VARIATION IN CRANIAL BASE FLEXION AND CRANIOFACIAL MORPHOLOGY IN MODERN HUMANS

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Abstract

Cranial base flexion has been used extensively as a baseline or standard from which to interpret differences in craniofacial growth and morphology. Lateral cephalometric radiographs of 414 adults representing seven samples from around the world were compared for variation in cranial base and facial morphology. The samples represent Australian Aboriginal, New Zealand Maori (Polynesian), Thai, Chinese, white American, African Sotho/Xhosa/Zulu and African Khoi/San populations. Seven angles of cranial base flexion, five craniofacial angles and nine cranial base and facial dimensions were measured on tracings of lateral cephalometric radiographs.

Numerous significant correlations were found between cranial base flexion angles, craniofacial angles and dimensions of the cranial base and craniofacial skeleton. A positive correlation was found between the orientation of the foramen magnum, clivus and the anterior cranial base, with a negative correlation between these angles and the orientation of the hard palate. There was also a parallel relationship between the orientation of the foramen magnum and the anterior cranial base (measured from pituitary point to nasion). Cranial base flexion, craniofacial angles and dimensions differed significantly between some samples. Despite this, there was no evidence of distinct facial types between samples. Multivariate statistics revealed some discrimination between some samples for dimensions; however, if angles were used alone, less than 50% of individuals could be correctly assigned to their sample of origin. Most of the variation could be attributed to variation between individuals, rather than variation between samples.

The range of variation in cranial base flexion is considerable, and needs to be taken into account when comparing samples. Flexion of the cranial base is generally insufficient to distinguish people from different geographic samples. The functional and evolutionary significance of the relationship between the orientation of the foramen magnum and cranial base flexion is discussed for its potential usefulness as a reference line for interpreting craniofacial morphology.

Statement

This work contains no material which has been accepted for the award of any other degree of diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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Chapter 1: Introduction

OUTLINE:

General introduction to the cranial base
Description of measurement techniques of the cranial base
Overview of cranial base growth
Growth changes in cranial base flexion
Evolution of cranial base flexion
Inter-population variation in the cranial base of modern humans
Aims of the present study

General introduction to the cranial base

The cranial base has been extensively studied for its role in craniofacial growth and development. Information on the cranial base has been applied to fields of comparative anatomy, primatology, human evolution, and craniofacial growth and development. Incorporating the ethmoid, sphenoid and basioccipital bones, the cranial base has close, structural relationships with the neurocranium, inner ear and walls of the nasal fossa and orbits. The cranial base also articulates with the vertebral column at its posterior, inferior extension (basioccipital). Phylogenetically, the cranial base is the oldest part of the craniofacial skeleton (Kardong, 1995; Larsen, 1998). It forms a support for the brain, and has suspended from it the structures involved in respiration, swallowing, and vocalisation. It has major connections with the sensory organs (visual, auditory), and is involved in the movement of the pharynx inferiorly during early childhood that is thought to be essential for production of complex vowel sounds (Reidenberg, 1988). In studies of craniofacial growth, early researchers assumed that the bones of the cranial base grew at a similar rate to the brain, and that little growth occurred after about seven years. As a result, most studies of the growth of the skull use the stability of the cranial base as a reference to assess growth in other bones of the craniofacial skeleton.

Variation in craniofacial morphology is evident during development and growth. It occurs as variation between individuals; between males and females; between people from different geographic areas of the world; and between modern humans, fossil hominins, and primates. Much of this variation arises during growth, with some influence from mechanical factors. This variation is the result of the same growth-regulating hormones acting in various ways on body tissues so that they grow at different rates (Bijlsma, 1983; Dixon and Sarnat, 1982; Goss, 1972; Raisz, 1988). The resulting differential growth arises from variation in the rate and duration of growth of the craniofacial bones, and occurs from early stages of embryonic development until after puberty, and possibly well into adulthood (Dixon et al., 1997; Enlow, 1990; Lewis and Roche, 1988). It produces differences in size (isometry) and in shape (allometry) (Huxley, 1924; Moss et al., 1984; Thompson, 1942). In some individuals, a disturbed pattern of differential growth can also lead to malocclusion of the teeth or disproportion in facial morphology (Cantu et al., 1997; Enlow and Azuma, 1975; Nanda, 1955; Pirinen et al., 1994; Richtsmeier, 1985; Ricketts, 1960; Simmons, 1999; Trenouth, 1985; Wilhelm et al., 2001). Despite the recognised variation in craniofacial morphology, it remains conventional to group people according to shared features or similarities, and to derive average values and estimates of the extent of variation in these groups. Generating average values may expose individuals who differ from the normal standards. It has been found, however, that many individual growth patterns in the craniofacial skeleton do not follow the average pattern when compared across age categories. Researchers have commented on the individual variation in growth of the craniofacial skeleton that only becomes apparent upon examination of longitudinal data (Björk, 1955; Brodie, 1941; Zuckerman, 1955). While average values show a gradual, but stable, progression of increases in size and changes in shape over a time period, the data of a single individual often show significant fluctuation around the mean. This individual variation is obscured when average values are used to describe processes of development. Further information is lost when the average values are based on an arbitrary measure, such as chronological age, as is typical. Average values are also of little clinical significance when it is the individual person who requires treatment.

This review will present a summary of the research that has gone into cranial base flexion and craniofacial morphology as it relates to the aims of the present study. This includes an overview of cranial base growth, a description of studies on cranial base flexion and the various hypotheses regarding the evolution of cranial base flexion in humans. With the background to the study established, the aims and hypotheses of the current research will be explained in more detail.

Description of measurement techniques of the cranial base

The irregular morphology of the cranial base, and its location deep in the head, created a need to develop specialised measuring techniques. On the living, non-invasive visualization of the cranial base has been achieved by taking lateral radiographs of the head. This has sometimes been supplemented by surgically implanting metallic markers at various sites within the bones of the cranial base and face, and observing their relative locations within bones over periods of time (Björk and Skieller, 1972). The principle behind this technique is that the hard tissue surrounding the implants will change as remodelling occurs, but the markers will not move, thus the direction of growth changes (resorption/apposition) can be determined. This technique has not been widely used in humans, due to the invasive method of inserting the implants.

Imaging in orthodontics (for example cephalometric radiographs) is an attempt to obtain the “anatomic truth” of three-dimensional structures in a two-dimensional image (Quintero et al., 1999). However, there are a number of problems associated with data taken from lateral radiographs (Bookstein, 1983; Moyers and Bookstein, 1979). Among the issues these researchers address is the problem of two-dimensional representation of three-dimensional structures. Often, results are interpreted purely in relation to what is seen in the radiograph, with little consideration given to the real-life situation. Also, when lines and angles are drawn on the tracing between selected data points, these often ignore the shapes of the bones around the lines, which may substantially affect the growth of the bones, and the relationships between different structures. Another factor associated with cephalometric radiographs is that of parallax which causes possible misalignment of bilateral structures around the midsagittal plane. Other sources of error include radiographic enlargement and distortion of the image (Wei, 1968b), and measurement error during data acquisition including location of landmarks caused by a lack of definition in outlines (Quintero et al., 1999). All of these authors stress that the reliability of tracing and locating landmarks needs to be established and accounted for in the analysis. Other methods of studying the cranial base, and cranial base flexion that have arisen in the last 20 years or so include digitisation of landmarks, which allows the application of sophisticated statistical methods such as Fourier analysis, Finite Element analysis and Thin-Plate Spline analysis, among others (Lestrel, 1997a; Lestrel, 1982; Lestrel, 1989; Lestrel, 1997b; Lestrel and Brown, 1976; Lestrel and Huggare, 1997; Lestrel and Roche, 1986; McIntyre and Mossey, 2003; Molvray et al., 1993; Motoyoshi et al., 2002; Ohtsuki et al., 1982a; Ohtsuki et al., 1993; Ohtsuki et al., 1997; Quintero et al., 1999; Rosas and Bastir, 2002).

Despite their limitations and the development of new techniques of imaging and analysis, cephalometric radiographs remain a widely used tool in clinical orthodontic practice (Quintero et al., 1999). Although valuable three-dimensional information is lost in two-dimensional radiographs, and there are a number of issues associated with interpretation of results, the advantages of the material outweigh the disadvantages. These include standardised exposure and measurement protocol, thorough testing of techniques for reliability, the potential for multiple exposures on the same person over a number of years (longitudinal), a well established, comprehensive data pool, *in vivo* information, as well as demographic details on the individuals measured (age, sex, population of origin, treatment, etc).

Reference lines are a means of comparing variations in shape on a uniform basis (Björk 1955). The selection of a reference line is dependent on the purpose of the comparison. For example, if the various structures of the face and cranium are to be compared, the line can be more or less arbitrary, provided it can be readily defined and located. An example of this line is the Frankfurt Horizontal. If the purpose of establishing a line of reference is to provide a basis to describe the growth changes in a number of individuals over time, the reference line must take into consideration the growth sites of the skull (Björk, 1955). The ideal reference line is one that is stable in individuals over time. Any changes seen could then be recognised as movement of specific points relative to the stable references. However, no reference point has been found in the skull that shows no change over time. Minimal changes have been recorded in the anterior cranial fossa (nasion-sella) after 12 years (Björk, 1955). Finding a reference line in neonatal samples is difficult due to the considerable movement between bones during prenatal development (Björk, 1955). The occipital condyles and the foramen magnum have been suggested by some researchers as good reference points, as it is stated that the joint between the condyles and the vertebral column does not change with growth, due to the ligamentous connections with the anterior arch of the atlas and the dens axis (Zuckerman, 1955). According to Zuckerman, growth occurs above and below this area, and any increases in the foramen are supposedly due to alterations at opisthion, the posterior border of the foramen magnum in the midline.

Once the method of measurement has been decided upon, analysis of the growth processes can take a number of different forms. Due to the lack of a single "centre" of growth in the skull, any changes should be interpreted relative to a selected reference. This has caused a number of problems, both in the selection of the reference, and in the stability of these references over time. Studies attempting to identify a stable region in the head have been undertaken, and this issue has still not been resolved (Baumrind et al., 1976; Ghafari et al., 1987; Moore, 1971; Ricketts et al., 1976; Ross, 1995; Wei, 1968b; Wisth and Böe, 1975).

One area where differential growth has clearly been operating over time is in basicranial flexion. Comparisons between primates and modern humans have found that flexion is greater than expected in modern humans compared to their relative encephalisation (Ross and Henneberg, 1995). Furthermore, Lieberman and colleagues (2000) found that, contrary to earlier beliefs, flexion in primates does not steadily increase during evolution. Instead, it has been found that some primate lineages show increases in cranial base flexion, while others do not. Cranial base flexion has been defined in a number of different ways. In orthodontic research, this angle is typically measured as the angle between basion, sella and nasion. This measures the angle between the anterior and posterior cranial base, with the angle being at the midpoint of the pituitary fossa. Other researchers have considered other landmarks in establishing cranial base flexion; for example, Bolton point-sella-nasion (Broadbent Sr et al., 1975), or basion-sella-internal frontal bone (fronton) (George, 1978). Table 1.1 lists the numerous angles that researchers have used to measure cranial base flexion. These angles are organized by the landmark representing the anterior extension, or chord, of the angle, the point of flexion, and the posterior extension, or chord. This list is by no means exhaustive, but shows the amount of study that has been invested into the measurement of cranial base flexion. As can be seen from the table, the most commonly used angle in the literature is the angle between the landmarks basion, sella and nasion. Other angles have been used by a number of authors, but most are used in only one or two studies. This table also helps to show that any interpretation of studies using the cranial base as a reference will depend on the landmarks used in each analysis. Most studies propose reasons for selecting particular combinations of landmarks, but few have tested the inter-relationships of the variables as a means of describing actual, anatomical cranial base flexion.

Table 1.1: Different cranial base angles in the literature:

Anterior chord	**Point of flexion**	**Posterior chord**	**References**
anterior cranial base point (between the anteriormost point of cribriform plate and the uppermost part of the nasal septum)	sella (constructed centre of sella turcica)	basion	(Kvinnsland, 1971)
Anterior cranial base point (intersection between frontal bone and anterior point of cribriform plate)	prosphenion	basion	(Cramer, 1977)
cribriform plate plane	Intersection of the two planes	clival plane	(Moss and Greenberg, 1955)
ethmoidale (lowest point on anterior cranial base)	sella	basion	(Stramrud, 1959)
foramen caecum	sella	basion	(Cramer, 1977; Lieberman et al., 2000; Lieberman et al., 2001b; Lieberman and McCarthy, 1999; McCarthy, 2001; Scott, 1958; Spoor, 1997)
foramen caecum	sella	clival plane	(Lieberman et al., 2000; Lieberman et al., 2001b; Lieberman and McCarthy, 1999; McCarthy, 2001)
fronton	sella	basion	(George, 1978)
fronton	sphenoidale	basion	(George, 1978)
fronton	sphenoidale	clival line (main axis of superior border of clivus, not passing through basion)	(George, 1978)
hormion plane		clival plane	(Lieberman and McCarthy, 1999)
nasion	sella	basion	(Andria et al., 2004; Anton, 1989; Bacon et al., 1992; Björk, 1955; Bordeaux, 1972; Burdi, 1968; Burdi, 1969; Cameron, 1924; Diewert, 1983; Diewert and Lozanoff, 1993; George, 1978; Houghton, 1978a; Huggare et al., 1988; Kasai et al., 1995; Kean and Houghton, 1982; Kerr and Adams, 1988; Kerr, 1979; Kieser et al., 1999; Kreiborg et al., 1981; Kuroe et al., 2004; Lestrel, 1974; Michejda, 1975; Michejda and Lamey, 1971; Nanda, 1990; Peterson-Falzone and Figueroa, 1989; Read and Lestrel, 1986; Roche et al., 1972; Rothstein and Phan, 2001; Sirianni and van Ness, 1978; Smahel and Skvarilova, 1988a; Smahel and Skvarilova, 1988b; Solow, 1966; Solow and Siersbaek-Nielsen, 1992; Stramrud, 1959; Ursi et al., 1993; van den Eynde et al., 1992)

Table 1.1 continued

Anterior chord	Point of flexion	Posterior chord	References
nasion	sella	condylion (most supero-posterior point on the condylar head)	(Solow, 1966)
nasion	sphenoidale (uppermost midline point of tuberculum sellae)	basion	(George, 1978)
nasion	prosphenion, spheno-ethmoid suture or wing point (anterior curvature of lesser wings of sphenoid in midline)	basion	(Duckworth, 1904; Ford, 1956; Huxley, 1863; Huxley, 1867; Zuckerman, 1955)
nasion	sella	bolton	(Anderson and Popovich, 1983; Levihn, 1967)
nasion	tuberculum sellae ("pituitary point")	basion	(Ashton, 1957; Cameron, 1924; Cameron, 1925; Radoiévitch et al., 1961; Zuckerman, 1955)
nasion	sella	articulare	(Björk, 1955; Hopkin et al., 1968; Järvinen, 1984; Tanabe et al., 2002); (Solow, 1966)
nasion	pituitary point (point of greatest convexity between anterior sella and sphenoidal plane)	anterior point of occipital condyle	(Knott, 1971)
nasion	ethmoidale (the most inferior point on the cribriform plate of the ethmoid bone	basion	(Solow, 1966)
optic foramen	sella	basion	(Rosenberg et al., 1997)
orbitale (midpoint of plane joining superior and inferior orbital margins)	sella	basion	(Anton, 1989)
planum sphenoideum	sella	basion	(Lieberman et al., 2000; Lieberman et al., 2001b; Lieberman and McCarthy, 1999; McCarthy, 2001)
planum sphenoideum (tuberculum sellae to sphenoid as it starts to curve inferiorly)	Intersection of the two planes	clival plane (cranial border of clivus from below posterior curvature of dorsum sellae to basion)	(Biegert, 1957; Lieberman et al., 2000; Lieberman et al., 2001b; Lieberman and McCarthy, 1999; McCarthy, 2001; Robinow and Roche, 1973; Ross, 2004; Ross and Henneberg, 1995; Ross and Ravosa, 1993; Strait, 1999; Strait, 2001; Strait and Ross, 1999)
point midway between greater wings of sphenoid	pituitary point (see above)	anterior point of occipital condyle	(Knott, 1971)
prosphenion	sella	basion	(Kvinnsland, 1971)
prosthion	hormion	basion	(Laitman et al., 1978)

Overview of cranial base growth

The origin of the head and consequently the cranial base can be traced to the specialisation of metameric segments in early organisms. In animals, specialisation of segments led to the development of cephalisation in the anterior-most segments with the initial contact with the environment. This area required close communication between the central nervous system, major sensory systems, a system for nutrient intake, and some form of protection. As a result of this, the brain, eyes, nose, ears and mouth all formed in the same area, and became protected by the intramembranous bones of the face and skull (Larsen, 1998). However, the cranial base is a remnant of the axial endochondral skeleton before specialisation of the segments, and its history is reflected in the similarities between these bones and the other segmented areas of the skeleton, in particular the axial skeleton. Segmentation in the cranial base is not as obvious as the segmentation of the post-cranial skeleton. While initial segmentation of the cranial base is evident in the development of some cranial nerves and their associated muscles and vessels, segmentation is not readily distinguishable in the more mature skull. It is suggested that the early development of the sensory capsules, in particular the otic capsules in the temporal bone, and their incorporation into the craniofacial skeleton, obscures the segmentation of the cranial base (Rogers, 1992).

The endochrondral bones contributing to the cranial base in the midline are the basioccipital, sphenoid and ethmoid bones. In fetal life, the sphenoid bone is made up of the pre-sphenoid and post-sphenoidal bones, separated by the inter-sphenoidal synchondrosis; however, this joint ossifies soon after birth and is considered to be a single bone in humans (Ford, 1958). Some researchers also consider the frontal bone to be part of the cranial base, as it forms part of the anterior cranial fossa. However, the true bones of the cranial base are distinguished by their method of ossification, rather than by their location in the skull, and the frontal bone differs from the bones of the basicranium on this account. The occipital, sphenoid and ethmoid bones all ossify endochondrally, and resemble vertebral bodies in their formation and ossification (Kjaer, 1990; Kjaer et al., 1993). Ossification of the occipital bone resembles the pattern seen in vertebrae, in the development of different parts of the bone (Kjaer et al., 1993). Kyrkanides and colleagues (1993) observed further similarities between the development of cranial base bones and other endochondral bones. For example, significant, positive correlations were found between the length of the basal occipital bone and the length of the humerus (as well as with age and crown rump length). These researchers suggest that similar growth mechanisms are in operation during formation of these bones at distant parts of the body, and attribute this to the endochondral origin of these bones (Kyrkanides et al., 1993), however, an alternative interpretation is that the similarities in growth are due to similar timing. All endochondral bones develop from condensations of cartilaginous precursor cells, which undergo hypertrophy and hyperplasia, following which they are converted to bone. Continuing growth occurs at the surfaces of the bone, through ossification at the epiphyseal surfaces (Larsen, 1998; Rogers, 1992).

The cartilaginous precursors of the bones of the cranial base develop from mesenchyme around the 40th day of gestation (Laine, Nadel & Braun, 1990 cited in Myer, 1995). Ossification then progresses in a caudo-rostral direction from the basioccipital to the ethmoid bone (Kjaer, 1990). Ford (1958) found that the presphenoid and basisphenoid fuse shortly before birth, but cartilage remains here for some time. At the time of birth, growth centres in the cranial base are between basisphenoid and basioccipital (spheno-occipital synchondrosis), and between presphenoid and frontal bones. After birth, during the first year, the mesethmoid centre appears in the area of the cribriform plate. This permits growth anteriorly and posteriorly between frontal and sphenoid bones while cartilage persists. Ford (1958) analysed skulls of different ages to determine the ages of active growth of growth centres between sphenoid and mesethmoid, mesethmoid and frontal, and within the frontal bone. After measuring differences in a cross-sectional collection of skulls, grouped into dental ages, it was found that growth at the spheno-occipital synchondrosis continues through adolescence. Growth at the spheno-mesethmoid synchondrosis ceases after seven years. The cribriform plate ceases to grow by about two years, while the thickness of the frontal bone continues to increase through adolescence. Between 30% and 60% of the growth of the craniofacial complex is complete by birth (Thilander, 1995), while over 80% of the growth of the cranial base is complete by six years (Myer, 1995).

The differences in origin and function of the cranial base compared to the braincase and facial skeleton are reflected in differences in growth rates. The neural pattern of growth affects the brain and surrounding bones, and is characterised by rapid growth in the first two to three years, with steady decreases thereafter, and ceases at about seven to eight years. The general growth pattern of somatic tissues, including those of the face and facial skeleton, is a steady increase from birth to adulthood, with an adolescent growth spurt. The cranial base is generally expected to have a growth pattern intermediate between these two, and this holds true when considering the cranial base as a whole unit. However, Ford's study (1958) shows that the individual bones can follow either a neural or a general growth pattern. Increases in distances between nasion and foramen caecum and between sella and basion follow the general, somatic growth pattern.

Foramen caecum to sella and the sagittal length of the foramen magnum show a neural pattern, which means that growth areas around the foramen magnum are silent by the time of eruption of the first molar (Ford, 1958; Zuckerman, 1955). Once the brain has ceased growing, the anterior cranial base still needs to grow to allow for facial development. This occurs through the development of the frontal and ethmoidal air sinuses, with development of the supraorbital region and the interorbital septum. In a comparison of cranial base growth in primates, examining samples of infants, juveniles and adults, it was found that the anterior cranial base growth seems to follow the pattern of the facial skeleton, rather than the brain or endocranial cavity. In contrast, the posterior regions of the cranial base follow the growth pattern of the endocranial cavity (Michejda, 1975).

From early life, it has been found that males and females differ in the onset, rate and duration of growth. This leads to sexual dimorphism, which, while operating from childhood, becomes most evident during puberty. Sexual dimorphism in the head differs from the development of sexual dimorphism in the rest of the body (Baughan and Demirjian, 1978), since it is generally established before puberty, becoming evident at six years, although there does seem to be a pubertal spurt in cranial dimensions in boys, but not girls, at puberty (Lewis et al., 1985). Ursi and colleagues also found differences between males and females in the growth of the basicranium, in addition to the rest of the face (Ursi et al., 1993). Growth changes are typically described by changes in size and/or shape. However, the time at which changes occur is equally important, as is the rate and duration of growth. In a study of the anterior and vertical relationships in children and adolescents between four to 16 years, differences were found in the time that different elements reach their mature dimensions. It was found that head height is the first to reach its mature form, followed by the anterior and then the posterior cranial base, and then various elements of the facial skeleton. Females attain their mature form before males (Buschang et al., 1983a). In another study (Ohtsuki et al., 1982a), factor analysis was applied to cranial base measurements of serial radiographs. Children of each sex were divided into age groups of zero to three years, four to six years, seven to nine years, ten to twelve years, and 13 to 15 years. Factor analysis was applied to determine which variables accounted for more than 80% of the variance in a given sex and age bracket. Variables selected by the analysis varied between the age groups, and between boys and girls, and differences were especially apparent between ages zero and three and the older age groups. In the earliest age group in boys, rapid increases in growth occur in all dimensions. In later age groups, the factor pattern changes, and timing of these changes seems to be consistent with the initiation of differential growth patterns, at the ages of three, seven and 15 years in boys, and at three, seven and 13 years in girls (Ohtsuki et al., 1982b). It appears that each region/segment in the cranial base has an individual growth pattern. Initial growth is generalised, growth at older ages shows segments having developed independent patterns. Growth depends on local apposition and resorption (Enlow, 1990; Melsen, 1974), and the timing of different events in development, for example, the time when sutures ossify. Fronto-ethmoid suture growth ceases around 3 years (Scott, 1958). Timing of ossification of sutures also varies between males and females, especially in the ossification of the spheno-occipital synchondrosis, which is an explanation for the change in factor pattern for girls after 12 years. Growth rates are presumably controlled by the same mechanisms in both sexes, and it is more likely to be just the timing that differs.

Studies on the growth of the head have attempted to document the normal growth of the cranial base at different ages. Many of these have taken the form of longitudinal, serial measurements of craniofacial growth (Bambha, 1961; Bhatia and Leighton, 1993; Fishman, 1969; George, 1978; Kohn, 1989; Lestrel and Brown, 1976; Lestrel and Roche, 1986; Peterson-Falzone and Figueroa, 1989; Schneiderman, 1992; Subtelny and Rochester, 1959). An equal number have investigated growth cross-sectionally (Bartlett et al., 1992; Brodie, 1941; Bromage, 1989; Buschang et al., 1983a; Diewert, 1982; Friede, 1981; Kjaer, 1990; Kyrkanides et al., 1993; Scheideman et al., 1980; Sgouros et al., 1999; van den Eynde et al., 1992; Zuckerman, 1955). In addition, experimental manipulations of craniofacial form have increased the understanding of the growth of the cranium (Babler and Persing, 1982; Babler et al., 1987; DuBrul and Laskin, 1961; Reidenberg, 1988; Rosenberg et al., 1997; White, 1996).

In numerous discourses on craniofacial development, Enlow and colleagues investigated craniofacial development and variation (Duterloo and Enlow, 1970; Enlow, 1966a; Enlow, 1966b; Enlow, 1976; Enlow and Azuma, 1975; Enlow et al., 1971a; Enlow et al., 1971b; Enlow and McNamara, 1973; Enlow and Moyers, 1971; Enlow et al., 1969; van der Linden and Enlow, 1971). Enlow and Moyers (1971) include a section on the morphogenetic basis for variation in craniofacial form. They note that all components of the facial skeleton are closely related during growth. For example, the anterior cranial base is equivalent to the upper nasomaxillary complex, which is closely related to the inferior part of the maxilla. Any changes in size or displacement of any of these regions will influence the others. In a description of the growth of the craniofacial skeleton through remodelling and displacement through serial tracings registered on vertical and horizontal reference lines, it is noted that most of the significant changes in growth of the cranial base and movement of the maxilla are not apparent if sella-nasion is used as a reference plane (Enlow and Moyers, 1971). Increases in length of the cranial base occur posterior to sella, which means that sella is moved relatively forward. The endocranial surface of the clivus, and the middle cranial fossa are resorptive, while deposition occurs ectocranially. This causes anterior relocation of the clivus and anterior wall of the middle cranial fossa. Simultaneously, superior displacement of the entire skull occurs by growth at the occipital condyles. Growth of the cranial base causes inferior and anterior displacement of the maxilla and mandible, but the effects are less evident in the mandible because of the angle of inclination of the cranial base relative to the mandible. The authors also note that the sella-nasion plane is not an anatomically effective dimension to represent the upper face and/or cranial base. It passes across different bones that have different patterns and sites of growth, it is not related to an architecturally important landmark in the skull, and it does not include the posterior regions of the anterior cranial base.

In a landmark study about age changes in the cranial base, Zuckerman studied dry, modern human skulls, not separated into sexes or racial groups, to avoid the possibility of "increasing the variance of the observations, and therefore of obscuring age differences which might actually exist" ((Zuckerman, 1955), p. 524). While the author recognised the problems associated with pooling all data, he argued that the immature sample was too small to justify separating into smaller groups. Age groups were determined by dental ages - for example by the number of erupted teeth. Ages ranged from under one year to senile skulls. The adolescent period was substantially under-represented, including only four individuals between nine and 14 years. Results show that the cranial base is more than 50% of its adult size by eight years. Basioccipital, basisphenoid, presphenoid and ethmoid all continue to grow until adulthood. The posterior part of the cranial base, measured from basion to the pituitary point, is longer in skulls with permanent dentition compared to those with deciduous dentition, and is longer in adults than in those with only the 2nd molar erupted. Similar results are seen for the anterior cranial base. The sagittal diameter of the foramen magnum shows significant differences between juveniles with deciduous dentition and those with the permanent teeth erupting (six to eight years), but no differences are present between the latter group and adult skulls. These data suggest that the posterior parts of the cranial base cease growing sooner than the anterior parts, which continue growing up to and beyond puberty, and contribute to the adolescent growth spurt. This paper is useful for establishing general growth trends, but does not consider the growth patterns of individuals. Zuckerman notes that there is no reason to say that the growth patterns in the cranial base will correspond to dental ages in individuals, especially with adolescence where averages will underestimate growth changes. In addition, orthodontic or dental ages are possibly time frames that are too lengthy to accurately measure changes in the basicranial axis, and the pooling of males and females may have increased variances.

Melsen (1974) was the first person to histologically examine the cranial base. Samples of the middle cranial base were taken from autopsy material, age range 0 to 20 years, comprising 76 males and 50 females. She used tetracycline staining techniques to identify surfaces where bone apposition was occurring. It was found that the endocranial surface of the anterior cranial base, consisting of the frontal bone and cribriform plate, ceases remodelling activity in most cases by four years of age. Apposition occurs on the anterior sphenoid surface (*jugum sphenoidale*), which has the effect of raising the level of the bone, as mentioned by Björk (1955). Growth in length of this part of the cranial base occurs by growth at fronto-ethmoidal, spheno-frontal and spheno-ethmoidal sutures. In the spheno-frontal and spheno-ethmoidal sutures, no growth was seen after about seven years. Individual variation was considered but not assessed due to the small number of sutures studied. Due to the inactivity of growth processes at early ages in this area, any increases in anterior cranial base length through the development of the frontal sinus and thickening of frontal bone at glabella were attributed to surface remodelling on the external frontal bone. Individual variation exists in the development of anterior cranial base length and in remodelling. Therefore, averages of age categories are inadequate to describe the growth pattern of individuals (Melsen, 1974).

In a study on boys between 12 and 20 years, Björk (1955) found that the cranial base increases in length by sutural growth. The anterior cranial fossa stops growing around 10 years, and the growth of the upper face after this point is mostly by apposition on the frontal bone. The posterior cranial base increases in length through growth at the spheno-occipital synchondrosis, causing an endocranial displacement of basion. Lateral growth of the posterior cranial base also occurs, through growth at the sutures, and continues as long as there is growth in the upper face. Changes in the cranial base do not appear to be reflected in movement of the sella, representing the sphenoid bone in this instance. The nasion-sella line is stable in relation to the floor of the anterior cranial fossa during adolescence. The anterior cranial base lengthens ventrally through apposition at glabella. As demonstrated by a case study of achondroplasia, the normal development of the cranial base is largely dependent on the normal growth of the spheno-occipital synchondrosis. Changes in the cranial base with age continue as long as the head and face continue to grow. Angles of the cranial base and face show a lot of individual variation in both directions with age. Therefore, while the mean changes with age may be small, changes within individuals may be highly variable. Individual variation in length of the cranial base is most prevalent in clival length, at 69%, while individual variation in sella-nasion is 50%. Due to the variation in growth rates between individuals, the standard deviations of craniofacial measurements increase with age for both shape and size. In the summary it is noted that the general growth patterns do not give any information about the "dynamic development" which only becomes clear with individual data. It is also noted that individual changes may not necessarily coincide with the average growth trends with age because the changes may be in any direction and of varying magnitude. In 1972, Björk studied the facial development and tooth eruption of a longitudinal sample of males and females between nine and 20 years. He found rotation of the face involving both upper and lower jaws during development. A majority of subjects showed rotation in the forward direction, in relation to n-s line, with an average of -6 degrees in the mandible, and -2.5 degrees for the maxilla. These had a significant correlation of 0.75. Rotation was found to influence the eruption of teeth and, therefore, had an effect on occlusion and spacing. The location of the centre of rotation is also a factor in the path of eruption. A relationship existed between condylar growth and rotation. Remodelling of the posterior and lower borders of the mandible can mask rotation. In the maxilla, eruption of the teeth is contributed to by rotation (i.e., it is not purely eruption) (Björk and Skieller, 1972).

Growth changes in cranial base flexion

Studies of cranial base flexion in prenatal individuals are necessarily cross-sectional, and it has been found by some researchers that the angle increases during prenatal development (Ford, 1956; Lieberman et al., 1972). According to Diewert (1983), the average cranial base angle between basion-sella-nasion in a sample of fetuses increases from 117 degrees (sd = 4) to 127 degrees (sd = 11) between crown-rump lengths of 18.1 mm and 49.0 mm (Diewert, 1983). However, another study of embryos at the time of formation of the primary palate found that cranial base flexion did not change, despite the altering relationship between the developing brain and facial regions (Diewert and Lozanoff, 1993). George states that the angle at birth is 142 degrees, and has stabilised to 130 degrees by the age of five years (George, 1978). Cranial base flexion measured in longitudinal studies appears to show little change from 2 years after birth (Lieberman and McCarthy, 1999). In a sample of children from the Belfast Growth Study the basion-sella-nasion angle was measured at 129 degrees in the oldest age group (15 years), with a standard deviation of about two degrees (Kerr, 1978). In additional work, examining the same children over a ten-year period, it was found that the average angle of cranial base flexion remained constant. However, when individual cases were studied, in some subjects the angle increased, in others it decreased, and in the remainder of the group it did not change, with a range of change from -9 to +10 degrees (Kerr, 1979).

Different cranial base angles measured nasion-sella-basion are related to different craniofacial forms. Rotation of the cranial base is related to rotation of the brain case and rotation of the facial skeleton. This is apparently related to interactions between different growth processes during development, producing a wide range of individual variation. A decreased cranial base angle will produce a more prognathic face, as measured by the protrusion of the upper and lower jaws (maxilla and mandible). Changes in cranial base flexure or shape can produce a relocation of the glenoid fossa in relation to the anterior areas of the cranial base (Björk 1955; Kieser, Panting et al. 1999). However, protrusion of the mandible is also dependent on the growth processes occurring in the mandible, such as growth at the condylar processes in different directions, apposition or resorption at gnathion, and remodelling/growth at the gonial angle.

In a longitudinal and cross-sectional study of the cranial base angle it was found that the cranial base angle decreases during the first two years of life (George, 1978). These decreases were recorded in three different angles of cranial base flexion: nasion-sella-basion, internal frontal bone point-sella-basion, and the clival inclination relative to the sphenoidale-frontal line. Following this, flexion shows individual patterns, with flexion increasing in some individuals and decreasing in others. It is suggested that in early childhood there are two patterns of growth, one operating until two years, and one after two years. The later pattern of growth may also be interpreted as growth adjustments occurring in other areas. Considering the similar results of Björk (1955), it seems that the growth during the early postnatal period follows a fixed pattern of growth, as shown by high correlation between means and standard deviations, with individual variation (George, 1978).

With older children, growth spurts in cranial base flexion have been identified, as well as differences between males and females. Lewis and Roche (1977) studied change in the cranial base angle (nasion-sella-basion) in a longitudinal sample of boys and girls.

It was found that the angle is larger in males until about 18 years. In adults there is a slight tendency for the angle to be larger in females, but the small sample sizes are small enough to reduce reliability. A reduction in flexion with age was noted in all groups studied, including both sexes and different occlusal relationships. The rate of reduction is increased during infancy resulting in about 5º change, and then slows until a few years after puberty, when it stabilises. Some individuals experience large changes in cranial base flexion during growth; these are usually decreases in the angle and can be as much as 17 degrees.

Kvinnsland (1971) found high correlations between different angles in the cranial base, these angles were between the anterior and posterior cranial base, intersecting at sella, which decrease in flexion with increasing developmental size. The angle between prosphenion-sella-basion measures the angle of the sphenoidal and occipital parts of the cranial base, and shows considerable individual variation, but no real relationship to developmental stage. The angle of the anterior base is measured by the anterior cranial base point-prosphenion-sella. The intersection between the most anterior part of the cribriform plate, and the more vertical uppermost part of the nasal septum, in the midsagittal plane can be measured as a further angle in the cranial base, representing the spheno-ethmoid part of the anterior cranial base. It shows an increase (i.e., flattening) in the sample measured. All these angles were positively correlated. It was also found that individuals with a large cranial base angle had large anterior face height, measured from nasion-gnathion and a relatively more posterior rotation of the mandible. Increased growth was observed in the anterior cranial base compared to the posterior cranial base, with contributions from sphenoid and ethmoid parts of the anterior cranial base being fairly equal. It is suggested that most of the angular changes in the anterior cranial base occur around the spheno-ethmoid junction (*prosphenion*) (Kvinnsland, 1971).

May (1999) measured the growth changes in two estimates of craniofacial flexion between different groups of hominoids. The angles were internal flexion angle, measured between the anterior end of cribriform plate-tuberculum sellae-basion, of the cranial base, and a craniofacial angle staphylion-hormion-basion. In this investigation, sagittal radiographs of juvenile crania of gorillas, chimpanzees and modern humans were studied. Ages of crania were estimated as belonging to one of four groups, based on molar occlusion. Comparisons were also made to juvenile fossil crania. It was found that the internal flexion angle increases during growth in gorillas. The same angle in chimpanzees and modern *Homo sapiens* remained relatively stable during development, with a slight decrease in the angle in *Homo* (more flexed, average decrease of less than 5º). The craniofacial angle increased in both chimpanzees and gorillas, but decreased in humans. Comparisons to australopithecine fossils show craniofacial flexion intermediate between anthropoid apes and modern humans (May and Sheffer, 1999).

Cranial base variation has been found in a number of developmental disorders. Most evident are the obvious deviations in the facial skeleton. However, the fact that the cranial base also shows differences from the norm in individuals with these syndromes suggests a fundamental connection. Differences occur in the size of bones, the proportional relationships between bones, and the flexion of the cranial base (Grayson et al., 1985). In Crouzon's disease, Apert's syndrome, and frontonasal dysplasia, differences are seen in overall cranial base shape, but cranial base flexion does not differ significantly from normal individuals. Pfeiffer's syndrome and Treacher Collins syndrome (mandibulofacial dystostosis) show angles of cranial base flexion that differ from the normal cranial base, being more flexed in individuals with these syndromes. No differences are seen in the cranial base in cases of craniofacial microsomia compared to normal subjects (Grayson et al., 1985). One possible problem with this study is that they pooled values from children aged from less than 5 years to over 15 years. Their descriptions of the differences between the syndrome subjects and the age- and sex-matched norms are based on mean values over the entire sample for each syndrome. Their conclusions fail to consider possible growth changes that may occur as subjects grow older. It is unreasonable to assume that the considerable data generated on age changes in the cranial base, especially around puberty, will be the same in the syndrome children and "normal" children, bearing in mind that it is the growth processes that cause the initial differences in craniofacial form. In individuals with cleidocranial dysostosis the cranial base angle is more flexed and the anterior and posterior cranial base elements are shorter when compared to normal controls (Kreiborg et al., 1981). The clivus is frequently distorted or flexed, the pituitary fossa is shallow and the dorsum sellae is bulbous. It is thought that the smaller cranial base angle may be due to the flexed clivus, while the smaller cranial base size corresponds to the short stature of the individuals with this syndrome. In a longitudinal study of cranial base angle changes in subjects with mandibulofacial dysostosis, it was concluded that the appearance of an abnormal, highly flexed angle may be time-dependent (Peterson-Falzone and Figueroa, 1989). Males seem more likely to show significant change in cranial base angle over time, and flexion increases with age. The causes of progressively increasing flexion appear to be related to remodelling changes in the cranial base. At this stage it is unknown why the differences between males and females are present. In a group of shunt-treated hydrocephalic children studied for two years the cranial base was found to be initially flat (obtuse) but then flexion increased and values of cranial base flexion approaching normal were seen once treatment was applied (Huggare et al., 1988).

There have been a number of studies investigating the angle of flexion of the cranial base in different facial forms or malocclusion patterns. For example, in a sample of boys aged around ten years, Kerr and Adams found a decrease in the nasion-sella-basion cranial base angle with the progression of malocclusions according to Angle's classification system (Class II to III) (Kerr and Adams, 1988), where a decrease in the angle was related to increased prognathism of the mandible. Rothstein and Yoon-Tarlie also examined the role of cranial base flexion in Class II, Division 1 malocclusion, in a sample aged between 10 and 14 years and found that the cranial base angle is larger in the Class II individuals compared to normal controls. No relationship was found between the angle of the cranial base and the position of the mandible (Rothstein and Phan, 2001; Rothstein and Yoon-Tarlie, 2000). However, other studies examining the same relationship in different samples found that the cranial base is not a primary cause of malocclusion (Bacon et al., 1992; Dhopatkar et al., 2002). Rather, it appears that the malocclusions are primarily influenced by the length of the jaw, which differs significantly between the Angle classes of malocclusion, where individuals of Class II have a longer maxilla in Class II, and individuals of Class III have a longer mandible (Dhopatkar et al., 2002).

Variation in adult forms is described as the result of an interaction between general changes in scale that are placed over individual differences in proportion (Buschang et al., 1983b). These workers identify three components of the craniofacial skeleton that are seen in multivariate analysis. These are: anterior facial proportions; cranial height and cranial base length; and mandibular and maxillary relationships. These components were found to be age and sex independent, and thus are a reflection of individual variation of epigenetic traits.

Evolution of cranial base flexion

A number of studies have been undertaken to investigate variation in cranial base flexion in modern humans, fossil hominins and hominoids with the aim of understanding evolution of cranial base flexion. In 2001 McCarthy reported the results of investigations on the cranial base angle in 18 anthropoid species. The non-human primate species included representatives of *Pan*, *Gorilla* and *Pongo*, as well as other primates. The sample of modern human skulls included 60 individuals from five geographically diverse samples, with six males and 6 females in each sample. The samples consisted of Australians, Chinese, Italians, Egyptians and Ashanti (sub-Saharan Africans). Two of the cranial base angles measured by McCarthy are the angle basion-sella-foramen caecum, and the clival plane-sphenoidal plane angle. He found that the modern human sample had angles considerably more flexed than the anthropoid and non-anthropoid primates). The anthropoid primates (gorillas, chimpanzees and orang-utans had angles that were moderately flexed, while the non-anthropoid primates had angles that were even less flexed.

