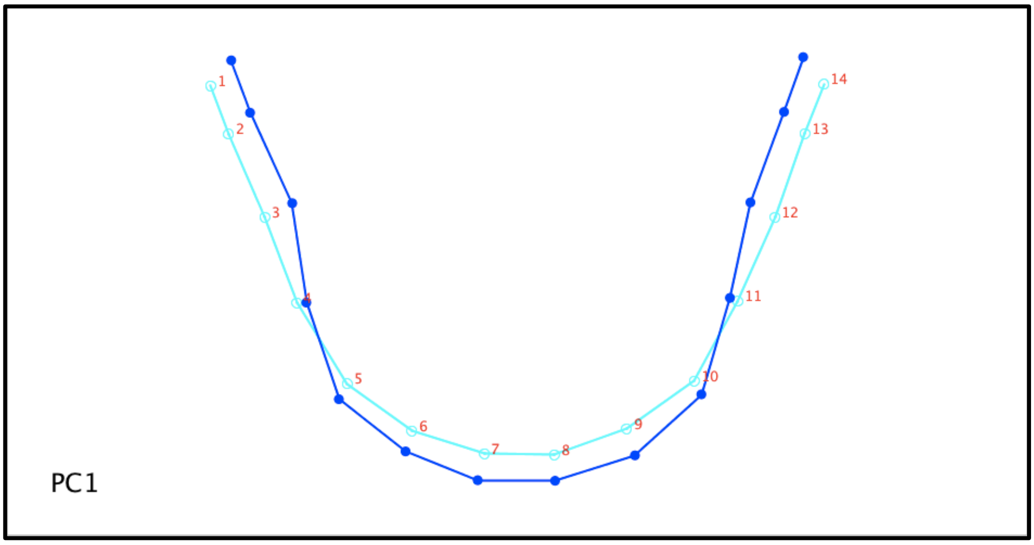


Figure 7.35: Wireframe graph for Chinese group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses showed significant difference between males and females Chinese with a p value < 0.05. According to the discriminant analysis of shape, males and females of the Chinese could be better classified compared to the previous two groups. About 77.5% of female Chinese were correctly classified while 80.0% of male Chinese were correctly classified according to arch shape. When the results were cross-validated, the percentages of correctly classified individual dropped to just 60% in both females and males.

7.6.2.5 Indians

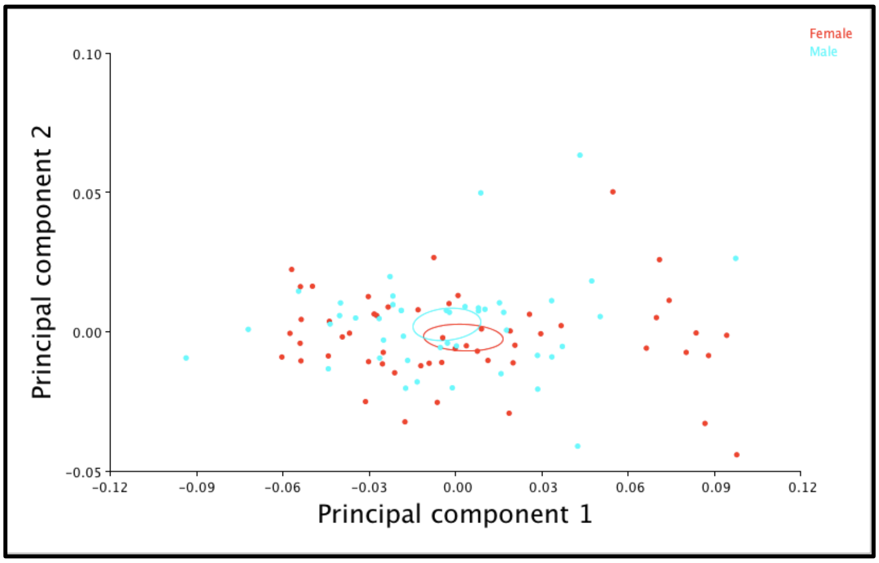


Figure 7.36: Indian group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

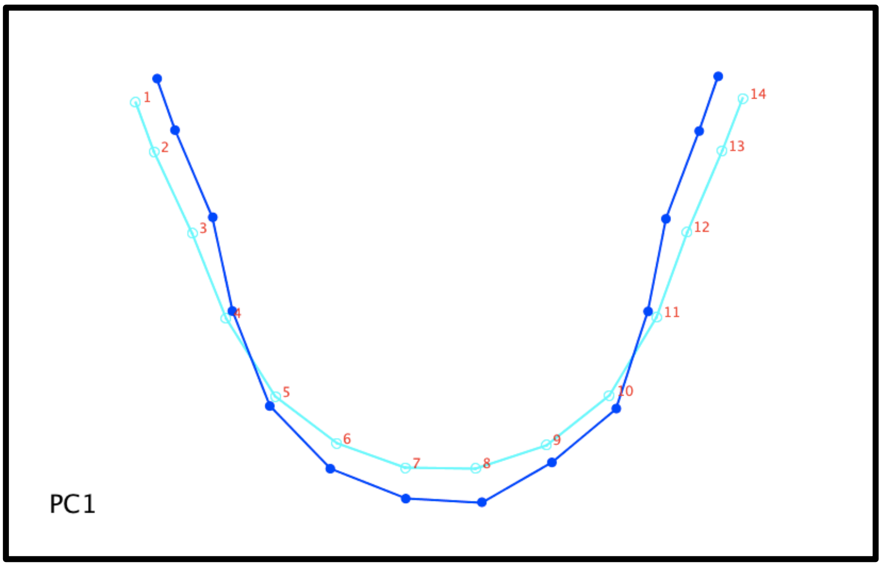


Figure 7.37: Wireframe graph for Indian group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses showed no significant difference between males and females Indians with a p value > 0.05. According to the discriminant analysis of shape, males and females of the Indians could be better classified compared to the previous groups. About 74.1% of female Indians were correctly classified while 75.6% of male Indians were correctly classified according to arch shape. When the results were cross-validated, the percentages of correctly classified individual dropped to just 46.3% for females and 55.6% for males.