Koppe (1999) measured cranial base flexion in extant hominoids (humans and great apes). Basicranial flexion was measured as the angle between the sphenoidal and clival planes, and was measured in a sample of ten modern humans, ten *Pan*, ten *Gorilla* and eleven *Pongo* (Koppe et al., 1999). From the results, Koppe was able to conclude that the flexion in modern humans was about 15 to 20 degrees more than in other extant anthropoids. Koppe related the increase in flexion in modern humans to the size of the sphenoidal sinuses, where an increase in flexion was related to a smaller sinus. A similar relationship was observed by Radoiévitch in a sample of 159 modern humans (Radoiévitch et al., 1961). In each of these studies, the researchers concluded that posture is an important factor in basicranial flexion in humans, but is not the only one, since other factors such as the size of the sphenoidal sinus also play a role.

Other research conducted on cranial base flexion includes that of Cramer (1977), who found the angle basion-sella-foramen caecum was 135 degrees in a sample of sample of 43 Tzompantli Indians (Mexico). When compared to samples of *Pan paniscus* and *Pan troglodytes*, the angle measured 140 and 145 degrees respectively. Cramer also found considerable overlap of ranges between these three samples (Cramer, 1977).

In a study on the calvaria of a Pleistocene *Homo erectus* skull from Java (Sm 4), Baba and colleagues (2003) found that the basion-sella-foramen magnum angle was 141 degrees, and the clival plane-sphenoidal plane was 97 degrees. After comparing these measurements to those seen in modern human samples, in which the basion-sella-foramen magnum angle ranged between 128 and one half and 141 degrees and the clival plane angle ranged between 92 and 135 degrees, these researchers concluded that the flexion observed in this *Homo erectus* skull was similar to that of modern humans. They suggest that the flexion of the cranial base was not related to reduction in facial prognathism or increased “globularity” of the brain, based on the finding of “strong” flexion in this single skull (Baba et al., 2003).

Spoor (1997) investigated cranial base flexion in fossil hominins, modern humans and other hominins. He found that basicranial shape is highly correlated with relative brain size, and is therefore a prime factor in determining cranial base morphology (Spoor, 1997). Spoor measured the basion-sella-foramen caecum angle in 17 species of extant non-human primates (42 individuals), 48 modern human crania (diverse geographical origin) and Sts 5, an *Australopithecus africanus* skull. He also studied the flexion of three other hominins: OH 5 *A. boisei*), KNM-WT 17000 (*A. boisei/aethiopicus*) and Sangiran 17 (*H. erectus*). An interesting feature of Spoor's work is that he also measured the orientation of the foramen magnum and petrosal pyramids, and related these to the orientation of the anterior cranial base (sella-foramen caecum). The results of Spoor's analysis show that the Sts 5 and KNM-WT 17000 skulls had angles that were significantly different from modern humans, and resembled the great ape values. The Sangiran 17 and OH 5 skulls were not significantly different from modern humans in their basion-sella-foramen caecum angles. In the sample of non-human primates, the range was measured as between 148 degrees (seen in a sample of six chimpanzees) and 185 degrees (in a single individual of *Alouatta seniculus* or red howler monkey). With regard to the results of the orientation of the foramen magnum relative to the sella-foramen caecum plane, the modern human sample had an average difference of seven degrees, the OH 5 individual had a difference of six degrees, and the Sangiran 17 individual had a difference of minus four degrees. The other individuals had values significantly different from the modern human sample with regard to the orientation of the foramen magnum relative to the sella-foramen caecum plane, such as a difference of 25 degrees in the KNM-WT 17000 individual and a difference of 27 degrees in Sts 5. The non-human primate range was between 29 and 70 degrees, again with the smallest values seen in the chimpanzee sample and the largest value in the red howler monkey. Spoor concluded that an increase in relative brain size is related to increased cranial base flexion, an inferiorly facing foramen magnum and more coronally oriented petrous pyramids. He found support for Gould's hypothesis (Gould, 1977) that flexion of the cranial base and an inferior orientation of the foramen magnum are related to increased brain size and shortened basicranium. He also concluded that while Sts 5 followed a non-human primate pattern, resembling chimpanzee values, the other fossil hominins had a foramen magnum more inferiorly rotated than was predicted by regression analysis. This suggests that factors other than brain-size are influential on cranial base in these individuals, such as adaptations to bipedalism. Spoor suggests that in hominins such as *Homo erectus* flexion of the cranial base is a response to increased brain size as well as adaptations to bipedalism (Spoor, 1997). In a later study, Spoor (2000) studied the cranial base in 19 African and Asian Plio-Pleistocene hominins, and investigated cranial base flexion (which, although not specified in the paper, is assumed to be the angle basion-sella-foramen caecum), foramen magnum orientation and posterior petrosal surfaces, using CT scans. Spoor concludes that based on the results, the inferior orientation of the foramen magnum seen in more recent fossil hominins such as *Homo ergaster* predates the development of increased flexion of the cranial base. This is based on the finding that the orientation of the foramen magnum and petrous pyramids resembled modern human morphology, the cranial base flexion was more similar to that seen in non-human anthropoids (Spoor, 2000).

Among the other studies reporting cranial base flexion in primates and fossils hominins, Lieberman and McBratney (2001) state that flexion of the cranial base in modern humans is about 15 degrees more than in fossil hominins, however they do not state the angle measured to obtain this figure (Lieberman and McBratney, 2001). In 1995 Ross and Henneberg conducted a study on the clival plane-sphenoidal plane angle of cranial base flexion. They measured this angle in a sample of modern humans, non-human anthropoids (*Pan*, *Pongo* and *Gorilla*) and a number of fossil hominins. The hominin fossils included Sts 5 (*A. africanus*), MLD 37/38 (*A. africanus*), OH 9 (*H. erectus)* and the Kabwe skull (archaic *H. sapiens*).

It has been established that modern humans have more flexion in the cranial base when compared to other primates (Lieberman and McCarthy, 1999; Ross and Ravosa, 1993). While studies have found that the cranial base flexion of modern humans lies within the range of that measured in fossil hominins (Ross and Henneberg, 1995), the common perception in the literature seems to be that the cranial base angle in modern humans is at the most flexed extreme of the primate range (Ross et al., 2004; Ross and Ravosa, 1993; Strait, 1999), especially when relative brain size is taken into consideration. Compared to other primates, the anterior vertical dimension of the craniofacial complex is proportionately greater. Furthermore, modern humans possess an upright head posture. The features are related to reduction of the masticatory apparatus, rotation of the facial complex in a downward and backward direction, and increased height of the nasal cavity. It is suggested that the flexion seen in modern humans has developed through evolution of the craniofacial and post-cranial skeleton. There are a number of theories that have been proposed to explain the acute basicranial flexion seen in humans. These can be divided into neural hypotheses (Gould, 1977; Ross, 1993; Ross and Henneberg, 1995; Ross and Ravosa, 1993; Strait, 1998; Strait and Ross, 1999), speech and language hypotheses (Laitman, 1985; Laitman and Heimbuch, 1982;

Laitman et al., 1978; Lieberman and Crelin, 1971; Lieberman et al., 1972) and postural/bipedalism hypotheses (Ashton, 1957; Bolk, 1915; Weidenreich, 1924). With regard to the various hypotheses on the evolution of basicranial shape, it is worth noting that factors influencing the cranial base may be structural or functional. Most hypotheses on cranial base flexion relate to structural principles, where changes in the cranial base have a causative effect on other anatomical structures. A few of the hypotheses are functional, and these arguments relate to changes in the cranial base affecting the function of other structures, producing a mechanical or behavioural advantage (Strait, 2001). These hypotheses differ in their predictions of which basicranial characteristics will be correlated with other characteristics.

Supporters of the neural hypotheses of cranial base flexion in modern humans state evidence correlating increased relative brain size and flexed basicrania (Gould, 1977). Ross and Ravosa support Gould's hypothesis, in that a bigger brain and smaller basicranium results in cranial base flexion, with the finding that significant correlations exist between cranial base flexion and relative brain size (neurocranial volume relative to cranial base length) in haplorhine primates, but not in strepsirhine primates (Ross and Ravosa, 1993). Further studies have also found similar results in hominins, with correlations between relatively larger brains and increased flexion of the cranial base. For example, Strait (1999) found significant correlations between relative brain size and cranial base flexion in 29 primate species. Cranial base flexion was measured as the angle between the clival plane and the pre-sphenoidal plane. A decrease in the angle represents an increase in flexion. Relative brain size was measured by the index of relative encephalisation (neurocranial volume relative to basicranial length). As flexion increased, so did relative brain volume. Ross and Henneberg (1995) suggested that the maximum possible flexion in cranial base was reached around the time of *Australopithecus africanus*, which would explain no recent changes in flexion with increased cranial capacity. In another, earlier study, significant correlations were also found between head neck angle and the angle of orbital inclination (Strait and Ross, 1999). These authors note a number of possible factors that may have influenced their results, especially the factor of limited sample sizes, which means that individual variation was not fully considered. Head and neck posture does not seem to be the primary determinant of cranial base flexion; it is more notably influenced by relative brain size.

In support of the hypothesis relating cranial base flexion to the development of speech and language, Lieberman, Crelin and associates (1972) conducted a number of studies on the relationship between basicranial flexion and the location of upper laryngeal structures in the neck. These researchers took sagittal sections of heads of newborn humans, adult humans and chimpanzees. In addition, they compared the craniometric anatomy of newborn and adult and infant humans, chimpanzees and a Neanderthal skull, although it should be noted that the extrapolations about the soft tissues of the Neanderthal were based on a number of assumptions. They found similarities between newborn humans, chimpanzees and Neanderthals in their laryngeal anatomy, which were different from the vocal tract of adult humans. They suggest that the modifications of the adult vocal tract allow the production of particular vowel sounds. Infant humans and chimpanzees cannot produce these sounds. These latter sounds can be produced by different combinations of the vocal tract, whereas iteration of the former sounds is limited by the location of the supralaryngeal structures, making their production only possible in modern human adults (Lieberman et al., 1972). It is suggested that the adult vowel sounds can only be produced with a combination of a flexed cranial base, relatively shorter distance between the palate and basion, and the hyoid and larynx positioned low in the neck (Laitman, 1985; Lieberman and Crelin, 1971; Lieberman et al., 1972).

The only Neanderthal, in fact, the only Middle Palaeolithic, fossil to be found with an intact hyoid bone is the Kebara hominin. Despite the fact that no cranium was found with the fossil, the mandible, hyoid bone and cervical vertebrae allow some conclusions to be made about the anatomy of the larynx (Arensburg et al., 1990). It is suggested that the anatomy of the mandible and hyoid bone is more important in reconstructing laryngeal dimensions than basicranial flexion. It is concluded that the Kebara hominin, dated to about 60,000 years old, had cervical and laryngeal anatomy that was within the range of modern humans. This implies that it would have been as capable of speech as modern humans, and casts some doubt on the premise that a flexed basicranium was necessary for speech.

The language-based hypothesis for cranial base flexion has been questioned by a number of researchers (Houghton, 1993; Lieberman and McCarthy, 1999). Houghton (1993) questioned the anatomical validity of the reconstructions of the supralaryngeal tract and other oral and pharyngeal dimensions of Neanderthals used as evidence by Lieberman and colleagues. Lieberman and McCarthy (1999) found that the growth of the internal and external cranial base was not related to the development of the larynx, and, therefore, this structure should not be used to extrapolate relationships in fossils (where soft tissues can only be estimated). However, experimental study has shown that induced flexion of the cranial base also causes changes in the position of the supralaryngeal structures (Reidenberg and Laitman, 1991). It was found that 13-day old rats with their spheno-occipital synchondrosis totally removed had increased basicranial flexion, and larynx and hyoid bone positioned lower in the neck than rats with partial removal or no removal. This suggests a direct, mechanical relationship between cranial base and soft tissues, which is susceptible to influences during growth. Partially operated rats had slightly greater flexion and inferiorly located larynx and hyoid than normal ones, possibly due to the removal of the longus capitis muscle during surgery (no pressure on the bone). Reidenberg and Laitman's paper has important ontogenetic and phylogenetic implications. The cranial base in operated animals was not measured for size, however it is suggested that the clivus in these animals would be shorter in length. In addition to this, the growth centres of the calvaria would not be affected, causing the brain and associated structures to continue growing, and place different pressure on the cranial base, causing it to flex (Reidenberg and Laitman, 1991).

Postural hypotheses of basicranial flexion relate to the change from pronograde to orthograde posture (Strait, 2001) and the associated ventral rotation of many basicranial features. These hypotheses focus on the change in centre of mass with the adaptation to bipedalism, which required a re-orientation of the foramen magnum and consequently alterations in cranial base flexion. This is based on the observations that the location of the foramen magnum varies in different primate species. For example, in arboreal primates it is located at the rear of the skull, in chimpanzees it is positioned more ventrally, and in hominin fossils and modern humans it is located under the skull (Ashton, 1957; Bolk, 1915). The re-orientation of the foramen magnum is thought to occur through a bending of the posterior cranial base relative to the anterior cranial base, which remains in a horizontal position to retain rostral orientation of the orbits (Dabelow, 1929; Weidenreich, 1924). A more recent investigation of the posture of the head and neck with regard to basicranial flexion was undertaken by Strait and Ross (1999). While the main conclusion of the study is that relative brain size has a greater influence than posture on cranial base flexion, they also find a consistency of orientation (relative to gravity) of the orbital axis in all primates, including humans, which may make it a useful reference plane for functional studies. Strait (1999) further investigated the relationship between relative brain size, cranial base flexion and basicranial length in different primate taxa. His results suggest that while the relationship between relative brain size and flexion exists, there does not seem to be a causal relationship between increased brain size and increased flexion. Strait suggests that the relationship between cranial base angulation and basicranial length is better explained by changes in the non-cortical elements of the brain, rather than the relative brain size. Strait's later work (2001) examined different primate taxa for evidence of integration of basicranial structural and functional characters at the inter-specific level. In every factor analysis, three variables were found to be important. These were: the inclination and position of the foramen magnum; external flexion of the cranial base, measured as the angle between basion-hormion and the orbital plane; and the inclination of the nuchal plane. These characters were correlated with brain size in hominoids and neck posture in cercopithecoids. Strait also found only moderate functional correlations between basicranial variables, at a level considerably less than expected, and comments that findings such as this should alert people to the possibility that other studies might overestimate the significance of functional correlations (Strait, 2001).

It is evident that head posture is difficult to assess accurately because of limitations with data collection, such as the possibility of unnatural head posture of individuals when data are collected. An inherent problem is that most of the pre-existing samples of lateral cephalometric radiographs consist of individuals with their heads in artificial positions, such as having Frankfurt Horizontal parallel to the floor. It is generally accepted that Frankfurt Horizontal measures habitual head posture in modern humans; however, it is also accepted that variation exists between people, where Frankfurt Horizontal does not represent their individual natural head posture. This was originally done to address problems of data standardisation and reduce error, but has resulted in a large number of samples where natural head posture cannot be accurately assessed. A notable exception is the work conducted by Solow and Tallgren on the relationship between head posture and craniofacial morphology (Solow, 1966; Solow et al., 1982; Solow and Siersbaek-Nielsen, 1992; Solow and Tallgren, 1976). In a sample of 120 Danish males aged between 22 and 30 years lateral cephalometric radiographs were taken of individuals standing with their preferred natural head posture, and also as the individuals were looking at themselves in a mirror. They found that measurements were similar for both types of head position (Solow and Tallgren, 1976). In the same study, they found that flexion of the head on the neck was associated with a small cranial base angle and a backward downward orientation of the foramen magnum relative to the cranial base. In contrast, extension of the head on the neck was associated with a large cranial base angle and a backward upward orientation of the foramen magnum relative to the cranial base (Solow and Tallgren, 1976). In a study investigating the reliability of head posture, Peng (1999) found that natural head posture has long-term clinical reproducibility over a 15-year period (Peng and Cooke, 1999). Another study investigated the biomechanical influences of head posture on occlusion, and found that changes in occlusion may affect head posture, whereas changes in head posture do not directly affect occlusion (Motoyoshi et al., 2002). Other studies have been conducted where body posture was artificially altered in non-human samples, and corresponding changes in craniofacial morphology were observed (Moss, 1961; Riesenfeld, 1967; Riesenfeld, 1969). In his 1955 study, Björk found a relationship between head posture and craniofacial morphology, so it follows that the head posture would alter with an increase in cranial base flexion. However, in cases of pathological cranial growth any conclusions based on findings of normal growth must always be interpreted with the recognition that changes may be influenced by abnormal growth.

This review of the literature on the development of basicranial flexion in modern humans reveals a number of hypotheses that are not necessarily mutually exclusive. The increase in relative brain size and the development of bipedal posture both seem to be influential in the increased flexion of the cranial base in humans compared to other primates (Strait, 2001; Strait and Ross, 1999). The spatial packing hypothesis suggested by Gould (1977) and corroborated by Ross and Ravosa (1993) and Ross and Henneberg (1995) proposes an interaction between increases in relative brain size, leading to flexion, and other constraints, such as the size of the pharynx. This would also coincide with features of the linguistic hypothesis favoured by Laitman, Lieberman (Snr) and colleagues (Laitman, 1985; Laitman and Heimbuch, 1982; Laitman et al., 1978; Lieberman and Crelin, 1971; Lieberman and Crelin, 1974; Lieberman et al., 1972), due to the relationship between the pharynx, upper respiratory tract and speech/vocalisation.

Inter-population variation in the cranial base of modern humans

A number of studies have investigated population differences in cranial base morphology. In most cases, differences between populations have been established, and have been reported as being significant. For example, in a study comparing regional differences in the facial skeleton, Vidarsdottir and colleagues (2002) found a population-specific pattern in the craniofacial complex that was established as early as the first year in life. The variables selected for the study were external facial landmarks only. Discriminant function analysis on this sample was able to correctly classify about 70% of individuals according to their population of origin based on these variables. The samples examined in this study included people from ten geographically distinct populations (Vidarstdottir et al., 2002). They concluded that facial shape was adequate to distinguish populations, regardless of the age or sex of the individual. They also found that of the ten samples of their study, the Polynesians and Caucasoids (British/French) were the most distinct, with large numbers of significant differences between vectors in each population. The Polynesians were also recognised for having larger angles between craniofacial landmarks, representing a more distinct ontogenetic trajectory.

It is generally asserted that the average value of cranial base flexion in modern humans (when measured as the angle basion-sella-nasion) is about 130 degrees. In one of the studies reporting average cranial base flexion Dhopatkar et al. (2002) state that the average angle of cranial base flexion, measured as basion-sella-nasion, is between 130 and 135 degrees, however no data are given in support of this (Dhopatkar et al., 2002). A comparison of studies investigating the angle of cranial base flexion reveals numerous studies reporting average angles of flexion in a single sample, but only a few that compare multiple samples. Of the studies investigating cranial base flexion angles in different samples, most have found the average angle measured as basion-sella-nasion to be around 130 degrees in modern human adults (Table 1.2) (Björk, 1955; Kasai et al., 1995; Kean and Houghton, 1982; Kieser et al., 1999; Solow, 1966). Other studies examining less conventional angles of cranial base flexion have measured the angle of cranial base flexion between basion, sella and the foramen caecum (Lieberman et al., 2000b), and found average values for different populations between 131 and 136 degrees in Ashanti, Australians, Chinese, Egyptians and Italians, with a combined average of 134 degrees. Similar measurements by Lieberman and McCarthy (1999), who referred to the angle as CBA 1 in their study, found an average angle of 135 degrees in a modern human sample (white Americans) (Lieberman and McCarthy, 1999).

The studies listed in Table 1.2 generally report significant differences between people from geographically distinct samples. For example, Kuroe and colleagues (2004) assessed variation in the skulls of representative African, European and Asian samples. Angles and linear dimensions in the facial skeleton and cranial base were measured. The reference lines selected were the PM plane and FH. The cranial base angle was defined as the posterior maxillary plane sella-nasion to sella-basion, which is assumed to mean the sella-nasion-basion angle. The results showed that the orientation of the cranial base and the length of the clivus were sufficient to discriminate between the three samples. They found a significant difference in cranial base flexion between European and Asian samples, with a smaller angle observed in the European sample. There were no significant differences seen between European and African samples and between Asian and African samples. With regard to the length of the clivus, the

European sample had a significantly smaller dimension compared to the Africans and Asians. The African sample had a significantly smaller clivus compared to the Asian sample (Kuroe et al., 2004).

Table 1.2: Examples of studies from the literature including the angle basion-sella-nasion (limited to modern human adults).

Sample	Sample composition	Basion-sella-nasion (degrees) Mean	St.dev.	Study
Scandinavia	102 males	129.6	5.2	(Solow, 1966)
Scandinavia	243 males	131.6	4.5	(Björk, 1955)
African Ibo	26 males/ 22 females	135.5	3.8	(Kuroe et al., 2004)
Japanese Ainu	16 males/ 8 females	138.1	4.4	(Kuroe et al., 2004)
English caucasoids	36 males/ 36 females	135.2	5.1	(Kuroe et al., 2004)
Moriori (historic Maori, New Zealand)	20*	143.6	4.8	(Kieser et al., 1999)
South Island Maori (New Zealand)	21*	138.4	6.3	(Kieser et al., 1999)
North Island Maori (New Zealand)	19*	138.8	3.7	(Kieser et al., 1999)
Modern Indians (location unknown)	26*	132.2	6.1	(Kieser et al., 1999)
New Zealand Polynesians	60 male	140.3	5.6	(Kean and Houghton, 1982)
Archaic Indians (Fiji)	8*	129.9	6.2	(Kieser et al., 1999)
New Zealand caucasoids	21 males	127.8	5.5	(Kieser et al., 1999)
New Zealand caucasoids	23 females	130.9	5.3	(Kieser et al., 1999)
Southern Chinese (in Australia)	23 females	132.0	3.7	(Wei, 1968a)
Southern Chinese (in Australia)	84 males	129.6	5.0	(Wei, 1968a)
Japanese (modern)	46 males	134.0	5.3	(Kasai et al., 1995)
American caucasoids	16 males	125.4	5.7	(Ursi et al., 1993)
American caucasoids	16 females	125.8	4.3	(Ursi et al., 1993)
American blacks	42 males	131.6	5.8	(D'Aloisio and Pangrazio-Kulbersh, 1992)
American blacks	58 females	132.5	6.3	(D'Aloisio and Pangrazio-Kulbersh, 1992)

* No sample numbers of males and females included in the paper

Hanihara has conducted numerous studies on craniofacial variation among human populations (Hanihara, 1992a; Hanihara, 1992b; Hanihara, 1993; Hanihara, 1996; Hanihara, 1997). While he did not include cranial base flexion among the variables of the studies, some general conclusions relating to the facial skeleton are of relevance to the present study, such as the finding of a clinal distribution of cranial features in the Afro-European and Australasian/East Asian regions. It was also found that no consistent relationship exists between craniofacial variation of a geographical population and their geographical distribution, for example, the finding that the Australian samples were more similar to African samples than to Melanesian samples (Hanihara, 1996).

Aims of the present study

Despite the large amount published research described above, it appears that a comprehensive analysis of the range of variation present in the human cranial base and related structures has not yet been attempted. Studies have focused on documenting average values of cranial base development and shape of specific populations, species, ages, sexes and syndromes. The present study investigates comprehensively the range of variation present in the cranial base in the modern human species. This has been considered in three ways – variation in cranial base flexion, variation in the orientation of the facial structures to the cranial base, and variation in the size of the cranial base and facial skeleton. A number of samples representing populations around the world have been investigated, and population variation and sexual dimorphism have been considered in addition to individual variation. There are three main aims of the present study: (i) to investigate the range of variation in cranial base flexion and craniofacial morphology in a modern human sample; (ii) to investigate sample differences in cranial base flexion and craniofacial morphology with the null hypothesis that no differences exist between samples; (iii) to investigate the theory of a postural origin of cranial base flexion, based on the orientation of the foramen magnum. The rationale behind the first aim is based on a search of the literature that failed to reveal any results documenting the possible range of variation in cranial base flexion. While some studies present averages of a number of populations or samples worldwide, the variation between and within samples is not adequately addressed. This leaves the impression that samples around the world are significantly different from each other, while in fact this does not seem to have been sufficiently tested. The second aim is an attempt to interpret variation in cranial base flexion with regard to craniofacial structures. As stated previously, numerous orthodontic papers interpret variation in the craniofacial complex relative to the flexion of the cranial base. However, it is likely that without adequate investigation of the variation in cranial base flexion (Aim 1), any interpretation of craniofacial variation based on an average cranial base flexion will be suspect. The third and final aim attempts to interpret variation in cranial base flexion with regard to possible evolutionary influences on the development of flexion in modern humans. Some researchers have speculated on the flexion of the cranial base as an adaptation to bipedal posture. However, the relevance of the orientation of the foramen magnum and its relationship with cranial base flexion and other structures in the craniofacial complex has not been studied sufficiently.

Chapter 2: Materials and Methods

Samples

Thirteen samples of lateral cephalometric radiographs were accessed from a number of geographically distinct populations of modern humans. In the context of the present study, modern humans are interpreted as those existing during the Holocene era (Figure 2.1). These were selected according to the following criteria: the need for various populations to be represented, access to the collection, time available and funding constraints. The samples of the present study are summarized in Table 2.1. The samples were housed in the University of Adelaide in South Australia, the University of Otago in New Zealand, Wright State University and George Washington University in the U.S.A, and the University of the Witwatersrand in South Africa. Radiographs were already available at all locations apart from the University of the Witwatersrand. At this university, skulls were radiographed by the author. Most samples included information on age and sex of individuals, which was recorded when radiographs were examined. Some samples had limited information regarding age, and estimates or averages had to suffice. Many of the Australian aboriginal people from Yuendumu in Australia had birth dates that were unknown, and ages were subsequently estimated by the researchers who took the initial radiographs. The individual ages of the Southern Chinese radiographs from the Dental School of the University of Adelaide were not known, and in published literature their ages are classified as young adult, ranging between 18 and 29 years, with an average of 22 years (Wei, 1968a). The San skulls from the R.A. Dart collection and the Polynesian and Thai skulls had sex and age previously estimated by other researchers. Using the details provided with these samples, only radiographs labelled as adult, aged, mature or similar were used. The white American samples of the Fels and Denver Longitudinal Studies were limited to adults only (over 18 years).

No attempt was made to classify individuals according to the standard orthodontic Classes of occlusion. Such categorisation of face types was deemed to be extraneous to the current study, the purpose of which was to assess the amount of variation present in craniofacial morphology in modern humans.

Figure 2.1: Original geographic location of the seven samples of the present study.

Specific information about the samples studied and the radiographic technique used in the different collections is detailed below. The exclusion of three individuals for "abnormal" craniofacial configurations was done after histograms and descriptive statistics for each variable and for each sample were examined. Any individual with a measurement of three standard deviations above or below the sample average was excluded. The purpose of the study was to investigate variation in a sample of normal individuals, and an individual with values greater or less than three standard deviations from the average may not have a normal craniofacial configuration. Such variation, while interesting from a clinical perspective, is beyond the scope of the present study.

Table 2.1: Information on the samples studied:

Sub-sample	Sample	Source of radiograph	M	F	Total
Yuendumu, Central Australia	Australian Aboriginal	Living	34	34	68
Denver Growth Series	White American	Living	14	10	24
Fels Longitudinal Growth Study	White American	Living	20	20	40
Moriori, New Zealand	Polynesian	Skeletal	13	7	20
North Maori, New Zealand	Polynesian	Skeletal	12	6	18
South Maori, New Zealand	Polynesian	Skeletal	13	5	18
Chinese, residing in Australia	Chinese	Living	31	22	53
Thai	Thai	Skeletal	8	15	23
Khoi, Africa	African K/S (Khoi-San)	Skeletal	9	2	11
San, Africa	African K/S (Khoi-San)	Skeletal	11	8	19
Sotho, Africa	African S/X/Z (Sotho/Xhosa/Zulu)	Skeletal	20	20	40
Xhosa, Africa	African S/X/Z (Sotho/Xhosa/Zulu)	Skeletal	19	20	39
Zulu, Africa	African S/X/Z (Sotho/Xhosa/Zulu)	Skeletal	21	20	41
TOTAL			225	189	414

Australian Aboriginal (Yuendumu)

The radiographs of Australian Aboriginal people came from a study conducted by the Dental School at the University of Adelaide, South Australia. Initiated in 1951, the study was designed to provide information on growth and dental characteristics of people living in the settlement of Yuendumu in Central Australia (Barrett et al., 1963;

Brown and Barrett, 1964). While much of the data represent longitudinal measurements of children, a number of young adults were also included. The age range of these young adults was approximately 16 to 31 years, although actual birth dates of individuals were not known. The mean age for both males and females was 22 years (calculated from estimated ages of individuals). In 1961, lateral head radiographs were taken following the technique of Björk (1947), using a cephalostat for standardisation. The tube to film distance was 195 cm and the median sagittal plane to film distance was 15 cm. Linear enlargement was calculated to be 8.3% (Barrett et al., 1963; Brown and Barrett, 1964). Of the sample described above, only individuals over 18 years were selected for inclusion in the present study. One male individual (male 543) was excluded from the sample due to having an unusually small nose height (more than three standard deviations below the sample mean).

Southern Chinese

These individuals were selected from students at the University of Adelaide, South Australia, on the basis of Chinese ancestry, the absence of dental and craniofacial deformity, and a history of no orthodontic treatment. The majority of individuals originated from Malaysia, Singapore and Hong Kong, and had grandparents who were born in China. All individuals were young adults, ranging between 18 and 29 years of age, with a mean age of 23 years for males and 21.5 years for females. During the taking of lateral head radiographs, a cephalostat was used for standardization. The tube to median sagittal plane distance was 180 cm and the mean sagittal plane to film distance was 13 cm. Linear enlargement was calculated to be 7.2 % (Wei, 1968a).

Fels Longitudinal Growth Series

This is a well-known, longitudinal growth study based on a white community in South-west Ohio, U.S.A. Subjects are reported to be of middle socio-economic background and normal in physical health. For most cases, annual radiographs were taken between the 1930s and the late 1970s, so that most individuals have serial data extending into adulthood (Lewis and Roche, 1972). The Fels data are not well standardized. This is mostly due to issues of alignment, as a cephalostat or similar equipment was not used until the 1970s. Before this time, each subject was aligned using the observer's hand on his or her head. It is also not clear how they were oriented to the film, such as Frankfurt Horizontal, natural head position, or some other plane. Forty adult individuals (20 males and 20 females) were selected by the curators from the Fels database for the present study. The only selection criterion in this instance was the completeness of the longitudinal series for each individual (infancy to adulthood), rather than specific biological criteria such as occlusal pattern or face type. The latest (oldest) radiograph of the series of each individual was selected for measurement, resulting in a range of 17 to 44 years and an average of 26 years. Linear enlargement was calculated using the results of Israel (Israel, 1973) who published the enlargement factors specific to the year that radiographs were taken. In the present study, the dates of the radiographs ranged from 1948 to 1978. While the mid-sagittal plane-to-film distance remained constant, different tube-film distances were used at different times during the longitudinal study. For the radiographs taken between 1948 and 1962 the tube-film distance was 60 inches (150 cm), giving a radiographic enlargement of 10%. For the radiographs taken between 1963 and 1978 the tube-film distance was 72 inches (180 cm), resulting in an enlargement of 9% (after Israel, 1973). Dimension measurements were subsequently corrected for the appropriate enlargement.

Maori and Moriori (Polynesian)

The skulls of this collection were excavated in New Zealand and the Chatham Islands, and are believed to belong to the period between about 1500 and 1700 A.D (Huggare and Houghton, 1996; Kieser et al., 1999). It is generally thought that the early Polynesians settled on the islands of New Zealand around the eighth century AD (Houghton, 1978b). The Polynesian skulls in the study sample, while presumptively classified as South Island, North Island and Moriori, can be considered essentially homogeneous, as they all came from a limited eastern Polynesian gene pool (Buranarugsa and Houghton, 1981). Previous researchers had designated each skeleton as originating from the North or South Island of New Zealand, or as being Moriori, a group of Polynesians from the Chatham Islands (Kieser et al., 1999). It is believed that all the individuals in the sample were born before European contact was made, and were native to the region. The radiographs were taken at the University of Otago Dental School. Ball-bearings were placed at craniometric landmarks on the skull prior to radiography. The age and sex of individuals had previously been determined by other researchers (Huggare and Houghton, 1996), using established dental, cranial and pelvic criteria (Krogman, 1962), and only those individuals classified as adult or mature were included in the present study. Radiographic enlargement was 9.09%, calculated from a scale recorded on the radiographs (enlargement = 1- (true size/film size) x 100). This equation was applied to measurements since the actual tube-film distance was not known.

Thai

These skulls were excavated from Khok Phanom Di, which is located in the Chonburi Province, Central Thailand. The site, a temple surrounded by a cemetery, was occupied between 2000 and 1500 B.C. One hundred and fifty four skeletons were excavated from the site, of which 23 adults were available for use in the present study. Sex and age were determined by previous researchers (Tayles, 1999) using standard morphologic analysis and only those individuals classified as adult or mature were included in the present study. The skulls were radiographed at the University of Otago Dental School, under similar conditions to those of the Moriori and Maori samples. Radiographic enlargement was therefore the same for this sample at 9.09%.

Denver Growth Series

The Denver Growth Series is a longitudinal growth study of 15 males and 13 females, conducted by the Child Research Council, University of Colorado School of Medicine. The study was conducted between 1931 and 1966, and involved white American children being radiographed at the ages of one month, three months, six months and nine months, and subsequently every 12 months until they reached adulthood. The radiographic distance was 7.5 feet (2.25m), and both lateral and frontal cephalometric radiographs were taken. A cephalostat was used for subjects aged one year nine months and older, prior to this children were hand-held (Lieberman et al., 2001a). In the current study, 14 males and 10 females were included. One male and two female subjects were excluded for not being 18 years of age when the oldest cranial radiograph was recorded; another female (subject ID 119) was excluded due to an unusual relationship between the relative angles of the palate and the anterior cranial base (more than three standard deviations from the sample mean). In published studies using data from the Denver Growth Study, researchers stated that the long distance (7.5 feet/2.25m) between the x-ray tube and the subject meant that radiographic enlargement was minimal (0.4 mm for every 10 mm) (Lieberman and McCarthy, 1999; Nanda, 1955) citing (Merow and Broadbent, 1990), consequently, dimension measurements were not initially corrected for this sample. However, as described below in the section regarding grouping of samples, significant differences between Fels and Denver samples were seen for the dimension differences, suggesting that radiographic enlargement was present. As a result, the dimensions of the Denver sample were corrected for an enlargement of 4.0%, which led to there being no significant differences in dimensions between the Denver and Fels samples. For more details about the Denver sample, refer to the work of McCammon (McCammon, 1970).

Africans – Khoi, San, Sotho, Xhosa and Zulu skulls.

In 1923 Raymond A. Dart began collecting skeletons of African origin, and curating them in the University of the Witwatersrand anatomy museum. Most of the skeletons were prepared as anatomical specimens, but others were excavated from archaeological sites. Today, the Raymond A. Dart collection comprises individuals of known sex, race and tribe, as well as either known or estimated age, from all over the African continent (De Villiers, 1968). Traditionally, the people of South Africa have been classified by various means, the most common groups being based on physical characteristics, geographical dispersion and/or linguistic divisions (Nurse et al., 1985). According to Nurse and colleagues, the conventional distinction of the people of Southern Africa as being either Caucasoid, Negroid or of Khoi-san origin is not unjustified, providing the diversity of these groups is taken into consideration in addition to their unifying features. This is because the main composition of these groups has largely remained homogeneous over time; however, miscegenation and the formation of multiple other groups also occurred (Nurse et al., 1985). For this study, samples of Khoi and San individuals were included, as well as three representative groups of South African Negroid morphology. The three groups consisted of males and females from Sotho, Xhosa and Zulu tribes, according to their classification in the Raymond A. Dart Collection (Sotho = Sotho speaking, Xhosa = Xhosa speaking, Zulu = Zulu speaking). For each of the Sotho, Xhosa and Zulu (African S/X/Z) samples, 40 adult skulls with minimal damage were selected for radiography. The smaller sample sizes of the Khoi and San groups (African K/S) meant that all available individuals were included, regardless of the condition of the skull. As most of the skulls from the R.A. Dart collection had been prepared for anatomical specimens, the cranial vault was often separated from the rest of the skull by a transverse saw cut. These were prepared for radiography by fastening the cranial vault to the skull with masking tape. If mandibles were present, and if occlusion was satisfactory (some were edentulous or had damaged mandibular condyles), these were also fixed onto the skull using tape. The skull was orientated in a lateral position, and supported on the radiography table with foam pads, and an identification number was placed near the skull. A feature of the radiograph equipment allowed a preview of the skull to obtain the best orientation of bilateral structures and reduce parallax. A bag containing saline fluid was fixed on the x-ray tube to compensate for the absence of soft tissues on the skull, and produce a better density radiograph. Exposure was 90Kv/16Mas, with a tube to film distance of 115 cm. Radiographic enlargement was calculated from a scale placed on one of the radiographs, and was 3.7%. All radiographs were taken by the author under the supervision of a trained radiographer. One Xhosa individual (400 male) was found to be an outlier with an unusual relationship between the angles clivus-sella-nasion and basion-SE-nasion, and was excluded from the sample (more than three standard deviations from the sample average).

Methods

With all radiographs, the same tracing procedures were followed. All tracings were done by the author in darkened conditions. Radiographs were aligned in Frankfurt Horizontal orientation and fixed to a light-box. A sheet of 3M Unitek™ Cephalometric Tracing Film acetate was fixed over the radiograph. A mechanical pencil with a lead diameter of 0.5 mm was used to trace the image. Cephalometric landmarks were located and marked on the acetate at this time. Next, electronic images were created of the tracings to allow controlled duplication of images for measurement. Tracings were scanned using a Hewlett Packard scanner (Scanjet 6100c), and printed on a Hewlett Packard laser printer. Following this, the printed tracings were duplicated using a Docutech copying machine (University of Adelaide Image and Copy Centre). This process was directed by a need for multiple copies of the tracings, with no detriment to the original tracing. The possibility of distortion of original traced images caused by the duplication process was determined by photocopying a page of graph paper (marked in a grid of intersecting lines) onto a transparent page. The transparency was laid over the original grid pattern and checked for any distortion of the lines. For the copying machine used, a slight distortion (less than 1 mm) of the most outside edges was noted. When this was checked using an original tracing of a cephalometric radiograph with the transparency overlaid on a photocopy of the original, the centre of the page where the cranial base and face were placed had no distortion. Since this was the area of interest for the present study, it was concluded that a slight distortion at the outer edges of the page would not influence measurements taken using the photocopied image. Two data sets were produced for the present study. On the first one, cranial base and craniofacial angles were drawn and measured. The second data set was used to measure cranial and facial dimensions. The two data sets were separated for two reasons – to reduce the number of lines drawn at each landmark and thus improve the accuracy of the measurements, and for increased independence of the landmarks to reduce the effect of spurious correlations between the values due to use of the same data points (refer to Solow, 1966).

Structures traced

On each radiograph, the following structures were traced: the cranial vault outline, lateral and inferior orbital margins, external auditory meatus, ear rod shadow (where present) sphenoid and frontal sinuses, cranial base, greater wings of the sphenoid, cribriform plate, hard palate, nasal bone, piriform aperture, glenoid fossa, pterygomaxillary fissure and occipital condyle. For radiographs of living people, the soft tissue profile, C1 and C2 vertebrae and mandible were also traced. Bilateral structures were traced in the case of the greater wings of the sphenoid and the mandible. The outlines of molar teeth, orbital margins and occipital condyles were averaged according to standard radiographic techniques (Merow and Broadbent, 1990). Table 2.2 shows the landmarks identified in the tracings, and the common abbreviation for each point. Some traditional landmarks used in orthodontic or craniometric analyses were excluded from the study due to a paucity in the number of subjects with intact or visible structures. For example, the landmark prosthion was not included in the study due to a large number of skulls exhibiting damage to this area. No measurements on the mandible were taken, as mandibles were only present in the living subjects, or, on dry skulls where mandibles were present, there was often some uncertainty as to the alignment of mandibles in the glenoid fossa. Measurements on the teeth were not undertaken due to the large number of missing teeth in all samples (both living subjects and dry skulls). The landmark foramen caecum, which has been used by a number of researchers as the point defining the most anterior projection of the cranial base (Cramer, 1977; Lieberman et al., 2000; Lieberman et al., 2001b; Lieberman and McCarthy, 1999; Lieberman et al., 2000b; McCarthy, 2001; Scott, 1958; Spoor, 1997), was found to be difficult to locate on radiographs and was not used in the study. Also, the conventional craniometric landmarks of the hard palate, staphylion and naso-spinale (as defined by Martin, 1957), were rejected in favour of the hard tissue landmarks Anterior Nasal Spine (ANS) and Posterior Nasal Spine (PNS), due to their clear visualization in the mid-sagittal plane on radiographs.