7.6.2.6 Orang Asli

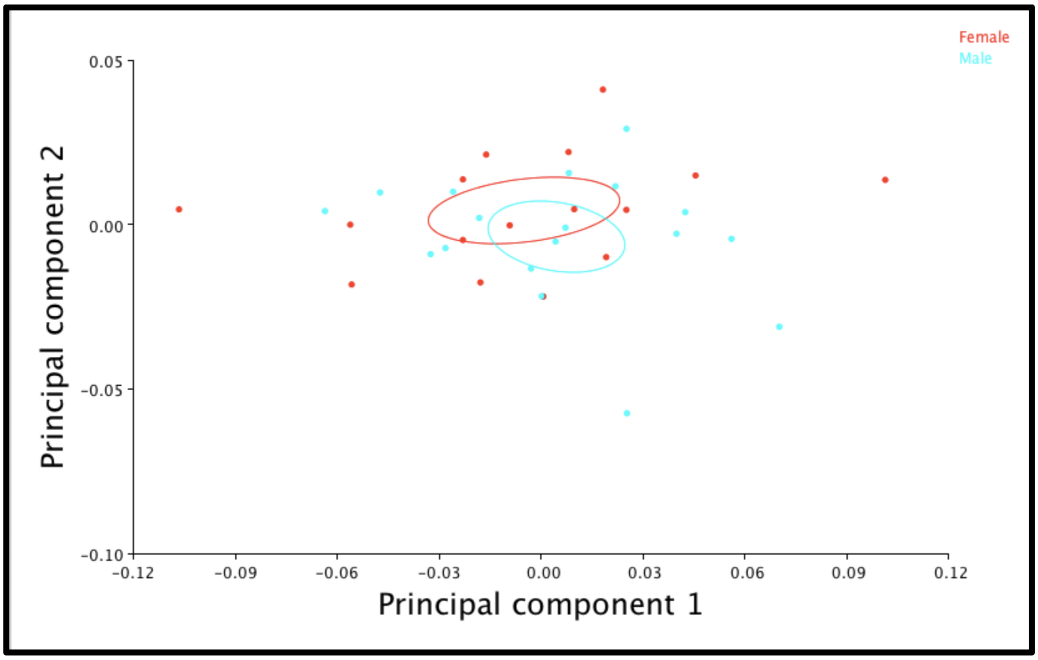


Figure 7.38: Orang Asli group overall shape. Scatter plot of the first two principal components (PCs) of shape variables

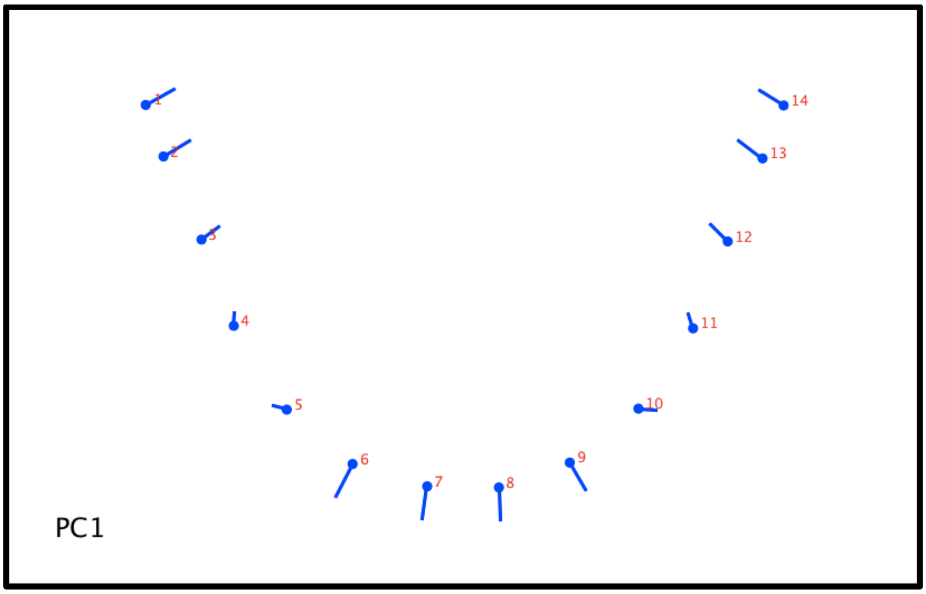


Figure 7.39: Wireframe graph for Orang Asli group mean shape using thin-plate spline derived from the difference between the reference form (sample mean shape)

Discriminant Function Analysis

The results of the discriminant analyses showed no significant difference between the shape distance of males and females Orang Asli with a p value > 0.05. However, according to the discriminant analysis of shape males and females of the Orang Asli, they could be correctly classified to as high as 93.8% for females and males. When the results were cross-validated, the percentages of correctly classified individual dropped to just 62.5% for females and 50.0% for males.

7.6.3 Comparison between PCA of mandibular dental arch

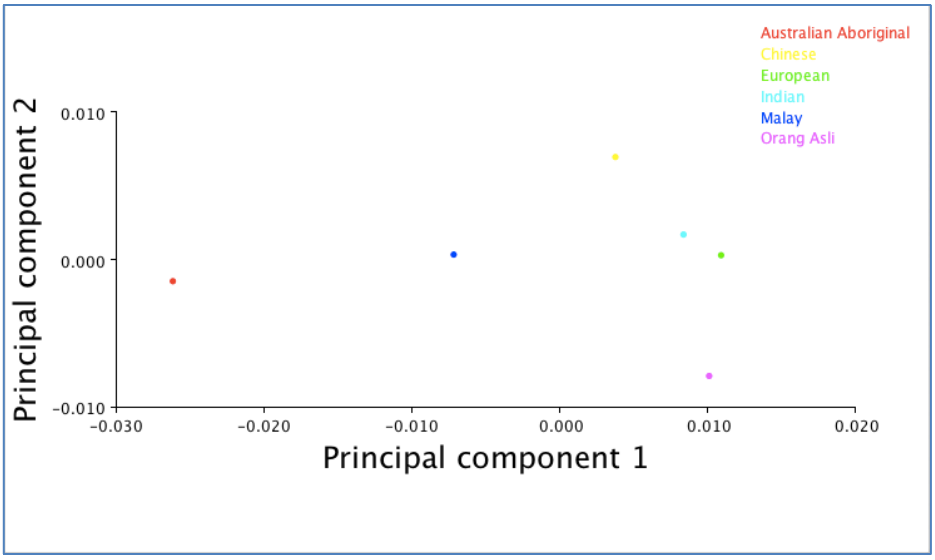


Figure 7.40: PC1 v PC2 of mandibular dental arch shape

Figure 7.40 shows a scatter plot of the average of lower arch shape coordinates among population groups. The scatter plot of the first two PCs of shape showed a clear separation between all the populations. PC1 shows that there is a large separation between the Australian Aboriginals and the other populations. The Europeans and the Indians showed a close relationship. PC2 showed separation between the Orang Asli and the rest of the populations.

7.7 Discussion

Dental arch shape variation was influenced by the degree of curvature of the arch. The second largest cause of dental arch shape variation was displacement of the incisors, a feature observed in all of the groups. The third principal shape variation was in angulation of the canines in all populations. Dental alignment patterns can also be affected by other parameters. There can be an influence from environmental factors with regard to malalignment, such as caries and trauma that might affect the normal developmental sequence of eruption.

The shape similarity numbers derived here provide measures of similarity of the dentition, and provide the first insight into shape variability of the human dentition. These findings are a step forward in understanding what constitutes shape difference in the human dentition.

This study was performed using a patient pool of convenience relevant only to the demographic locality. Extrapolation to other areas or countries in which dental care may be minimal or lacking entirely is not intended. In such regions there may be large proportions of the population with gross malocclusions and other dental defects that result in a broader range of possible individualizing dental characteristics.

Chapter 8: General Discussion

The use of teeth for forensic identification purposes forms the foundation of the work done by forensic odontologists. Credibility of a forensic odontologist relies on the ability of these experts to assist in identification in day-to-day casework, natural disaster situations or even terrorist threat attacks. It has been accepted that the work done by these experts has contributed positively to most disaster situations, in which usually more than half of the total identifications have been based on dental evidence. Disaster events include those in the Bali bombings in 2002, where more than 60% of victims were identified using dental evidence (Iain et al., 2003), 2004 Thailand Tsunami, almost 90% of the identification whether as primary identifier or as one of the contributing identifier were through dental comparison (James, 2005) and in the 2009 Victorian bushfire disaster in Australia where majority of victims were identified by dental comparison (Cordner et al., 2009).

Commonly, positive identification was achieved through comparison of shapes of dental restorations or other treatments and certain osseous structures such as unusual root anatomy, frontal sinus morphology, and occasionally, dental pulp morphology (Johansen and Bowers, 2013). The focus on the use of dental morphology and/or dental arches (size and shape) to achieve a positive identification is not a common practice as there may be problems in obtaining a comparable images (antemortem and postmortem) as they were possibly obtained at various unrecorded settings (Johansen and Bowers, 2013).

8.1 Methodology

Previously the gold standard for measuring tooth size has been measurements performed directly on the tooth. The limitation of this gold standard is the time factor and the lack of convenience of having to make the measurement directly. The alternative to gold standard is to measure the size of teeth on study casts. The problem with study casts is always the issue of storage. If all dental practitioners were required to keep study casts of their patients, archiving them would be a hassle. There has been an increase in the amount of research work focussing on the measurement of dental crown size using photographic images with computer software (2D) and also more lately use of 3D technology. To ensure that this particular research work is up to date with current requirements, I took the initiative to source a 3D scanner for the use of our research group. Whilst it may be difficult for every dental practitioner to have a 3D scanner to archive their patients' study casts, this current research has highlighted the value of both 2D and 3D images and the ways of standardising the images easily to enable future comparisons.

8.2 Measurement reliability

Measurement reliability refers to "the extent to which a measurement and its technique are consistent" (Kieser, 1990). Reliability has been referred to using various terms depending on the nature of the research. Precision and accuracy are two aspects of reliability (Harris and Smith, 2009). Accuracy is better described as validity; it refers to how close the measured value is to the actual value. Precision, on the other hand, is more commonly known as reproducibility; it refers to the repeatability of measurements (Kieser, 1990; Harris and Smith, 2009).

Based on the review of the literature finding, the best ways of minimising measurement error can be challenging. Errors can result from variation in the equipment and operator factors. Two of the techniques for reducing errors include accurate identification of landmarks (Robinson et al., 2002) and training the investigator (Harris and Smith, 2009). Errors associated with preparing a specimen, making an impression of teeth, or casting procedures can be minimised by following manufacturer's instructions. Other errors both instrumental (e.g. scanning) and personal (e.g. digitisation), also need to be quantified and minimised. Whilst validation of the scanner is part of minimising scanner error, the task was not discussed in this current research. Scanner validation was carried out as part of a separate postgraduate research project (Handayani, 2011) where the findings indicate that the generated 3D data from the Optix 400S laser scanner were found to be excellent in accuracy and precision testing.

Harris and Smith (2009) suggested using either an intraclass correlation coefficient to estimate the repeatability of measurements or using Dahlberg's d value (Dahlberg, 1940). The results of tests of measurement error in the present study in terms of intra-operator reliability were congruent with the findings of a previous study (Smith et al., 2009a) where it was found that 3D scanned images are accurate and provide excellent material for the investigation of human teeth (ICCC value of 0.937 to 1.000).

8.3 Dental crown size

This research has confirmed that there are variations between the six selected population groups, with Australian Aboriginals displaying the largest dental crown measurements and Europeans and Indians sharing the smallest size. The causes of these differences in dental crown size are due to the effects of genetic, epigenetic and/or environmental factors, as demonstrated in previous research looking at variation between other ethnic groups (Brook et al., 2008). This research has also confirmed that there are significant sex differences in dental crown size of the permanent teeth in different ethnic groups. Using discriminant Function Analysis, the assignment of sex was around 60% correct. For maxillary teeth, there was a 65.3% chance of obtaining the correct assignment for females and a 63.2% chance of correct assignment for males. Comparing between the arches, mandibular dental crown size tended to provide a slightly better discrimination than maxillary dental crown size (75.6% for males and 71.8% for females).

This information is of significance when carrying out investigative procedures, such as profiling of individuals using dental crown size. Analyses are more likely to be correct when mandibular teeth are used.

8.4 Dental arch size

Data on dental arch size could also be used to explore variations between individuals. Whilst individual dental crown size could give specific measurements of each tooth, dental arch size gives a general overview of arch size of an individual. The pattern of data distribution of dental arch size was similar to those displayed in dental crown size, where Australian Aboriginals displaying the largest dental arch width measurements and Europeans showing the smallest dental arch width. Multivariate analysis of the combination of measurement of dental crown size and dental arch size highlights the ability to discriminate between populations.

8.5 Dental arch shape

Dental arch shape could also contribute to the study of population variation and population assignment. Whilst a simple assessment of shape according to geometrical reference could be an option, a more objective assessment is needed in order to better discriminate between population groups. In other words, quantifying this shape and at the same time maintaining its biological meaning can be of value especially in forensic identification. In this research, dental arch shape analyses were performed using two approaches, fourth-order polynomial and Geometric Morphometrical Analysis. Both have shown good potential in analysing shape and differentiating between groups. Geometric Morphometric Analysis is a better option in visualising changes to arch shape.

8.6 Relevance of study findings

Dental crown size and dental arch size and shape have been described using traditional tools limited to selected dental variables or very simple indices. The collected information is limited and does not describe dental variation visually. With developments in the field of imaging (i.e. 3D scanners) and the increased knowledge of multivariate shape statistics (i.e. GMA), it has been possible to overcome many previous limitations and describe dental variation with a high degree of accuracy and precision. This new knowledge not only provides improved clinical discrimination but it also opens up new lines of research to obtain better understanding of the underlying developmental processes that occur during odontogenesis.

It is important here to note that the general aim of this research is to provide an insight into the use of normal dental features as a way to predict the individuality of a person, rather than focussing on the following features: missing-present teeth, dental restorative work or any form of dental pathology such as carious teeth, retained root or tooth wear.

Besides helping to differentiate between different groups, sophisticated statistical modeling approaches also enable researchers to investigate the contributions of different etiological factors to observed variation, such as genetic, epigenetic and environmental factors (Townsend et al., 2011). A better knowledge of the complexity of the interrelated factors that might create dental variations, when linked to morphogenetic field theory, should help to clarify which teeth are likely to be most affected by agenesis, i.e. second premolars and lateral incisors (Townsend et al., 2009b, Brook et al., 2014a), and, furthermore, give an idea about the variability within the dentition to later use for individualisation. Such knowledge will also help the forensic dentist to fully utilise the information found in sound dentitions. This is particularly relevant in the age of ‘minimal intervention dentistry’ when we have traditionally been relying on the ‘problems’, i.e. patterns generated by fillings and extractions.

8.7 Preliminary suggestions on probability theory

The science of forensic identification, including DNA, fingerprint and handwriting experts, all of whom may be called upon to give evidence in court, have looked at ways to reduce the subjectivity of their procedural analysis, and refine their approaches for making conclusive findings. This is essentially the ultimate aim of this project, to progress the foundation of odontology decision-making. In order to propose a framework to develop a model that enables the examiner to assess within a subset of a population that there is the likelihood of getting a match between records or better yet the likelihood of not getting a match among a group of individuals. The idea is not to identify a unique person, but to find the chances that within a known population there will not be a duplicate. Franco et al., (2014) in their most recent review article have stated the unproven concept of ‘uniqueness’ despite the various methodologies employed to ‘prove’ it.