Measurements were made by using a ruler to create a line between two or more landmarks, and then either measuring the angle between them using a protractor or the distance between them using a ruler. These measurements were then entered into a computer spreadsheet (Microsoft Excel). Linear measurements were measured to the nearest 0.5 mm. Angles were measured to the nearest 0.5°. For a summary of the variables and their abbreviations, refer to the Appendix.

Table 2.2 – Landmarks on the radiographs

Landmark	Abbreviation	Definition
Anterior nasal spine	ANS	the most anterior point on the maxillary body at the level of the nasal floor
A-point	A	the deepest point on the curvature of the alveolar surface of the maxilla in the midline
Basion	ba	the most postero-inferior point on the clivus
Endocranial Clival Plane	ECP	the line representing the main orientation of the endocranial surface of the clivus on visual inspection (George, 1978; Moss, 1958)
Nasion	na	the anterior end of the frontonasal suture, in the median sagittal plane
Opisthion	op	the point at which the external and internal surfaces of the occipital bone meet on the posterior margin of the foramen magnum in its median plane (Buranarugsa and Houghton, 1981)
Orbitale	or	on the orbital rim at the most inferior point of curvature
Pituitary point	pp	"the anterior edge of the groove for the optic chiasma, just in front of the pituitary fossa" (Zuckerman, 1955) – but defined in (McCarthy, 2001) as "the projection onto the MSP of the bulging convexity that forms the inferior border of the optic canal" (this is inside the pituitary fossa). Also defined by Björk as the point "sphenoidale", being the most superior, midline point on the tuberculum sellae (Björk, 1955)
Planum sphenoideum point		superior-most point on the sloping surface of the pit in which the cribriform plate is set (Ross and Ravosa, 1993)
Porion	po	the superior point of the external auditory meatus
Posterior nasal spine	PNS	the most posterior point of the maxillary body at the level of the nasal floor at the articulation of the hard and soft palates
Sella	s	centre of the sella turcica (hypophyseal fossa), independent of the clinoid processes
Spheno-ethmoid	SE	the point where the margin of the greater wing of the sphenoid bone intersects with the planum sphenoidale or cribriform plate (overlying the spheno-ethmoid synchondrosis in the midline). Also referred to as prosphenion or wing point
Spheno-occipital synchondrosis	SOS	located on the endocranial border of the spheno-occipital synchondrosis, defined as the area on the clivus before the dorsum sellae curves posteriorly. It was first defined by Cartmill (1970, unpublished Ph.D. thesis) and introduced into the published literature by Ross and Ravosa (1993), making it possible to locate in individuals who have undergone ossification at the synchondrosis

A total of seven angles of cranial base flexion were measured using the landmarks described above. The lines used to define these angles are shown in Figure 2.2.

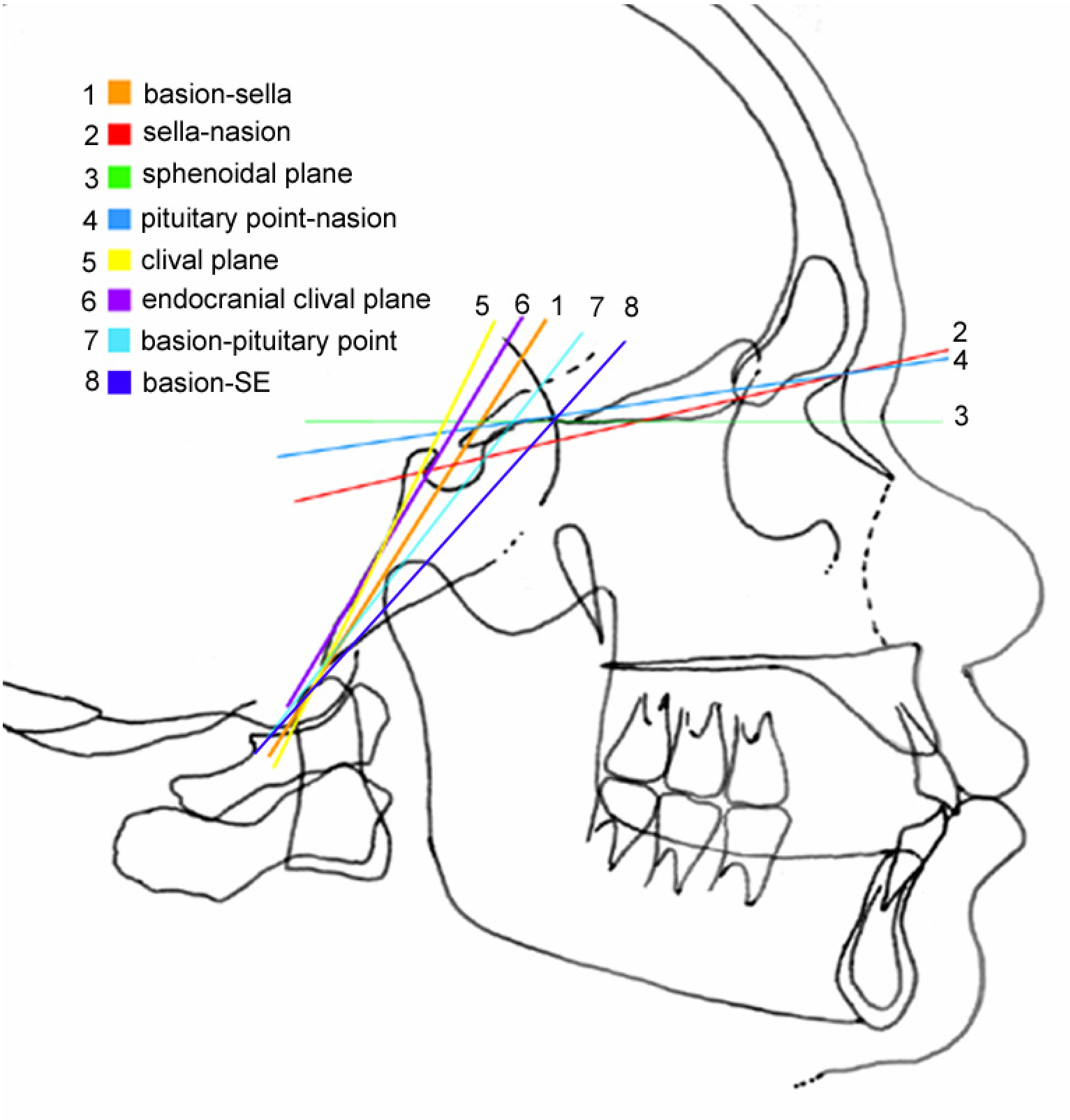

Figure 2.2: Lines used to create the seven angles of cranial base flexion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations

These angles were selected for numerous reasons. Some were selected for their common use in the literature, for example basion-sella-nasion and clival plane-sphenoidal plane. Others were selected for their proposed usefulness in effectively describing cranial base flexion for example basion-pituitary point-nasion, basion-pituitary point-sphenoidal plane, or for historical reasons, such as the angle basion-SE-nasion.

1. Basion-sella-nasion: The angle basion-sella-nasion was included since it is the most commonly used angle of cranial base flexion. Early researchers on cranial base flexion considered the pituitary fossa region to be the site where flexion occurs (Cameron, 1924).

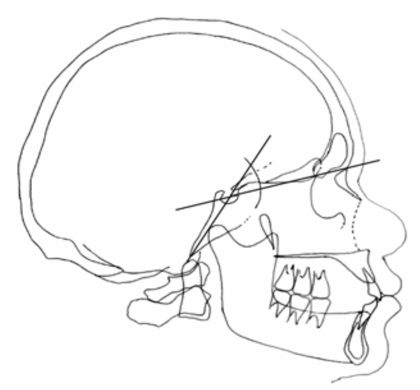

Figure 2.3: Cranial base angle basion-sella-nasion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

2. Clival plane-sphenoidal plane: The clival plane connects basion and the spheno-occipital synchondrosis, while the sphenoidal plane is the line between the pituitary point and the planum sphenoideum point. The angle is measured at the intersection of these two lines, and measures cranial base flexion along the median sphenoidal plane of orientation rather than along the sella-nasion plane. This angle was selected as it was deemed to be an angle that came close to describing the actual bony outline of the cranial

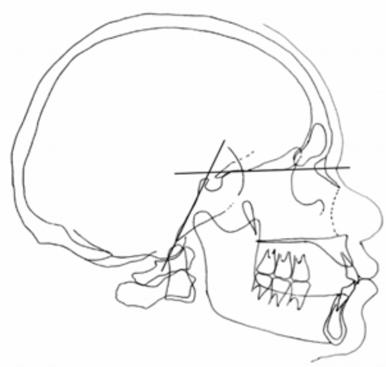

Figure 2.4: The cranial base angle clival plane-sphenoidal plane. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

base, to the anterior point on the cribriform plate on the ethmoid bone. This angle was first defined by Cartmill in an unpublished Ph.D. thesis in 1970, and was introduced into the literature by Ross and Ravosa (1993). Ross and Ravosa used this angle to study the relationship between the cranial base, relative brain size and facial kyphosis in numerous primate species, and it has been subsequently used by other researchers as a measurement of cranial base flexion (see for example (Lieberman et al., 2000b; McCarthy, 2001; McCarthy and Lieberman, 2001; Ross and Henneberg, 1995).

3. Basion-pituitary point-sphenoidal plane: this angle is similar to the previous angle of clival plane-sphenoidal plane, but uses a clival plane which passes through the visual centre of the clivus for its posterior chord, rather than between basion and the spheno-occipital synchondrosis.
endocranial surface of the clivus. The anterior parts of the two angles use the same landmarks (pituitary point to planum sphenoideum point), so the differences between these two angles can be interpreted by the differences in their posterior extensions.

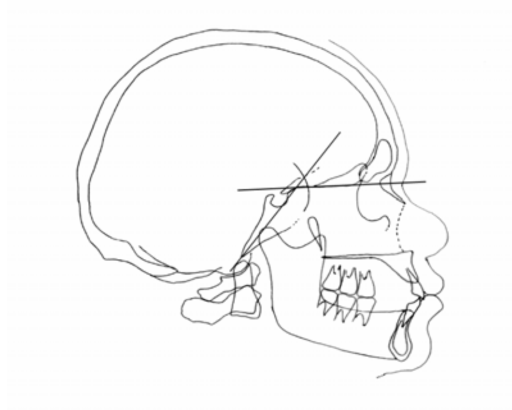

Figure 2.5: The cranial base angle basion-pituitary point-sphenoidal plane. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

4. Basion-pituitary point-nasion: this angle is similar to the basion-sella-nasion angle but the point of flexion is located on the pituitary point landmark rather than sella. Differences in the angles therefore reflect differences in the location of the point of flexion (sella in the first case, pituitary point in the latter).

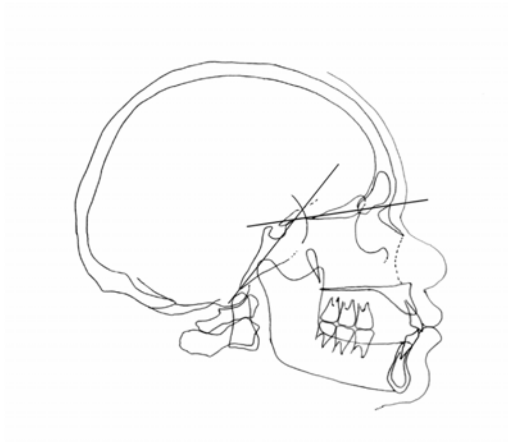

Figure 2.6: The cranial base angle basion-pituitary point-nasion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

5. Basion-SE-nasion: this is an angle incorporating flexion at the spheno-ethmoidal junction rather than within the middle of the sphenoid bone (also referred to as prosphenion). This angle was chosen as it was found on visual inspection that the line between basion and SE more often than not passed through the main axis of the basi-sphenoid bone, and that interpretation of this might be a more realistic measure of true basicranial flexion. It was also believed to be the site of flexion by earlier researchers (Scott, 1958).

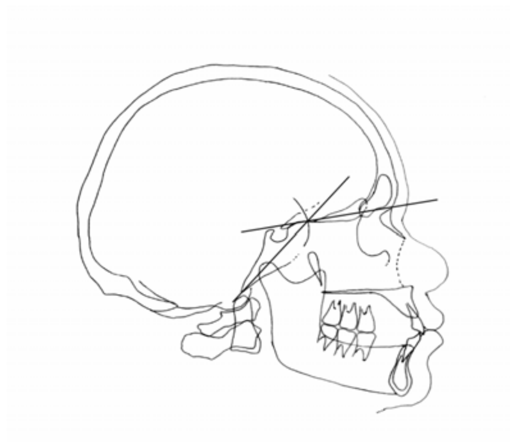

Figure 2.7: The cranial base angle basion-SE-nasion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

6. Clival plane-sella-nasion: this angle is similar to the clival-plane-sphenoidal plane angle; however it uses the sella-nasion plane as its anterior extension. The clival plane connects the landmarks basion and the spheno-occipital synchondrosis. Other researchers referred to the clival plane as the clival tangent line (Huggare and Houghton, 1996; Lieberman and McCarthy, 1999; Ross and Ravosa, 1993).

Figure 2.8: The cranial base angle clival plane-sella-nasion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

7. Endocranial clival plane-sella-nasion: this angle is similar to the previous one; however, the posterior chord passes along the endocranial margin of the occipital clivus rather than between basion and the spheno-occipital synchondrosis used in the previous angle. The ECP has been referred to in other studies as the endocranial plane of the clivus (Moss, 1958) and the clival plane (George, 1978). In the present study, this posterior chord is referred to as the ECP, to avoid confusion with the clival plane (Angle 6 above, Figure 2.8). The endocranial clival plane is abbreviated to ECP in the text and diagrams.

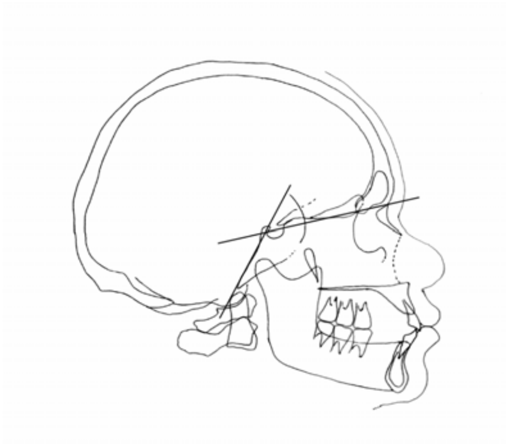

Figure 2.9: The cranial base angle endocranial clival plane-sella-nasion. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

Five craniofacial angles were used in this study (Figure 2.10). These angles represent craniofacial structures, or planes, that have been found to vary according to different face types. In order to compare the planes to each other, they were measured relative to a reference plane, in this case, the basion-pituitary point plane of the clivus. Therefore, the actual value of the plane measured relative to the clivus, is presented as an angle. In this study, the term craniofacial "plane" is used to describe the variables listed below, even though they have been measured on two-dimensional images and are actually lines, rather than planes. However, in orthodontic literature, these variables are commonly referred to as planes, after the three-dimensional structures they describe, and this practice has been duplicated here. Selection of the basion-pituitary point plane as a reference was chosen in preference to the other basi-sphenoid lines for its reliance on fixed cranial base landmarks (as opposed to the "floating" landmarks of sella and SE) and the fact that on visual inspection it usually lies approximately mid-way between the internal and external borders of the posterior cranial base (the main axis), describing the orientation of the entire clivus rather than one of its borders. It was also found to have highly significant correlations with the other cranial base angles. The five craniofacial angles are described and illustrated below.

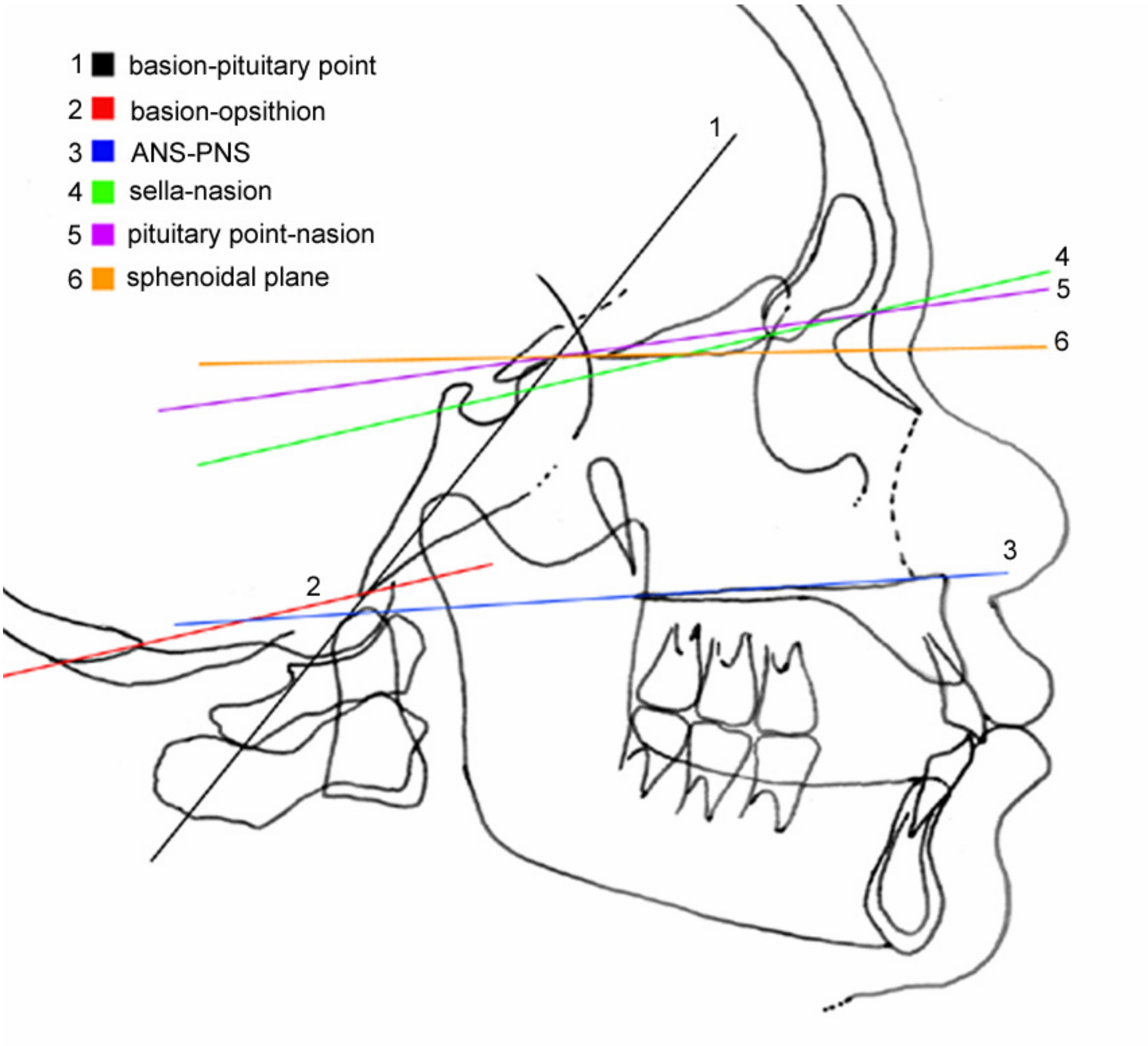

Figure 2.10: Lines used to create the five craniofacial angles (all measured relative to the basion-pituitary point plane). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations. The orientation of all craniofacial angles was that which resulted in a value that was less than 180 degrees.

1. Basion-opisthion: the angle of intersection between the foramen magnum plane (basion-opisthion) and basion-pituitary point plane. Basion is the apex of the angle which is shown as the superior angle between opisthion, basion and the pituitary point. The basion-pituitary point plane has also been referred to as the foraminal plane (Huggare and Houghton, 1996), while Strait (2001) measured the orientation of the basion-opisthion line relative to the orbital axis, and referred to it as the foramino-basal line.
2. ANS-PNS: the angle of intersection between the hard palate (measured from the anterior nasal spine (ANS) to the posterior nasal spine (PNS) and the basion-pituitary point plane, with basion as the apex of the angle. The angle was initially measured endocranially as the posteriorly oriented angle between the palatal plane and the

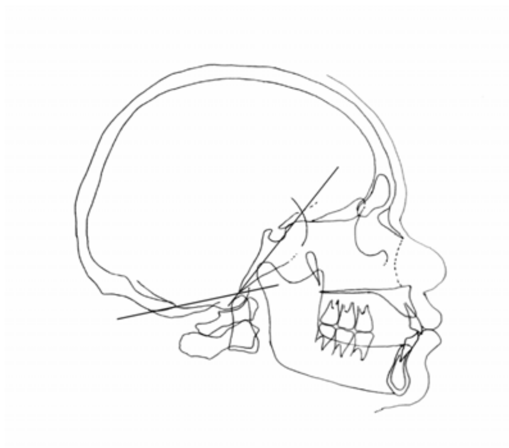

Figure 2.11: Orientation of the basion-opisthion plane relative to the clivus (basion-pituitary point). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

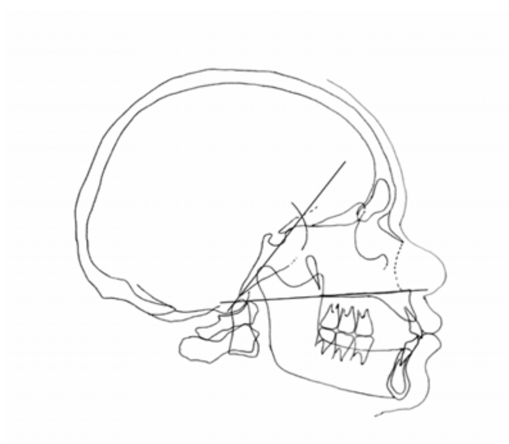

Figure 2.12: Orientation of the hard palate (ANS-PNS) relative to the clivus (basion-pituitary point). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

clivus. These measurements were later transformed to the subtended angle by subtracting the measurement from 180°, for the purpose of interpretation of the relationships between the planes. The ANS-PNS to clivus angle is also referred in the text as the “palate” angle.

3. Pituitary point-nasion: the angle of intersection between the anterior cranial base (measured from the pituitary point to nasion) and the basion-pituitary point plane. The pituitary point forms the apex of the angle and it is measured as the inferior angle between basion, pituitary point and nasion. This angle is the same as basion-pituitary point-nasion measured as an angle of cranial base flexion, but is included here to enable comparisons with the other craniofacial angles..

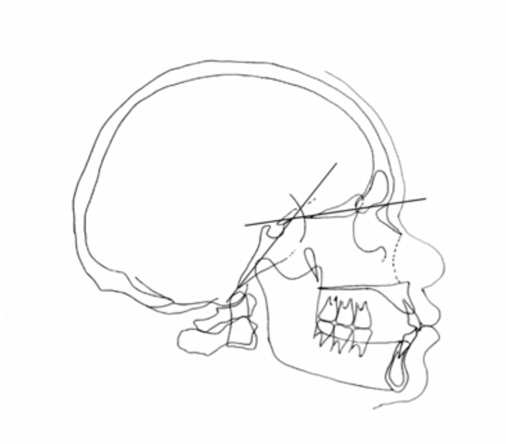

Figure 2.13: Orientation of the pituitary point-nasion plane relative to the clivus (basion-pituitary point). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

4. Sella-nasion: the angle between the traditional anterior cranial base plane (measured from sella to nasion) and the basion-pituitary point plane. This angle was used to compare the differences in orientation between the sella-nasion and pituitary point-nasion planes. The apex is formed by the intersection of the sella-nasion plane with the basion-pituitary point plane, and the angle is measured inferiorly.

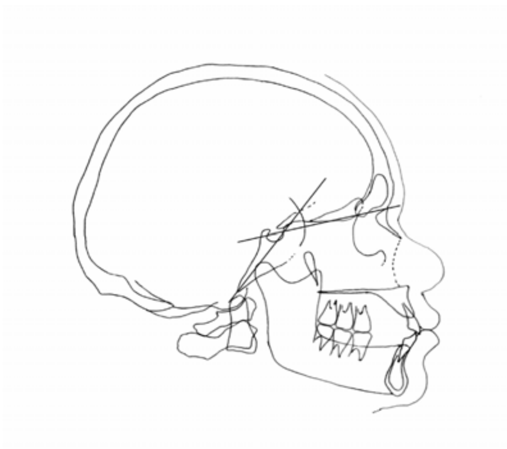

Figure 2.14: Orientation of the sella-nasion plane relative to the clivus (basion-pituitary point). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

5. Pituitary point-sphenoidal plane: the angle between the clivus (basion-pituitary point plane) and the sphenoidal plane of the anterior cranial base (pituitary point to planum sphenoideum point). The apex of the angle is located at the pituitary point. The angle is formed inferiorly by the lines between basion, pituitary point and the sphenoidal plane. This is the same basion-pituitary point-sphenoidal plane angle measured for cranial base flexion, and is included here to enable comparisons with the other craniofacial angles.

Figure 2.15: Orientation of the sphenoidal plane relative to the clivus (basion-pituitary point). Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

Craniofacial dimensions were also measured on all individuals. The dimensions selected were ones commonly used in the orthodontic and anatomical literature for measuring the size of various parts of the cranial base and skull (Figure 2.4). The dimensions measured included basion-sella, sella-nasion, basion-nasion, basion-opisthion, basion-PNS, PNS-ANS, PNS-A point, nasion-ANS and nasion-A point. Although dimensions using the planum sphenoidal point and pituitary point were considered, these landmarks, although straightforward to measure as lines, showed considerable unreliability in a pilot study. This is because these points are included in the group of "floating points", meaning that they are located on areas defined, for example, in the case of the planum sphenoideum point, as the superior-most point on the sloping surface of the pit in which the cribriform plate is set (Ross and Ravosa, 1993). Locating landmarks such as this becomes quite subjective when the exact location is needed (for measuring dimensions). However, when these landmarks are used as angular measurements they become considerably easier to locate since the ruler can be placed along the plane and the superior-most point can be located in this way. Similar problems were associated with the location of opisthion, since, while it is not a "floating" landmark, in radiographs the exact landmark can become obscured by surrounding hard tissue. However, this landmark was included since one of the aims of the present work was to investigate the importance of the plane of the foramen magnum in its association with other cranial base and craniofacial variables.

There were a number of limitations to the sample that made the use of some variables commonly used in craniofacial studies not possible. Mandibles were often missing, since a large number of individuals were from skeletal samples (for example the Thai and Polynesian skulls from the University of Otago, and the African skulls from the R.A. Dart Collection). Many individuals also had post-mortem tooth loss, or were edentulous. A number of individuals from the Aboriginal Australian sample had missing upper central incisors, believed to be a result of ceremonial tooth avulsion. The result of this was that the alveolar anatomy in these individuals was affected by re-modelling changes, and commonly used landmarks such as prosthion could not be identified in a number of individuals. In other cases, the anterior nasal spine was damaged, and to compensate for this, the orthodontic landmark A-point was also used. In the African samples, while it was a skeletal collection, mandibles were present in only about half of the specimens. If enough teeth were present, it was possible to temporarily fasten the mandible to the maxilla for the purpose of taking the radiograph (refer to the previous description of the African samples). However, it is possible that in so doing, the occlusion observed was not that actually occurring in those individuals during life. In addition, most of the Thai, Polynesian and African San individuals had no mandible present. As mandibles were either not present or could not be relied upon for accuracy in a large proportion of the sample, no mandibular measurements were recorded in this study. The dimensions measured and used in the present study are described and illustrated below.

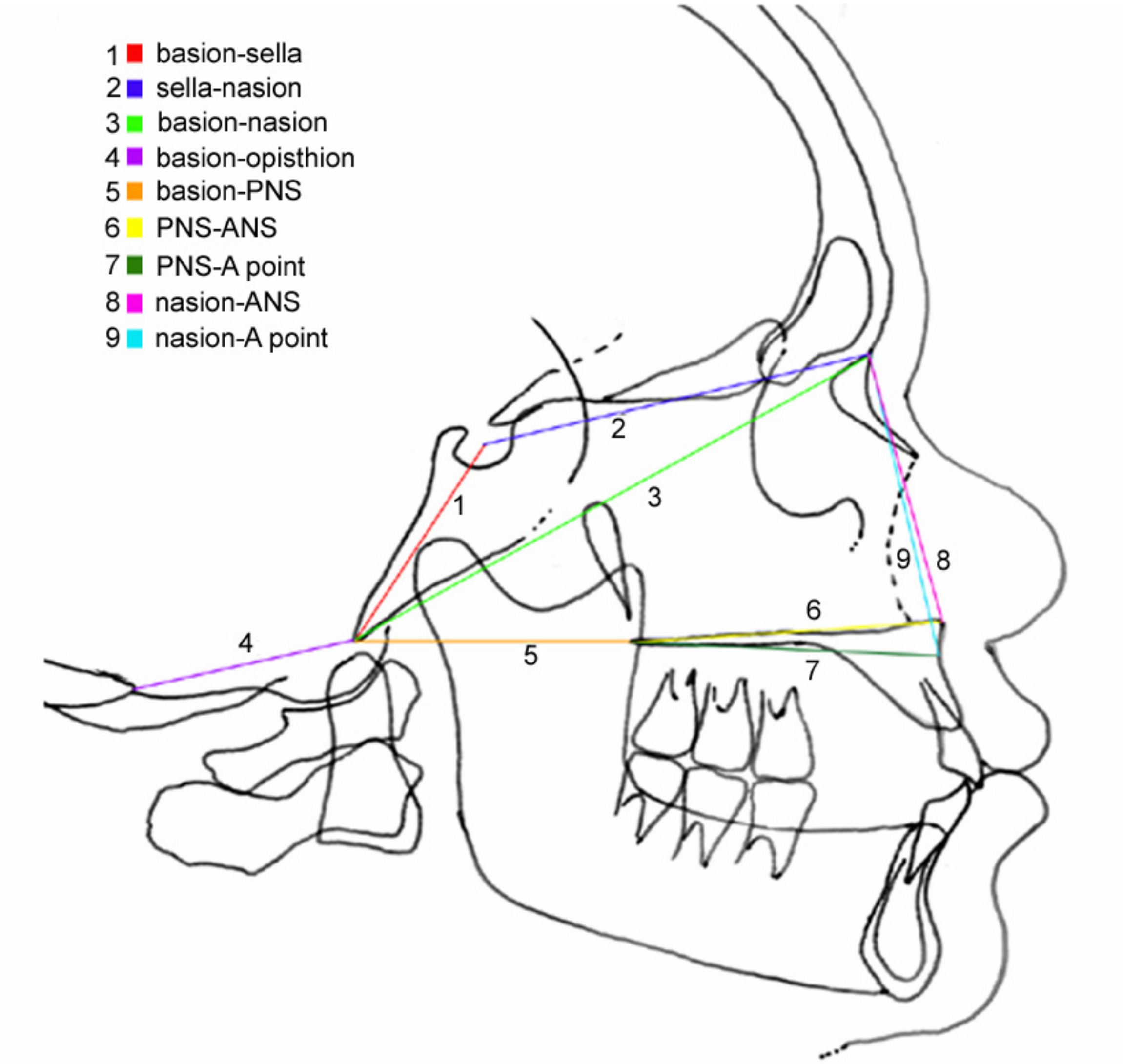

Figure 2.16: Dimensions measured in the present study. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

1. Basion-opisthion: maximum antero-posterior diameter of the foramen magnum in the mid-sagittal plane.

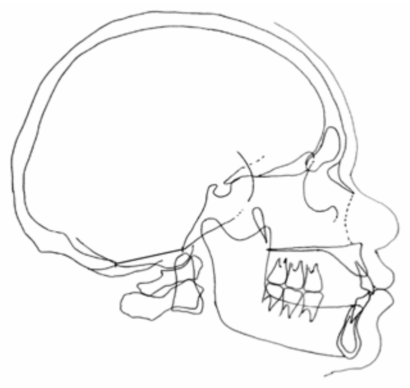

Figure 2.17: Basion-opisthion dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

2. Basion-PNS: distance between basion and the posterior nasal spine, a measurement of the horizontal depth of the superior pharynx.

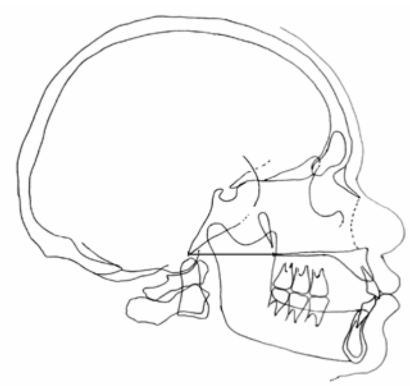

Figure 2.18: Basion-PNS dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

3. Basion-sella: distance between basion and sella, a measurement of the posterior cranial base length in the midsagittal plane. Also referred to as length of the clivus.

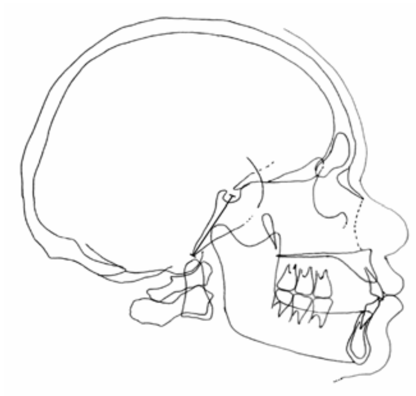

Figure 2.19: Basion-sella dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

4. Basion-nasion: distance between basion and nasion, a measurement of overall cranial base length in the midsagittal plane.

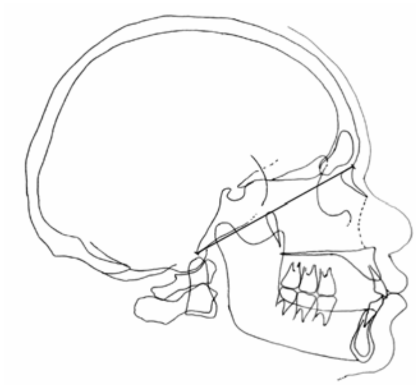

Figure 2.20: Basion-nasion dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

5. PNS-ANS: hard palate length (1). This dimension could not be measured in some samples due to damage of the ANS in some individuals. For this reason, a second measurement of hard palate length was also used (see PNS-A point)

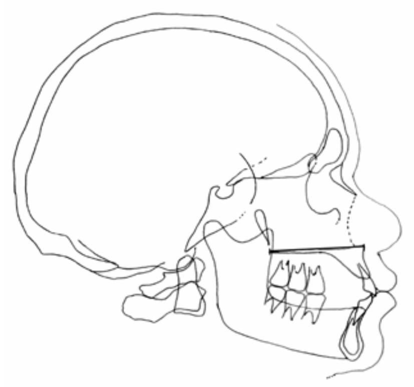

Figure 2.21: PNS-ANS dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

6. PNS-A point: hard palate length (2) (a secondary measurement due to the fact that ANS was damaged in some cases).

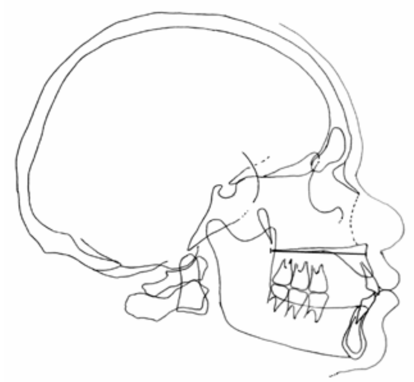

Figure 2.22: PNS-A point dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

7. Nasion-ANS: mid-face height (1), representing the height of the nasal aperture in the mid-sagittal plane.

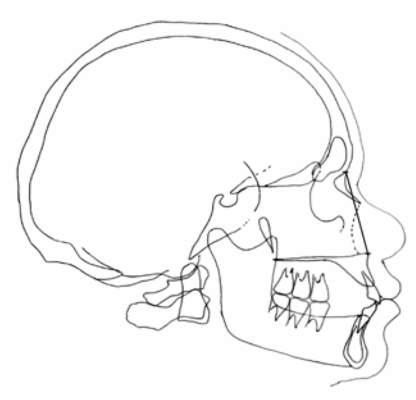

Figure 2.23: Nasion-ANS dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

8. Nasion-A point: mid-face height (2) (see descriptions of Dimensions 5 and 6 above).

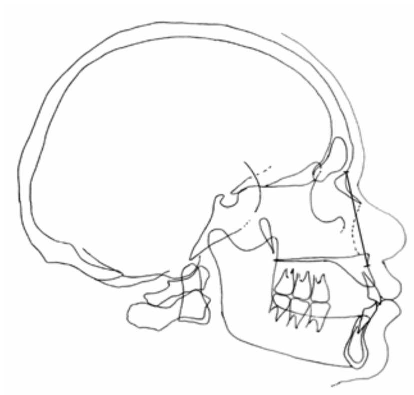

Figure 2.24: Nasion-A point dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

9. Sella-nasion: distance between sella and nasion, a measurement of the anterior cranial base length in the midsagittal plane.

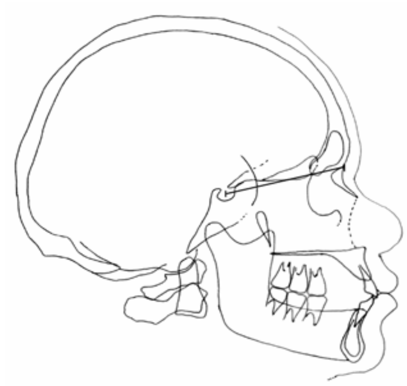

Figure 2.25: Sella-nasion dimension. Refer to Table 2.2 and the appendix for landmark definitions and abbreviations.

Analysis

Microsoft Excel and SPSS (Microsoft, Version 11.0) were the data analysis tools used. Calculations included t-tests, correlations, one- and two–way ANOVA and multivariate statistical analyses such as Principal Components Analysis and Discriminant Function Analysis. Where multiple comparisons occurred, Bonferroni's correction was applied to significance levels. This is used to calculate an appropriate cut-off level for significance testing that takes into account the fact that repeated comparisons are made. To calculate the cut-off level, the customary level of significance (for example 0.05) was divided by the number of comparisons made. Applied to the present study, any value generated from comparing the seven cranial base angles to each other is tested against the p value of 0.007, which is 0.05/7. The adjusted p critical level for the five cranial base planes is 0.01, while the adjusted level for the nine dimensions is 0.006. Any comparisons using all variables in the study had an adjusted p value set at 0.0025, which takes into account the twenty variables of the study.

Measurement error

Intra-observer measurement error, or Technical Error of Measurement (TEM) was calculated as test-re-test differences between the same individuals. Intra-observer error of measurement was the only test of measurement error performed, as the same person was responsible for all tracings, landmark location and measurements performed. Measurement error of all variables was calculated for a sub-sample of the total sample (N = 28). This sub-sample consisted of individuals who had two radiographs taken. There were no repeats available for the Chinese, Australian, Zulu, San or Denver samples. Repeats were available for one individual from the Fels sample and two individuals from the Moriori sample. The Khoi sample had repeats available for all individuals, as did most of the Thai sample. Repeat radiographs for three individuals from the Sotho sample and one from the Xhosa sample were also taken. The duplicated radiographs were traced, scanned, printed and measured using the same methods as for the original radiographs. This provided test-retest values that were then used to calculate method error using the following formula of Dahlberg (Dahlberg, 1940):

$$TEM = \sqrt{\sum diff^2 / 2N}$$

The calculation provides estimates of error that are in the same units as the original measurements. Therefore, all the measurements of planes and angles are in degrees, and all the dimension measurements are in mm.

Reliability of measurements was calculated as a fraction of true variance in the total variance. The total variance contains true variance and the variance of error. Thus, true variance can be estimated by subtracting error variance from total variance.

Grouping of samples

Some samples were compared to determine if their results could be pooled. This was done by comparing samples hypothesized to be similar based on geographical region or historical background. While the results from these comparisons have usually been used as the basis to pool samples together, it should be noted that statistical analysis carried out on small samples (less than 30 individuals in each group) have reduced robusticity. In the present study, a balance was sought between pooling results of similar samples (to increase sample sizes and enhance reliability of results) and preserving group individuality for further testing of individual differences and group relationships. For this reason, the Chinese, Thai and Australian samples were not considered for the possibility of pooling samples, while differences between the two white American samples (Fels and Denver), the five African samples (Khoi, San, Zulu, Sotho and Xhosa), and the three Polynesian (Moriori, North and South Island Maori) samples were tested. The results were tested using t-tests for independent samples and ANOVA, where appropriate.

The two white American samples of the Denver Growth Series and the Fels Longitudinal Growth Study were tested for significant differences between them for all cranial base and facial variables used in this study. While similarities between the two sub-samples were expected, based on their common origin of primarily white American/European ancestry, it was decided to test for sample differences before pooling of data. A test of similarity was undertaken based on average stature estimates for each sub-sample from the literature. Since the Denver sample lived at the relatively high altitude of 5000 feet, it was suggested that there might be some effect on the growth of these individuals compared to the Fels sample, who lived at a relatively low altitude in the farm country of Ohio. Stature estimates of the Denver sample were not readily available from the literature. However, examination of a figure in a report by Ounsted and colleagues (1986) on the Denver Growth Series allowed estimation of the stature of about 150 boys and girls at about six years and nine months of age. The figure shows that the average height for boys at this age is approximately 124 cm, while the average height for girls is approximately 122 cm (Ounsted et al., 1986). Data from the National Center of Health Statistics present percentile growth curves from about 500 children participating in the Fels Longitudinal Growth Study. The 50th percentile values of boys and girls at six and a half and seven years were examined. These show stature measurements of 118.2 and 121.3 cm for girls at six and a half and seven years respectively. Corresponding measurements for boys are 119.3 cm at six and a half years, and 122.4 cm at seven years (Statistics, 1977). Although no statistical analysis was carried out on these data, due to the paucity of information on the Denver sample, it can be seen that the results are quite similar. Furthermore, when the 25th and 75th percentiles of the Fels children are examined, it shows that girls range between 115.2 and 121.2 at six and a half years, and 117.9 and 124.3 at age seven years, while boys range between 116.3 and 122.7 at six and a half years, and 119.4 and 125.8 cm at seven years of age. Thus, the Denver children, aged about six years and nine months, fall well within the 25th and 75th percentiles of the Fels children at the same age. It was concluded that the average stature of Denver and Fels participants was similar, and consequently that general growth patterns would correspond between the two samples. The two samples were then compared for similar values in the variables of the present study. The Fels data had been previously corrected for radiographic enlargement, while the Denver data were not corrected, following the methods of other researchers (Lieberman and McCarthy, 1999; Merow and Broadbent, 1990; Nanda, 1955). A t-test for independent samples found that four of the dimensions differed significantly between the two samples (Table 2.3, Figure 2.5). These dimensions were basion-sella, basion-nasion, and the two horizontal measurements of the hard palate, ANS-PNS and PNS-A point. All these dimensions were found to be greater in the Denver sample (see the highlighted dimensions in Figure 2.26). On further inspection of the sample averages, it was found that all dimensions were larger in the Denver sample. This suggests that some radiographic enlargement of these data is in fact present, since only one of the angles of cranial base flexion and craniofacial angles was found to differ significantly between the two samples. This variable was the orientation of the hard palate (ANS-PNS) relative to the basion-pituitary point plane (see Table 2.3). Consequently, the dimension data of the Denver sample were adjusted for radiographic enlargement. Calculations showed that correction of the Denver data for enlargement of 4% resulted in no significant differences for dimensions when they were compared to the Fels data (Table 2.4). The angle measuring the orientation of the hard palate relative to the clivus (basion-pituitary point plane) was consequently the sole variable to differ between the samples. The data for the Fels and Denver samples were consequently pooled into a single group of Americans for the remainder of the study.

Table 2.3: T-test results for the two American samples before correction of the Denver sample for radiographic enlargement (significance corrected for multiple comparisons).

Variable	Variable	Denver	Fels	t	df	p (2-tailed)
Cranial base flexion angles	BA.S.N	128.9	127.8	0.9	62.0	0.366
	CLIV.SPH	107.8	103.9	2.3	62.0	**0.026**
	BA.PP.SP	120.4	119.0	1.0	62.0	0.336
	BA.PP.N	130.8	131.6	-0.7	62.0	0.501
	CLIV.S.N	121.1	119.5	1.2	62.0	0.251
	ECP.S.N	124.9	122.0	2.3	60.6	0.027
	BA.SE.N	145.7	146.7	-0.7	62.0	0.466
Craniofacial angles	O.B	133.1	131.1	1.1	61.0	0.289
	PALATE	50.6	54.4	-3.4	59.0	**0.001**
	S.N	134.0	134.0	0.0	62.0	0.981
	PP.N	131.9	130.0	1.6	58.1	0.112
Dimensions	S.N	69.8	67.3	2.2	62.0	**0.035**
	BA.S	48.9	44.0	5.4	62.0	**0.000**
	BA.N	106.8	100.3	3.9	62.0	**0.000**
	BA.O	36.8	35.1	1.5	61.0	0.145
	BA.PNS	46.0	42.8	2.9	62.0	**0.005**
	PNS.ANS	54.5	49.8	4.8	59.0	**0.000**
	PNS.A	50.9	46.7	4.9	58.0	**0.000**
	N.ANS	52.7	50.6	2.0	59.0	**0.046**
	N.A	57.7	55.4	2.0	58.0	0.052

Table 2.4: Average values of cranial base and facial dimensions, showing the Denver results before and after correction for radiographic enlargement.

	Denver		Fels
Dimensions	Uncorrected measurements	With 4% correction	Corrected
BA.S	48.9	45.5	44.0
BA.N	106.8	99.3	100.3
BA.O	36.8	34.2	34.2
BA.PNS	46.0	42.8	42.8
PNS.ANS	54.5	50.7	49.8
PNS.A	50.9	47.3	46.7
N.ANS	52.7	49.0	50.6
N.A	57.7	53.6	55.4

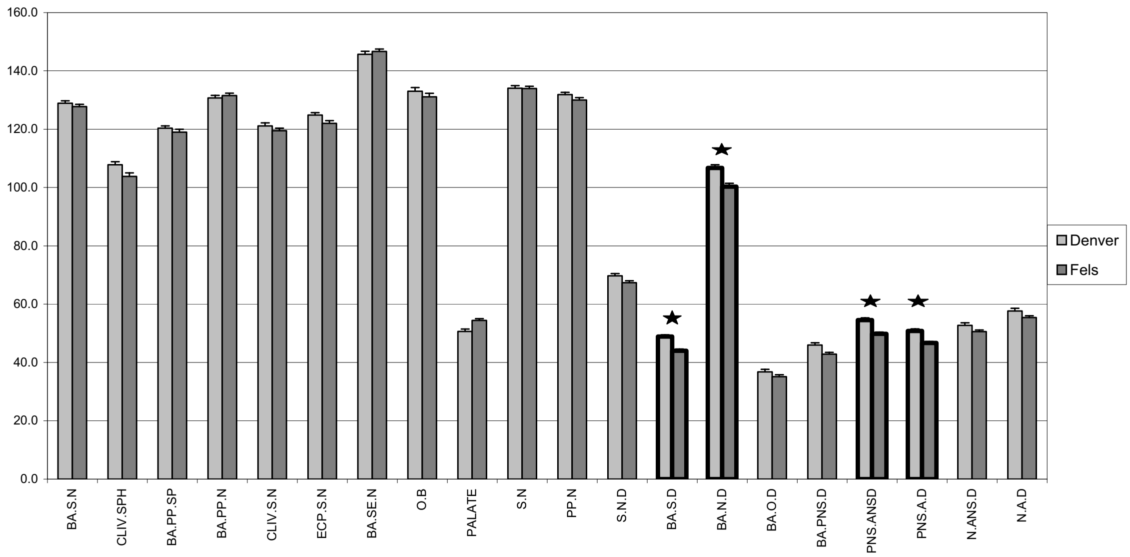

Figure 2.26: Differences between the Denver and Fels samples. Variables that differ significantly are highlighted (significance corrected for multiple comparisons).

Due to the well established historical separation of the African Khoi-San people and the other samples of Zulu, Xhosa and Sotho, historically referred to as South African Negroes (De Villiers, 1968), or as representatives of Bantu speaking people (Nurse et al., 1985), the five African sub-samples have been organised into two groups: one consisting of the Zulu, Sotho and Xhosa samples (collectively labelled African S/X/Z) and the other a Khoi-San group (African K/S), and the historical and cultural groups preserved (see for example (Nurse et al., 1985)).The three African S/X/Z samples were tested for significant differences between them (one-way ANOVA). No significant differences were found between the Sotho, Xhosa and Zulu sub-samples for any variables. Results are shown in the ANOVA table (Table 2.5). Differences between the African Khoi and San samples were analysed using a t-test for independent samples. No significant differences were found between the two sub-samples for any variable (Table 2.6).

Table 2.5: Results of one-way ANOVA for the five African samples (significance level adjusted for multiple comparisons).

	Variable		Sum of Squares	df	Mean Square	F	Sig.
Cranial base flexion	BA.S.N	Between Groups	15.0	2	7.5	0.2	0.806
		Within Groups	4069.8	117	34.8		
		Total	4084.8	119			
	CLIV.SPH	Between Groups	90.9	2	45.5	0.8	0.454
		Within Groups	6694.2	117	57.2		
		Total	6785.2	119			
	BA.PP.SP	Between Groups	59.6	2	29.8	0.5	0.585
		Within Groups	6477.8	117	55.4		
		Total	6537.4	119			
	BA.PP.N	Between Groups	90.6	2	45.3	1.1	0.338
		Within Groups	4842.8	117	41.4		
		Total	4933.3	119			
	CLIV.S.N	Between Groups	0.8	2	0.4	0.0	0.99
		Within Groups	4471.4	117	38.2		
		Total	4472.1	119			
	ECP.S.N	Between Groups	8.7	2	4.4	0.1	0.905
		Within Groups	5072.6	117	43.4		
		Total	5081.3	119			
	BA.SE.N	Between Groups	163.3	2	81.7	1.8	0.168
		Within Groups	5236.3	116	45.1		
		Total	5399.6	118			
Craniofacial angles	O.B	Between Groups	10.3	2	5.1	0.1	0.896
		Within Groups	5453.7	117	46.6		
		Total	5463.9	119			
	ANS.PNS	Between Groups	62.0	2	31.0	1.3	0.279
		Within Groups	2787.0	116	24.0		
		Total	2848.9	118			
	S.N	Between Groups	59.3	2	29.7	1.0	0.371
		Within Groups	3469.1	117	29.7		
		Total	3528.4	119			
	PP.N	Between Groups	79.6	2	39.8	1.0	0.376
		Within Groups	4718.2	117	40.3		
		Total	4797.8	119			
Dimensions	S.N	Between Groups	44.6	2	22.3	1.6	0.215
		Within Groups	1674.0	117	14.3		
		Total	1718.6	119			
	BA.S	Between Groups	18.5	2	9.2	0.6	0.571
		Within Groups	1917.5	117	16.4		
		Total	1936.0	119			
	BA.N	Between Groups	30.9	2	15.5	0.5	0.628
		Within Groups	3877.3	117	33.1		
		Total	3908.3	119			
	BA.O	Between Groups	73.3	2	36.7	2.1	0.133
		Within Groups	2087.9	117	17.8		
		Total	2161.2	119			
	BA.PNS	Between Groups	14.5	2	7.3	0.4	0.676
		Within Groups	2161.2	117	18.5		
		Total	2175.8	119			

Table 2.5 continued

Variable		Sum of Squares	df	Mean Square	F	Sig.
PNS.ANS	Between Groups	64.6	2	32.3	2.0	0.139
	Within Groups	1862.8	116	16.1		
	Total	1927.4	118			
PNS.A	Between Groups	65.3	2	32.6	2.2	0.121
	Within Groups	1680.2	111	15.1		
	Total	1745.4	113			
N.ANS	Between Groups	6.9	2	3.5	0.3	0.779
	Within Groups	1609.4	116	13.9		
	Total	1616.3	118			
N.A	Between Groups	12.1	2	6.0	0.4	0.662
	Within Groups	1618.5	111	14.6		
	Total	1630.5	113			

Table 2.6: Results of the t-test between African Khoi and San sub-samples (significance adjusted for multiple comparisons).

		Khoi		San		t-test for Equality of Means		
	variable	average	sd	average	sd	df	t	Sig. (2-tailed)
Cranial base flexion angles	BA.S.N	133.2	4.7	134.4	7.0	28	-0.5	0.598
	CLIV.SPH	110.1	5.5	109.5	9.9	28	0.2	0.816
	BA.PP.SP	122.5	5.4	123.0	9.9	28	-0.2	0.868
	BA.PP.N	134.6	5.4	136.0	7.7	28	-0.5	0.605
	CLIV.S.N	125.4	6.3	125.7	6.2	28	-0.1	0.902
	ECP.S.N	129.8	6.5	129.1	6.0	28	0.3	0.772
	BA.PRO.N	145.8	7.7	149.5	7.1	28	-1.4	0.186
Craniofacial angles	O.B	133.6	6.2	135.9	7.4	28	-0.9	0.402
	ANS.PNS	49.0	6.0	48.3	5.8	28	-0.3	0.770
	S.N	137.3	4.5	139.6	6.8	28	-1.0	0.313
	PP.N	134.5	4.6	136.2	7.6	28	-0.7	0.505
Dimensions	S.N	72.4	2.3	72.9	3.5	28	-0.4	0.710
	BA.S	46.5	1.9	45.5	3.2	28	1.0	0.349
	BA.N	108.9	2.8	108.7	5.7	27	0.2	0.861
	BA.O	41.2	5.1	39.5	4.8	28	0.9	0.381
	BA.PNS	49.4	4.9	51.4	4.9	28	-1.1	0.270
	PNS.ANS	52.5	3.6	50.7	3.1	24	1.4	0.172
	PNS.A	52.2	3.6	49.8	2.8	27	1.6	0.120
	N.ANS	50.9	3.5	50.2	4.2	24	0.4	0.673
	N.A	56.2	4.2	54.7	4.1	27	0.9	0.353

Comparisons between the three samples of Polynesian origin (Moriori, North Island Maori and South Island Maori) found no significant differences in mean values for the three groups after Bonferroni's correction for multiple comparisons was applied (Table 2.7). These three samples were consequently combined into one group.

Table 2.7: Results of one-way ANOVA for the three Polynesian sub-samples (North Island Maori, South Island Maori and Moriori (significance level adjusted for multiple comparisons).

Variable			Sum of Squares	df	Mean Square	F	p.
Cranial base flexion angles	BA.S.N	Between Groups	154.5	2	77.2	3.1	.053
		Within Groups	1316.6	53	24.8		
		Total	1471.1	55			
	CLIV.SPH	Between Groups	73.5	2	36.7	.7	.518
		Within Groups	2925.3	53	55.2		
		Total	2998.7	55			
	BA.PP.SP	Between Groups	239.8	2	119.9	2.5	.093
		Within Groups	2562.2	53	48.3		
		Total	2802	55			
	BA.PP.N	Between Groups	232.3	2	116.1	3.7	**.033**
		Within Groups	1684.1	53	31.8		
		Total	1916.4	55			
	CLIV.S.N	Between Groups	31.5	2	15.7	.5	.605
		Within Groups	1642.7	53	31.0		
		Total	1674.1	55			
	ECP.S.N	Between Groups	77.1	2	38.5	.9	.404
		Within Groups	2217	53	41.8		
		Total	2294.1	55			
	BA.SE.N	Between Groups	151.6	2	75.8	2.1	.134
		Within Groups	1887.9	52	36.3		
		Total	2039.5	54			
Craniofacial angles	O.B	Between Groups	77.8	2	38.9	.7	.489
		Within Groups	2839.6	53	53.6		
		Total	2917.3	55			
	ANS.PNS	Between Groups	16.4	2	8.2	.4	.703
		Within Groups	1200.3	52	23.1		
		Total	1216.7	54			
	S.N	Between Groups	147.5	2	73.7	3.3	**.043**
		Within Groups	1168.5	53	22.0		
		Total	1315.9	55			
	PP.N	Between Groups	226.6	2	113.3	3.5	**.037**
		Within Groups	1703.9	53	32.2		
		Total	1930.5	55			
Dimensions	S.N	Between Groups	8.8	2	4.4	.4	.704
		Within Groups	657.6	53	12.4		
		Total	666.4	55			
	BA.S	Between Groups	28.2	2	14.1	1.1	.341
		Within Groups	680	53	12.8		
		Total	708.2	55			
	BA.N	Between Groups	4.7	2	2.3	.1	.930
		Within Groups	1696.8	53	32.0		
		Total	1701.4	55			
	BA.O	Between Groups	3.3	2	1.7	.3	.738
		Within Groups	290.6	53	5.5		
		Total	293.9	55			

Table 2.7 continued

Variable		Sum of Squares	df	Mean Square	F	p.
BA.PNS	Between Groups	21.4	2	10.7	.9	.399
	Within Groups	607.8	53	11.5		
	Total	629.3	55			
PNS.ANS	Between Groups	29.4	2	14.7	1.2	.321
	Within Groups	593.9	47	12.6		
	Total	623.3	49			
PNS.A	Between Groups	7.5	2	3.7	.4	.669
	Within Groups	395.5	43	9.2		
	Total	403	45			
N.ANS	Between Groups	65.3	2	32.6	2.0	.144
	Within Groups	743.5	46	16.2		
	Total	808.8	48			
N.A	Between Groups	167.3	2	83.6	3.9	**.029**
	Within Groups	933.7	43	21.7		
	Total	1101	45			

As a result of pooling of these samples, seven samples were used for the remainder of the analysis. These final samples are referred to as Australian, Chinese, Thai, African S/X/Z, African K/S, Polynesian and American.

Chapter 3: Results and Discussion

Introduction to the results section

The results of the present investigation have been divided into a number of sections, which are briefly summarized below to assist the reader with interpretation of the results. Initially, data were examined for internal consistency and validity, and the results of Technical Error of Measurement are discussed (part of this examination was reported in the Methods section, where some individuals were excluded for having measurements lying more than three standard deviations from the sample averages). Also in this section are comparisons between the basic data of this study and published work that has been undertaken on similar samples. This should prepare the reader for the next section, where the descriptive statistics of the three types of measurement (cranial base angles, angles of orientation of craniofacial angles, and dimensions of the cranial base and craniofacial skeleton) are introduced. Following this, the relationships between the three different types of measurement were examined using correlations and multivariate statistical methods of Discriminant Function and Principal Components Analyses. The variation present in the data was then examined with regard to the amount of individual variation present in the total sample. In this way, the aims of the current study were addressed – specifically, to document the range of variation in cranial base flexion in the sample, to examine the relationship between cranial base flexion and other craniofacial variables, and to test the hypothesis that there are no population differences in cranial base flexion.

Internal consistency and validity of the data

The following section examines the data for Technical Error of Measurement (TEM), specifically intra-observer measurement error, and reliability of the data. Comparisons are also made between the data of each sample and published studies of results from the same or similar samples.

Investigation of TEM was undertaken using the procedure outlined in the Methods section. Results of the TEM calculation are shown in Table 3.1. They show that the TEM of the angle measurements varied between a minimum of 1.5 degrees for the angle between the clival plane and the sella-nasion plane, and a maximum of 3.4 degrees for the angle basion-pituitary point-nasion. For the plane data, the measurement error ranged between 1.5 degrees for the measurement of the sella-nasion plane relative to basion-pituitary point, and 3.0 degrees for the basion-opisthion plane relative to basion-pituitary point. Dimension measurement error varied between 0.9 mm for the PNS-ANS distance, and 3.5 mm for the diameter of the foramen magnum (basion-opisthion).

These estimates of error were within 5% of the average size for all variables except the diameter of the foramen magnum (basion-opisthion), for which the error represented nearly 10% of the average size. This is not an unexpected result for this variable, as there is some difficulty with locating the landmark opisthion, as it can often be obscured by lateral structures on the radiographs. There is often also some difficulty locating the landmark basion; however, this can be made easier in radiographs where the vertebrae are also shown, as the position of the dens axis can often be used as a guide for locating basion on radiographs. It was concluded that the amount of technical error of measurement in the data was unlikely to affect the conclusions of this work. Estimates of reliability are also shown in Table 3.1. These correspond to the estimates of Technical Error of Measurements. Reliability ranges from high values of about 95% to not less than 50%, with most variables showing more than 90% reliability.

Table 3.1: Intra-observer Technical Error or Measurement (TEM) and Reliability on a sub-sample of the data (N = 28).

	variable	TEM	Reliability
cranial base flexion angles (degrees)	Basion-sella-nasion	1.6	0.949
	Clival plane-sphenoidal plane	1.8	0.954
	Basion-pituitary point-sphenoidal plane	2.5	0.895
	Basion-pituitary point-nasion	3.4	0.777
	Basion- SE-nasion	2.0	0.918
	Clival plane-sella-nasion	1.5	0.960
	Endocranial clival plane-sella-nasion	2.5	0.900
Craniofacial angles (degrees)	Opisthion-basion	3.0	0.836
	ANS-PNS	1.5	0.931
	Sella-nasion	1.9	0.917
	Pituitary point-nasion	3.4	0.777
	Sphenoidal plane	2.5	0.895
Dimensions (mm)	Sella-nasion	1.0	0.958
	Basion-sella	1.2	0.910
	Basion-nasion	2.1	0.924
	Basion-opisthion	3.5	0.529
	Basion-PNS	1.7	0.908
	PNS-ANS	0.9	0.956
	PNS-A	1.2	0.929
	Nasion-ANS	1.3	0.904
	Nasion-A	2.0	0.811

Of the thirteen samples included in the study, most had previously been investigated, and the results of these published studies were compared to the results of the current study using t-tests. Comparisons were conducted on the following samples: Chinese, American (Fels and Denver samples) Polynesian, African (S/X/Z) and Australian. No comparable measurements were available for the Thai or African K/S samples. While Tayles (Tayles, 1999) conducted a comprehensive study on the sample from Khok Phanom Di (the same Thai sample of the present study, none of her variables (taken on dry skulls) were the same as the measurements of the present study. Similarly, Huggare

(1996) measured the angle between the clival tangent line (main axis of the clivus) and the sphenoidal plane in the Thai sample, but this measurement was not used in the present study.

Chinese

The Chinese data of the present study were compared to the published study of Wei (1968) who examined individuals from the same sample. Wei's study, "A roentgenographic cephalometric study of prognathism in Chinese males and females" measured tracings of 84 males and 23 females (Wei, 1968a), while the present study examined data from 31 males and 22 females. Variables common to both studies are the cranial base angle basion-sella-nasion, and the dimensions basion-nasion, sella-nasion and basion sella. Means and standard deviations were used to calculate differences in averages between the studies (t-test) (Table 3.2). The results show significant differences between the samples for the variables basion-sella-nasion and basion-nasion in males, and for the angle basion-sella-nasion in females, but no significant differences for the dimension basion-sella. The results show that the measurements of the Chinese sample in the present study are similar to those published by Wei. Some slight differences with the values of the males of the present study being smaller than those of the males in the other study can be attributed to the larger sample size of Wei's study. Differences between the females of each sample are more difficult to interpret, but are probably due to some variation in measurement technique, for example in the location of landmarks.

Table 3.2: Results of the t-test between the data of Wei (1968) and the Chinese sample of the present study (t-test, p = 0.05).

	Males						Females					
Variable	Wei (1968) (N = 84)		Present study (N = 31)				Wei (1968) (N = 23)		Present study (N = 22)			
	mean	sd	mean	sd	t	p	mean	sd	mean	sd	t	p
ba-s-n	129.6	5.0	125.6	5.0	8.5	0.05	132.0	3.7	128.9	4.6	7.1	0.05
ba-n	101.3	3.9	98.8	4.3	5.7	0.05	95.1	4.1	94.5	4.6	1.5	0.05
s-n	64.9	3.1	64.4	3.6	1.3	0.05	61.4	2.2	61.9	2.8	1.4	0.05
ba-s	46.5	2.6	46.7	2.7	0.5	0.05	42.9	3.7	42.7	3.3	0.5	0.05

American

The American sample of the current study was made up of individuals from two different groups – the Denver Growth Series and the Fels Growth Series. In the current study these groups have been pooled into one sample (see Methods section), but for the purposes of the present comparison they will be examined independently. Published studies using individuals from the Denver Growth Series include those of Lieberman and colleagues (Lieberman and McCarthy, 1999). Among the variables selected by Lieberman and co-workers their angle of basicranial flexion CBA 4, which is the angle between the clival plane and the pre-sphenoid plane, was initially thought to correspond to the clival plane-sphenoidal plane angle of the current study. However, upon examining their definition of landmarks, a difference existed in the location of the pituitary point as the posterior landmark of the sphenoidal plane. In the current study the pituitary point landmark followed the definition of Zuckerman (1955), which placed it at the anterior edge of the groove for the optic chiasma, in front of the pituitary fossa. The definition given by Lieberman and colleagues was that the pituitary point was "…the projection onto the midsagittal plane of the bulging convexity that forms the inferior border of the optic canal" (McCarthy, 2001, p.51) (this is located inside the pituitary fossa, and appears to refer to the tuberculum sellae landmark). As a result of this discrepancy the two angles could not be compared for sample differences.

Two other studies conducted on the Denver Growth Series were those of George (1978) and Klocke (2002). Each of these measured longitudinal growth in children up to 5 years and 9 months, and so cannot be compared to the data of the present study, which only included adult individuals (George, 1978; Klocke et al., 2002). Another study on individuals from the Denver Growth Series was that of Nanda (1955), investigating the rates of growth of several facial components. A comparable measurement in that study and the current study was the dimension sella-nasion. This had an average of 74.0 mm in a sample of ten boys (aged 17 years) and 67.9 mm in a sample of five girls (aged 17 years) (Nanda, 1955). In the current study, the average size of the nasion-sella dimension in the male sample (14 individuals) was 69.1 mm, and for females (10 individuals) the average size was 64.9 mm. However, Nanda did not include estimates of standard deviations in the study, and consequently tests of significant difference between the two studies could only be done approximately using standard deviations from the current study (4.3 for males and 3.7 for females) The resulting t-test found significant differences between the two samples for males ($t = 2.75$, $p > 0.05$), but not for females ($t = 1.48$, $p > 0.05$). In this comparison, differences can be attributed to the very small sample sizes, and the fact that standard deviations from the present study had to be used instead of the actual standard deviations of Nanda (1955), which were not reported in that study.

The data from the Fels sub-sample were compared to the results of Israel (1973) (Israel, 1973). In this study, Israel compared various craniofacial dimensions of adult females from the Fels study. These were selected on the basis of having one radiograph taken during early adulthood and one taken during later adulthood. The younger group had a mean age of 35.4 years, which is much closer to that of the sample used in the present study (average age = 26.3 years) compared to the older group, which had an average age of 54.9 years. The measurements that Israel took that were the same as those in the present study include the length of the hard palate (ANS-PNS), the height of the nose (nasion- ANS), nasion-basion, nasion-sella and sella-basion. He also measured cranial base flexion, between the landmarks nasion, sella and basion. Results are shown in Table 3.3 below. The t-test revealed that the variables nasion-ANS, ANS-PNS and sella-nasion were all significantly different between the two samples, with the results of the present study being smaller than the average values of Israel (1973). The remaining variables (basion-nasion, basion-sella and basion-sella-nasion) had no significant differences between the two samples. The dimensions basion-nasion, and basion-sella were also larger in Israel's sample, while the average value of the angle basion-sella-nasion was larger in the present study, although not significantly. Most of the differences in this comparison can be attributed to the small sample sizes of each study, which will consequently be more affected by the presence of variation in individual measurements. An additional interesting finding is that standard deviations appear to be different in the two samples, with the most extreme example being the length of the hard palate (ANS-PNS). It is likely that considerable differences in samples have influenced the results, for example, location of particular landmarks or the presence of outliers.

Table 3.3: Comparison between results of Israel (1973) and the present study (sample of Fels females) (t-test, p = 0.05)

	Israel (1973) (N = 21)		Present study (N = 20)			
Variable	mean	sd	mean	sd	t	p
nasion-ANS	52.9	2.2	49.0	3.6	1.6	0.05
ANS-PNS	57.1	6.8	47.4	2.9	1.6	0.05
sella-nasion	71.9	3.3	64.5	4.4	1.6	0.05
basion-nasion	102.0	4.8	95.8	5.9	0.7	0.05
basion-sella	44.3	3.8	41.6	2.9	0.8	0.05
basion-sella-nasion	121.3	7.2	128.0	5.1	0.6	0.05

Polynesian

Comparable studies to the sample of Polynesians (Maori and Moriori) were found in the work of Kean and Houghton (1982). In this study they took measurements from tracings of radiographs of 60 adult males. Dimensions corresponding between that study and the current sample of Polynesians were nasion-sella, sella-basion and PNS-basion, and angular measurements of nasion-sella-basion corresponded to some of those used in the present study (Table 3.4). Other studies, such as Huggare (1996) and Kean and Houghton (1990) had no measurements that could be compared to the present study (Huggare and Houghton, 1996; Kean and Houghton, 1990). The results of the t-test conducted between the results of Polynesian males of the present study and Kean and Houghton's 1982 sample showed significant differences between all variables measured except the angle of cranial base flexion, basion-sella-nasion. Since the variables of the present study were all larger than those of Kean and Houghton (1982), it is possible that different corrections for radiographic enlargement were applied. The finding that the two samples had similar angles of cranial base flexion, a variable that is unaffected by radiographic enlargement supports this. Kean and Houghton (1982) mention that measurements on radiographs were corrected for enlargement, but do not mention the extent of radiographic enlargement in their sample.

Table 3.4: Results of t-test between Polynesian males studied by Kean and Houghton (1982) and Polynesian males of the present study (t-test, p = 0.05).

	Kean & Houghton (1982) (N = 60)		Present study (N = 38)			
Variable	mean	sd	mean	sd	t	p
nasion-sella	66.2	3.7	69.8	3.4	5.1	0.05
sella-basion	43.3	2.9	45.7	3.7	3.4	0.05
PNS-basion	45.7	3.7	48.4	3.6	3.4	0.05
nasion-sella-basion	140.3	5.6	141.4	4.8	1.0	0.05

The study of Schendel and colleagues measured skulls of Hawaiians, which through their evolution history are included in the Polynesian group (Schendel et al., 1980). These researchers published the results of a sample of 79 individuals (males and females) (Schendel et al., 1980) that are compared to the Polynesians of the present study (38 males and 18 females) in Table 3.5 below. The variables found to be significantly different between the two samples were nasion-sella, PNS-ANS, basion-opisthion and the angle basion-sella-nasion. The Hawaiian sample of Schendel had larger values of nasion-sella, PNS-ANS and basion-opisthion compared to the results of the present study. In contrast, the angle of flexion basion-sella-nasion was larger in the present study compared to the angle measured in Schendel's sample. The other variables sella-basion and nasion-ANS were not significantly different between the two samples. The differences observed between the two samples of Polynesians, although significant in some variables, are not especially large (around 3 mm).

Table 3.5. Results of the Hawaiian sample of Schendel et al (1980) compared to results of the Polynesian sample of the present study (t-test, p = 0.05).

	Schendel et al., (1980) (N = 79)		Present study (N = 56)			
Variable	mean	sd	mean	sd	t	p
nasion-sella	72.2	3.2	68.8	3.5	5.7	0.05
sella-basion	45.9	3.3	45.5	3.6	0.7	0.05
PNS-ANS	52.6	4.1	55.0	3.6	3.6	0.05
nasion-ANS	55.5	4.3	55.0	4.1	0.7	0.05
basion-opisthion	33.5	4.3	36.0	2.3	4.4	0.05
nasion-sella-basion	137.6	4.9	140.8	5.2	4.0	0.05

According to Houghton (1978) the angle of cranial base flexion in a sample of 60 Polynesian adults (measured basion-sella-nasion) was 142 degrees, with a standard deviation of 5.7 (Houghton, 1978a). In the current study, the same angle of basicranial flexion measured in the sample of 56 Polynesians was 143 degrees, with a standard deviation of 4.3. This was found to be not significant ($t = 1.07$, $p > 0.05$). Thus there does not appear to be a difference between these samples for this angle. However, standard deviations for these two sample means were found to be different. This suggests that while average values of cranial base flexion are similar between these two samples, there are differences in sample composition that gave rise to differences in standard deviations.

African

The African S/X/Z sample results of the present study were compared to a sample of Bantu speaking Africans from the RA Dart collection studied by Jacobson (1978). Jacobson studied the craniofacial skeleton in a sample of 23 males and 23 females. Jacobson reported the anterior cranial base length (sella-nasion) was 69.8mm in males (standard deviation = 3.08), and 65.9mm in females (standard deviation = 4.59) (Jacobson, 1978). The African S/X/Z samples of the present study had sella-nasion lengths of 73.5 mm (standard deviation = 3.7) in a sample of 60 males, and 71.2 mm (standard deviation = 3.6) in a sample of 60 females (Table 3.6). Results of a t-test found a significant difference between both males and females ($t = 4.86$, $p>0.05$ in males, $t = 5.39$, $p>0.05$ in females). The significant differences in the sella-nasion dimension of these samples most probably reflect slight differences in sample composition (Jacobson mentioned selection of Bantu speaking individuals with excellent occlusion, without mentioning the specific tribe names). Furthermore, Jacobson did not report details on radiographic techniques or any correction or adjustment for radiographic enlargement, both of which are likely to be different from the present study. The work of De Villiers (1968) on the skull of the South African Negro (similar to the African S/X/Z sample of the present study) included descriptions of skull shape, the measurements were taken on dry skulls and could not be compared to the measurements of the present study, which were undertaken on radiographs (De Villiers, 1968). Similarly, the work of Kieser and colleagues reports on the diameter of the foramen magnum measured on dry skulls, and could not be compared to the present study (Kieser and Groeneveld, 1990). Finally, no studies were found that reported cephalometric measurements on the craniofacial skeleton of African K/S samples.

Table 3.6: Results of t-test between Bantu Africans studied by Jacobson (1978) and African S/X/Z of the present study (t-test, p = 0.05).

	Males						Females					
Variable	Jacobson (1978), N = 23		Present study, N = 60				Jacobson (1978) N = 23		Present study, N =60			
	mean	sd	mean	sd	t	P	mean	sd	mean	sd	t	P
nasion-sella	69.8	3.08	73.5	3.7	4.86	0.05	65.9	4.59	71.2	3.6	5.39	0.05

Thai

No references could be found that compared similar mid-sagittal variables on radiographs of Thai samples. The work of Tayles (1999) reports measurements on dry skulls not comparable to those of the present study.

Australian

Measurements on lateral cephalometric radiographs were taken by Brown and published in two studies (Brown, 1999; Brown and Barrett, 1964). T-tests between the results of Brown (1964) and those of the present study revealed no significant differences between any of the four variables compared (Table 3.7).

Table 3.7: Results of t-test between Australians studied by Brown (1964) and Australians of the present study (t-test, p = 0.05).

	Males						Females					
Variable	Brown (1964) (N = 31)		Present study (N = 34)				Brown (1964) (N = 27)		Present study (N = 34)			
	mean	sd	mean	sd	t	p	mean	sd	mean	sd	t	p
nasion-sella	70.5	3.2	71.1	3.8	0.69	0.05	66.3	2.3	66.8	3.2	0.71	0.05
sella-basion	45.5	3.3	43.7	3.0	2.30	0.05	41.0	2.5	40.7	2.4	0.75	0.05
basion-nasion	105.4	4.2	103.6	3.8	1.80	0.05	98.2	3.5	97.6	3.2	0.54	0.05
nasion-sella-basion	129.4	4.2	128.0	5.7	1.13	0.05	131.3	4.9	129.5	5.1	1.40	0.05

The previous comparisons between the results of the present study for the seven samples and other comparative samples of published studies found differences between sample means in a number of comparisons. It is also evident that in some samples there are differences in standard deviations (in particular the results of the Fels sample of Israel (1973) and the present study, and the results of Polynesian sample of Houghton (1978) and the present study). These differences are likely to be the result of variation in measurement technique between studies (for example landmark definition and location), and overall variation in sample composition. However, on the whole the results of the present study are quite similar to those presented elsewhere on similar samples. This is sufficient to establish that the following analyses on the data can be interpreted as representative of the samples studied.

Results of cranial base flexion

The following section presents the results for the cranial base angles according to sexual dimorphism, individual variation and population variation. When interpreting these results, it must be remembered that what is described as an increase in flexion of the cranial base is shown by a smaller angle, and a decrease in flexion is represented by a larger angle (a more obtuse angle). Refer to the Methods chapter for illustrations and descriptions of each of the angles measured (Figures 2.2 to 2.9), and to the appendix for abbreviations of the landmarks.

The average values of the cranial base angles measured in the present study are shown in Table 3.8. The results show that for the total sample, the average value of cranial base flexion measured using the most common angle of basion-sella-nasion was 132.5 degrees. Similar to this was the angle basion-pituitary point-nasion with an angle of 134.4 degrees. This shows the difference in the position of the central landmark (the pituitary point is anterior to the sella point), resulting in a less flexed angle for basion-pituitary point-nasion. The angle between the clival plane-sphenoidal plane was 108 degrees. This cannot be properly compared to the basion-sella-nasion angle due to the different landmarks used to assess the orientation of the clivus. However, the angles basion-pituitary point-nasion (134.4 degrees) and basion-pituitary point-sphenoidal plane (121.9 degrees) show that the difference between the two anterior cranial base planes is on average 12.5 degrees, with the sphenoidal plane being more flexed relative to the clivus than the sella-nasion plane. The two angles used to measure the less commonly used angle of the orientation of the clivus relative to the sella-nasion plane have a difference of 3.5 degrees between them on average, with the clival plane-sella-nasion angle (from basion to the spheno-occipital synchondrosis) measuring 124.3 degrees and the angle endocranial clival plane-sella-nasion (along the main axis of the endocranial margin of the clivus), measuring 127.8 degrees. Finally, the angle basion-SE-nasion, which uses the spheno-ethmoid point as the point of flexion had an average value of 147.5 degrees in the whole sample.

Table 3.8: Descriptive statistics for the angles of cranial base flexion (N = 414)

Variable	Mean (degrees)	Std. Deviation	Minimum	Maximum	Coefficient of Variation
BA.S.N	132.5	7.1	115.5	152.0	5.4
CLIV.SPH	108.0	8.4	86.0	132.5	7.8
BA.PP.SP	121.9	7.7	103.5	145.0	6.3
BA.PP.N	134.4	7.2	117.0	153.0	5.3
CLIV.S.N	124.3	7.5	104.0	145.5	6.0
ECP.S.N	127.8	7.9	106.5	150.0	6.2
BA.SE.N	147.5	7.0	129.0	167.0	4.7

Comparison of the average values for males and females reveals that in most cases the values are greater in females than in males; however, differences are rarely more than 1 degree. No significant differences were present in the total sample (t-test for independent samples, significance level = 0.05). The results are displayed in Table 3.9.

Table 3.9: Male and Female means and standard deviations for cranial base angles (p = 0.05).

Angle	Males (N= 225)		Females (N = 189)			
	Mean (degree)	Std.Deviation	Mean (degree)	Std.Deviation	t	p
BA.S.N	132.2	7.5	132.8	6.7	-0.87	0.387
CLIV.SPH	107.6	8.7	108.5	8.0	-0.99	0.322
BA.PP.SP	121.7	7.9	122.1	7.4	-0.63	0.531
BA.PP.N	134.4	7.5	134.5	6.7	-0.07	0.942
CLIV.S.N	124.0	7.9	124.7	6.9	-0.88	0.380
ECP.S.N	127.7	8.5	127.9	7.2	-0.29	0.773
BA.SE.N	147.7	7.3	147.2	6.5	0.79	0.432

Despite finding no significant differences in cranial base flexion between males and females for the whole sample, two samples showed some sexual dimorphism. When t-tests for independent samples were conducted between males and females of each sample, the Chinese and African K/S samples were found to have significant differences. Among the Chinese sample, all angles except basion-pituitary point-nasion and basion-SE-nasion were significantly different. In all these cases, the flexion of the cranial base in males was about three or four degrees more than in females. Among the African K/S individuals, a significant difference was found between males and females for the angle basion-SE-nasion, with males having about six degrees more flexion than females, and for the angle basion-clival plane-sella-nasion, where males were about three degrees more flexed than females. No significant differences between males and females were present in any of the other samples (Table 3.10). When looking at the mean values for each sample, with the exception of the Polynesian sample females usually have larger angles of cranial base flexion than males. In the Polynesian sample this relationship is reversed with males having larger angles on average than females. Two-way ANOVA found no significant interaction between sample and sex for each of the cranial base angles studied.

Table 3.10. Male and Female angles (degrees) for each sample, numbers in bold denote differences (significant at 0.05) between males and females.