Johansen and Bowers (2013) also highlighted the use of metric analysis of anatomical features found within the human dentition that may yield a positive identification. Johansen and Bowers (2013) also stressed the context of using this method in identification process is within a closed population (and in their case of 5 victims). The idea of individualising dental features using metric analysis should also be stressed that it is within a certain subset of population and the intention is not trying to individualise from whole-world population.

In a forensic situation this is practical because identification processes are usually carried out after other circumstantial evidence has been adduced. There is known information with which to compare. The task is to know, between ante-mortem (before) and post-mortem (after) data sets, what is the likelihood that we may get the same pattern. The idea of moving from a subjective to an objective assessment is usually achieved by some form of statistical concepts. It has previously been used in order to arrive at a more probative value to support opinions.

The use of Bayes' theorem for example can be used in two situations, one with the aim to evaluate and the other one to investigate. The investigative stage, in the context of forensic odontology, and particularly in the identification process, may be similar to the process of 'profiling' the evidence. The evaluative level involves using likelihood ratio with the combination of several variables observed within a piece of evidence.

More often than not, the task of comparing dental features associated with treatment, particularly those with radiographic evidence, offers promise of yielding a positive outcome. Forensic odontologists may be more cautious in their opinion when the written notes or dental charting only state that teeth are sound or present (i.e. where no treatment has been performed). It is a difficult task to come up with a specific probability when the only source of information is cryptic dental notes. The written dental notes commonly only state the types and description of the dental treatment carried out during the appointment. A major contribution of this research is to show the value of using imaging to highlight the morphological features of teeth and dental arches. Weighting for identification is usually increased when there are radiographic, photographic or other hard evidence like study models, taken for diagnostic purposes or treatment purposes. By highlighting the individualistic features of morphology of teeth and dental arches, this research shows that there is an opportunity to move forensic odontology forward into a new era.

In order to discuss the probability of an event, there are three common components that need to be familiarised:

The probability of event A = P (A)
The probability of event B = P (B), ... P (X)
The space where the events occurred denote as S.

The probability of an event occurring in any given place will always be more than one. $P(A) \geq 0$. The certainty that one event will occur in a space is equal to 1.

If A1, A2, A3,... is a finite or infinite sequence of mutually exclusive events of S, then

$P(A1 \cup A2 \cup A3 \cup \ldots) = P(A1) + P(A2) + P(A3) + \ldots\ldots$

Probabilistic models can be developed based on observation of past events, underlying conditions occurred within a space or by assumptions. Sometimes, all possible outcomes within a space of events are assumed to have occurred equally. In the case of the probability of having a dentition that is different to others has been postulated in the past. Using basic mathematical concepts, the probability that any given person having 32 teeth present had been based on the assumption that the incisor, canine and molar are each equally likely to be present. However, it has been shown through past experience, that due to the concept of odontogenic polarity, different timing of tooth emergence, correlation between left and right, effect of sex dimorphism and others, the postulation of equal probability may not be a suitable pathway to predict the chance of having a particular dentition.

There are many ways of predicting possible events in space and, in this case, in order to predict this, observation of dental pattern can be done by looking at the presence or absence of teeth, presence of dental treatments or presence of dental pathology. These have been done in the past. Another possible methodology to predict sets of events is by measuring the size of the tooth. Whilst the nature of different classes of teeth creates different events it can contribute to the development of patterning within the dentition.

In addition to the first rules of probability highlighted earlier in this section, more rules associated with postulation of a probabilistic model are also important:

*If A and A' are complementary events in a sample space A, then $P(A') = 1 - P(A)$

*If A and B are events in a sample space S and $A \subset B$, then $P(A) \leq P(B)$

*If A and B are any two events in a sample space S, then $P(A \cup B) = P(A) + P(B) - P(A \cap B)$.

Based on these additional rules, in order to treat each of the different events, they must be at least in a similar dimension. In the case of the human dentition, we are already aware that different classes of teeth present with different forms (size and shape). Whilst metric measurement gives a more quantitative assessment of their differences, standardisation of these values will give a better comparable estimate between them. Therefore, it was decided that each value would be standardised using principal component analysis in order to generate discriminant scores comparable within the same dimension.

8.8 Future research

In this research, the possibilities of using normal dental morphological features in Forensic Odontology, such as dental crown size and dental arch size and shape, have been highlighted. It is time that we focus more on the nature and extent of this variation to differentiate between population groups. Information like this, if explored in detail, can be used to generate probabilistic models to enable individualising or exploring singularity (Lucas and Henneberg, 2014) of an unknown person within a selected group.

Whilst we have demonstrated that measurements made using both 2D and 3D techniques do not display significant differences, application of 3D imaging offers great promise for the future in terms of defining new dental phenotpyes that cannot be quantified with simpler 2D systems, e.g. contours, areas and volumes. Based on the results from the current study it is suggested that dental crown size and dental arch size and shape are valuable features for investigating or developing models to differentiate between individuals. This is an alternative to the traditional forensic approach which has utilised patterns in dentition relating to the status of dental treatments (i.e. restorations, extractions and prostheses).

The use of multiple measurements of dental crown and dental arch variables can be useful whether they to be used independently or in combination. When multiple data are used, it is useful to standardise the data into similar dimensional values. By transforming these data to eigenvalues, equations can be derived to ‘score’ an individual according to their dental phenotype.

8.9 Collaborative efforts and research limitations

Collaborative efforts between various research centres around the world will ensure more optimal research work using the best methodology available. Throughout this research, a collaborative approach was used with groups in Liverpool, industrial companies and personal communications to ensure the best possible outcome. It was fortunate that this research was generously supported by various grants and funding. This includes grants from the Australian Dental Research Foundation, funding from the South Australia Police, funding from the School of Dentistry and the Faculty of Health Sciences, University of Adelaide. This funding was required for the purposes of buying equipment and instruments needed for the project, as well as for travelling costs to conferences to share knowledge.

After purchasing a new Optix 400S laser scanner, a considerable amount of user familiarisation was needed which affected the time required to finish the research project. Due to this time factor, it has been highlighted in the Chapter 4.0 Materials and Methods that the number of samples able to be scanned in 3D was less than 2D photographs. Despite that, based on this research, it is important to note that if all methodology is standardised, both techniques can produce similar results hence underlining the advantages of both methodologies. It is recommended that, if finances permit, future research should focus on the use of 3D images when looking at measuring dental features.

Details of the presentations I made at various conferences and all published articles related to this project are listed in Chapter 11: Appendices.

Chapter 9: Conclusion

9.1 Research Objectives

With regards to the specific objectives of this research:

1. *To develop accurate and precise methods of measuring dental features.*

This aim was achieved by using two different methods, two-dimensional and three-dimensional imaging, to accommodate researchers or practitioners who may have access to only one of these methods or who are looking at alternative methods.

Techniques were developed to capture an image for each subject that is standardised in order to ensure repeatability and to reduce subjective assessment by the operator.

The null hypothesis was that two-dimensional and three-dimensional imaging of teeth is not sufficiently accurate or precise to quantify dental crown size in anthropological and forensic situations. This null hypothesis was rejected. With standardisation of techniques used to measure the parameters, both two-dimensional and three-dimensional imaging systems can provide measurements that are accurate and precise.