SAMPLE	ANGLE	MALES		FEMALES			
		Mean	St.dev.	Mean	St.dev	t	p
CHINESE	BA.S.N	**125.5**	5.0	**128.9**	4.6	-2.50	**0.02**
(N = 65)	CLIV.SPH	**102.9**	7.7	**107.6**	5.4	-2.59	**0.01**
	BA.PP.SP	**117.9**	6.9	**121.7**	6.3	-2.06	**0.04**
	BA.PP.N	128.3	5.2	130.9	6.6	-1.61	0.11
	CLIV.S.N	**117.1**	5.7	**121.1**	4.9	-2.67	**0.01**
	ECP.S.N	**120.2**	6.1	**123.5**	4.9	-2.14	**0.04**
	BA.SE.N	144.8	4.8	144.8	5.9	-0.01	0.99
AMERICAN	BA.S.N	128.0	5.2	128.3	4.3	-0.25	0.80
(N = 64)	CLIV.SPH	104.5	6.6	106.3	7.1	-1.07	0.29
	BA.PP.SP	119.0	4.6	120.1	6.3	-0.85	0.40
	BA.PP.N	131.3	5.0	131.2	4.3	0.15	0.88
	CLIV.S.N	120.0	6.2	120.2	4.8	-0.09	0.93
	ECP.S.N	123.3	5.9	122.8	5.1	0.43	0.67
	BA.SE.N	146.6	5.8	146.0	4.5	0.52	0.61
AFRICAN K/S	BA.S.N	132.5	6.1	137.1	5.3	-2.02	0.05
(N = 30)	CLIV.SPH	109.8	9.6	109.7	6.1	0.03	0.98
	BA.PP.SP	122.7	9.6	123.0	5.9	-0.07	0.95
	BA.PP.N	133.9	6.9	138.6	6.0	-1.80	0.08
	CLIV.S.N	124.3	6.6	128.1	4.4	-1.62	0.12
	ECP.S.N	**128.1**	6.7	**132.1**	3.5	-2.14	**0.04**
	BA.SE.N	**146.1**	7.0	**152.4**	6.5	-2.36	**0.03**

Table 3.10 continued

SAMPLE	ANGLE	MALES		FEMALES			
		Mean	St.dev.	Mean	St.dev	t	p
POLYNESIAN	BA.S.N	141.4	4.8	139.6	5.9	1.29	0.20
(N = 56)	CLIV.SPH	116.3	7.6	113.9	6.9	1.14	0.26
	BA.PP.SP	129.2	7.6	127.3	6.2	0.97	0.34
	BA.PP.N	142.7	5.9	141.0	5.8	1.03	0.31
	CLIV.S.N	133.4	5.1	131.1	6.1	1.47	0.15
	ECP.S.N	138.4	5.9	135.5	7.3	1.60	0.11
	BA.SE.N	155.0	6.4	153.8	5.7	0.73	0.47
AFRICAN S/X/Z	BA.S.N	134.6	5.5	135.8	6.2	-1.15	0.25
(N = 121)	CLIV.SPH	108.9	6.6	110.9	8.4	-1.46	0.15
	BA.PP.SP	122.0	6.7	123.1	8.1	-0.77	0.44
	BA.PP.N	135.9	6.3	136.2	6.6	-0.25	0.80
	CLIV.S.N	126.8	5.7	128.4	6.5	-1.40	0.16
	ECP.S.N	130.0	6.3	131.1	6.8	-0.93	0.36
	BA.SE.N	148.4	7.1	148.3	6.5	0.09	0.93
THAI	BA.S.N	131.2	7.5	132.0	6.2	-0.29	0.77
(N = 23)	CLIV.SPH	106.6	7.3	106.1	9.2	0.13	0.90
	BA.PP.SP	120.9	7.6	119.9	8.1	0.29	0.78
	BA.PP.N	132.5	7.7	132.0	6.7	0.16	0.87
	CLIV.S.N	122.0	7.1	123.4	6.5	-0.47	0.65
	ECP.S.N	126.2	7.5	127.1	6.2	-0.32	0.75
	BA.SE.N	146.5	5.4	145.1	6.3	0.52	0.61
AUSTRALIAN	BA.S.N	128.0	5.7	129.5	5.1	-1.12	0.27
(N = 68)	CLIV.SPH	102.2	7.5	104.4	7.4	-1.23	0.22
	BA.PP.SP	118.3	7.3	120.5	7.4	-1.26	0.21
	BA.PP.N	131.8	6.7	133.0	5.7	-0.79	0.43
	CLIV.S.N	119.3	5.9	120.7	5.1	-1.01	0.32
	ECP.S.N	123.0	5.6	124.8	5.3	-1.34	0.18
	BA.SE.N	143.7	7.1	143.8	5.4	-0.10	0.92

The average value of the angle basion-sella-nasion ranged between 127 degrees and 141 degrees in the samples studied (Table 3.11). Chinese, American and Australian samples had the smallest values, close to 128 degrees. Thai people had an angle of 132 degrees, which was the closest to the total average. The African K/S and African S/X/Z people had angles of 134 and 135 degrees respectively, and the Polynesian people had the largest angles, measuring nearly 141 degrees. The average angle between the clivus and the planum sphenoideum ranged between 103 degrees and 115 degrees among the samples. The smaller angles were seen in Australian, Chinese, American and Thai samples (around 105 degrees). The values for the African samples were slightly above the total average, close to 110 degrees. Polynesian people had angles that were considerably larger at 115.5 degrees. The angle between basion, pituitary point and the planum sphenoideum had average values ranging between 119 degrees and 129 degrees. Australian, American, Chinese, and Thai had the smallest angles, of around 120 degrees. The African K/S and S/X/Z people had angles of 122.5 and 122.8 degrees respectively. The Polynesian people had angles of nearly 129 degrees. The angle basion-pituitary point-nasion ranged between 129 and 143 degrees for the sample averages. Smaller angles were present in Chinese, American, Thai and Australian samples (around 132 degrees). African K/S people had an angle of 135.5 degrees, and African S/X/Z people had an average angle of 136 degrees. The largest angle was seen in the Polynesian sample, with a measurement of 142.3 degrees. Two different clival angles were measured, the clival plane-sella-nasion measuring the angle described by Lieberman and McCarthy (1999) (basion-spheno-occipital synchondrosis-sella-nasion), and the other representing the angle between the endocranial border of the basi-sphenoid, sella and nasion (endocranial clival plane). Group average values for the first angle ranged from 118 to 133 degrees, and from 129 to 138 degrees for the second angle. Chinese, Australian, American and Thai samples had the lowest values, around 121 degrees. The K/S people had a measurement of 125.5 degrees, and the S/X/Z people had a measurement of 127.5 degrees. Polynesians had the maximum mean value of 133 degrees. For the second angle, a similar distribution of mean values was seen, with smaller angles in Chinese, American, Australian and Thai samples (around 124 degrees). The values for K/S and S/X/Z people were slightly higher, with the mean values around 130 for each sample. Polynesian people had an average angle considerably larger at 137.5 degrees. The angle basion-SE-nasion had average values for the populations ranging between 143 and 155 degrees. The smaller values were seen in Australian, Chinese, Thai and American group (about 145 degrees). Both

African samples had average values of about 148 degrees. The Polynesian group had an average of 155 degrees for this angle. The results of this comparison show a consistent pattern among the samples, with the same samples (Chinese, American, Australian and Thai having average values at the smaller end of the distribution, the African samples having average values in the middle of the range, and the Polynesian people consistently having the highest average values.

*Table 3.11**:** Descriptive statistics of cranial base angles (degrees) for the samples*

GROUP	ANGLE	Mean	Std. Deviation	Minimum	Maximum
CHINESE	BA.S.N	127.0	5.1	115.5	140.5
(N = 65)	CLIV.SPH	104.9	7.2	86.0	117.0
	BA.PP.SP	119.5	6.8	103.5	136.5
	BA.PP.N	129.4	5.9	118.0	150.0
	CLIV.S.N	118.7	5.7	105.0	129.5
	ECP.S.N	121.6	5.8	106.5	133.5
	BA.SE.N	144.8	5.2	132.0	157.5
AMERICAN	BA.S.N	128.2	4.8	116.5	136.5
(N = 64)	CLIV.SPH	105.3	6.9	89.0	120.0
	BA.PP.SP	119.5	5.5	105.0	134.0
	BA.PP.N	131.3	4.6	121.0	140.5
	CLIV.S.N	120.1	5.6	104.0	134.5
	ECP.S.N	123.1	5.5	108.0	136.0
	BA.SE.N	146.3	5.2	135.5	159.0
AFRICAN K/S	BA.S.N	134.0	6.2	121.0	148.0
(N = 30)	CLIV.SPH	109.7	8.4	93.5	126.5
	BA.PP.SP	122.8	8.4	108.0	142.0
	BA.PP.N	135.5	6.9	123.0	151.0
	CLIV.S.N	125.6	6.1	112.0	136.5
	ECP.S.N	129.4	6.1	115.0	138.0
	BA.SE.N	148.2	7.4	135.0	162.0
POLYNESIAN	BA.S.N	140.8	5.2	128.0	152.0
(N = 56)	CLIV.SPH	115.5	7.4	102.0	129.0
	BA.PP.SP	128.6	7.1	113.0	145.0
	BA.PP.N	142.2	5.9	127.0	153.0
	CLIV.S.N	132.7	5.5	118.0	145.5
	ECP.S.N	137.5	6.5	123.0	150.0
	BA.SE.N	154.6	6.1	143.5	167.0
AFRICAN S/X/Z	BA.S.N	135.2	5.9	121.0	148.0
(N = 121)	CLIV.SPH	109.9	7.6	94.0	132.5
	BA.PP.SP	122.5	7.4	106.0	140.0
	BA.PP.N	136.1	6.4	122.0	150.0
	CLIV.S.N	127.6	6.1	111.0	143.0
	ECP.S.N	130.6	6.5	114.0	145.0
	BA.SE.N	148.3	6.8	131.0	167.0

Table 3.11 continued

GROUP	ANGLE	Mean	Std. Deviation	Minimum	Maximum
THAI	BA.S.N	131.7	6.5	121.0	142.0
(N = 23)	CLIV.SPH	106.2	8.4	89.5	122.0
	BA.PP.SP	120.2	7.8	106.0	134.0
	BA.PP.N	132.2	6.9	119.0	143.0
	CLIV.S.N	122.9	6.6	112.5	134.0
	ECP.S.N	126.8	6.5	114.0	139.0
	BA.SE.N	145.6	5.9	129.0	152.0
AUSTRALIAN	BA.S.N	128.7	5.4	116.0	142.0
(N = 68)	CLIV.SPH	103.3	7.5	89.0	122.5
	BA.PP.SP	119.4	7.4	104.0	141.0
	BA.PP.N	132.4	6.2	117.0	150.0
	CLIV.S.N	120.0	5.5	110.0	133.0
	ECP.S.N	123.9	5.5	114.0	139.0
	BA.SE.N	143.8	6.2	130.0	159.0

The cranial base angles measured in the present study were all moderately to highly positively correlated with each other. The correlation matrix for these angles is shown in Table 3.12. This shows that all angles effectively describe cranial base flexion, despite some variation in the selection of landmarks, for example, using pituitary point instead of sella as the point of flexion. Some correlations had less than 50% of the variance explained (correlations of less than 0.70). These usually included the angle basion-SE-nasion, which had the point of flexion located considerably anteriorly (at the spheno-ethmoid suture) compared to the other angles, which had their point of flexure either at sella or the pituitary point. The other angle with low to moderate correlation coefficients was basion-pituitary point-sphenoidal plane with both the clival plane-sella-nasion and the endocranial clival plane-sella-nasion angles. This may be due to the fact that there are fewer shared variables between these angles.

*Table 3.12**:** Correlations of angles for the total sample (numbers in bold indicate significant correlations) (N = 414)*

	BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	**0.759**					
BA.PP.SP	**0.718**	**0.911**				
BA.PP.N	**0.903**	**0.673**	**0.758**			
CLIV.S.N	**0.952**	**0.785**	**0.650**	**0.822**		
ECP.S.N	**0.923**	**0.759**	**0.643**	**0.806**	**0.961**	
BA.SE.N	**0.739**	**0.402**	**0.444**	**0.825**	**0.676**	**0.653**

All correlations are significant at 0.0001, (significance level corrected for multiple comparisons).

The pattern seen in the samples is that all correlations are significant and positive, but rather low, when the total sample is included in the analysis. When the samples of the present study are viewed individually, most correlations are significant, and are moderate to highly related to each other, with the exceptions being the correlations between basion-SE-nasion and the angles incorporating the sphenoidal plane of the anterior cranial base (clivus-sphenoidal plane and basion-pituitary point-sphenoidal plane). These are not significant in all samples except the African S/X/Z sample and the Australian sample. In the African S/X/Z sample, both angles are not significantly correlated, while in the Australian sample it is only the angle clivus-sphenoidal plane that is not significantly correlated with basion-SE-nasion. In addition, the Thai sample had correlations that were not significant for the angles basion-sella nasion and clivus-sphenoidal plane, and the endocranial border of the clivus with basion-SE-nasion. In the following tables of correlation coefficients for each sample (Table 3.13 to 3.19), all coefficients have had their significance level adjusted for Bonferroni's correction for multiple comparisons.

Table 3.13: Chinese correlation coefficients for cranial base angles (N = 65, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.699**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.702**	**0.902**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.900**	**0.606**	**0.748**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**			
CLIV.S.N	Correlation	**0.904**	**0.758**	**0.600**	**0.741**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**		
ECP.S.N	Correlation	**0.851**	**0.731**	**0.592**	**0.720**	**0.944**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.629**	0.150	0.253	**0.715**	**0.493**	**0.456**
	p. (2-tailed)	**0.000**	0.283	0.068	**0.000**	**0.000**	**0.001**

Table 3.14: American correlation coefficients for cranial base angles (N = 64, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.682**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.600**	**0.828**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.779**	**0.384**	**0.540**			
	p. (2-tailed)	**0.000**	**0.002**	**0.000**			
CLIV.S.N	Correlation	**0.927**	**0.712**	**0.480**	**0.659**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**		
ECP.S.N	Correlation	**0.903**	**0.695**	**0.488**	**0.660**	**0.949**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.580**	0.105	0.127	**0.765**	**0.548**	**0.579**
	p. (2-tailed)	**0.000**	0.410	0.316	**0.000**	**0.000**	**0.000**

Table 3.15: African K/S correlation coefficients for cranial base angles (N = 30, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.735**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.704**	**0.955**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.931**	**0.688**	**0.728**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**			
CLIV.S.N	Correlation	**0.880**	**0.659**	**0.588**	**0.814**		
	p. (2-tailed)	**0.000**	**0.000**	**0.001**	**0.000**		
ECP.S.N	Correlation	**0.824**	**0.615**	**0.532**	**0.732**	**0.955**	
	p. (2-tailed)	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.626**	0.153	0.201	**0.735**	**0.579**	**0.486**
	p. (2-tailed)	**0.000**	0.419	0.286	**0.000**	**0.001**	**0.006**

Table 3.16: Polynesian correlation coefficients for cranial base angles (N = 56, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.646**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.639**	**0.908**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.870**	**0.588**	**0.698**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**			
CLIV.S.N	Correlation	**0.887**	**0.709**	**0.540**	**0.745**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**		
ECP.S.N	Correlation	**0.780**	**0.621**	**0.458**	**0.651**	**0.896**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.729**	0.232	0.342	**0.829**	**0.572**	**0.493**
	p. (2-tailed)	**0.000**	0.088	0.011	**0.000**	**0.000**	**0.000**

Table 3.17: African S/X/Z correlation coefficients for cranial base angles (N = 121, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.792**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.738**	**0.915**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.854**	**0.673**	**0.771**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**			
CLIV.S.N	Correlation	**0.945**	**0.799**	**0.641**	**0.765**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**		
ECP.S.N	Correlation	**0.911**	**0.785**	**0.648**	**0.745**	**0.955**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.717**	**0.406**	**0.451**	**0.818**	**0.654**	**0.619**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.18: Thai correlation coefficients for cranial base angles (N = 23, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	0.482					
	p. (2-tailed)	0.020					
BA.PP.SP	Correlation	**0.584**	**0.947**				
	p. (2-tailed)	**0.003**	**0.000**				
BA.PP.N	Correlation	**0.952**	**0.507**	**0.647**			
	p. (2-tailed)	**0.000**	**0.014**	**0.001**			
CLIV.S.N	Correlation	**0.961**	**0.607**	**0.633**	**0.913**		
	p. (2-tailed)	**0.000**	**0.002**	**0.001**	**0.000**		
ECP.S.N	Correlation	**0.898**	**0.631**	**0.652**	**0.859**	**0.934**	
	p. (2-tailed)	**0.000**	**0.001**	**0.001**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.643**	-0.077	0.053	**0.701**	**0.548**	0.457
	p. (2-tailed)	**0.001**	0.727	0.809	**0.000**	**0.007**	0.029

Table 3.19: Australian correlation coefficients for cranial base angles (N = 68, significance level adjusted for multiple comparisons)

		BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N
CLIV.SPH	Correlation	**0.622**					
	p. (2-tailed)	**0.000**					
BA.PP.SP	Correlation	**0.663**	**0.887**				
	p. (2-tailed)	**0.000**	**0.000**				
BA.PP.N	Correlation	**0.894**	**0.529**	**0.719**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**			
CLIV.S.N	Correlation	**0.914**	**0.697**	**0.572**	**0.721**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**		
ECP.S.N	Correlation	**0.864**	**0.621**	**0.556**	**0.719**	**0.927**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
BA.SE.N	Correlation	**0.726**	0.277	**0.418**	**0.858**	**0.594**	**0.580**
	p. (2-tailed)	**0.000**	0.022	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.20: Results of the One-way ANOVA for cranial base angles, showing differences between samples.

		Sum of Squares	df	Mean Square	F	P
BA.S.N	Between Groups	8650.08	6	1441.68	47.49	0.000
	Within Groups	12355.04	407	30.36		
	Total	21005.11	413			
CLIV.SPH	Between Groups	6211.61	6	1035.27	18.52	0.000
	Within Groups	22750.33	407	55.90		
	Total	28961.94	413			
BA.PP.SP	Between Groups	3720.34	6	620.06	12.17	0.000
	Within Groups	20730.24	407	50.93		
	Total	24450.58	413			
BA.PP.N	Between Groups	6226.98	6	1037.83	28.16	0.000
	Within Groups	14998.74	407	36.85		
	Total	21225.72	413			
CLIV.S.N	Between Groups	9348.90	6	1558.15	45.84	0.000
	Within Groups	13833.27	407	33.99		
	Total	23182.16	413			
ECP.S.N	Between Groups	10788.54	6	1798.09	48.52	0.000
	Within Groups	15083.82	407	37.06		
	Total	25872.36	413			
BA.SE.N	Between Groups	4379.31	6	729.89	19.04	0.000
	Within Groups	15521.91	405	38.33		
	Total	19901.22	411			

Analysis of variance (ANOVA) was performed on the cranial base angle data, in conjunction with a Bonferroni *post hoc* test (with a significance level corrected for multiple comparisons at 0.007). All angles showed significant differences between groups (Table 3.20). The Bonferroni post-hoc test revealed which of the samples were significantly different for the angles of cranial base flexion. A major finding was that the Polynesian sample was consistently different from all the other samples, for all cranial base angles.

Some angles showed more variation between samples than others. For example, the angle basion-pituitary point-sphenoidal plane showed that, with the exception of the Polynesian sample, all other samples were similar. A similar finding was seen in the results for the angle basion-SE-nasion. All samples were significantly different from the Polynesians, and the Australian and African S/X/Z samples differed significantly, but no other significant differences were present.

The other angles showed more complex relationships between samples. For example, the angles basion-sella-nasion, basion-pituitary point-nasion, clival plane-sella-nasion and endocranial clival plane-sella-nasion all had similar patterns of significant differences. These showed that the Chinese, American and Australian samples seemed to fall into one group, while the two African samples were another. The Thai sample was similar to all other samples apart from the Polynesians, and the Polynesians were significantly different from all other samples.

The following array of figures depicts significant differences between the samples for the cranial base angles (Figures 3.1 to 3.7). In all figures, the average value for the total sample is shown to the far right of the figure. Error bars represent the standard error of the mean for each sample.

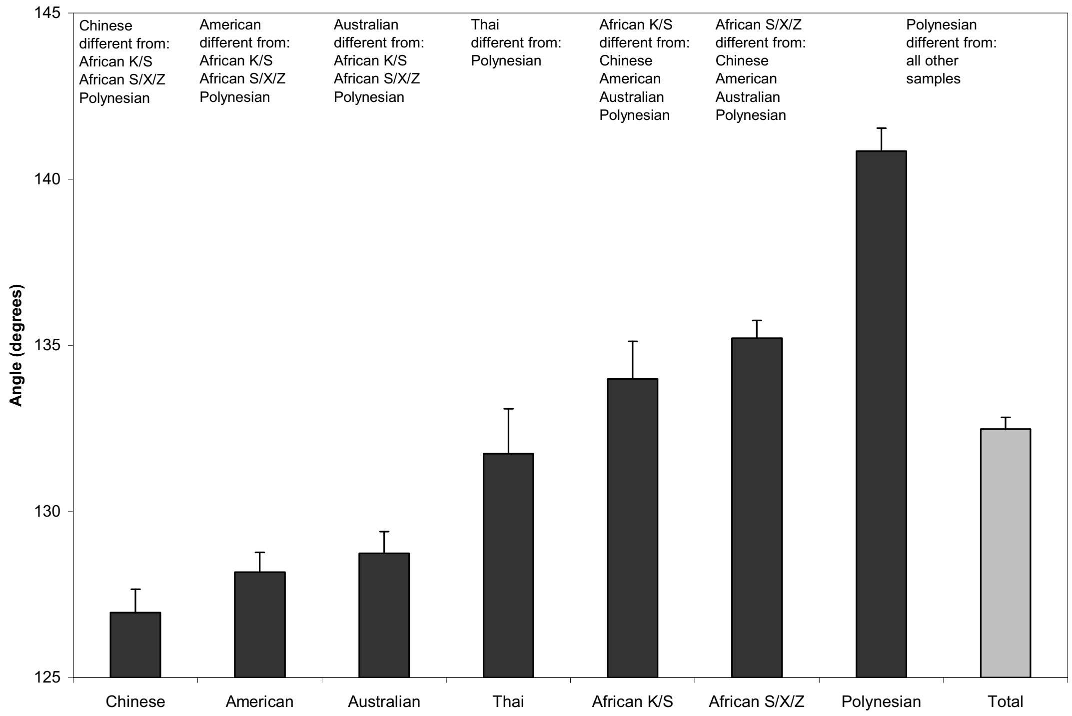

Figure 3.1: Average values of the angle basion-sella-nasion for the samples, showing the total average and significant differences between samples.

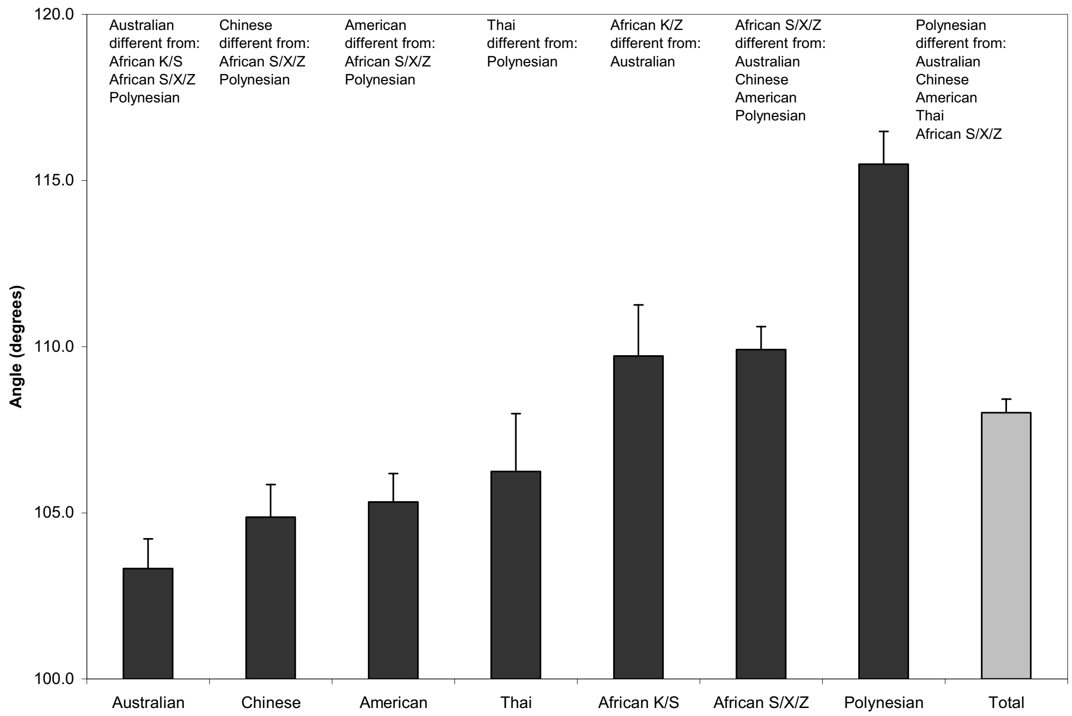

Figure 3.2: Average values of the angle clival plane-sphenoidal plane for the samples, showing the total average and significant differences between samples.

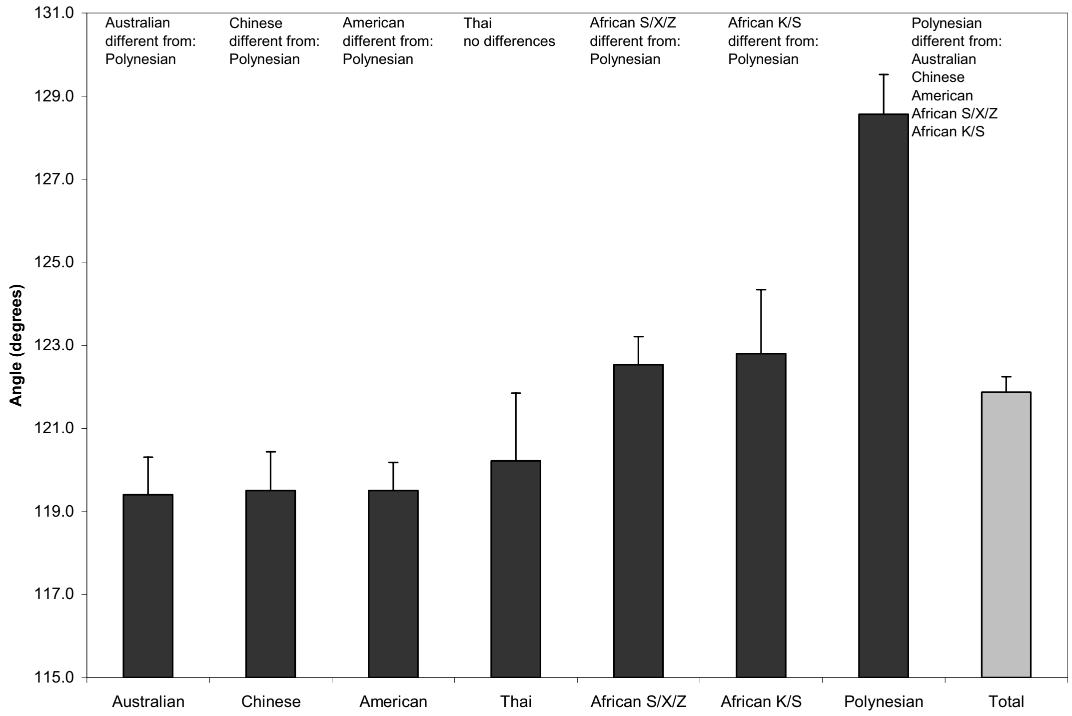

Figure 3.3: Average values of the angle basion-pituitary point-sphenoidal plane for the samples, showing the total average and significant differences between samples.

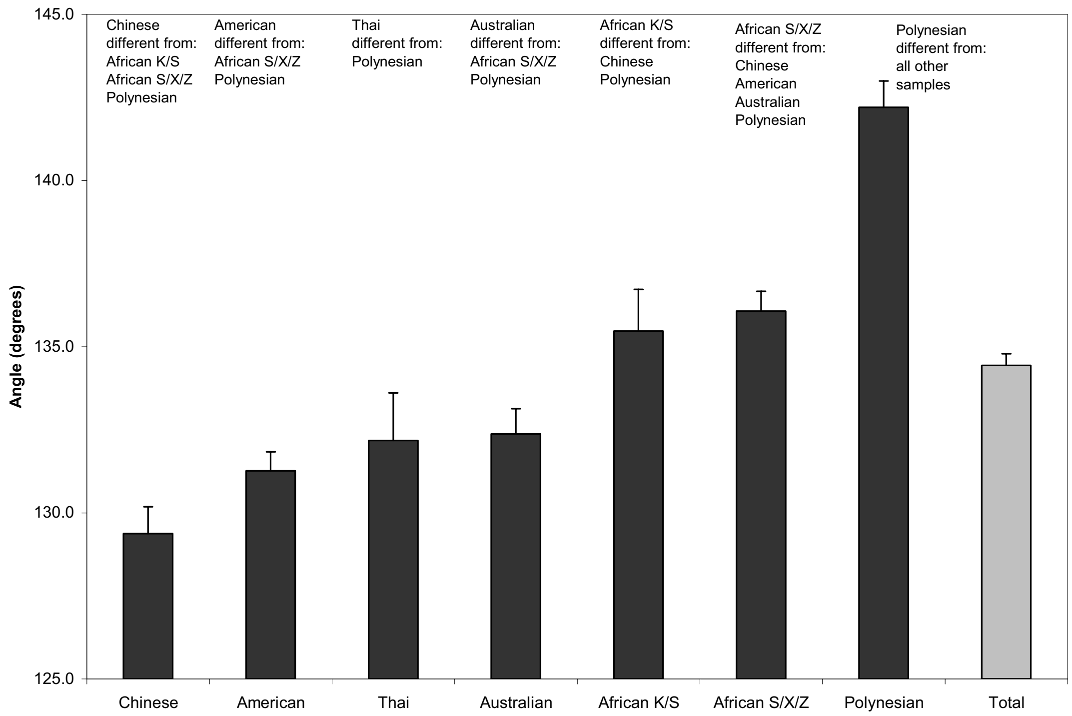

Figure 3.4: Average values of the angle basion-pituitary point-nasion for the samples, showing the total average and significant differences between samples.

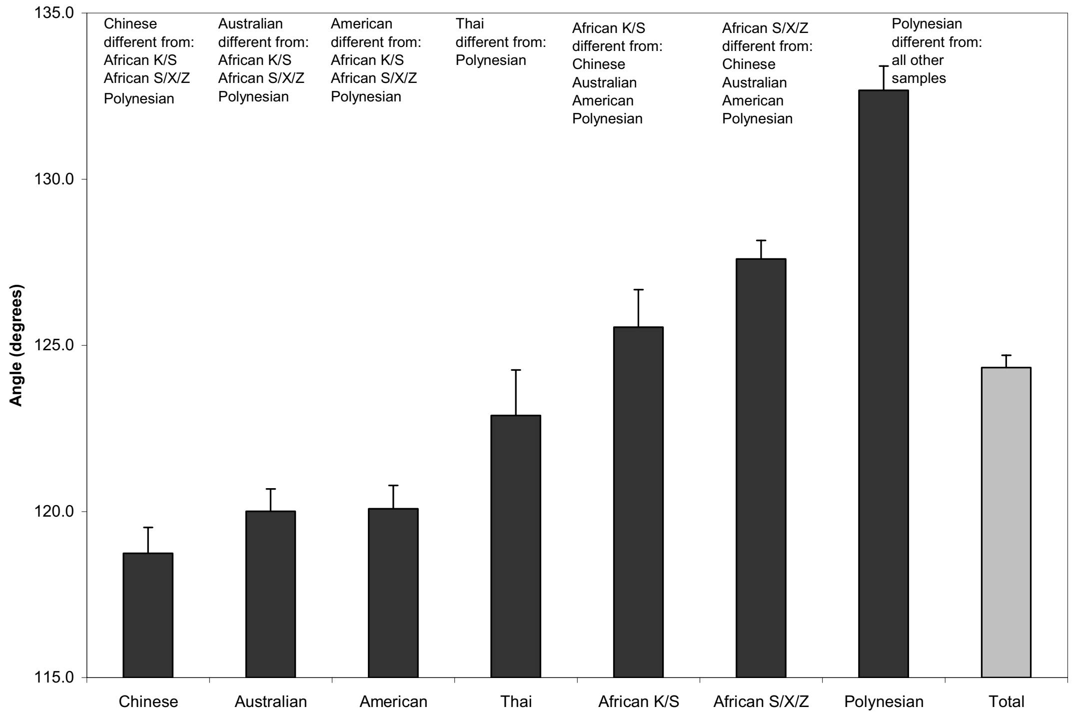

Figure 3.5: Average values of the angle clival plane-sella-nasion for the samples, showing the total average and significant differences between samples.

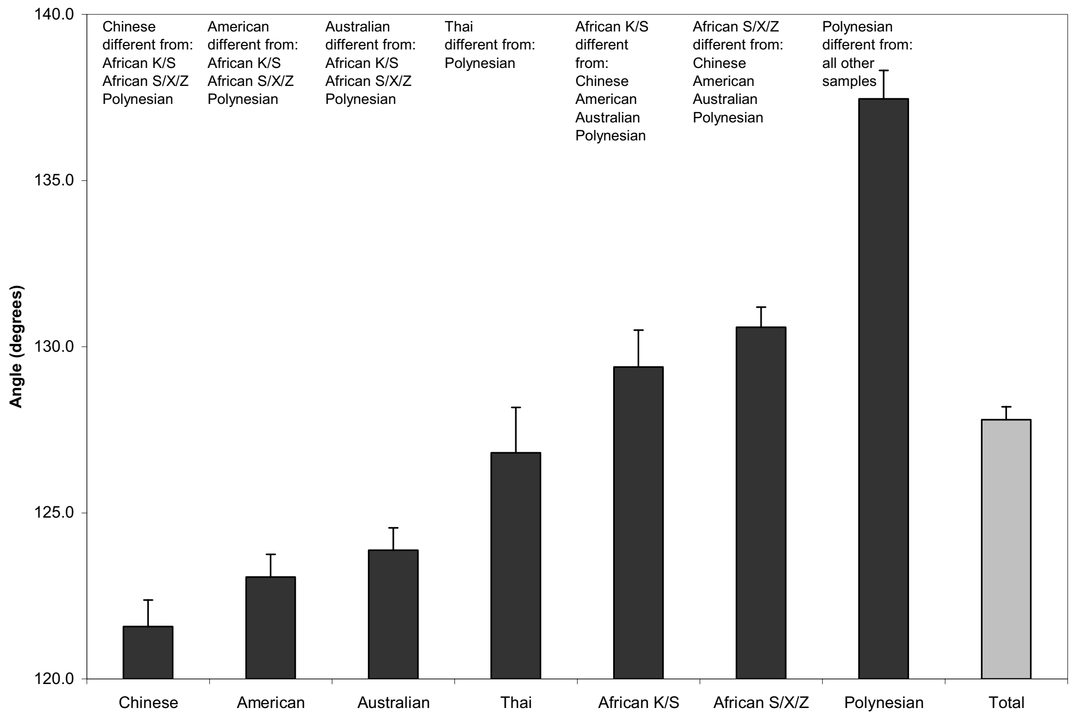

Figure 3.6: Average values of the angle endocranial clival plane-sella-nasion for the samples, showing the total average and significant differences between samples.

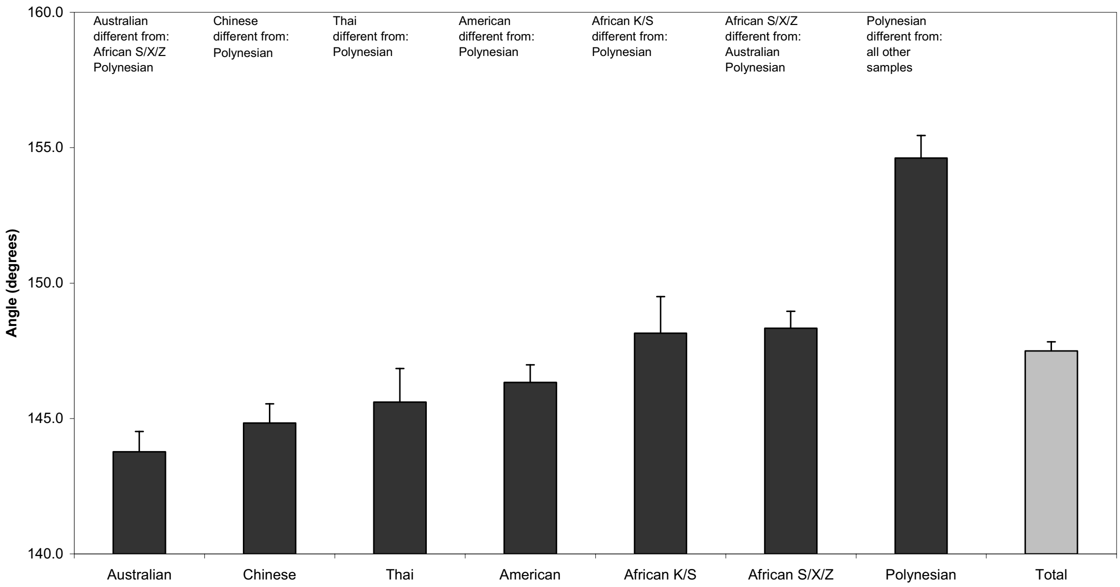

Figure 3.7: Average values of the angle basion-SE-nasion for the samples, showing the total average and significant differences between samples.

A measure of the amount of individual variation can be obtained from the results of the ANOVA, by considering the amount of variation within groups. This shows that for all variables of cranial base flexion, within group variation contributes more than 58% to the total variation. Percentage values of within group variation are shown in Table 3.21. The percentages for within group variation range between 58.3% for the angle endocranial clival plane-sella-nasion and 84.8% for the angle basion-pituitary point-sphenoidal plane. The corresponding between-group variation percentages range between 14.2% for the angle basion-pituitary point-sphenoidal plane and 43.33% for the angle endocranial clival plane-sella-nasion.

Table 3.21: The percentage of within and between group variation contributing to the total variation of angles of cranial base flexion.

	Within group variation (%)	Between group variation (%)	Total variation (%)
BA.S.N	58.82	41.18	100
CLIV.SPH	78.55	21.45	100
BA.PP.SP	84.78	14.22	100
BA.PP.N	70.66	29.34	100
CLIV.S.N	59.67	43.33	100
ECP.S.N	58.30	41.70	100
BA.SE.N	77.99	22.01	100

Range of variation:

One of the aims of the current study was to establish the range of variation in cranial base flexion in the sample. This aim was developed to enhance the current studies in the literature that commonly present averages and standard deviations. It was also developed to present an estimation of "normal" variation of cranial base flexion in modern humans, to enable better and more accurate comparisons with individuals showing craniofacial abnormalities, as well as fossil hominins and other species. Results show that the range of cranial base flexion for the total sample (N = 414) is generally around 40 degrees for each angle (Table 3.22). The smallest range is seen for the angle basion-pituitary point-nasion, with 36.0 degrees, and the angle basion-sella-nasion is similar to this with an angle of 36.5 degrees. The largest range is seen for the clival plane-sphenoidal plane angle, with 46.5 degrees. Since these variables are normally distributed, the difference between minimum and maximum values is equivalent to three standard deviations above and below the mean value. This encompasses nearly 100% of the variation for each angle, whereas the range between one standard deviation above and below the mean only accounts for about 68% of the variation. The ranges of the various cranial base flexion angles of the present study are reported here; however, other studies tend to only report values of the mean and standard deviation. While the range (approximately three standard deviations above and below the mean) can be easily calculated from these statistics, most published studies focus on estimates of central tendency, and ignore the considerable variation clearly present.

Table 3.22: Descriptive statistics of cranial base flexion showing the range of variation (N = 414).

	Mean	Std. Deviation	Minimum	Maximum	Range
BA.S.N	132.5	7.1	115.5	152.0	36.5
CLIV.SPH	108.0	8.4	86.0	132.5	46.5
BA.PP.SP	121.9	7.7	103.5	145.0	41.5
BA.PP.N	134.4	7.2	117.0	153.0	36.0
CLIV.S.N	124.3	7.5	104.0	145.5	41.5
ECP.S.N	127.8	7.9	106.5	150.0	43.5
BA.SE.N	147.5	7.0	129.0	167.0	38.0

Conclusion of cranial base angles

Seven different cranial base angles were measured in this part of the study. The angles ranged from those most commonly used in analyses of cranial base flexion (basion-sella-nasion), to those attempting to describe the flexion of the anterior cranial base with more anatomical accuracy (for example those angles incorporating the main axis of the clivus or the sphenoidal plane. Results showed that all angles used to measure the flexion of the cranial base were positively and significantly correlated with each other. However, these correlations can largely be attributed to topographical correlations (Solow, 1966), which are to be expected when there is a close anatomical relationship between variables. Sexual dimorphism in cranial base flexion was not evident when the total sample was examined; however, in the Chinese and African K/S samples the males had some angles that were significantly smaller than in females.

Among the Chinese, the differences were present in the angles basion-sella-nasion, clival plane-sphenoidal plane, basion-pituitary point-sphenoidal plane, clival plane-sella-nasion, and endocranial clival plane-sella-nasion (the only angles not significantly different were basion-pituitary point-nasion and basion-SE-nasion). In the African K/S sample, a significant difference existed between males and females for the angle basion-SE-nasion, with females having a larger angle than males. Sample differences were tested using ANOVA, and it was found that significant differences between samples were evident in all angles. Results showed a consistent pattern among the samples with the Polynesians having larger values, on average, than the other samples for all the angles measured. The smallest angles were usually the American, Australian or Chinese samples, while both of the African samples were usually in the mid to high end of the range of variation. The results of this analysis generated average values of cranial base flexion for a large sample of individuals with normal craniofacial anatomy, representing various samples around the world.

The range of variation for each angle was generally around 40 degrees. Variation within groups was found to be larger than variation between groups. Most angles showed about 60% to 80% variation within groups, compared to between 20% to 40% variation between groups. This shows that individual variation contributes the most to the total variation for measurements of cranial base flexion.

Results of craniofacial angles

In this study, the lines of orientation of craniofacial structures are referred to as planes, despite them actually being lines on two-dimensional tracings of skulls. These lines result from the mid-sagittal plane intersecting various more or less horizontal planes defined by structures of the skull, for example the palate or foramen magnum. Since the lines represent planes in the craniofacial complex, they have often been referred to as planes in the orthodontic literature, similarly, in this study they are referred to as planes.

The orientation of each of the five planes used in this study to describe craniofacial variation is measured relative to the basion-pituitary point line. This enables comparisons between the planes, using the basion-pituitary point line as a constant. The basion-pituitary point line was selected to represent the orientation of the clivus as, on visual inspection, it passes through the main axis of the clivus compared to the other landmarks (Figure 2.10). The craniofacial angles are: the orientation of the foramen magnum (opisthion-basion), the orientation of the maxilla, measured along the hard palate (anterior nasal spine-posterior nasal spine) and three planes representing the anterior cranial base: sella-nasion, pituitary point-nasion and the sphenoidal plane (Figures 2.10 to 2.15).

The descriptive statistics of these planes for the whole sample (N = 414) are presented in Table 3.23. It can be seen that the average values for the opisthion-basion plane and the pituitary point-nasion plane are virtually parallel (they have the same angle relative to the basion-pituitary point plane). The remaining angles show various relationships to each other and to the basion-pituitary point plane. For example, the anterior nasal spine-posterior nasal spine plane is about 5 degrees more flexed than the opisthion-basion and pituitary point-nasion planes, the sphenoidal plane is about 12 degrees more flexed, and the sella-nasion plane is about 4 degrees less flexed.

Table 3.23: Descriptive statistics of the craniofacial angles (N = 414).

	Mean (degrees)	Std. Deviation	Minimum	Maximum	Coefficient of Variation
O.B	135.0	7.4	117.0	157.0	5.5
PALATE	50.3	5.7	33.5	66.0	11.4
S.N	138.3	6.6	122.0	156.0	4.8
PP.N	134.6	7.2	116.0	153.5	5.3
BA.PP.SP	121.9	7.7	103.5	145.0	6.3

Males and females were compared in the total sample and in each sample. A t-test for independent samples showed that the angle basion-opisthion with the clivus was the only one to show significant differences in the total sample, with males having a smaller angle than females. The other angles were not significantly different between males and females (Table 3.24).

Table 3.24: Male and female averages and standard deviations for craniofacial angles for the total sample, numbers in bold indicate significant differences (p = 0.05).

ANGLE	MALES (N = 225)		FEMALES (N = 189)		t	p
	MEAN	STD.DEV	MEAN	STD.DEV		
O.B	**133.8**	7.3	**136.3**	7.2	-3.47	**0.001**
ANS.PNS	50.4	5.9	50.1	5.5	0.64	0.524
S.N	138.1	7.1	138.5	6.0	-0.63	0.531
PP.N	134.6	7.6	134.6	6.7	-0.05	0.961
PP.SP	121.7	7.9	122.1	7.4	-0.63	0.531

When t-tests for independent samples were conducted for each sample separately, some samples had significant differences between males and females for some variables, while others were not significantly different (Table 3.25). The populations with significant differences were Chinese, American and African K/S. For the Chinese sample, males had significantly smaller angles than females for the angles opisthion-basion, sella-nasion and pituitary point-sphenoidal plane. Both American and African K/S males had a significantly smaller angle between the foramen magnum and the clivus compared to the females of the same samples.

Table 3.25: Male and female differences in each sample, numbers in bold indicate significant differences between males and females (p = 0.05).

GROUP	ANGLE	MALE		FEMALE		*t*	*p*
		MEAN	STD. DEV	MEAN	STD.DEV		
CHINESE	O.B	130.5	6.3	133.8	7.5	-1.7	0.089
	ANS.PNS	**57.0**	3.7	**53.9**	5.5	2.5	**0.016**
	S.N	**132.5**	4.9	**135.6**	5.2	-2.2	**0.031**
	PP.N	128.9	5.3	131.2	6.6	-1.4	0.164
	BA.PP.SP	**117.9**	6.9	**121.7**	6.3	-2.1	**0.045**
AMERICAN	O.B	**130.1**	6.7	**133.9**	7.0	-2.2	**0.031**
	ANS.PNS	53.1	3.5	53.0	5.3	0.1	0.921
	S.N	133.3	5.0	134.8	4.1	-1.3	0.190
	PP.N	130.2	5.1	131.3	4.5	-0.9	0.391
	BA.PP.SP	119.0	4.6	120.1	6.3	-0.8	0.400
AFRICAN K/S	O.B	**133.3**	6.0	**138.7**	7.6	-2.1	**0.041**
	ANS.PNS	49.4	6.2	46.9	4.7	1.1	0.266
	S.N	137.3	6.1	141.8	5.0	-2.0	0.051
	PP.N	134.3	6.7	138.0	6.0	-1.5	0.151
	BA.PP.SP	122.7	9.6	123.0	5.9	-0.1	0.947
POLYNESIAN	O.B	137.9	7.7	138.4	6.6	-0.2	0.830
	ANS.PNS	45.9	5.2	46.4	3.6	-0.3	0.750
	S.N	146.7	4.8	144.5	5.0	1.6	0.117
	PP.N	143.4	5.9	141.4	5.9	1.2	0.234
	BA.PP.SP	129.2	7.6	127.3	6.2	1.0	0.336
AFRICAN S/X/Z	O.B	135.5	6.8	137.6	6.6	-1.7	0.098
	ANS.PNS	48.1	4.8	47.4	5.0	0.7	0.495
	S.N	140.2	5.3	140.6	5.7	-0.5	0.635
	PP.N	136.3	6.2	136.4	6.6	0.0	0.966
	BA.PP.SP	122.0	6.7	123.1	8.1	-0.8	0.440
THAI	O.B	134.4	5.9	136.8	7.4	-0.8	0.444
	ANS.PNS	51.9	5.1	52.6	4.1	-0.4	0.720
	S.N	136.2	7.9	136.5	5.8	-0.1	0.906
	PP.N	132.3	7.4	131.8	6.0	0.2	0.868
	BA.PP.SP	120.9	7.6	119.9	8.1	0.3	0.775
AUSTRALIAN	O.B	133.4	7.5	135.9	7.7	-1.4	0.172
	ANS.PNS	51.2	5.3	51.4	4.1	-0.1	0.888
	S.N	135.9	5.7	136.7	5.2	-0.6	0.522
	PP.N	131.9	6.5	133.4	6.0	-1.0	0.342
	BA.PP.SP	118.3	7.3	120.5	7.4	-1.3	0.212

The average sample differences for the craniofacial angles are as follows: All samples generally have the same average pattern of craniofacial angles relative to the basion-pituitary point plane. The greatest flexion is seen in the sphenoidal plane and the least amount of flexion is seen in the sella-nasion plane. The plane of the hard palate (anterior nasal spine-posterior nasal spine) is more flexed than the opisthion-basion and pituitary point-nasion planes, which are for the most part quite similar in angular measurements. The Polynesian sample has much higher average values than the other groups, and the Chinese sample has smaller average values. American, Australian, Thai and African samples are similar in average values (Table 3.26). The interesting parallel nature of the opisthion-basion and pituitary point-nasion planes is seen most clearly in African K/S and African S/X/Z samples. The other samples generally have about two degrees difference, with the pituitary point-nasion angle being slightly more flexed than the opisthion-basion angle, except for the Polynesian group which has a four degree difference, and the opisthion-basion plane is more flexed relative to the basion-pituitary point plane than the pituitary point-nasion plane. Two-way ANOVA found no significant interaction between sample and sex for each of the craniofacial angles studied.

Table 3.26: Descriptive statistics of craniofacial angles among the samples.

SAMPLE	ANGLE	Mean	Std. Deviation	Minimum	Maximum
CHINESE	O.B	131.8	7.0	117.0	146.0
(N = 65)	ANS.PNS	55.7	4.7	44.0	66.0
	S.N	133.8	5.2	123.0	149.0
	PP.N	129.8	5.9	118.5	149.0
	BA.PP.SP	119.5	6.8	103.5	136.5
AMERICAN	O.B	131.9	7.0	119.0	154.5
(N = 64)	ANS.PNS	53.1	4.4	42.5	65.0
	S.N	134.0	4.6	123.0	141.0
	PP.N	130.7	4.8	119.5	140.0
	BA.PP.SP	119.5	5.5	105.0	134.0
AFRICAN K/S	O.B	135.1	7.0	119.0	150.0
(N = 30)	ANS.PNS	48.6	5.8	38.0	59.5
	S.N	138.8	6.1	128.0	152.0
	PP.N	135.5	6.6	124.0	150.0
	BA.PP.SP	122.8	8.4	108.0	142.0
POLYNESIAN	O.B	138.1	7.3	124.5	155.0
(N = 56)	ANS.PNS	46.1	4.7	33.5	57.0
	S.N	146.0	4.9	134.5	156.0
	PP.N	142.7	5.9	128.0	153.5
	BA.PP.SP	128.6	7.1	113.0	145.0
AFRICAN S/X/Z	O.B	136.5	6.8	123.0	157.0
(N = 121)	ANS.PNS	47.8	4.9	36.0	62.0
	S.N	140.4	5.4	129.0	154.0
	PP.N	136.4	6.3	123.0	153.0
	BA.PP.SP	122.5	7.4	106.0	140.0
THAI	O.B	136.0	6.9	122.0	150.0
(N = 23)	ANS.PNS	52.4	4.3	45.0	59.0
	S.N	136.4	6.4	123.5	145.0
	PP.N	132.0	6.3	119.0	141.0
	BA.PP.SP	120.2	7.8	106.0	134.0
AUSTRALIAN	O.B	134.6	7.6	117.0	153.0
(N = 68)	ANS.PNS	51.3	4.7	37.0	61.0
	S.N	136.3	5.4	122.0	151.5
	PP.N	132.6	6.2	116.0	150.0
	BA.PP.SP	119.4	7.4	104.0	141.0

Correlation coefficients were calculated between these angles, and are shown in Table 3.27. All angles are significantly correlated with each other (significant at 0.0025) when the sample is analysed as a whole. The plane of the foramen magnum was negatively correlated with the palatal plane, but was positively correlated with the anterior cranial base planes. The orientation of the hard palate also had a negative correlation with the anterior cranial base planes. The three anterior cranial base planes (sella-nasion plane, pituitary point-nasion plane and pituitary point-sphenoidal plane) were all positively correlated, especially the sella-nasion and pituitary point-nasion planes with a correlation of 0.96. These two correlated at about 0.75 with the sphenoidal plane.

Table 3.27: Correlation coefficients between the craniofacial angles (N = 414): All correlations in bold font are significant at 0.001 (significance level adjusted for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.540**			
S.N	Correlation	**0.578**	**-0.794**		
PP.N	Correlation	**0.594**	**-0.797**	**0.962**	
BA.PP.SP	Correlation	**0.511**	**-0.592**	**0.746**	**0.771**

The relationship between these planes can be described as follows. The positive correlations between the three planes representing the anterior cranial base show that as one angle changes, the others show corresponding changes. This is especially so for the two planes ending at nasion. The negative correlation between the angle of the foramen magnum and the hard palate relative to the clivus shows that as the angle between the clivus and the foramen increases, the angle between the hard palate and the clivus decreases, and *vice versa*. The negative correlations between the hard palate and the anterior cranial base planes show that as the angle between the clivus and the anterior cranial base increases, the angle between the palate and the clivus decreases. The positive correlations between the plane of the foramen magnum and the anterior cranial base planes relative to the clivus show that with increasing flexion of the cranial base the foramen magnum-clivus angle becomes smaller, and *vice versa*.

Considering the samples individually for correlations between the craniofacial angles, the pattern seen in the total sample is repeated (Tables 3.28 to 3.34). Correlations between the opisthion-basion orientation and the hard palate are negative, as are the correlations between the palate and the three anterior cranial base planes. The orientation of the foramen magnum is positively correlated with the orientation of the anterior cranial base, and all three angles representing the anterior cranial base are positively correlated. All relationships involving the hard palate (ANS-PNS) are significantly correlated at the level of 0.001. The same is true for the relationships involving each of the three anterior cranial base planes. The correlations between opisthion-basion and the other planes for the most part were at a significance level of 0.001. The exceptions are in the African K/S and Thai samples. Specifically, in the African K/S sample the anterior nasal spine-posterior nasal spine and sella-nasion planes are significantly correlated with opisthion-basion at 0.05, while the correlation between opisthion-basion and the sphenoidal plane is not significant. In the Thai sample, anterior nasal spine-posterior nasal spine and the sphenoidal plane are significantly and negatively correlated with opisthion-basion at a level of 0.05, while the other angles (pituitary point-nasion and sella-nasion) are not significantly correlated with the hard palate.

Table 3.28: Correlations of craniofacial angles among Chinese (N = 65), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.505**			
	p. (2-tailed)	**0.000**			
S.N	Correlation	**0.617**	**-0.800**		
	p. (2-tailed)	**0.000**	**0.000**		
PP.N	Correlation	**0.601**	**-0.788**	**0.961**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	
BA.PP.SP	Correlation	**0.484**	**-0.507**	**0.727**	**0.728**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.29: Correlations of craniofacial angles among Americans (N = 64), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.419**			
	p. (2-tailed)	**0.001**			
S.N	Correlation	**0.453**	**-0.448**		
	p. (2-tailed)	**0.000**	**0.000**		
PP.N	Correlation	**0.475**	**-0.600**	**0.834**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	
BA.PP.SP	Correlation	**0.525**	**-0.459**	**0.595**	**0.619**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.30: Correlations of craniofacial angles among African K/S (N = 30), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	-0.423			
	p. (2-tailed)	0.020			
S.N	Correlation	0.465	**-0.762**		
	p. (2-tailed)	0.010	**0.000**		
PP.N	Correlation	**0.560**	**-0.776**	**0.944**	
	p. (2-tailed)	**0.001**	**0.000**	**0.000**	
BA.PP.SP	Correlation	0.287	**-0.568**	**0.728**	**0.732**
	p. (2-tailed)	0.124	**0.001**	**0.000**	**0.000**

Table 3.31: Correlations of craniofacial angles among Polynesians (N = 56), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.515**			
	p. (2-tailed)	**0.000**			
S.N	Correlation	**0.649**	**-0.686**		
	p. (2-tailed)	**0.000**	**0.000**		
PP.N	Correlation	**0.722**	**-0.705**	**0.962**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	
BA.PP.SP	Correlation	**0.574**	**-0.552**	**0.700**	**0.746**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.32: Correlations of craniofacial angles among African S/X/Z (N = 121), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.462**			
	p. (2-tailed)	**0.000**			
S.N	Correlation	**0.501**	**-0.773**		
	p. (2-tailed)	**0.000**	**0.000**		
PP.N	Correlation	**0.493**	**-0.753**	**0.971**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	
BA.PP.SP	Correlation	**0.439**	**-0.598**	**0.766**	**0.780**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.33: Correlations of craniofacial angles among Thai (N = 24), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	-0.449			
	p. (2-tailed)	0.041			
S.N	Correlation	0.322	**-0.871**		
	p. (2-tailed)	0.134	**0.000**		
PP.N	Correlation	0.336	**-0.845**	**0.962**	
	p. (2-tailed)	0.117	**0.000**	**0.000**	
BA.PP.SP	Correlation	0.414	**-0.505**	0.571	**0.656**
	p. (2-tailed)	0.049	**0.020**	0.004	**0.001**

Table 3.34: Correlations of craniofacial angles among Australians (N = 68), significance level 0.01 (corrected for multiple comparisons).

		O.B	PALATE	S.N	PP.N
PALATE	Correlation	**-0.582**			
	p. (2-tailed)	**0.000**			
S.N	Correlation	**0.654**	**-0.773**		
	p. (2-tailed)	**0.000**	**0.000**		
PP.N	Correlation	**0.661**	**-0.760**	**0.958**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	
BA.PP.SP	Correlation	**0.544**	**-0.536**	**0.719**	**0.734**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**

Table 3.35: Results of ANOVA for the craniofacial angles, showing differences between groups.

		Sum of Squares	df	Mean Square	F	Sig.
O.B	Between Groups	1990.49	6	331.75	6.63	0.000
	Within Groups	20323.32	406	50.06		
	Total	22313.81	412			
PALATE	Between Groups	4027.26	6	671.21	29.11	0.000
	Within Groups	9223.17	400	23.06		
	Total	13250.43	406			
S.N	Between Groups	6443.58	6	1073.93	37.87	0.000
	Within Groups	11542.28	407	28.36		
	Total	17985.86	413			
PP.N	Between Groups	6689.01	6	1114.84	30.82	0.000
	Within Groups	14723.08	407	36.18		
	Total	21412.09	413			
BA.PP.SP	Between Groups	3720.34	6	620.06	12.17	0.000
	Within Groups	20730.24	407	50.93		
	Total	24450.58	413			

Analysis of variance (ANOVA) was conducted on the craniofacial angles. This revealed significant differences between groups for all planes (Table 3.35). The results for the Bonferroni *post hoc* test (with significance adjusted for multiple comparisons) describe the following differences between groups. The following array of figures (Figures 3.8 to 3.14) shows the relationships between the samples for the various craniofacial angles. For the orientation of the foramen magnum (opisthion-basion), few differences between samples were seen (Figure 3.8). The Chinese and American groups were different from the Polynesian and the African S/X/Z groups. No differences were found between any other groups. This angle shows the least differences compared to any other, and this may be a good reason for using it as a baseline for comparing differences between groups.

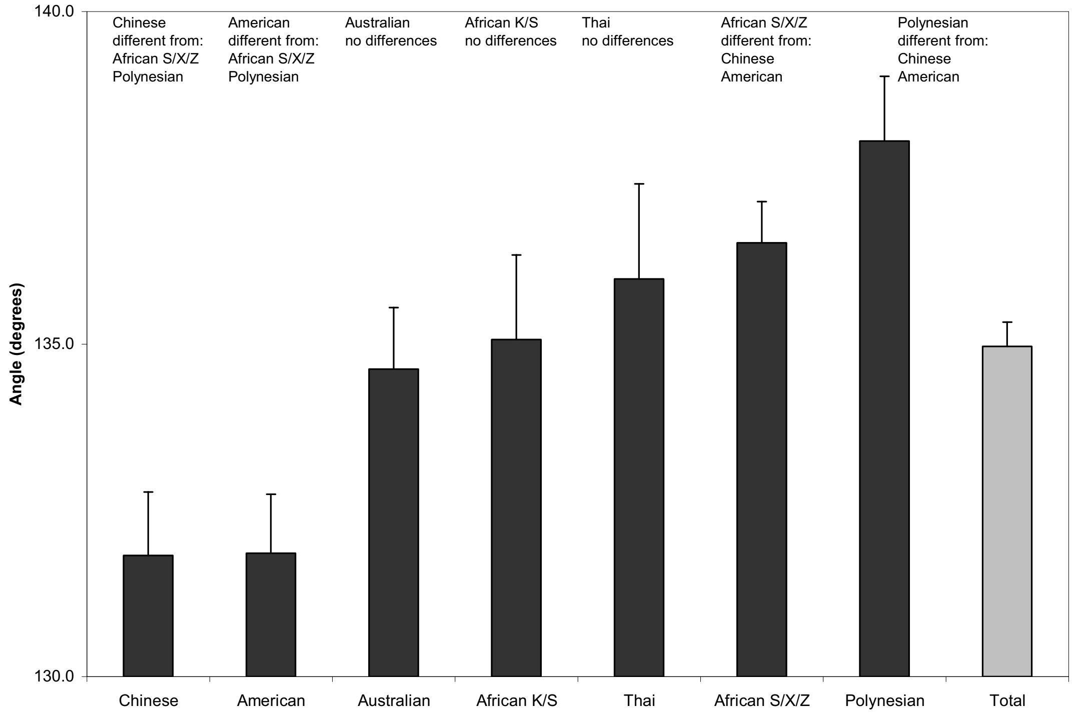

Figure 3.8: Sample averages for the angle between the foramen magnum and the basion-pituitary point plane, including the total average and showing significant differences between samples.

The angle of the hard palate relative to the clivus has significant differences between most groups. Figure 3.9 shows the results of the analysis in conjunction with sample means. For this comparison, the general trend of size of angles has been reversed, with the Polynesian and both African samples having smaller angles, and the Chinese and American samples showing the largest angles. The Polynesians showed significant differences with Chinese, American, Thai and Australians. The African S/X/Z sample was significantly different from Chinese, Americans, Thai and Australians, while the African S/X/Z group was significantly different from Chinese, American samples only. Australians were significantly different from Chinese, Polynesian and African S/X/Z samples, and the Thai group was significantly different from Polynesian and African S/X/Z people. The American sample was significantly different from Polynesian and both African samples. The Chinese sample was significantly different from both of the African groups, as well as Polynesian and Australian samples (Figure 3.9).

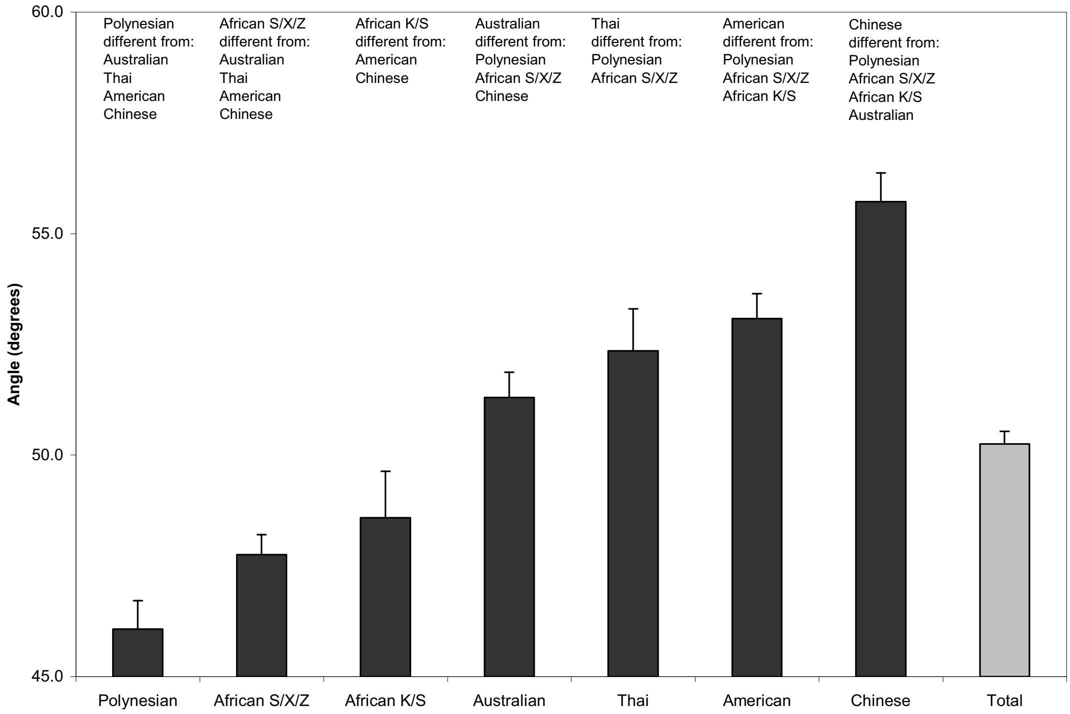

Figure 3.9: Sample averages for the angle between the hard palate (ANS-PNS) and the basion-pituitary point plane, including the total average and showing significant differences between samples.

Three angles were measured which represented different orientations of the anterior cranial base. These were sella-nasion, pituitary point-nasion and the sphenoidal plane. The orientation of the sella-nasion and pituitary point-nasion planes was similar when significant differences between groups were compared. The results are shown in Figures 3.10 and 3.11. For both planes, the Chinese were significantly different from Africans (both K/S and S/X/Z groups) and Polynesians. Americans were significantly different from both African groups, and the Polynesian group for the angle with the sella-nasion line, but for the pituitary point-nasion line they had significant differences with the African S/X/Z group and the Polynesian sample only. The Thai people showed significant differences from Polynesians in both angles. Australians were significantly different from Polynesians and African S/X/Z groups for both angles. The African K/S sample was significantly different from Chinese, American and Polynesian samples for the sella-nasion line. For the pituitary point-nasion line there was no significant difference from the American sample, but the other two samples remained significantly different from the African K/S sample. The African S/X/Z group was significantly different from Chinese, American, Australian and Polynesian samples for both the pituitary point-nasion line and the sella-nasion line. In both comparisons, the Polynesian sample was significantly different from all other sample averages.

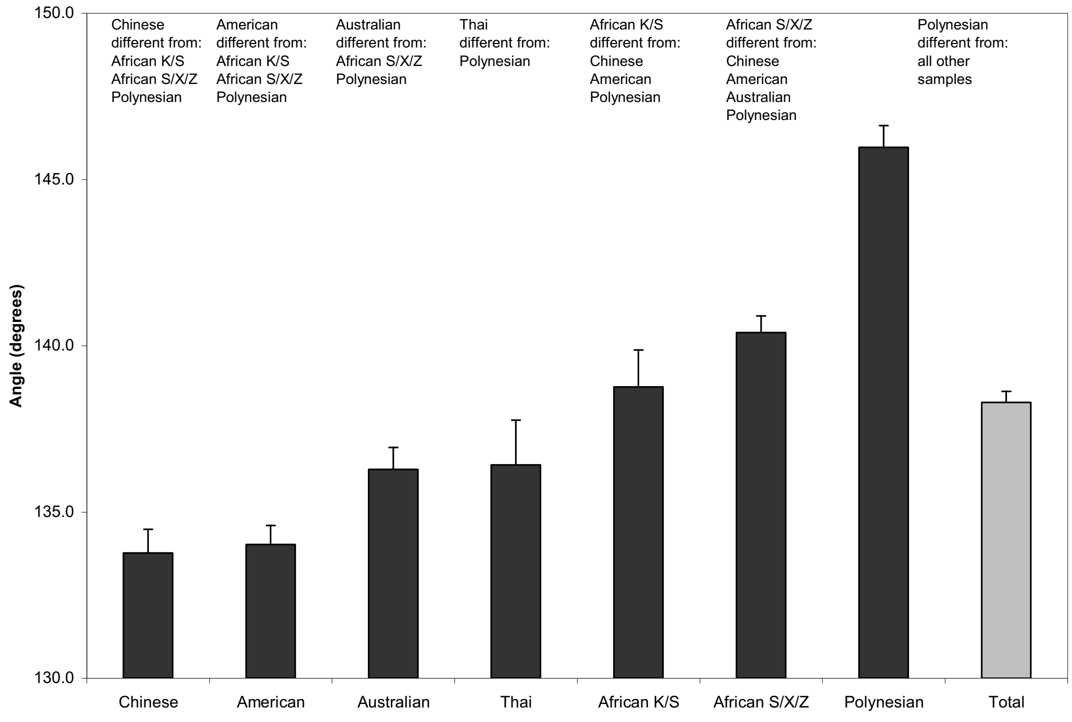

Figure 3.10: Sample averages for the angle between sella-nasion and the basion-pituitary point plane, including the total average and showing significant differences between samples.

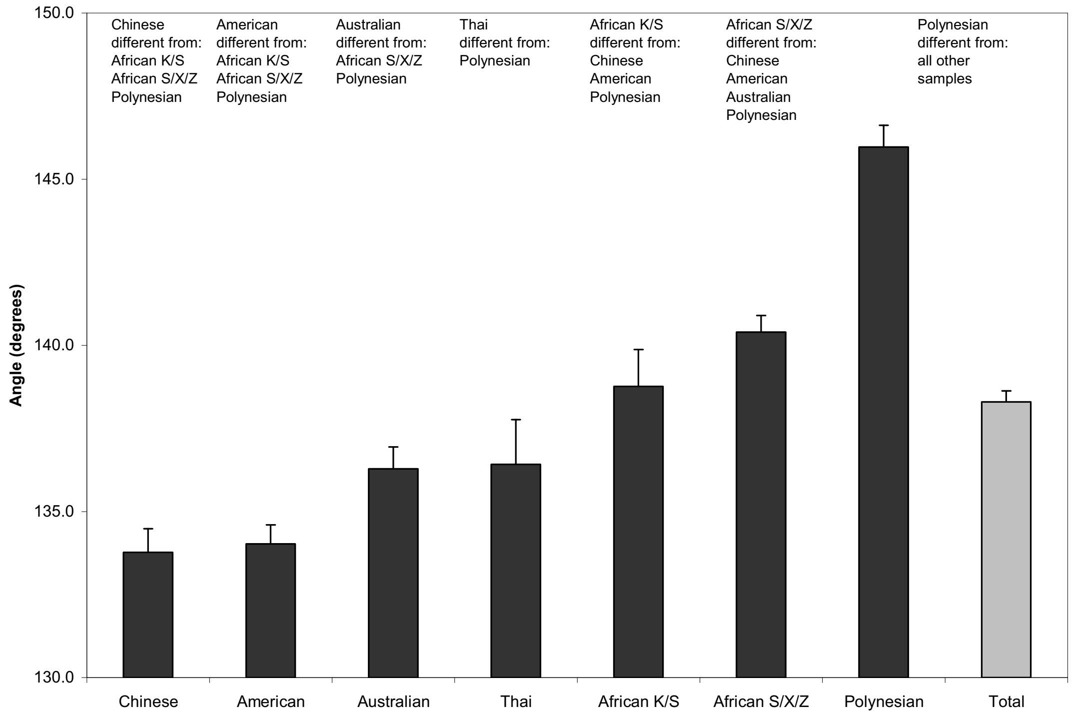

Figure 3.11: Sample averages for the angle between pituitary point-nasion and the basion-pituitary point plane, including the total average and showing significant differences between samples

The other angle measuring the orientation of the anterior cranial base relative to the clivus was along the plane of the sphenoid bone. This same angle was discussed in the earlier section on cranial base angles, but because of a different number of comparisons in this test (adjustment for multiple comparisons), the significance level was altered, and the results are slightly different. With the exception of the African K/S sample, all groups were significantly different from the Polynesian sample, but were not significantly different from each other. The African K/S sample was not significantly different from any of the samples (Figure 3.12).

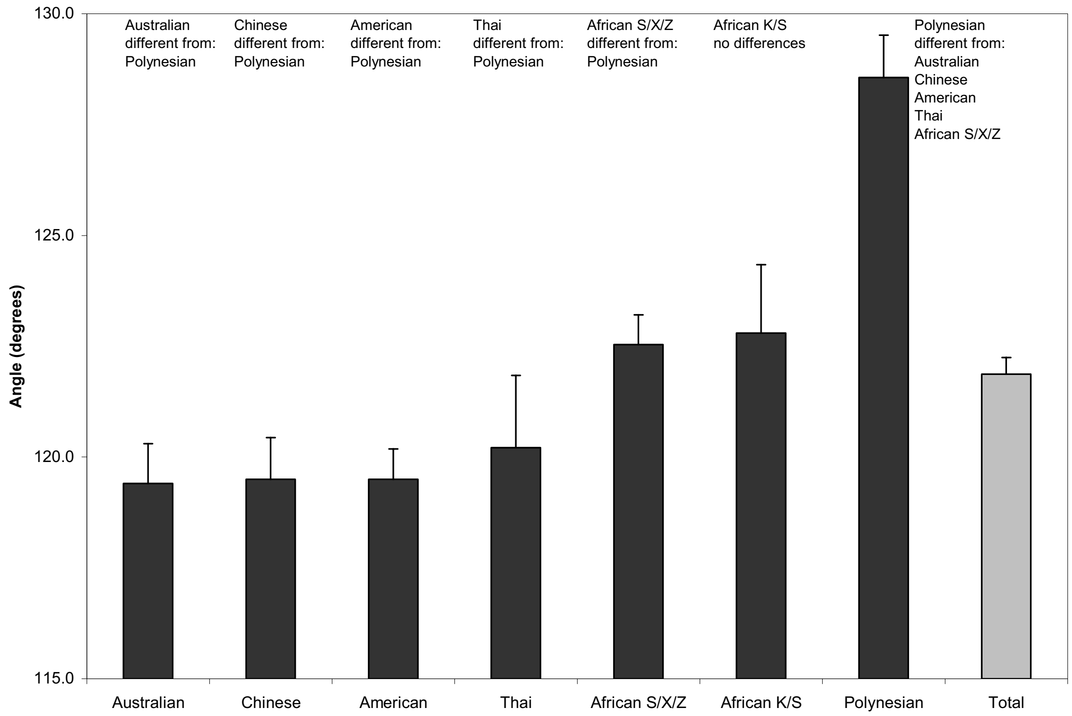

Figure 3.12: Sample averages for the angle between the sphenoidal plane and the basion-pituitary point plane, including the total average and showing significant differences between samples.

The amount of variation present among and within groups was calculated using the results from the ANOVA (Table 3.36). For these variables, the within group variation was substantial, contributing between 64% and 91% of the variation, while differences between groups ranged from between 9% and 36%. The variable with the largest amount of variation between individuals of the same sample was the angle of orientation of basion-opisthion relative to the clivus. The variable with the smallest amount of variation between individuals of the same sample was the angle of orientation of the sella-nasion plane relative to the clivus.

Table 3.36: The percentage of within and between group variation contributing to the total variation of angles of orientation of craniofacial angles

Variable	Within group variation (%)	Between group variation (%)	Total variation (%)
O.B	91.1	8.9	100.0
PALATE	69.6	30.4	100.0
S.N	64.2	35.8	100.0
PP.N	68.8	31.2	100.0
BA.PP.SP	84.8	15.2	100.0

Conclusion of craniofacial angles

In this section, the orientation of craniofacial angles relative to the clivus was measured. The five planes represented the anterior cranial base (measured three different ways between sella-nasion, pituitary point-nasion and the sphenoidal plane), hard palate and foramen magnum. Correlations between the five planes were all significant. Positive correlations were found between the opisthion-basion, sella-nasion, pituitary point-nasion and sphenoidal planes, while the orientation of the hard palate relative to the clivus was negatively correlated with the other planes. In the total sample, sexual dimorphism was present for the opisthion-basion plane, with females having a greater angle of orientation relative to the clivus compared to males (a difference of 2.5 degrees). When the samples were examined separately for sexual dimorphism, some samples showed differences while others did not. The samples displaying a significant difference between males and females were the Chinese, American and African K/S samples. The American and African K/S samples were only significantly different for the orientation of the basion-opisthion plane, while the Chinese sample had male/female differences for the orientation of the hard palate, sella-nasion and sphenoidal planes. Analysis of variance revealed significant differences between the samples for the five planes.

Summary of results for the dimensions of the cranial base and facial skeleton

A number of cranial base and facial dimensions were measured in the study. The cranial base measurements were described and illustrated in the Methods chapter (Figures 2.16 to 2.25). The dimensions consist of sella-nasion, a measurement of the anterior cranial base, basion-sella, a measurement of the clival length, and basion-nasion, an overall measurement of the cranial base size. The diameter of the foramen magnum was measured as the distance between basion and opisthion. The basion-PNS measurement describes the distance between the base of the clivus and the posterior limit of the hard palate, while PNS-ANS and PNS-A point measure the length of the hard palate in two different ways. The orthodontic landmark A point was added as a landmark of the anterior palate since a large number of skulls in the sample had indistinct ANS landmarks due to post-mortem damage. The height of the nose was measured from nasion-ANS and nasion-A point. Reduced sample numbers for the measurements including landmarks on the maxilla (anterior nasal spine and the orthodontic A point) were due to a number of skulls having damage to this region. The descriptive statistics of these dimensions in the whole sample are shown in Table 3.37. All measurements were corrected for radiographic magnification using percentages calculated for each sample (see Methods chapter).

Table 3.37: Dimension descriptive statistics for the total sample (N=414)

Dimension	Mean	Std. Deviation	Minimum	Maximum	N	Coefficient of Variation
sella-nasion	68.9	4.9	56.1	81.9	414	6.7
basion-sella	45.5	4.0	35.8	59.7	414	7.4
basion-nasion	104.6	7.6	86.0	128.1	414	6.3
basion-opisthion	35.7	5.1	23.8	53.4	413	12.3
basion-pns	47.3	5.6	28.2	64.0	414	9.5
pns-ans	51.6	4.3	40.4	64.5	395	6.9
pns-a point	49.6	4.5	37.6	64.0	385	6.3
nasion-ans	52.0	4.2	41.9	63.1	394	7.8
nasion-a point	56.4	4.6	44.6	70.4	385	7.5

Mean values for each sample are shown in Table 3.38, along with other descriptive statistics. The following relationships were found: the samples with the largest anterior cranial base (sella-nasion) measurements were the African S/X/Z and Khoi-San groups, followed by Australians, Polynesians and Americans. Thai and Chinese samples had the smallest anterior cranial base lengths. Clival length (basion-sella) followed a different pattern, with African S/X/Z people having on average a longer clivus than American and Khoi-San, Polynesian and Chinese people. Thai and Australian people had the smallest average clivus length. When comparing samples, the African S/X/Z and African K/S people had the largest dimensions of basion-nasion, followed by Polynesians, Americans, Australians, Thai and Chinese. The size of the foramen magnum (basion-opisthion) was greatest in the two African samples, with African K/S being slightly larger than African S/X/Z. The next largest was the Polynesian group, followed by American, Thai, Australian and Chinese groups. The distance between basion and the posterior extremity of the hard palate (PNS) was greatest in African S/X/Z and African K/S people respectively. Slightly smaller than these were Polynesian, Australian, American and Thai people, with Chinese people having the shortest distance. The length of the hard palate (PNS-ANS) reached its maximum in Polynesian people, followed by African S/X/Z and African K/S. Australians and

Americans had slightly smaller measurements, followed by Thai and Chinese people with the smallest palates. The corresponding dimension of PNS-A point showed a slight difference in the shape of the anterior, mid-sagittal maxillary shape between groups. African S/X/Z and Polynesians had similar measurements, followed by African K/S, Australian, American, Thai and Chinese. The height of the nose, measured from nasion to the anterior nasal spine (N-ANS) was greatest in Polynesian people. African S/X/Z, Chinese and Thai followed with the next largest nose heights, and American, African K/S and Australians had smaller measurements. When measured from nasion to A point, the pattern of results, from largest to smallest, was Polynesian, African S/X/Z, Chinese, American, African K/S, Thai and Australian.

Table 3.38. Descriptive statistics of dimensions in the samples

SAMPLE	Dimension	Mean	Std. Dev.	Minimum	Maximum
CHINESE (N = 65)	sella-nasion	63.4	3.5	56.6	71.9
	basion-sella	45.0	3.5	36.7	52.9
	basion-nasion	97.0	4.9	87.2	108.6
	basion-opisthion	30.5	3.0	24.1	38.5
	basion-pns	41.9	3.4	34.8	48.7
	pns-ans	46.6	2.9	40.4	52.4
	pns-a point	43.6	2.9	37.6	49.2
	nasion-ans	53.3	3.4	46.9	61.2
	nasion-a point	57.6	3.5	50.6	65.9
AMERICAN (N = 64)	sella-nasion	67.1	4.5	56.1	78.1
	basion-sella	45.0	3.3	38.6	52.5
	basion-nasion	101.0	6.4	86.0	115.5
	basion-opisthion	35.1	4.3	24.6	44.2
	basion-pns	43.3	4.1	32.2	53.4
	pns-ans	50.7	3.5	41.4	57.5
	pns-a point	47.4	3.0	40.5	54.3
	nasion-ans	50.6	4.0	41.9	58.9
	nasion-a point	55.5	4.2	44.6	63.9
AFRICAN K/S (N = 30)	sella-nasion	72.7	3.1	67.4	79.0
	basion-sella	45.9	2.8	39.5	52.0
	basion-nasion	108.8	4.8	99.7	121.8
	basion-opisthion	40.1	4.9	32.3	53.4
	basion-pns	50.7	4.9	43.3	61.6
	pns-ans	51.4	3.3	45.7	56.8
	pns-a point	50.6	3.2	45.7	56.3
	nasion-ans	50.4	3.9	42.4	56.3
	nasion-a point	55.2	4.1	47.7	64.5

Table 3.38 continued

SAMPLE	Dimension	Mean	Std. Dev.	Minimum	Maximum
POLYNESIAN (N = 56)	sella-nasion	68.8	3.5	61.4	79.1
	basion-sella	45.2	3.6	38.2	54.1
	basion-nasion	107.4	5.6	93.6	122.3
	basion-opisthion	36.5	2.3	29.1	41.4
	basion-pns	47.9	3.4	39.5	55.9
	pns-ans	55.0	3.6	47.3	62.7
	pns-a point	52.5	3.0	44.5	59.1
	nasion-ans	55.0	4.1	45.9	62.7
	nasion-a point	60.1	4.9	50.9	70.4
AFRICAN S/X/Z (N = 121)	sella-nasion	72.3	3.8	62.1	81.9
	basion-sella	48.2	4.1	39.0	59.7
	basion-nasion	111.2	5.8	100.2	128.1
	basion-opisthion	39.5	4.2	27.0	48.6
	basion-pns	52.4	4.3	40.4	64.0
	pns-ans	53.6	4.1	40.4	64.5
	pns-a point	52.6	4.0	39.5	64.0
	nasion-ans	53.5	3.7	44.8	63.1
	nasion-a point	58.2	3.8	49.6	67.4
THAI (N =23)	sella-nasion	63.5	3.5	58.2	68.6
	basion-sella	44.0	3.1	38.6	49.5
	basion-nasion	97.6	5.1	90.0	109.1
	basion-opisthion	32.8	3.7	26.4	39.5
	basion-pns	43.7	4.8	28.2	52.3
	pns-ans	47.3	2.3	43.2	51.8
	pns-a point	46.5	3.4	39.5	51.4
	nasion-ans	51.8	3.2	46.4	58.2
	nasion-a point	55.0	2.5	51.8	61.8
AUSTRALIAN (N = 68)	sella-nasion	69.0	3.3	63.3	78.4
	basion-sella	42.2	3.1	35.8	50.4
	basion-nasion	100.6	4.6	91.7	111.9
	basion-opisthion	31.8	3.5	23.8	41.3
	basion-pns	45.6	3.4	38.5	53.6
	pns-ans	51.4	2.9	46.3	56.9
	pns-a point	49.9	2.9	43.1	56.4
	nasion-ans	48.3	2.4	44.0	54.1
	nasion-a point	51.8	2.9	47.2	61.9

Table 3.39. Male and female mean values and standard deviations for dimensions.