A three-dimensional method is applicable and useful when more comprehensive analyses of dental crown size are required and it overcomes the problem of visualizing a 3D structure such as tooth, in only two-dimensions which can lead to introduction of errors when measuring rotated or tilted teeth.

2. *To quantify variation of dental features in a number of ethnic groups.*

This was achieved by examination of dental crown size and dental arch size across several different populations to clarify factors that might affect the development of a probabilistic model for generalisation across populations or to be applied to a specific population.

The null hypothesis was that there is no pattern of size differences between the teeth of different population groups. This null hypothesis was rejected and the related conclusion drawn from the study was that the explained variance among group membership is generally larger in the anterior than in the posterior region. Moreover, this pattern usually is consistent with Morphogenetic Field Theory. This finding was the same for both sexes. Within population groups there was some evidence of a pattern whereby the anterior teeth seemed to be more strongly affected by size differences.

3. *To establish population-specific variation (ethnicity, age, sex, etc).*

This was done through multivariate analysis of a combination of variables. Principal Component Analysis (PCA), in which all variables are standardised with similar weighting, and Discriminant Function Analysis, with particular emphasis on certain variables, were applied to assist in separation of ethnic groups.

The null hypothesis was that there are no significant differences in dental crown size and dental arch size and shape between populations. This null hypothesis was rejected and the related conclusion drawn was that there are significant differences in dental crown size and dental arch size and shape between all population groups studied.

The mean size values decreased progressively from Australian Aboriginal to Malaysian Orang Asli.

4. *To plan probabilistic models to positively discriminate between individuals within a given group and to assign an individual to a specific population that will satisfy the requirements of the judicial system.*

The use of principal components to observe various dental morphology parameters leads towards an approach for individualisation. However, this falls outside the scope of this thesis and requires further exploration and testing in different study cohorts.

9.2 Findings

Based on an extensive review of the literature relating to forensic odontology, together with the findings from this current research, it is clear that examination of dental features can play an integral part in identifying unknown human subjects. Dental structures are known to be the most resistant to post-mortem changes and destruction compared to other methods of identification, i.e. fingerprints, DNA, personal belongings.

Identification outcomes resulting in either positive identification, probable identification or possible identification are contributed through the availability of good dental record-keeping derived from a dentist's notes, radiographs, dental models or photographs. From these, the presence of pathological conditions such as caries or other forms of dental treatments, including amalgams or composite restorations, crown or bridges and root canal treatment, provide additional value in the comparison process. Problems with identification usually arise when the teeth are present but there are no dental problems or treatments.

The considerable morphological variation present within the dentition provides the basis for developing a method of individualisation of humans using teeth. It is known that everyone's teeth are different. As the field of forensic identification grows, so the importance of the field grows to meet current issues. One is the move from subjective opinion by experts to the requirement to provide more quantitative supporting arguments. Previous utilisation of teeth for identification when there is a lack of information, such as restorations, can limit the ability to make a definite identification. However, with the availability of imaging techniques, whether it is two or three-dimensional, the ability to quantify normal morphologic information very precisely and reliably is now possible. Not only will this provide better supportive evidence for identification, but it will also allow better comparisons of the morphology of teeth when other forms of dental information (such as restorations) are not present.

Part of this research was conducted with the objective of designing a standardised technique to aid in the investigation of metric characteristics of the dentition and dental arches. It was discovered that three-dimensional imaging could provide ease of use and, with the help of computer software, standardisation could be achieved without human subjectivity. Two-dimensional imaging is equally useful, provided that it is standardised to ensure that every image used in the investigation is similar. If two-dimensional imaging were to be employed for the purpose of studying and measuring dental features, standardisation of the captured image must be an integral part of the methodology.

The documentation of two and three-dimensional images, if implemented for record keeping, would provide important information for forensic investigations. They provide accurate, detailed images that can overcome international codes and language barriers. However, their use should be implemented with caution to ensure that when pre- and post- event comparisons are made, both images have been similarly standardised.

It's important to recognize the limitations of this work. Firstly, the dental features studied were limited to dental crown dimensions and dental arch dimensions and shapes. Other dental features could be studied in future, including morphological crown traits and occlusal characteristics. Secondly, although statistically significant differences were noted for many features between sexes and ethnic groups, this does not mean that these features will be necessarily valuable in forensic situations. The difference between 'statistical significance' and 'practical significance' in a forensic context is an important concept to bear in mind in this type of research.

Nonetheless, it is recommended that dentists should obtain, keep and archive two dimensional or three dimensional images of the dental casts of their patients in order to enable better comparisons to be made of ante-mortem and post-mortem records in forensic cases.

9.3 Future Directions

The potential use of dental morphological features, both individual dental crowns and also entire dental arches, for anthropological and forensic purposes has been highlighted in this study. Like any other method for forensic dental identification, the availability of prior information to make comparisons still requires input from dental practitioners. However, variations presented for both dental crown size and dental arch size and shape warrant for further investigations. We have been relying on the comparison of dental treatments and pathological work, but it is now time to explore existing variation observed within the dentition for this purpose.

Future research could be directed at the value of radiographic assessment of teeth using similar approaches to those described in this thesis: 2-dimensional and 3-dimensional. Further analysis on dental crown shape could also be explored in greater detail.

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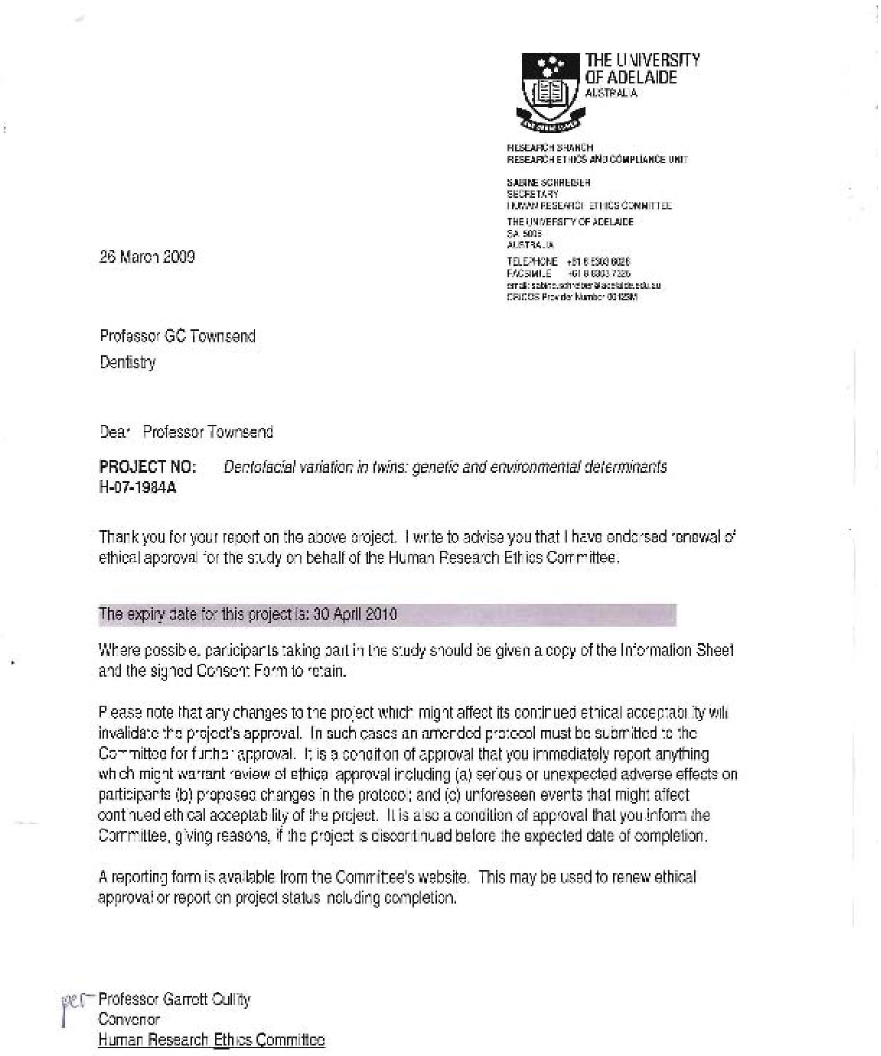
Chapter 11: Appendices