Dimension	Males (N = 226)		Females (N = 190)			
	Mean	Std. Dev.	Mean	Std. Dev.	t	*p*
sella-nasion	**70.3**	4.6	**67.2**	4.7	5.8	**0.000**
basion-sella	**46.8**	3.7	**44.0**	3.8	6.5	**0.000**
basion-nasion	**107.0**	7.0	**101.7**	7.4	6.5	**0.000**
basion-opisthion	36.2	5.2	35.0	5.0	1.8	0.074
basion-pns	**48.3**	5.4	**46.1**	5.7	3.4	**0.001**
pns-ans	**52.7**	4.3	**50.2**	4.0	5.5	**0.000**
pns-a point	**50.5**	4.5	**48.5**	4.3	4.0	**0.000**
nasion-ans	**53.4**	4.1	**50.4**	3.7	6.8	**0.000**
nasion-a point	**57.7**	4.5	**54.9**	4.3	5.7	**0.000**

Males were found to have significantly larger dimensions than females in all cranial base and facial measurements except basion-opisthion (t-test for independent samples, significance level = 0.05) (Table 3.39). However, when t-tests for significant differences between males and females were performed on each sample for the cranial base and facial dimensions, there were varying results (t-tests for independent samples, with a significance level set at 0.05) (Table 3.40). In the Chinese sample, all dimensions were statistically significant except for the measurements sella-nasion, basion-opisthion, basion-PNS, and ANS-PNS. In American people, all dimensions were statistically significant except for the measurement basion-opisthion. Among African K/S people, no differences were found for any of the dimensions measured. The Polynesian people had significantly greater dimensions in males for the dimensions sella-nasion, basion-nasion, basion-opisthion, PNS-ANS and PNS-A point. Among the African S/X/Z sample, all dimensions were significantly different except basion-opisthion and basion-PNS. In the Thai group, the dimensions basion-sella, basion-nasion, and PNS-ANS were significantly different. Male and female differences in the Australian group were significant for all the dimensions except basion-opisthion, PNS-ANS and PNS-A point. Two-way ANOVA found no significant interaction between sample and sex for each of the dimensions studied.

Table 3.40: Male and female differences. Numbers in bold show significant differences between means (t-test, p =0.05, Bonferroni's correction for multiple comparisons applied).

SAMPLE	DIMENSION	MALES		FEMALES		*t*	*p*
		MEAN	STD. DEV	MEAN	STD. DEV		
CHINESE	sella-nasion	64.4	3.6	61.9	2.8	2.7	0.008
	basion-sella	**46.7**	2.7	**42.7**	3.3	4.9	**0.000**
	basion-nasion	**98.8**	4.3	**94.5**	4.5	3.6	**0.001**
	basion-opisthion	31.3	2.8	29.3	2.9	2.5	0.017
	basion-pns	42.2	3.7	41.6	2.9	0.6	0.573
	pns-ans	47.4	3.0	45.5	2.4	2.5	0.017
	pns-a point	**44.5**	3.0	**42.3**	2.2	2.9	**0.006**
	nasion-ans	**55.0**	2.7	**50.8**	2.8	5.4	**0.000**
	nasion-a point	**59.3**	2.7	**55.3**	3.2	5.0	**0.000**
AMERICAN	sella-nasion	**69.1**	4.3	**64.9**	3.7	2.0	**0.047**
	basion-sella	**47.1**	2.4	**42.7**	2.6	2.3	**0.023**
	basion-nasion	**104.6**	5.4	**97.0**	4.9	2.7	**0.010**
	basion-opisthion	35.7	4.7	34.4	3.9	-0.6	0.563
	basion-pns	**45.4**	3.7	**40.9**	3.2	2.8	**0.006**
	pns-ans	**52.8**	2.7	**48.2**	2.7	3.9	**0.000**
	pns-a point	**48.9**	2.6	**45.6**	2.5	3.2	**0.002**
	nasion-ans	**52.1**	3.6	**48.9**	3.7	1.9	**0.062**
	nasion-a point	57.1	3.7	53.5	3.9	1.6	0.109
AFRICAN K/S	sella-nasion	73.0	3.3	72.2	2.8	0.7	0.501
	basion-sella	45.9	2.5	45.8	3.4	0.1	0.884
	basion-nasion	108.7	4.5	109.0	5.7	-0.2	0.851
	basion-opisthion	39.8	4.6	40.9	5.6	-0.6	0.572
	basion-pns	50.9	5.5	50.2	3.7	0.4	0.690
	pns-ans	51.4	3.2	51.3	3.8	0.1	0.956
	pns-a point	50.3	3.1	51.0	3.5	-0.8	0.416
	nasion-ans	50.4	3.7	50.5	4.6	-0.1	0.950
	nasion-a point	54.9	4.0	55.9	4.3	-0.6	0.562
POLYNESIAN	sella-nasion	**69.8**	3.4	**66.6**	2.5	3.4	**0.001**
	basion-sella	45.7	3.7	44.2	3.2	1.4	0.172
	basion-nasion	**109.0**	5.2	**104.0**	4.8	3.4	**0.001**
	basion-opisthion	36.9	2.1	35.6	2.6	2.1	0.040
	basion-pns	48.4	3.6	46.9	2.7	1.5	0.129
	pns-ans	**56.4**	3.1	**52.0**	2.6	4.9	**0.000**
	pns-a point	**53.7**	2.6	**50.4**	2.5	4.1	**0.000**
	nasion-ans	56.0	3.9	52.9	3.8	2.6	0.013
	nasion-a point	61.1	4.6	58.4	5.2	1.8	0.075
AFRICAN S/X/Z	sella-nasion	**73.5**	3.7	**71.2**	3.6	3.5	**0.001**
	basion-sella	**49.6**	3.9	**46.8**	3.7	4.1	**0.000**
	basion-nasion	**113.4**	5.7	**108.8**	4.8	4.8	**0.000**
	basion-opisthion	40.3	4.7	38.7	3.7	2.0	0.046
	basion-pns	53.1	4.2	51.7	4.3	1.9	0.059
	pns-ans	**54.6**	4.1	**52.5**	3.7	2.9	**0.005**
	pns-a point	**53.6**	4.3	**51.4**	3.2	3.0	**0.003**
	nasion-ans	**54.9**	3.5	**52.0**	3.4	4.6	**0.000**
	nasion-a point	**59.6**	3.8	**56.8**	3.3	4.2	**0.000**

Table 3.40 continued

SAMPLE	DIMENSION	MALES MEAN	STD. DEV	FEMALES MEAN	STD. DEV	*t*	*p*
THAI	sella-nasion	65.8	2.0	62.3	3.5	2.6	0.016
	basion-sella	**46.3**	1.7	**42.8**	3.0	3.0	**0.007**
	basion-nasion	**101.7**	5.4	**95.4**	3.3	3.0	**0.013**
	basion-opisthion	32.6	4.0	33.0	3.7	-0.2	0.838
	basion-pns	46.1	3.4	42.3	5.0	1.9	0.068
	pns-ans	**49.5**	1.3	**46.1**	1.8	4.1	**0.001**
	pns-a point	47.5	3.7	45.8	3.1	1.0	0.324
	nasion-ans	53.7	3.4	50.8	2.7	2.0	0.063
	nasion-a point	55.4	2.8	54.7	2.4	0.4	0.717
AUSTRALIAN	sella-nasion	**71.1**	3.0	**66.8**	2.2	6.7	**0.000**
	basion-sella	**43.7**	3.0	**40.7**	2.4	4.6	**0.000**
	basion-nasion	**103.6**	3.8	**97.6**	3.2	7.0	**0.000**
	basion-opisthion	32.1	4.0	31.6	2.8	0.5	0.595
	basion-pns	**47.1**	3.2	**44.1**	2.9	4.1	**0.000**
	pns-ans	51.9	2.8	51.0	2.9	1.2	0.217
	pns-a point	50.6	2.8	49.2	2.8	2.0	0.051
	nasion-ans	**49.4**	2.4	**47.3**	1.8	4.0	**0.000**
	nasion-a point	**53.1**	2.9	**50.4**	2.1	4.3	**0.000**

Calculation of bivariate correlation coefficients revealed significant correlations between all dimension variables for the whole sample (Table 3.41). All these correlations are in the positive direction. Separate correlation matrices for males and females showed that the correlations remain consistent in each sex, as all are positive and significant (Tables 3.42 and 3.43).

Table 3.41: Correlation coefficients between cranial base and facial dimensions in the total sample (N =414), all correlations in bold are significant (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	**0.491**							
BA.N	Correlation	**0.865**	**0.734**						
BA.O	Correlation	**0.562**	**0.435**	**0.602**					
BA.PNS	Correlation	**0.647**	**0.540**	**0.813**	**0.515**				
PNS.ANS	Correlation	**0.668**	**0.431**	**0.639**	**0.383**	**0.445**			
PNS.A	Correlation	**0.681**	**0.476**	**0.715**	**0.498**	**0.575**	**0.914**		
N.ANS	Correlation	**0.303**	**0.410**	**0.461**	**0.266**	**0.319**	**0.271**	**0.275**	
N.A	Correlation	**0.274**	**0.423**	**0.461**	**0.342**	**0.292**	**0.263**	**0.258**	**0.881**

Table 3.42: Correlation coefficients between cranial base and facial dimensions in males (N =225), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	**0.217**							
	p. (2-tailed)	**0.001**							
BA.N	Correlation	**0.826**	**0.559**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	**0.386**	**0.262**	**0.448**					
	p. (2-tailed)	**0.000**	**0.000**	**0.000**					
BA.PNS	Correlation	**0.701**	**0.366**	**0.815**	**0.383**				
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**				
PNS.ANS	Correlation	**0.471**	**0.254**	**0.586**	**0.318**	**0.329**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**			
PNS.A	Correlation	**0.559**	**0.296**	**0.650**	**0.356**	**0.463**	**0.936**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**		
N.ANS	Correlation	0.042	**0.424**	**0.346**	**0.188**	0.105	**0.299**	**0.251**	
	p. (2-tailed)	0.539	**0.000**	**0.000**	**0.006**	0.127	**0.000**	**0.000**	
N.A	Correlation	0.033	**0.434**	**0.339**	**0.216**	0.098	**0.298**	**0.262**	**0.931**
	p. (2-tailed)	0.636	**0.000**	**0.000**	**0.002**	0.157	**0.000**	**0.000**	**0.000**

Table 3.43: Correlation coefficients between cranial base and facial dimensions in females (N =189), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	**0.491**							
	p. (2-tailed)	**0.000**							
BA.N	Correlation	**0.865**	**0.734**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	**0.562**	**0.435**	**0.602**					
	p. (2-tailed)	**0.000**	**0.000**	**0.000**					
BA.PNS	Correlation	**0.647**	**0.540**	**0.813**	**0.515**				
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**				
PNS.ANS	Correlation	**0.668**	**0.431**	**0.639**	**0.383**	**0.445**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**			
PNS.A	Correlation	**0.681**	**0.476**	**0.715**	**0.498**	**0.575**	**0.914**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**		
N.ANS	Correlation	**0.303**	**0.410**	**0.461**	**0.266**	**0.319**	**0.271**	**0.275**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	
N.A	Correlation	**0.274**	**0.423**	**0.461**	**0.342**	**0.292**	**0.263**	**0.258**	**0.881**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**

When the samples were examined separately for correlations between dimensions, some variation was apparent (Tables 3.44 to 3.50).

Table 3.44: Correlation coefficients between cranial base and facial dimensions in Chinese (N =65), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	0.338							
	p. (2-tailed)	0.013							
BA.N	Correlation	**0.879**	**0.596**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	0.156	0.346	0.135					
	p. (2-tailed)	0.266	0.011	0.336					
BA.PNS	Correlation	**0.487**	0.208	**0.631**	-0.074				
	p. (2-tailed)	**0.000**	0.135	**0.000**	0.599				
PNS.ANS	Correlation	0.292	0.076	0.196	0.337	-0.052			
	p. (2-tailed)	0.034	0.587	0.160	0.013	0.709			
PNS.A	Correlation	**0.440**	0.100	0.352	**0.380**	0.148	**0.852**		
	p. (2-tailed)	**0.001**	0.476	0.010	**0.005**	0.291	**0.000**		
N.ANS	Correlation	**0.387**	**0.527**	**0.541**	0.216	0.079	0.295	0.291	
	p. (2-tailed)	**0.004**	**0.000**	**0.000**	0.119	0.573	0.032	0.034	
N.A	Correlation	**0.382**	**0.535**	**0.515**	0.224	0.052	**0.363**	0.299	**0.934**
	p. (2-tailed)	**0.005**	**0.000**	**0.000**	0.107	0.714	**0.007**	0.030	**0.000**

Table 3.45: Correlation coefficients between cranial base and facial dimensions in Americans (N =64), significant coefficients shown in bold (significance level0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	**0.403**							
	p. (2-tailed)	**0.001**							
BA.N	Correlation	**0.858**	**0.721**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	**0.356**	0.141	0.228					
	p. (2-tailed)	**0.004**	0.271	0.072					
BA.PNS	Correlation	**0.608**	**0.543**	**0.763**	0.137				
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.283				
PNS.ANS	Correlation	**0.668**	**0.647**	**0.755**	0.248	**0.633**			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.056	**0.000**			
PNS.A	Correlation	**0.645**	**0.624**	**0.732**	0.216	**0.654**	**0.908**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.100	**0.000**	**0.000**		
N.ANS	Correlation	**0.478**	**0.488**	**0.623**	**0.402**	**0.407**	**0.548**	**0.555**	
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	**0.000**	
N.A	Correlation	**0.496**	**0.476**	**0.637**	**0.381**	**0.335**	**0.505**	**0.481**	**0.884**
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.003**	**0.009**	**0.000**	**0.000**	**0.000**

Table 3.46: Correlation coefficients between cranial base and facial dimensions in African K/S (N =30), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	0.330							
	p. (2-tailed)	0.075							
BA.N	Correlation	**0.768**	**0.635**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	0.364	0.332	0.436					
	p. (2-tailed)	0.048	0.073	0.016					
BA.PNS	Correlation	**0.587**	0.237	**0.699**	0.154				
	p. (2-tailed)	**0.001**	0.207	**0.000**	0.418				
PNS.ANS	Correlation	0.367	**0.530**	0.481	0.171	0.037			
	p. (2-tailed)	0.065	**0.005**	0.013	0.402	0.856			
PNS.A	Correlation	0.189	0.445	0.373	0.148	-0.083	**0.924**		
	p. (2-tailed)	0.326	0.016	0.046	0.445	0.669	**0.000**		
N.ANS	Correlation	0.488	0.324	0.451	0.301	0.116	0.399	**0.527**	
	p. (2-tailed)	0.011	0.106	0.021	0.136	0.571	0.043	**0.007**	
N.A	Correlation	0.329	0.310	0.292	0.355	-0.076	0.483	**0.555**	**0.885**
	p. (2-tailed)	0.082	0.102	0.124	0.059	0.694	0.015	**0.002**	**0.000**

Table 3.47: Correlation coefficients between cranial base and facial dimensions in Polynesians (N =56), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	0.301							
	p. (2-tailed)	**0.024**							
BA.N	Correlation	**0.854**	**0.673**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	0.062	0.055	0.055					
	p. (2-tailed)	0.648	0.687	0.687					
BA.PNS	Correlation	**0.606**	**0.502**	**0.759**	-0.151				
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.266				
PNS.ANS	Correlation	**0.508**	0.261	**0.476**	0.025	0.127			
	p. (2-tailed)	**0.000**	0.067	**0.000**	0.865	0.381			
PNS.A	Correlation	0.332	0.276	0.357	0.014	0.088	**0.926**		
	p. (2-tailed)	0.024	0.063	0.015	0.928	0.563	**0.000**		
N.ANS	Correlation	0.264	0.254	**0.394**	0.050	0.165	0.469	0.385	
	p. (2-tailed)	0.066	0.078	**0.005**	0.734	0.258	0.001	0.010	
N.A	Correlation	0.122	0.229	0.306	0.163	0.188	0.221	0.265	**0.851**
	p. (2-tailed)	0.418	0.126	0.039	0.279	0.210	0.149	0.075	**0.000**

Table 3.48: Correlation coefficients between cranial base and facial dimensions in African S/X/Z (N =121), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	**0.416**							
	p. (2-tailed)	**0.000**							
BA.N	Correlation	**0.776**	**0.728**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	0.098	0.077	0.109					
	p. (2-tailed)	0.289	0.401	0.237					
BA.PNS	Correlation	**0.409**	**0.369**	**0.622**	0.158				
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.084				
PNS.ANS	Correlation	**0.509**	**0.461**	**0.564**	0.041	0.011			
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.660	0.906			
PNS.A	Correlation	**0.474**	**0.501**	**0.589**	0.111	0.102	**0.912**		
	p. (2-tailed)	**0.000**	**0.000**	**0.000**	0.241	0.282	**0.000**		
N.ANS	Correlation	**0.301**	**0.408**	**0.459**	0.018	0.218	**0.365**	**0.361**	
	p. (2-tailed)	**0.001**	**0.000**	**0.000**	0.845	0.017	**0.000**	**0.000**	
N.A	Correlation	0.221	**0.379**	**0.411**	0.006	0.146	**0.367**	**0.326**	**0.923**
	p. (2-tailed)	0.018	**0.000**	**0.000**	0.951	0.121	**0.000**	**0.000**	**0.000**

Table 3.49: Correlation coefficients between cranial base and facial dimensions in Thai (N =23), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	0.152							
	p. (2-tailed)	0.488							
BA.N	Correlation	**0.790**	0.456						
	p. (2-tailed)	**0.000**	0.029						
BA.O	Correlation	0.322	-0.110	-0.059					
	p. (2-tailed)	0.134	0.616	0.788					
BA.PNS	Correlation	0.013	0.215	0.388	-0.220				
	p. (2-tailed)	0.954	0.325	0.067	0.314				
PNS.ANS	Correlation	0.475	0.505	**0.715**	-0.109	0.393			
	p. (2-tailed)	0.046	0.033	**0.001**	0.666	0.107			
PNS.A	Correlation	0.308	0.356	0.485	-0.113	0.205	**0.925**		
	p. (2-tailed)	0.187	0.123	0.030	0.634	0.385	**0.000**		
N.ANS	Correlation	**0.678**	0.451	**0.776**	0.226	0.090	0.684	**0.722**	
	p. (2-tailed)	**0.002**	0.060	**0.000**	0.367	0.723	0.002	**0.002**	
N.A	Correlation	0.547	0.355	0.550	0.267	-0.242	0.572	0.425	**0.837**
	p. (2-tailed)	0.013	0.125	0.012	0.255	0.303	0.026	0.062	**0.000**

Table 3.50: Correlation coefficients between cranial base and facial dimensions in Australians (N =68), significant coefficients shown in bold (significance level 0.05, adjusted for multiple comparisons).

		S.N	BA.S	BA.N	BA.O	BA.PNS	PNS.ANS	PNS.A.	N.ANS.
BA.S	Correlation	0.310							
	p. (2-tailed)	0.010							
BA.N	Correlation	**0.800**	**0.625**						
	p. (2-tailed)	**0.000**	**0.000**						
BA.O	Correlation	-0.065	0.129	-0.008					
	p. (2-tailed)	0.600	0.295	0.946					
BA.PNS	Correlation	**0.547**	0.305	**0.711**	-0.149				
	p. (2-tailed)	**0.000**	0.011	**0.000**	0.226				
PNS.ANS	Correlation	0.279	0.291	**0.344**	-0.046	0.152			
	p. (2-tailed)	0.021	0.016	**0.004**	0.710	0.215			
PNS.A	Correlation	**0.319**	**0.357**	**0.403**	-0.020	0.188			
	p. (2-tailed)	**0.008**	**0.003**	**0.001**	0.874	0.124			
N.ANS	Correlation	0.231	**0.435**	**0.405**	0.018	0.135	0.238	0.309	
	p. (2-tailed)	0.058	**0.000**	**0.001**	0.882	0.274	0.051	0.010	
N.A	Correlation	0.245	**0.389**	**0.387**	0.061	0.115	0.298	**0.343**	**0.885**
	p. (2-tailed)	0.044	**0.001**	**0.001**	0.618	0.350	0.014	**0.004**	**0.000**

The ANOVA results for the cranial base and facial dimensions show that significant differences exist between samples for all dimensions measured (Table 3.51).

Table 3.51: Results of the ANOVA for dimensions, showing comparisons between samples.

		Sum of Squares	df	Mean Square	F	p.
S.N	Between Groups	4117.68	6	686.28	46.66	0.000
	Within Groups	5985.66	407	14.71		
	Total	10103.34	413			
BA.S	Between Groups	1698.64	6	283.11	22.57	0.000
	Within Groups	5105.99	407	12.55		
	Total	6804.64	413			
BA.N	Between Groups	11205.15	6	1867.53	59.98	0.000
	Within Groups	12671.99	407	31.14		
	Total	23877.14	413			
BA.O	Between Groups	4992.29	6	832.05	55.92	0.000
	Within Groups	6041.11	406	14.88		
	Total	11033.40	412			
BA.PNS	Between Groups	5934.03	6	989.01	61.13	0.000
	Within Groups	6584.72	407	16.18		
	Total	12518.75	413			
PNS.ANS	Between Groups	2697.92	6	449.65	36.78	0.000
	Within Groups	4743.16	388	12.23		
	Total	7441.08	394			
PNS.A	Between Groups	3428.46	6	571.41	51.46	0.000
	Within Groups	4197.43	378	11.10		
	Total	7625.88	384			
N.ANS	Between Groups	1741.13	6	290.19	21.99	0.000
	Within Groups	5106.79	387	13.20		
	Total	6847.91	393			
N.A	Between Groups	2628.90	6	438.15	28.74	0.000
	Within Groups	5763.20	378	15.25		
	Total	8392.10	384			

The Bonferroni *post hoc* test was conducted with a correction for multiple comparisons (significance level adjusted for multiple comparisons). This shows that there are differences between the samples depending on the dimension measured. For example, the results for the distance sella-nasion, which measured the length of the anterior cranial base, showed that the Chinese and Thai groups were similar to each other (Figure 3.13). They were both significantly different from the Polynesian, Australian and two African groups. The Chinese were also significantly different from the American sample, but the Thai sample was not. The American sample was significantly different from Chinese, Australian and both the African samples for the length of the anterior cranial base. The Polynesian sample had similar results to the

American sample, with significant differences with Chinese, Thai, and both African samples. There were no differences between the Polynesian and Australian samples. The Australian sample was significantly different from all other samples. The two African groups, K/S and S/X/Z, were similar to each other, but had differences with all other groups.

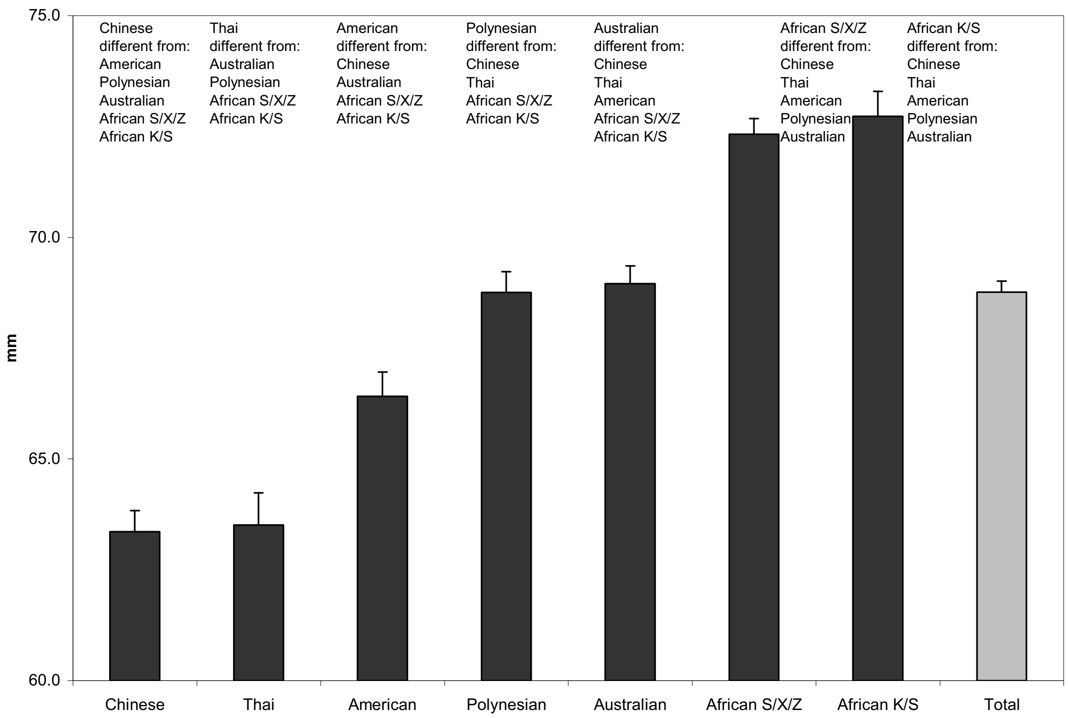

Figure 3.13: Average and standard error values of the samples for the dimension sella-nasion, showing the total average and the results of the ANOVA/Bonferroni significance tests

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A different pattern is seen in the dimension basion-sella, which measures the posterior cranial base length (Figure 3.14). The Australian sample had the smallest dimension, and was significantly different from all others at the larger end of the scale, which included the American, Chinese, Polynesian and both the African samples. The Thai sample had no significant differences with any sample except the African S/X/Z sample. The American sample was significantly different from the Australian and

African S/X/Z samples. The Chinese and Polynesian samples both had similar relationships with these samples. Neither of the American, Chinese or Polynesian samples were significantly different from each other. The African K/S group was significantly different from the Australian sample, but was not significantly different from any other sample for this dimension. Lastly, the African S/X/Z sample was significantly different from all samples except for the African K/S people.

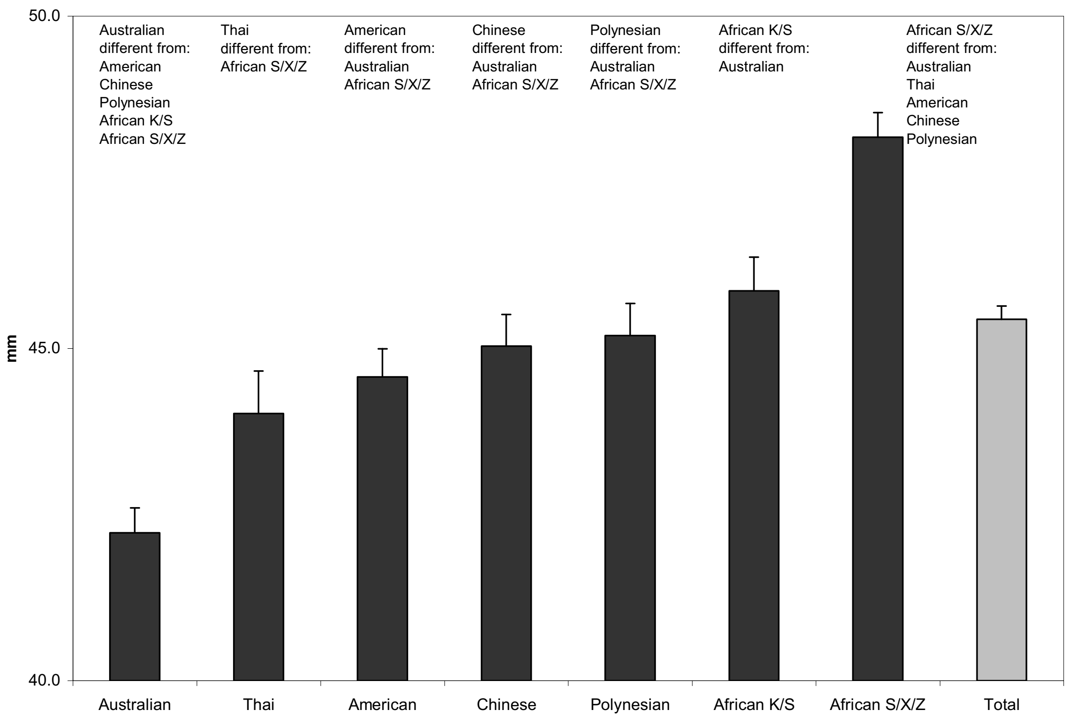


Figure 3.14: Average and standard error values of the samples for the dimension basion-sella, showing the total average and the results of the ANOVA/Bonferroni significance tests.

The dimension basion-nasion was not significantly different between Chinese, Thai, American and Australian samples. All of these samples had significant differences with Polynesian, African K/S and African S/X/Z samples. The mean value of basion-nasion in the Polynesian sample was significantly different from Chinese, Thai, American, Australian and African S/X/Z samples. The African K/S sample had significant differences from Chinese, Thai, American and Australian samples. Lastly, the African S/X/Z sample had the largest average basion-nasion dimension, and was significantly different from all samples except African K/S (Figure 3.15).

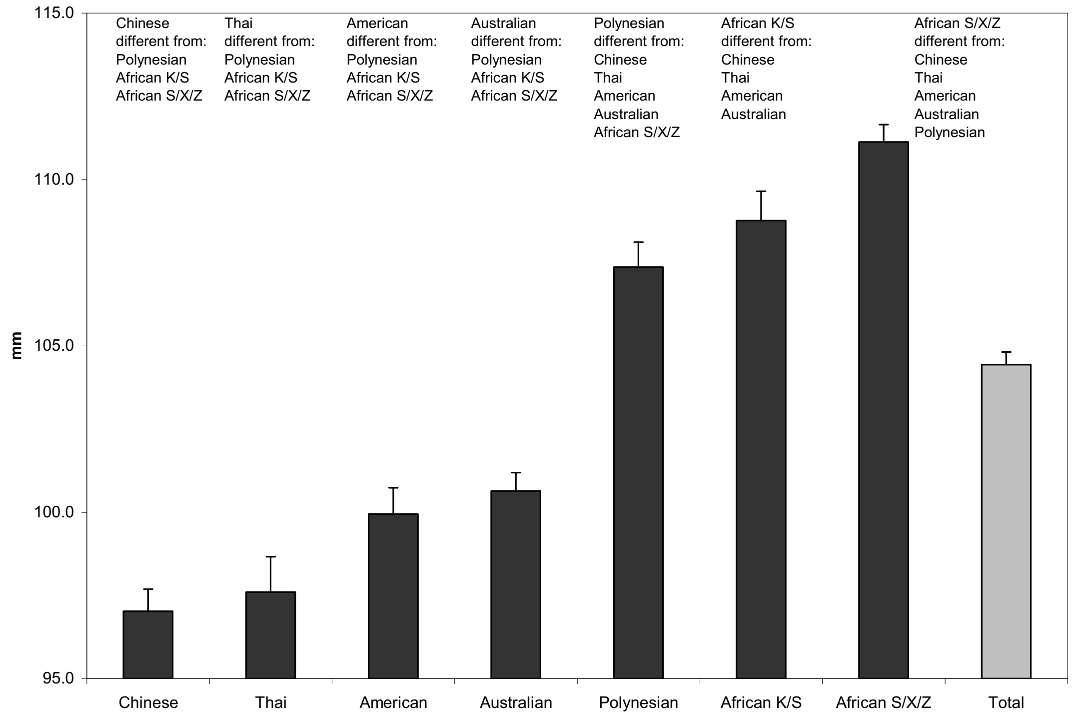


Figure 3.15: Average and standard error values of the samples for the dimension basion-nasion, showing the total average and the results of the ANOVA/Bonferroni significance tests.

With the diameter of the foramen magnum (dimension basion-opisthion), the following relationships were seen. Both Chinese and Australian populations were significantly different from American, Polynesian and both African groups. The Thai group was significantly different from the Polynesian and both African groups. The Polynesian sample was significantly different from Chinese, Australian, Thai and both African groups. The African samples were not significantly different from each other, but showed significant differences with Chinese, Australian, Thai, American and Polynesian samples (Figure 3.16).

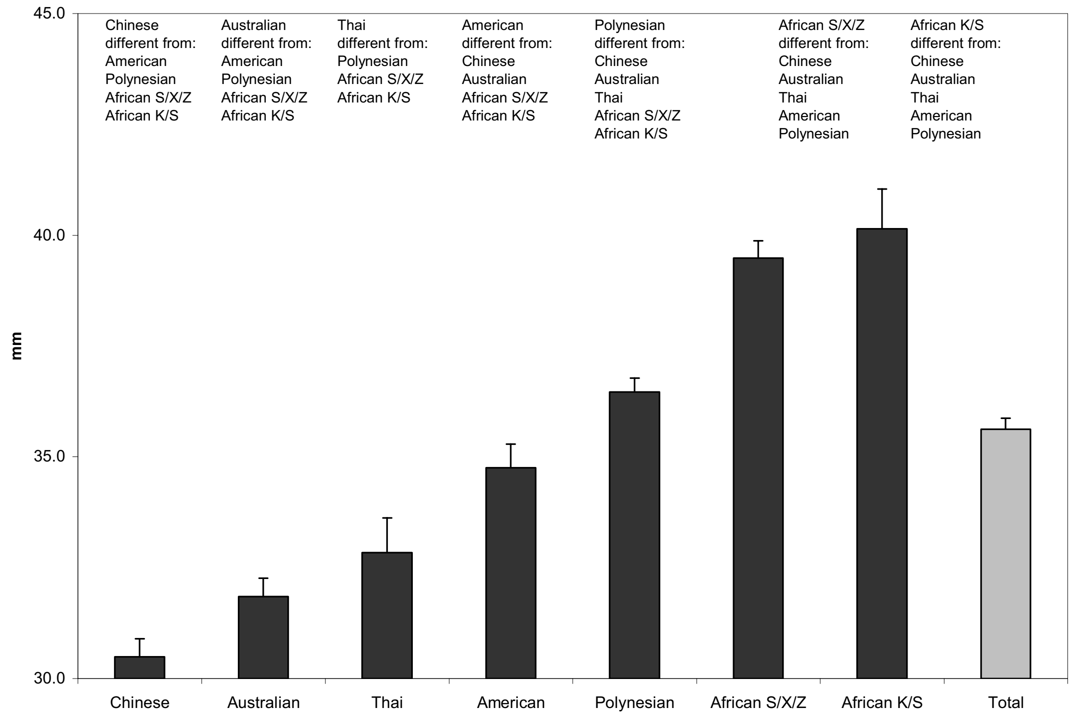


Figure 3.16: Average and standard error values of the samples for the dimension basion-opisthion, showing the total average and the results of the ANOVA/Bonferroni significance tests.

The length basion-PNS in Chinese people was significantly different from Australian, Polynesian, and African samples (both K/S and S/X/Z). Americans were significantly different from Australian, Polynesian, African K/S and African S/X/Z samples. The Thai sample had differences from Polynesian and both African samples. Australians were significantly different from Chinese and American samples, as well as both the African samples. The basion-PNS distance in the Polynesian sample was significantly different from Chinese, American, Thai and Australian samples. The African K/S sample was significantly different from Chinese, American, Thai and Australian samples. The African S/X/Z sample was significantly different from all samples except for the African K/S sample (Figure 3.17).

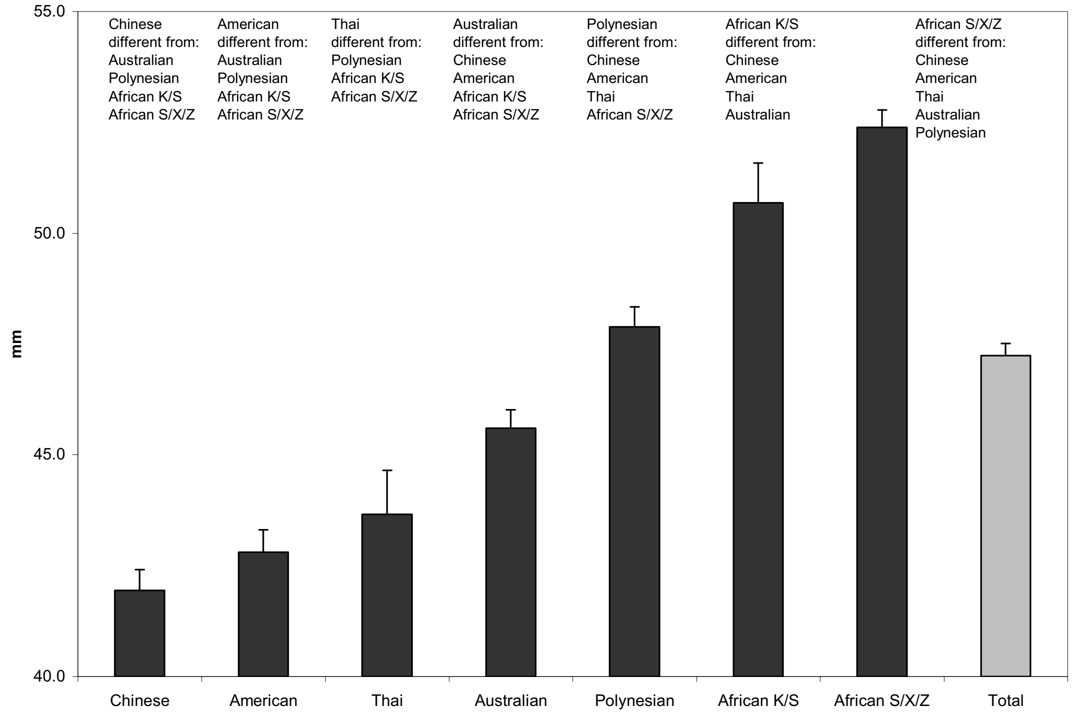


Figure 3.17: Average and standard error values of the samples for the dimension basion-PNS, showing the total average and the results of the ANOVA/Bonferroni significance tests.

Results for the dimension PNS-ANS, measuring the maximum length of the hard palate, are shown in Figure 3.18. The significance testing revealed no significant differences between Chinese and Thai samples for this dimension. However, the Chinese sample was significantly different from American, African K/S, Australian, African S/X/Z and Polynesian samples. The Thai sample was significantly different from the African K/S, Australian, African S/X/Z and Polynesian samples. Significant differences were seen between the American sample when compared to the Chinese, Australian African S/X/Z and Polynesian sample averages. The African K/S sample was significantly different from Chinese, Thai and Polynesian samples. The Australian sample was significantly different from Chinese, Thai, African S/X/Z and Polynesian samples. The average value for African S/X/Z was significantly different from Chinese, Thai, American and Australian samples. Finally, the Polynesian sample, which was the sample with the largest average hard palate length, was significantly different from Chinese, Thai, American and Australian sample averages.

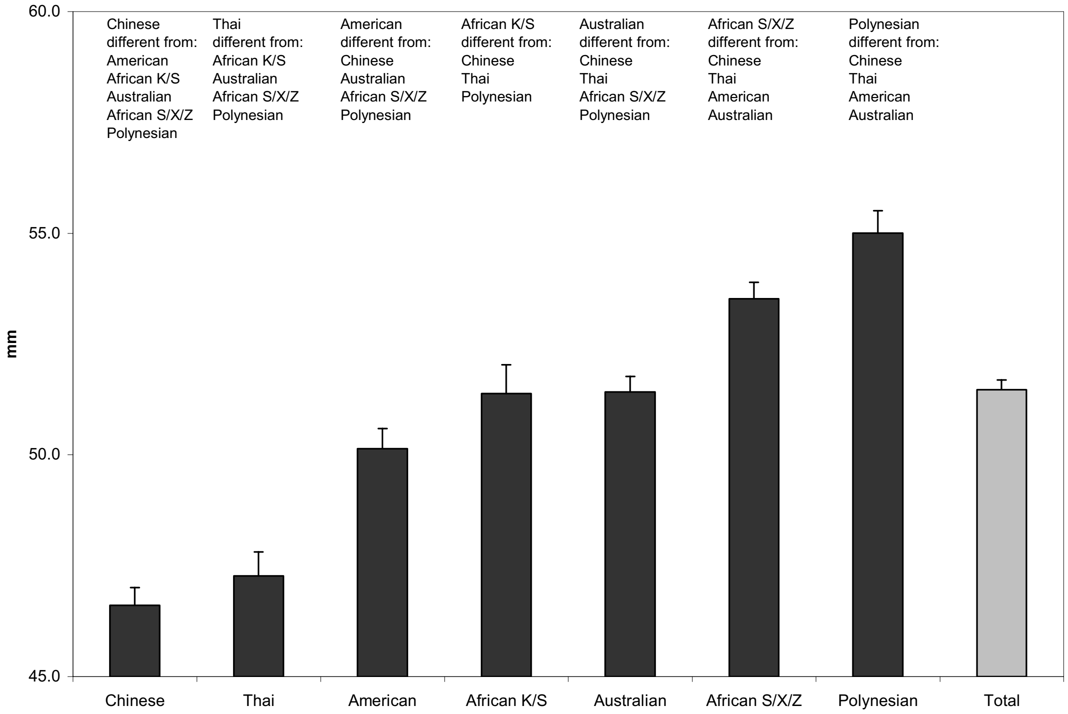


Figure 3.18: Average and standard error values of the samples for the dimension PNS-ANS, showing the total average and the results of the ANOVA/Bonferroni significance tests.

The alternative measurement of the hard palate was the distance between PNS and A point (Figure 3.19). The Chinese sample had the smallest average for this dimension, and was significantly different from all samples except for Thai. The Thai sample was significantly different from Australian, African K/S, Polynesian and African S/X/Z samples. The American sample was significantly different from all samples except the Thai sample. Australians were significantly different from Chinese, Thai, Polynesian and African S/X/Z samples. The African K/S sample was significantly different from Chinese, Thai and American samples. The Polynesian and African S/X/Z samples were not significantly different from each other, and both had significant differences with Chinese, Thai, American and Australian samples.