11.1 Ethical approvals



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26 March 2009

Professor GC Townsend
Dentistry

Dear Professor Townsend

PROJECT NO: *Dentofacial variation in twins: genetic and environmental determinants*
H-07-1984A

Thank you for your report on the above project. I write to advise you that I have endorsed renewal of ethical approval for the study on behalf of the Human Research Ethics Committee.

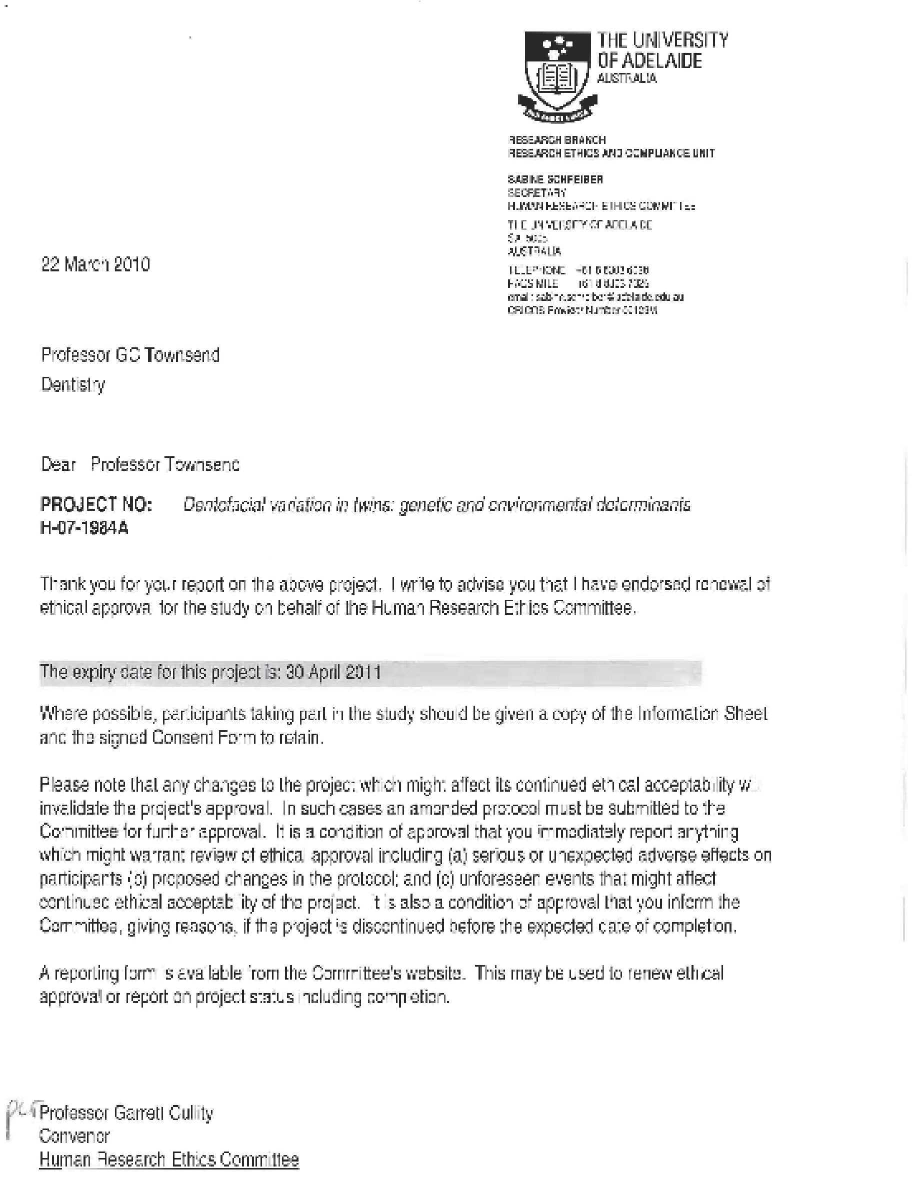
The expiry date for this project is: 30 April 2010

Where possible, participants taking part in the study should be given a copy of the Information Sheet and the signed Consent Form to retain.

Please note that any changes to the project which might affect its continued ethical acceptability will invalidate the project's approval. In such cases an amended protocol must be submitted to the Committee for further approval. It is a condition of approval that you immediately report anything which might warrant review of ethical approval including (a) serious or unexpected adverse effects on participants (b) proposed changes in the protocol; and (c) unforeseen events that might affect continued ethical acceptability of the project. It is also a condition of approval that you inform the Committee, giving reasons, if the project is discontinued before the expected date of completion.

A reporting form is available from the Committee's website. This may be used to renew ethical approval or report on project status including completion.

per Professor Garrett Cullity
Convenor
Human Research Ethics Committee



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22 March 2010

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13 April 2012

E-MAILED
24/4/12

Professor G Townsend
Dentistry

Dear Professor Townsend

PROJECT NO: H-07-1984A
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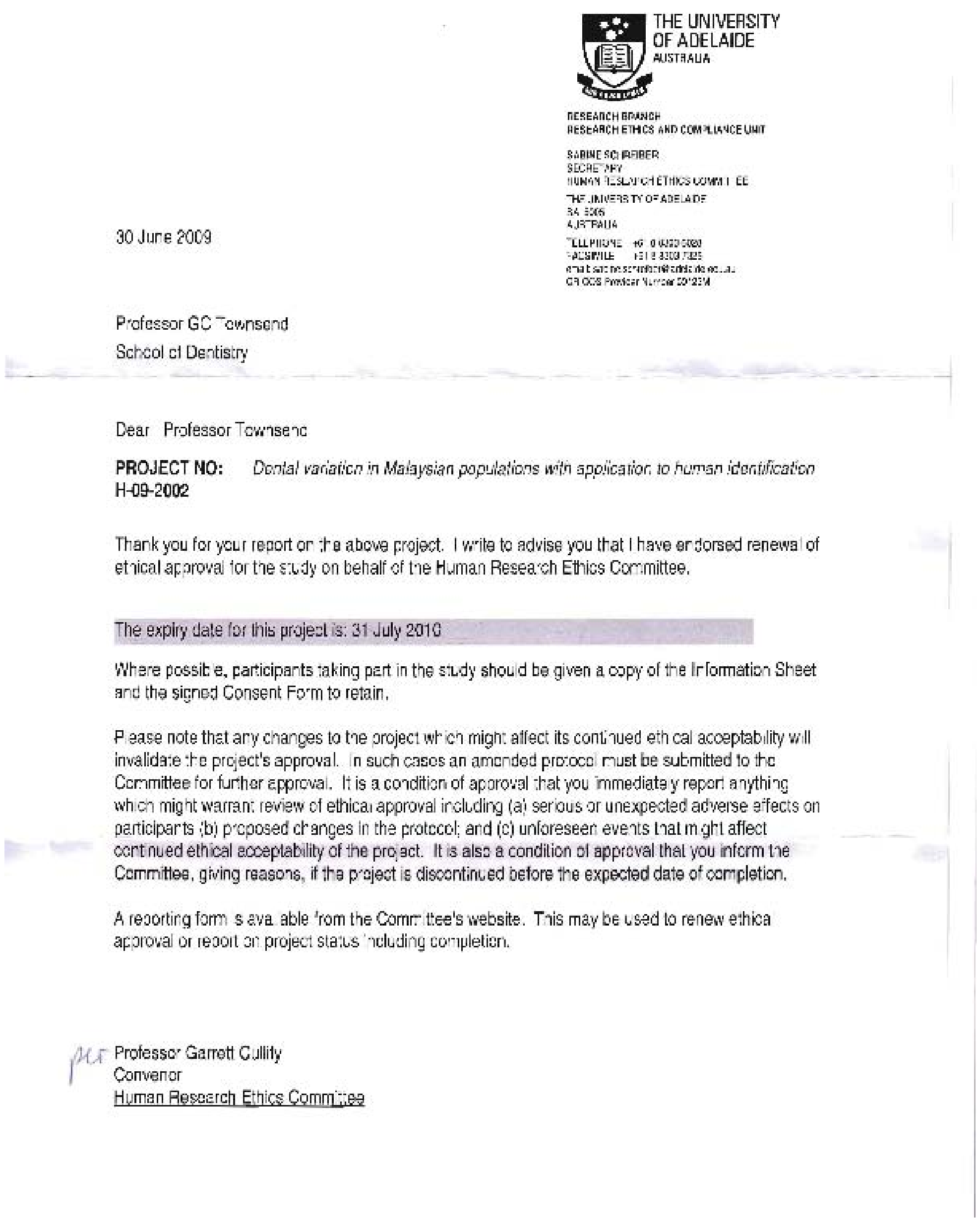

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30 June 2009

Professor GC Townsend
School of Dentistry

Dear Professor Townsend

PROJECT NO: *Dental variation in Malaysian populations with application to human identification*
H-09-2002

Thank you for your report on the above project. I write to advise you that I have endorsed renewal of ethical approval for the study on behalf of the Human Research Ethics Committee.

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23 June 2010

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School of Dentistry

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26 July 2011

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Thank you for your report on the above project. I write to advise you that I have endorsed renewal of ethical approval for the study on behalf of the Human Research Ethics Committee.

The expiry date for this project is: 31 July 2012

Where possible, participants taking part in the study should be given a copy of the Information Sheet and the signed Consent Form to retain.

Please note that any changes to the project which might affect its continued ethical acceptability will invalidate the project's approval. In such cases an amended protocol must be submitted to the Committee for further approval. It is a condition of approval that you immediately report anything which might warrant review of ethical approval including (a) serious or unexpected adverse effects on participants (b) proposed changes in the protocol; and (c) unforeseen events that might affect continued ethical acceptability of the project. It is also a condition of approval that you inform the Committee, giving reasons, if the project is discontinued before the expected date of completion.

A reporting form is available from the Committee's website. This may be used to renew ethical approval or report on project status including completion.

PROFESSOR GARRETT CULLITY
Convenor
Human Research Ethics Committee

THE UNIVERSITY of ADELAIDE

RESEARCH BRANCH
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY

PAULA ROSENDAUER
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11 April 2013

Professor G Townsend
School of Dentistry

Dear Professor Townsend

PROJECT NO: H-09-2002
Dental variation in Malaysian populations with application to human identification

Thank you for your report on the above project. I write to advise you that I have endorsed renewal of ethical approval for the study on behalf of the Human Research Ethics Committee.

The expiry date for this project is: 31 July 2015

Where possible, participants taking part in the study should be given a copy of the Information Sheet and the signed Consent Form to retain.

Please note that any changes to the project which might affect its continued ethical acceptability will invalidate the project's approval. In such cases an amended protocol must be submitted to the Committee for further approval. It is a condition of approval that you immediately report anything which might warrant review of ethical approval including (a) serious or unexpected adverse effects on participants (b) proposed changes in the protocol; and (c) unforeseen events that might affect continued ethical acceptability of the project. It is also a condition of approval that you inform the Committee, giving reasons, if the project is discontinued before the expected date of completion.

A reporting form is available from the Committee's website. This may be used to renew ethical approval or report on project status including completion.

Dr John Semmler
Convenor
<u>Human Research Ethics Committee</u>

11.2 Collection of abstracts presented during various conference throughout the candidature

IUAES/AAS/ASAANZ Conference 2011. July 5-8, 2011, Perth, Australia.

The application of 3D imaging system for anthropological and forensic purposes

Atika Ashar, Toby Hughes, Grant Townsend, Helen James, John Kaidonis.

Craniofacial Biology Research Group, School of Dentistry, University of Adelaide

The increasing availability of three-dimensional (3D) imaging systems enables researchers and clinicians to visualise, measure and compare various physical objects of interest with high precision and reliability. A number of studies have investigated various morphologic characteristics of teeth and dental arches using such methods. 3D surface scanners are devices that produce a digital map of the surface of an object, with the data represented as clouds of 3D Cartesian coordinates at variable density. In general, 3D scanners can be divided into contact and non-contact types. Non-contact 3D scanners reduce the risk of damaging the object that needs to be scanned, and hence are more suitable for forensic and anthropological research purposes. An Optix 400S 3D laser scanner *(3D DigitalCorp,Connecticut,USA)* was utilised to scan dental casts. The scanner allowed 3D image attainment with high accuracy (±0.03cm). The information contents of three-dimensional (3D) digital samples of upper and lower dentitions in European, Australian Aboriginal and Malaysian populations were compared. Measurements of dental variables including mesiodistal tooth dimensions, inter-arch width and occlusal surface area were calculated. The resulting values were compared using various parametric statistics. Reliability of the method was also explored statistically. With rapid advances in this field, it is likely that 3D scanning techniques will become more powerful, more affordable and hence more accessible in the coming years. Utilising 3D imaging to compare various features within and between human populations will facilitate research on the individuality of the human dentition, a key concept in forensic odontology.

Acknowledgements:

NHMRC, Minister for Police in South Australia and South Australian Police, Australian Society of Orthodontics Foundation for research and Education, Australian Dental Research Foundation, University of Adelaide

School of Dentistry, University of Adelaide Research Day 2010

Introduction/Background:
The increasing availability of three-dimensional (3D) imaging systems now provides researchers and clinicians with a valuable alternative to direct measurement and two-dimensional (2D) imaging of dental casts. 3D imaging can accurately capture the shape of teeth, allowing various dental phenotypes to be defined and recorded. Apart from measuring the size of dental traits, there is increasing interest in studying differences in shapes of teeth using the geometric morphometric approach. Geometric Morphometric Analysis (GMA) refers to a method of studying shape by means of point coordinates in two or three dimensions.

Objective: The primary objective of this study is to explore the potential of 3D scanning and GMA in studying variation of human teeth for identification purposes.

Methods: Images of dental casts belonging to twins of European ancestry, Aboriginal Australians, and also Malaysian Malays, Malysian Indians, Malaysian Chinese and Orang Asli are being captured using 2D and 3D systems. GMA will then be conducted by placing landmarks and semi-landmarks on the images of teeth. Landmarks are being chosen as precise locations that hold some developmental, functional, structural, or evolutionary significance. Comparisons of tooth size and shape will be made within and between populations.

Results: It is predicted that by incorporating the methods of 3D scanning and GMA, considerably more information about variation in the morphology of teeth will be obtained than can be derived by traditional methods. Dimensionally accurate 3D images of dental arches and teeth have already been obtained. Comparisons of 3D images from monozygotic co-twins have confirmed a strong genetic influence on dental morphology with subtle differences due to environmental and/or epigenetic influences.

Conclusion: The usefulness of geometric morphometric methods has been actively researched by many anthropologists to assess morphological differences among species. The method promises to provide significant contributions to the study of variation in dental morphology between individuals. 3D imaging will also enable new digital databases of rare collections of dental casts to be established, thus preserving valuable material for future investigation.

15th International Symposium on Dental Morphology. August 24-27, 2011, Northumbria University, Newcastle, United Kingdom.

Differentiating the indifferent within the human dentition: what should we look for?

Atika Ashar, Toby Hughes, Grant Townsend, Helen James, John Kaidonis.

Craniofacial Biology Research Group, School of Dentistry, University of Adelaide

The use of teeth as a measure of a person's identity has been well accepted. It has been used by forensic odontologists and anthropologists to 'correctly' identify a person based on comparison. Throughout the years, the contribution of researchers in studying tooth variation has greatly increased our knowledge and understanding of this area. For forensic identification, the presence of peculiar dental features such as various tooth anomalies or presence of dental work, including crowns and bridges, will often contribute to positively identifying a person. A number of dental features such as Carabelli trait and incisor shovelling could also be considered as population specific. These features can greatly assist in profiling the ancestry or geographical origin of a person. A gray area in the identification process arises when a person presents with a set of teeth with normal morphology and no peculiar tooth characteristics or any restorative work. Here, we present our findings based on comparisons of upper and lower teeth in pairs of identical twins of European ancestry and also in other population groups including Malaysians and Australian Aboriginals group. Using 2D and 3D approaches we have determined standardization protocols that are required when analysing metric measurements of dental features such as mesiodistal (MD) andbuccolingual (BL) crown diameters and interarch widths. The presence of a scale in 2D images is especially important. Different scanner settings can also affect the end result of the scanned object. These settings include *laser gain, stripe threshold, X-range limit and Z range cutoff.* Problems and issues that need to be overcome to ensure optimal outcomes have been evaluated. This has helped in identifying which metric measurements of these dental features are most suitable statistically for differentiating one person from another. We propose to combine multiple dental traits and use multivariate model to achieve better outcomes in human identification using the dentition.

Acknowledgements: NHMRC, Minister for Police in South Australia and South Australian Police, Australian Society of Orthodontics Foundation for research and Education, Australian Dental Research Foundation, University of Adelaide

11.3 List of presentation throughout the candidature

1. ASHAR A. (2010) **Unlocking the individuality of teeth.**
   University of Adelaide, Postgraduate Research Expo. September 1, 2010, Adelaide, Australia.
   (thesis in 3 minutes presentation - finalist)

2. ASHAR A, HUGHES T, TOWNSEND G, JAMES H, KAIDONIS J. (2010)
   The potential of 3D imaging in forensic odontology.
   University of Adelaide, Postgraduate Research Expo. September 1, 2010, Adelaide, Australia.
   (poster presentation)

3. ASHAR A, HUGHES T, TOWNSEND G, JAMES H, KAIDONIS J. (2010)
   Dental identification: 3D imaging and Geometric Morphometric Analysis.
   School of Dentistry, Colgate Research Day. August 27, 2010, Adelaide, Australia.
   (poster presentation + abstract)

4. 1st combined conference of the International Union of Anthropological and Ethnological Sciences (IUAES), the Australian Anthropological Society (AAS) and the Association of Social Anthropologists of Aotearoa / New Zealand (ASAANZ)IUAES/AAS/ASAANZ conference 2011
   http://www.anthropologywa.org/

5. 15th International Symposium on Dental Morphology. August 24-27, 2011, Northumbria University, Newcastle, United Kingdom.

6. ASHAR A, JAMES H, HUGHES T, TOWNSEND G, KAIDONIS J (2012)
   3D Imaging in forensic odontology.
   Australian and New Zealand Forensic Science Society: 21st International Symposium on the Forensic Sciences

7. HANDAYANI A, JAMES H, HUGHES T, ASHAR A, TOWNSEND G (2012)
   Validation of an Optix 400S 3D laser scanner for use in forensic odontology.
   Australian and New Zealand Forensic Science Society: 21st International Symposium on the Forensic Sciences

11.4 List of visitations, courses and attendances

Attended conference **"Forensic dentistry South Africa style"**, March 19-20, 2010, Perth Australia.

Attended **20th International Symposium on the Forensic Sciences, September 5-9, 2010, Sydney, Australia**.

Enroll in an online course: **Analysis of Organismal Form.** November 2010 - January 2011, **University of Manchester.**

Visited Prof Dr. Phrabhakaran Nambiar at the Faculty of Dentistry, University of Malaya for research collaboration, 2011

11.5 List of publications and grants

Publications:

ASHAR A, HUGHES T, JAMES H, KAIDONIS J, KHAMIS F, TOWNSEND G. (2012)
Chapter 6 Dental crown and arch size in Europeans and Australian Aboriginals.
In: *New Directions in Dental Anthropology: paradigms, methodologies and outcomes*. Eds:Townsend G, Kanazawa E, Takayama H. University of Adelaide Press, pp 65-80.

MIHAILIDIS S, ASHAR A, HUGHES T, BOCKMANN M, BROOK A, TOWNSEND G. (2012)
Dental phenomics: similarities and differences in monozygotic twins.
Dental Tribune , April 2013, A4-A5.

Grants

Australian Dental Research Foundation Grants
2011 The individuality of the human dentition: implications for forensic odontology.
A Ashar, T Hughes, H James, G Townsend, J Kaidonis.
Awarded: $7,000

2011 School of Dentistry Postgraduate Travel Scholarship – International
Monies awarded to assist with attendance of the 15th International Symposium on Dental Morphology. August 24-27, 2011, Northumbria University, Newcastle, United Kingdom.
Awarded: $1,500

ATR Travel Grant Research Scheme
Monies awarded to assist with attendance of the 15th International Symposium on Dental Morphology. August 24-27, 2011, Northumbria University, Newcastle, United Kingdom.
Awarded: $500

200 Faculty of Health Sciences, Postgraduate Travel Scholarship, International travel
Monies awarded to assist with attendance of the 15th International Symposium on Dental Morphology. August 24-27, 2011, Northumbria University, Newcastle, United Kingdom.
Awarded: $1,250