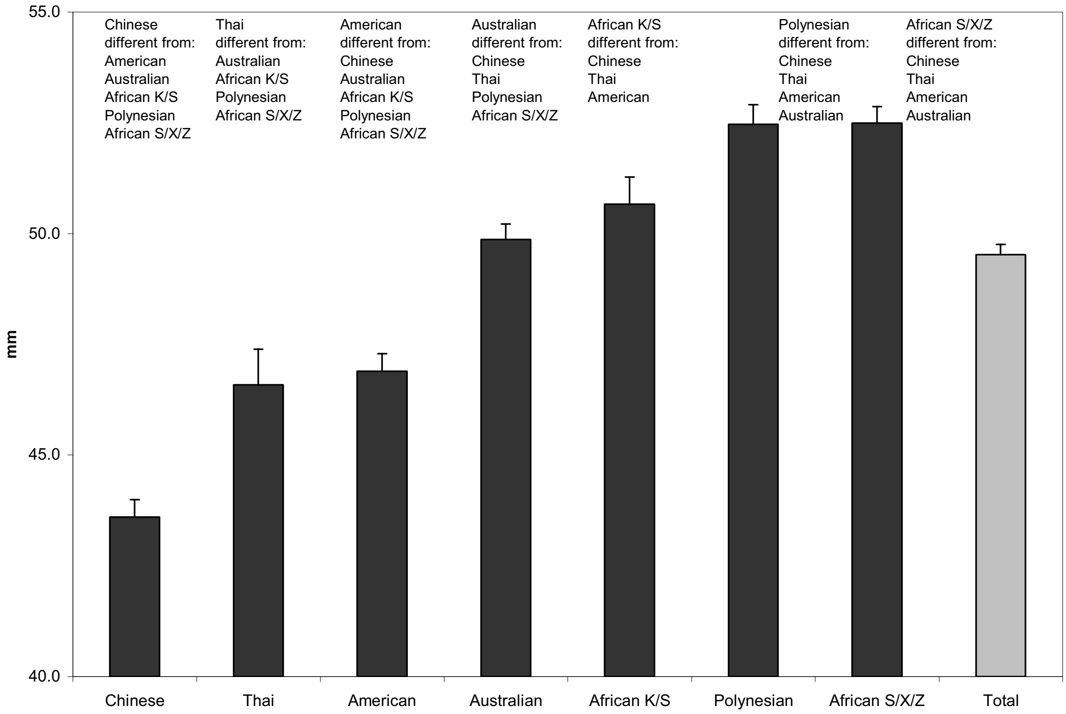


Figure 3.19: Average and standard error values of the samples for the dimension PNS-A point, showing the total average and the results of the ANOVA/Bonferroni significance tests.

The two measurements used to describe the length of the nasal opening were nasion-ANS and nasion-A point. The ANOVA/Bonferroni results for these dimensions are shown in Figures 3.20 and 3.21. For the more traditional dimension of nasion-ANS, the following differences between the samples were seen. The Australian sample had the smallest average dimension, and was significantly different from Thai, Chinese, African S/X/Z and Polynesian samples. The American sample was significantly different from Chinese, African S/X/Z and Polynesian samples. The African K/S sample was significantly different from the African S/X/Z and Polynesian samples. The Thai sample had no significant differences from any sample except for the Australians. Chinese people had an average dimension that was not significantly different from any sample except Australians and Americans. The African S/X/Z and Polynesian samples were not significantly different from each other, or from the Chinese and Thai samples, but had significant differences from Australian, American and African K/S samples.

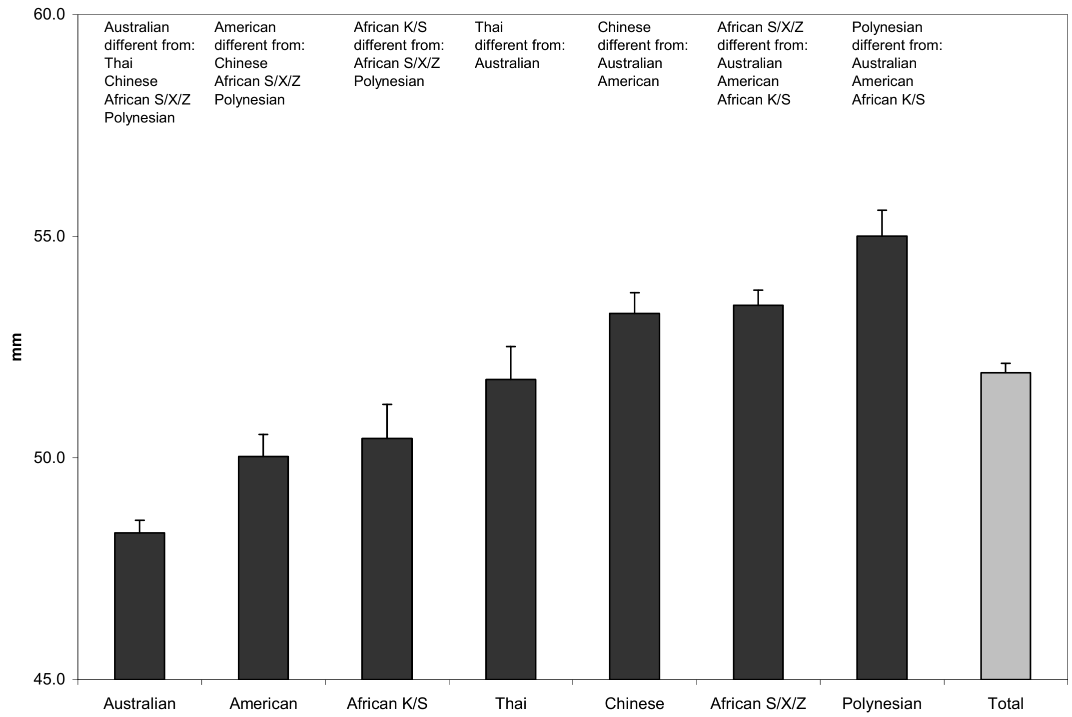


Figure 3.20: Average and standard error values of the samples for the dimension nasion-ANS, showing the total average and the results of the ANOVA/Bonferroni significance tests.

The dimension nasion-A point was smallest in the Australian sample and largest in the Polynesian sample. The Australian sample was significantly different from all other samples. The American sample was significantly different from Australian, Chinese, African S/X/Z and Polynesian samples. The Thai sample only had significant differences with the Polynesian sample. The African K/S sample was significantly different from Australians, African S/X/Z and Polynesians. The Chinese sample was similar to all samples except for the Australian and American samples. The average value for the African S/X/Z sample was significantly different from the average values of the Australian, American and African K/S samples. Lastly, the Polynesian sample was significantly different from Australian, American, Thai and African K/S samples.

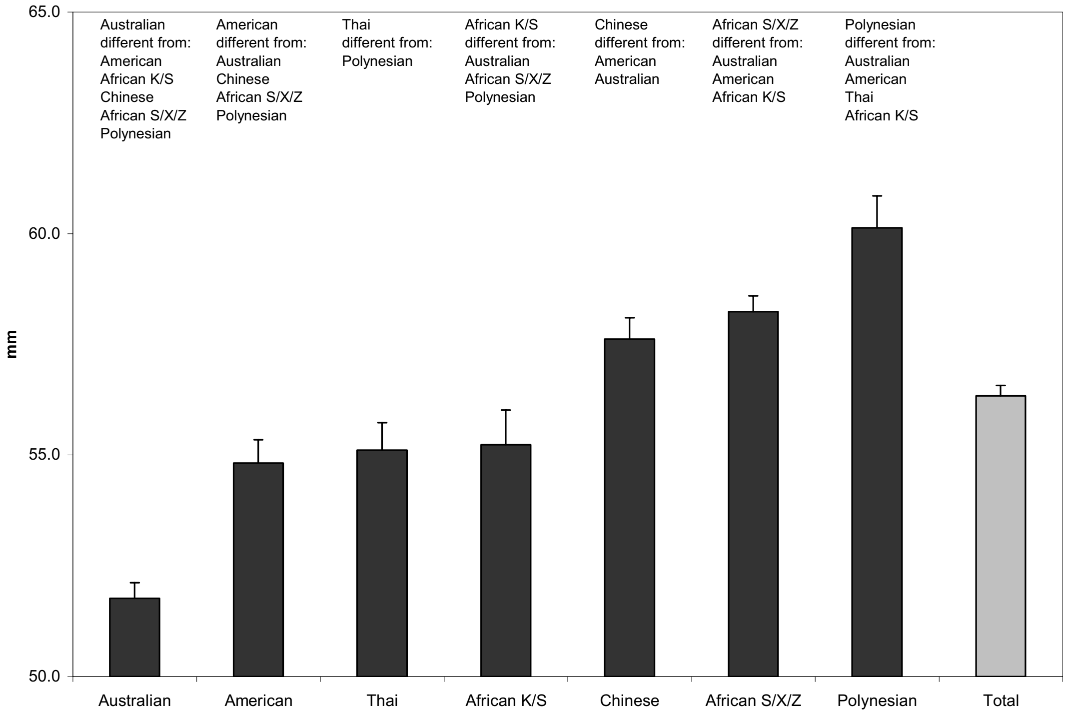


Figure 3.21: Average and standard error values of the samples for the dimension nasion- A point, showing the total average and the results of the ANOVA/Bonferroni significance tests.

As a result of these comparisons, the following conclusions were drawn about the samples of the study. Differences were apparent between samples, showing a general craniofacial pattern for each sample. The Chinese and Thai had no significant differences for all dimension variables in the Bonferroni *post hoc* ANOVA test. The two African groups differed only on the height of the nose (nasion-ANS and nasion-A point), which is greater in the S/X/Z group. American and Polynesian people had similar cranial base dimensions but differed in all facial dimensions. With the facial dimensions, the Americans had significantly smaller measurements for basion-PNS, the palatal length, and the height of the nose. Australians had significantly smaller measurements than Polynesians in all dimensions except the length of the anterior cranial base (sella-nasion) and the distance between basion and PNS. Americans and Australians differed in the vertical dimensions of the face and cranial base (basion-sella, basion-nasion, nasion-ANS and nasion-A point) but did not differ in the horizontal measurements (sella-nasion, basion-PNS and the palatal measurements). Americans had significantly larger dimensions than the Australians for all measurements, including the diameter of the foramen magnum.

The results of the ANOVA were used to calculate the contributions of within and between group variation to the total variation. For the nine dimensions of the present investigation, within group variation was always greater than between group variation. Variation within individuals of the same group ranged between 52.6% (basion-PNS) and 75% (nasion-ANS and basion-sella), while between group variation ranged between 25% (basion-sella, nasion-ANS) and just over 47% (basion-PNS) (Table 3.52)

Table 3.52: Comparison of between group and within group variation for dimension variables, total sample (N = 414).

Variable	between group variation (%)	within group variation (%)	Total variation (%)
S.N	40.8	59.2	100.0
BA.S	25.0	75.0	100.0
BA.N	46.9	53.1	100.0
BA.O	45.2	54.8	100.0
BA.PNS	47.4	52.6	100.0
PNS.ANS	36.3	63.7	100.0
PNS.A	45.0	55.0	100.0
N.ANS	25.4	74.6	100.0
N.A	31.3	68.7	100.0

Conclusion of dimensions

The findings of this analysis showed a general relationship between dimensions measured. Significant differences were observed between males and females for the total sample, with males having larger dimensions in every variable studied except the dimension basion-opisthion. This pattern of sexual dimorphism was observed when samples were examined individually, with some samples showing more differences than others. Based on the number of significant comparisons, the African K/S group had the smallest degree of sexual dimorphism, with no significant differences between males and females. The American sample had a large number of significant comparisons, as did the African S/X/Z sample. Correlation coefficients between dimension variables were all significant when the whole sample was examined. When correlation coefficients for males and females were examined separately, it was found that the female sample had significant correlations between all variables. The male sample had significant correlation coefficients between all variables, apart from some correlations with the basion-PNS dimension, which were not significant. The variables that were not significantly correlated with basion-PNS in males were the ones measuring the vertical height of the nose, or mid-face (nasion-ANS, nasion-A point).

When the samples were examined for differences between them, it was found that there were significant differences between the samples, and that the pattern of differences varied according to the dimension measured. This suggests an allometric relationship in craniofacial variation, rather than an isometric one. For example the Chinese sample was similar to the Thai sample for most dimensions, and had the smallest average values for the dimensions nasion-sella, basion-nasion, basion-opisthion, basion-PNS, PNS-ANS and PNS-A point. The Australian sample had the smallest dimensions for the remaining variables of basion-sella and the two variables measuring the height of the nose/mid-face (nasion-ANS and nasion-A point). Regarding the samples with the largest dimensions, it was usually either the African K/S or African S/X/Z sample, apart from some dimensions of the palate and nose, where the Polynesian sample had the largest dimensions (PNS-ANS, nasion-ANS, nasion-A point). The African K/S sample had the largest dimensions for the dimensions nasion-sella and basion-opisthion, while the African S/X/Z sample had the largest dimensions for basion-sella, basion-nasion, basion-PNS, and PNS-A point. The Chinese and Thai pattern has a long anterior cranial base and nose, but the reduced length of the other measurements results in a small face tucked under the anterior cranial base. Compared to the other groups, however, the anterior cranial base in the Chinese and Thai facial pattern is relatively short, resulting in a smaller face than that observed in the other samples. The pattern seen in the two African groups is one of greater size, combined with a longer anterior cranial base and shorter nose than the Chinese pattern. The palatal measurements are the same size as the nose height, compared to a much shorter palatal length in the Chinese people.

Correlations between the angles of cranial base flexion, craniofacial angles and dimensions

As stated in previous sections, the cranial base angles were all significantly and positively correlated with one another. Similarly, the craniofacial angles were all well correlated, as were the dimensions. This section discusses the inter-relationships between all these variables and their contributions to craniofacial morphology.

All of the seven cranial base angles were significantly correlated with the five craniofacial angles. A large number (over half of the comparisons) were strong ($r > 0.7$), with the remainder being moderately strong ($r > 0.45$ and <0.7), with the exception being the correlation between the opisthion-basion plane and the angle clival plane-sella-nasion, which was significantly correlated at 0.380). All variables were positively correlated with each other with the exception of the orientation of the palate with the clivus, which was negatively correlated with all cranial base angles. The relationship between these variables can be summarized in the following way. As the angle of cranial base flexion increases (resulting in a more obtuse angle), the angle between the plane of the foramen magnum and the clivus opens, resulting in a larger posterior cranial fossa. This produces what can be described as a "z" shape between the foramen magnum, clivus and anterior cranial base, which elongates as the angles increase, and shrinks as the angles decrease. Coinciding with this relationship is the negative correlation of the cranial base flexion and foramen magnum orientation with the angle between the palate and the clivus. Increases in this angle result in a more inferior location of the palate anteriorly, resulting in a longer nasal aperture, or mid-face height, which is seen in individuals with decreased (more acute) flexion of the cranial base.

Most cranial base angles were significantly correlated with the nine dimensions; however, magnitudes of the correlation coefficients were low, at around 0.2 for the majority of dimensions. The exceptions were basion-nasion and basion-PNS dimensions, which were both moderately correlated with the angles basion-sella-nasion, clival plane-sella-nasion and endocranial clival plane-sella-nasion. Interestingly, the dimension basion-sella did not correlate significantly with any of the angles. The diameter of the foramen magnum, basion-opisthion, was similarly poorly correlated, with significant correlations only present between basion-sella-nasion, the two angles of the clivus, and basion-SE nasion. The size of the foramen magnum did not correlate significantly with any of the angles incorporating the pituitary point as an axis (clival-sphenoidal plane, basion-pituitary point-nasion, basion-pituitary point-sphenoidal plane), or with basion-SE-nasion.

Correlations between the craniofacial angles and the dimensions were varied (Table 3.53). There was a moderate, negative correlation between the basion-nasion dimension and the orientation of the palate relative to the clivus. The orientation of the palate was also moderately negatively correlated with the basion-PNS dimension. The basion-PNS dimension was moderately positively correlated with the orientation of the sella-nasion plane relative to the clivus. All other dimensions had low correlations with the angle of orientation of craniofacial angles, or were not significantly correlated. An interesting association was the finding that the orientation of the foramen magnum and palate (both relative to the clivus), usually had negative correlations with the dimension variables, while the orientation of the anterior cranial base relative to the clivus (sella-nasion, pituitary point-nasion and pituitary point-sphenoidal plane) were usually positively correlated. One dimension that had negative correlations with all craniofacial angles was the basion-sella dimension (length of the clivus); however, this was only significantly correlated with the basion-opisthion orientation, and had a low correlation coefficient of -0.287.

Table3.53: Correlation coefficients between the angles of cranial base flexion, orientation of craniofacial angles, and dimension variables in the total sample (significance level adjusted for multiple comparisons using Bonferroni's correction).

			Cranial base flexion angles							Craniofacial angles			
			BA.S.N	CLIV.SPH	BA.PP.SP	BA.PP.N	CLIV.S.N	ECP.S.N	BA.SE.N	O.B	PALATE	S.N	PP.N
Craniofacial angles	O.B	Correlation	**0.517**	**0.413**	**0.511**	**0.563**	**0.421**	**0.380**	**0.420**	This area represents correlation coefficients that have been described in detail in previous sections of the results			
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**				
	PALATE	Correlation	**-0.779**	**-0.564**	**-0.592**	**-0.780**	**-0.724**	**-0.694**	**-0.584**				
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**				
	S.N	Correlation	**0.946**	**0.707**	**0.746**	**0.954**	**0.877**	**0.857**	**0.764**				
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**				
	PP.N	Correlation	**0.908**	**0.695**	**0.771**	**0.974**	**0.823**	**0.810**	**0.803**				
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**				
Dimensions of cranial base and facial skeleton	S.N	Correlation	**0.216**	0.087	0.054	**0.177**	**0.221**	**0.217**	0.130	-0.025	**-0.289**	**0.204**	**0.172**
		p. (2-tailed)	**0.000**	0.077	0.272	**0.000**	**0.000**	**0.000**	0.008	0.609	**0.000**	**0.000**	**0.000**
	BA.S	Correlation	0.019	0.018	-0.108	-0.092	0.079	0.059	-0.098	**-0.287**	-0.018	-0.059	-0.082
		p. (2-tailed)	0.698	0.709	0.028	0.062	0.107	0.229	0.047	**0.000**	0.716	0.229	0.095
	BA.N	Correlation	**0.455**	**0.295**	**0.206**	**0.354**	**0.472**	**0.454**	**0.273**	0.005	**-0.436**	**0.399**	**0.356**
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.919	**0.000**	**0.000**	**0.000**
	BA.O	Correlation	**0.213**	0.126	0.052	0.147	**0.233**	**0.219**	0.130	-0.018	**-0.224**	**0.172**	0.146
		p. (2-tailed)	**0.000**	0.011	0.290	0.003	**0.000**	**0.000**	0.008	0.713	**0.000**	**0.000**	0.003
	BA.PNS	Correlation	**0.496**	**0.338**	**0.255**	**0.383**	**0.503**	**0.453**	**0.271**	0.154	**-0.547**	**0.436**	**0.394**
		p. (2-tailed)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.002	**0.000**	**0.000**	**0.000**
	PNS.ANS	Correlation	**0.321**	**0.172**	0.114	**0.274**	**0.325**	**0.343**	**0.228**	0.038	**-0.312**	**0.286**	**0.272**
		p. (2-tailed)	**0.000**	**0.001**	0.024	**0.000**	**0.000**	**0.000**	**0.000**	0.453	**0.000**	**0.000**	**0.000**
	PNS.A	Correlation	**0.372**	**0.186**	0.127	**0.306**	**0.367**	**0.375**	**0.219**	0.089	**-0.372**	**0.333**	**0.301**
		p. (2-tailed)	**0.000**	**0.000**	0.013	**0.000**	**0.000**	**0.000**	**0.000**	0.081	**0.000**	**0.000**	**0.000**
	N.ANS	Correlation	**0.282**	**0.185**	0.125	**0.227**	**0.280**	**0.277**	**0.268**	0.007	0.050	**0.262**	**0.234**
		p. (2-tailed)	**0.000**	**0.000**	0.013	**0.000**	**0.000**	**0.000**	**0.000**	0.885	0.320	**0.000**	**0.000**
	N.A	Correlation	**0.282**	**0.213**	0.143	**0.219**	**0.285**	**0.277**	**0.253**	-0.006	0.008	**0.247**	**0.227**
		p. (2-tailed)	**0.000**	**0.000**	0.005	**0.000**	**0.000**	**0.000**	**0.000**	0.906	0.883	**0.000**	**0.000**

The correlation between cranial base flexion and the orientation of the foramen magnum has been recognised in previous studies (Smahel and Skvarilova, 1988a; Smahel and Skvarilova, 1988b). These investigations found a relationship between the flexion of the cranial base and the orientation of the foramen magnum, and that these two angles were positively correlated. Smahel and Skvarilova (1988a) measured the orientation of the foramen magnum as the angle sella-basion-opisthion, which is slightly different from the pituitary point-basion-opisthion angle of the present study; however, the difference in location between the sella and pituitary point landmarks will only produce minor differences in the angle (as shown by the approximately two degree difference [on average] in the angles basion-sella-nasion and basion-pituitary point-nasion in earlier sections of this study). Smahel and Skvarilova (1988a) found a correlation of 0.504 between basion-sella-nasion and the orientation of the foramen magnum (sella-basion-opisthion), while in the present study the angles basion-sella-nasion and opisthion-basion-pituitary point had a correlation coefficient of 0.517. The results of Smahel and Skvarilova also show low correlations between the lengths of the anterior and posterior cranial base elements (nasion-sella and basion-sella) and other variables in the study (Smahel and Skvarilova, 1988a), and in a later study, comment on the inability of these two variables to be predicted by other craniofacial variables(Smahel and Skvarilova, 1988b). They do note, however, the correlation between increased flexion of the cranial base and increased length of the clivus (correlated at -0.338), as does Solow (1966), who found a correlation of -0.21 between these variables. In a study on Scandinavian males, Björk (1955) found similar results, that increased flexion of the cranial base was correlated with a longer clivus, and that the relationships were constant with increasing age of the individuals (12 and 20 years). In the present study, the correlation between these two variables (nasion-sella-basion and basion-sella) was found to be not significant (0.019), however, a significant correlation was found between the length of the clivus and the orientation of the foramen magnum (-0.287). However, investigation of each sample individually found considerable variation in the relationship between these two variables. While a negative value was seen in all samples, the magnitude of the correlation varied. In the Chinese, African K/S, Polynesian, Thai and Australian samples, the length of the clivus and the orientation of the foramen magnum were moderately and significantly correlated (> -0.45 in each sample). The same two variables were significantly but only slightly correlated in the African S/X/Z sample, and not significantly correlated in the American sample. This variation accounts for the relatively low correlation coefficient seen in the results for the total sample. A negative correlation between the clivus length and the foramen magnum orientation implies that increases in the length of the clivus (basion-sella) coincide with a smaller angle between the foramen magnum plane and the clivus.

In the total sample, other variables appeared to be more closely related to cranial base flexion, such as the distance between basion and the posterior nasal spine, and the distance between basion and nasion. Most of the other dimension variables were slightly but significantly correlated with cranial base flexion, except for sella-nasion, basion-sella and basion-opisthion. In their investigation, Smahel and Skvarilova (1988b) conclude that the variables measuring the size of the anterior and posterior chords of the cranial base (basion-sella and sella-nasion) are consequently developmentally independent, based on their low correlations with other variables [Smahel, 1988a #95], and the same conclusions can be drawn here, with the addition of the basion-opisthion dimension.

The results of this study led the investigators to conclude that the flexion of the cranial base is influential on other aspects of craniofacial form (Smahel and Skvarilova, 1988a). They also conclude that few differences will be present between samples of other populations (referred to in their papers as different types of skull), since, when they compare their results to Solow (1966) and Anderson and Popovich (1983) they find similar results in all three studies. Furthermore, they cite a report by Doskočil (1962) finding a similar relationship in macaques between the orientation of the foramen magnum and the flexion of the cranial base, implying a relationship between these structures that may be important in interpreting the morphology of hominin skulls with regard to human evolution.

Multivariate Statistical Analysis

In the present study, investigation of the relationships revealed by the correlations was taken a step further by applying multivariate analyses, and exploring the effect of the parallel nature of the basion-opisthion and pituitary point-nasion planes on the interpretation of craniofacial morphology. Two methods of multivariate analysis were used on the data. These were Discriminant Function Analysis and Principal Components Analysis. The purpose of the Discriminant Function Analysis was to discover whether the variables discriminate between samples. The analysis initially was run using all of the variables measured, and subsequently on combinations of variables, such as those measuring cranial base flexion angles, craniofacial angles, and the dimensions of the face and cranial base. The set-up of the analysis included selection of a number of options used in the Discriminant Function Analysis on SPSS. First, the variable “group” was used as the grouping variable, with a range from one to seven. The "group" variable represented the seven different samples of the study (Chinese, American, African K/S, African S/X/Z, Thai, Polynesian and Australian). The independent variables consisted of combinations of the variables measured on the whole sample, depending on the purpose of the analysis. Independent variables were all entered together in the analysis (rather than by a stepwise method). For the classification option, it was requested that prior probabilities be calculated from group sizes. Plots of the first two discriminant functions in the total sample and individual samples were requested, as was a summary table of results.

When all of the variables were included in the analysis, 83.0% of individuals were correctly classified into their original sample (due to missing values the total number of individuals in this analysis was 371 out of a total of 414, or 89.6%). This analysis extracted six discriminant functions that were used in the analysis. These Eigenvalues and associated statistics are shown in Table 3.54. The first function accounts for 57.2% of the total variance, the second for 23.5% and the following four range from 9.4% to 1.2%. The cumulative percentage of variance explained by these six functions is 100%.

Table 3.54: Initial results of the Discriminant Function Analysis

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	3.3	57.2	57.2	0.9
2	1.4	23.5	80.7	0.8
3	0.5	9.4	90.1	0.6
4	0.4	6.0	96.1	0.5
5	0.2	2.7	98.8	0.4
6	0.1	1.2	100.0	0.3

The structure matrix (Table 3.55) describes the individual variables with the largest absolute correlation with each of the six discriminant functions (based on pooled within-group correlations). The first function includes most of the dimension variables of the study, and is consequently interpreted as explaining the effect of cranial base and facial size on group differences. Interestingly, it also includes the orientation of the hard palate relative to the clivus (basion-pituitary point). The second function has high correlations with the dimensions describing the height of the nose (or mid-facial height) (nasion-ANS and nasion-A point) and the length of the clivus (basion-sella). This can thus be interpreted as the function describing mid-face size. The third function discriminating between groups is that of cranial base flexion and foramen magnum orientation. It has high correlations with various angles of cranial base flexion (based on the sella-nasion line rather than the sphenoidal plane of the anterior cranial base), as well as the orientation of the foramen magnum relative to the clivus (basion-pituitary point). The fourth discriminant function had one high correlation: the angle basion-SE-nasion. The fifth discriminant function had no large correlations with any variables. The sixth function, however, was correlated with the two angles that included the sphenoidal plane as the anterior projection or chord of cranial base flexion. These were the angles clival plane-sphenoidal plane, and basion-pituitary point-sphenoidal plane.

Table 3.55: Pooled within-group correlations between independent variables and standardized canonical discriminant functions.

		Function					
Variable	Type	1	2	3	4	5	6
BA.PNS	Dimension	0.544*	0.165	0.079	-0.354	0.252	0.162
BA.N	Dimension	0.522*	0.276	0.068	-0.111	0.275	0.047
PNS.A	Dimension	0.512*	-0.016	-0.287	0.185	0.193	-0.269
S.N	Dimension	0.469*	-0.065	0.261	-0.082	0.196	0.176
BA.O	Dimension	0.437*	0.325	0.352	0.143	0.068	-0.060
PNS.ANS	Dimension	0.375*	0.027	-0.237	0.373	0.367	-0.230
PNS.ANS	Craniofacial angle	-0.346*	-0.105	0.246	-0.160	0.128	-0.048
N.A	Dimension	0.092	0.554*	-0.256	-0.106	0.223	0.214
N.ANS	Dimension	0.068	0.480*	-0.296	-0.231	0.174	0.090
BA.S	Dimension	0.185	0.374*	0.153	-0.287	0.347	-0.177
S.N	Craniofacial angle	0.292	0.210	-0.514*	0.182	-0.154	0.168
ECP.S.N	Cranial base angle	0.334	0.299	-0.479*	0.285	-0.229	0.174
PP.N	Craniofacial angle	0.257	0.177	-0.448*	0.250	-0.122	0.256
BA.S.N	Cranial base angle	0.338	0.312	-0.439*	0.221	-0.288	0.103
CLIV.S.N	Cranial base angle	0.333	0.336	-0.410*	0.214	-0.138	0.068
BA.PP.N	Cranial base angle	0.247	0.172	-0.391*	0.294	-0.141	0.123
O.B	Craniofacial angle	0.153	0.046	-0.231*	-0.014	-0.119	-0.007
BA.SE.N	Cranial base angle	0.137	0.264	-0.250	0.317*	-0.155	0.121
CLIV.SPH	Cranial base angle	0.173	0.275	-0.245	0.228	-0.051	0.320*
BA.PP.SP	Cranial base angle	0.123	0.169	-0.280	0.226	-0.072	0.303*

* Largest absolute correlation between each variable and any discriminant function

The first two discriminant functions were plotted against each other (Figure 3.22). The seven samples are shown in different colours, and it is apparent that there is grouping of samples around the total sample mean. Some overlap is also evident. The placing of group centroids, or means, identifies the samples that are most similar to each other for the variables of the present study. For example, the averages for the Chinese (Group 1) and Thai samples are near to each other along the axis of Function 2, but are more distant according to the axis of Function 1. Surprisingly, the group averages of American and Thai samples (Groups 2 and 6) are very close to each other. The averages of the two African samples (Groups 3 and 5) are quite near to each other, while the average for the Polynesians (Group 4) lies between the Thai and African K/S samples. The Australian sample appears to form a relatively distinct group near the bottom of the scatter-plot, with most people having low values for the second Function relative to the first Function.

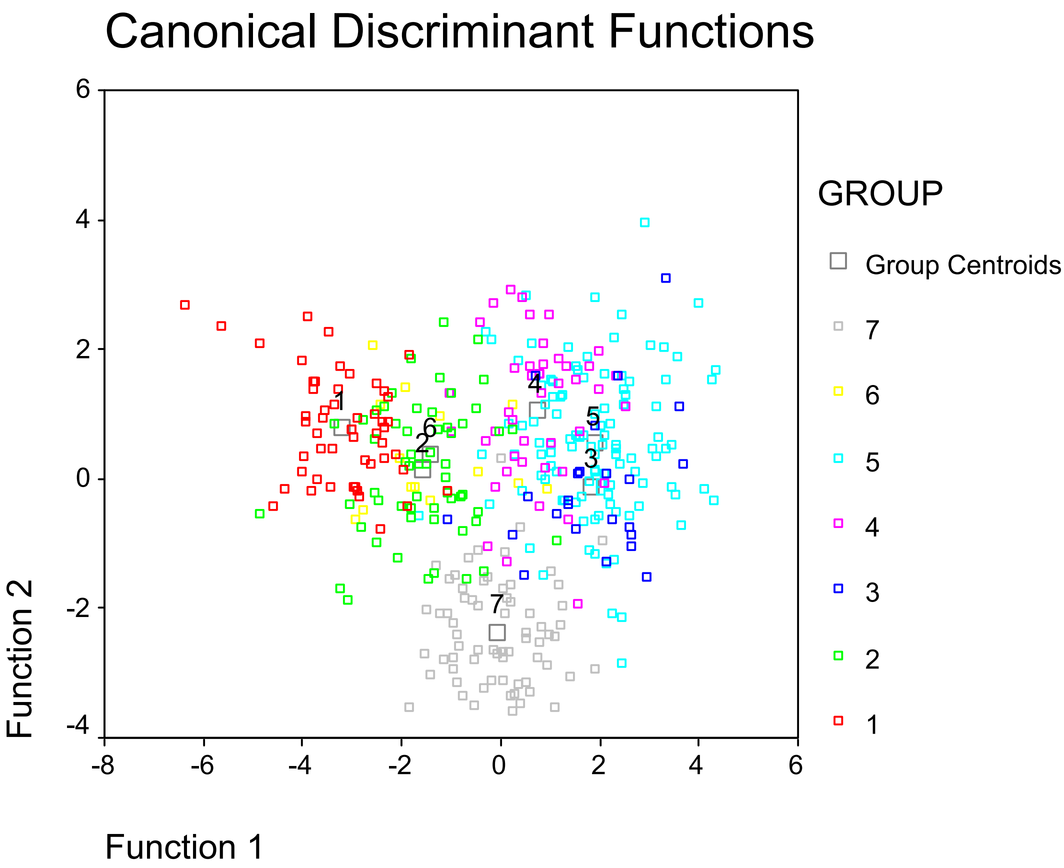


Figure 3.22: Scatter-plot of the first two functions, all variables included. The group numbers represent the following: Group 1: Chinese (red), Group 2: American (green), Group 3: African K/S (blue), Group 4: Polynesian (magenta), Group 5: African S/X/Z turquoise), Group 6: Thai (yellow), Group 7: Australian (grey).

The analysis was then re-run on different combinations of variables, including angles of cranial base flexion, craniofacial angles, and dimension measurements. When cranial base flexion angles were examined for discriminant functions, only 48.5% of individuals were correctly classified into their original sample (N = 412). When craniofacial angles were used, 44.8% of individuals were correctly classified (N = 406). However, when dimension values were used in the analysis, 77.5% of individuals were correctly classified. This finding, in conjunction with the above interpretation of the canonical discriminant functions from the total dataset, shows that the major factor discriminating between the samples of the study can be attributed to size rather than shape.

When the angles of cranial base flexion were examined independently of the other variables, six functions were found to be discriminating between groups. Correlations existed with the first and sixth of these functions. In the first function were the angles whose anterior line passed through the nasion landmark. In this analysis, this also included the angle basion-SE-nasion. The angles using the sphenoidal plane as the anterior projection were found to contribute to the sixth function.

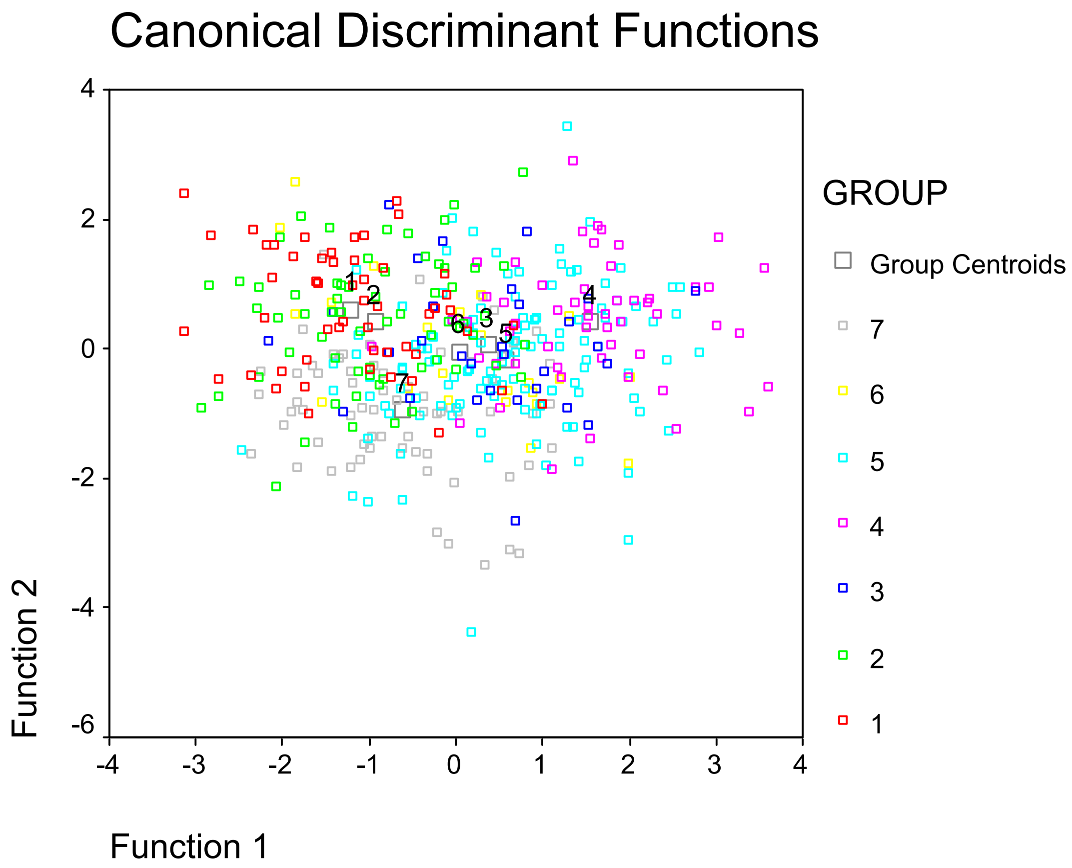


Figure 3.23: Scatter-plot of the first two discriminant functions, cranial base flexion angles only. The group numbers represent the following: Group 1: Chinese (red), Group 2: American (green), Group 3: African K/S (blue), Group 4: Polynesian (magenta), Group 5: African S/X/Z turquoise), Group 6: Thai (yellow), Group 7: Australian (grey).

For the variables measuring the craniofacial angles, five discriminant functions were extracted. The planes of sella-nasion, pituitary point-nasion, and the hard palate (ANS-PNS) were all included in the first function. The remaining two variables (opisthion-basion and pituitary point-nasion) were found to have correlations with the fifth function.

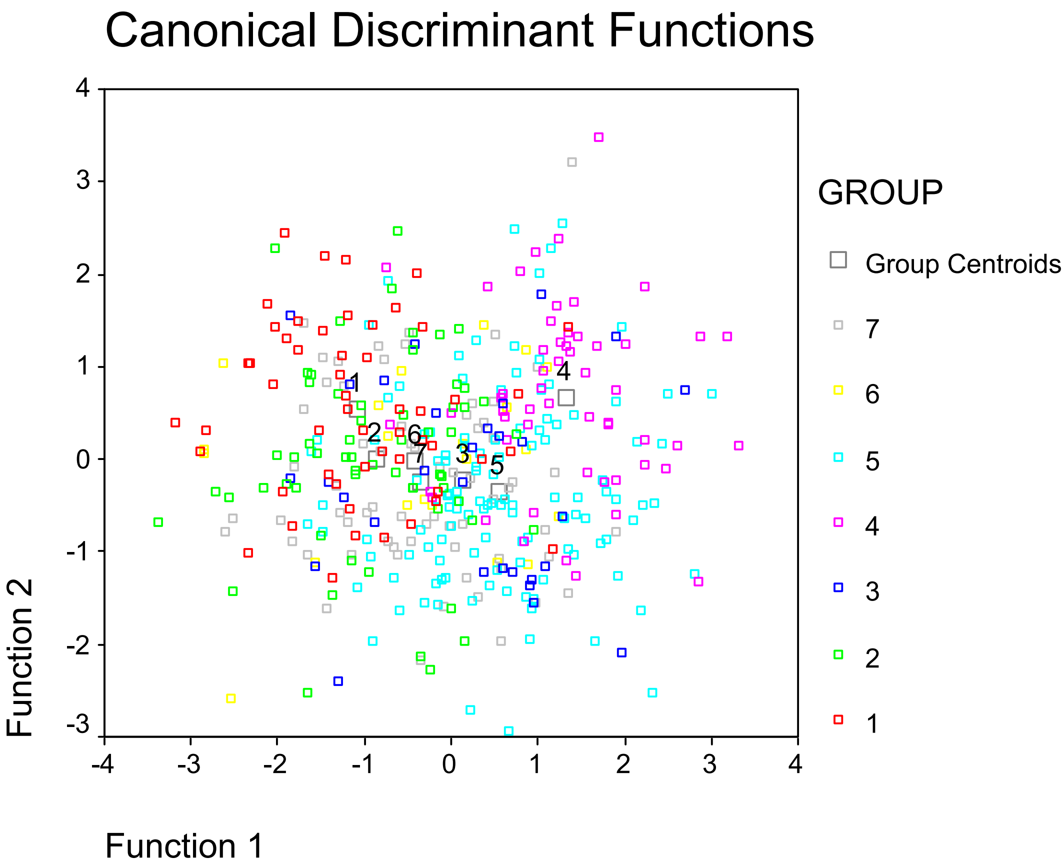


Figure 3.24: Scatter-plot of the first two discriminant functions, craniofacial angles only. The group numbers represent the following: Group 1: Chinese (red), Group 2: American (green), Group 3: African K/S (blue), Group 4: Polynesian (magenta), Group 5: African S/X/Z turquoise), Group 6: Thai (yellow), Group 7: Australian (grey).

Dimension results for Discriminant Function Analysis showed that six canonical functions were found to be discriminating between groups. The first function included correlations for the variables basion-PNS, basion-nasion, PNS-A point, sella-nasion, and basion-opisthion. The second function had correlations with the variables measuring the height of the nose (nasion-ANS and nasion-A point). The fifth function consisted of the variable measuring the length of the hard palate (PNS-ANS), while the sixth function was the variable measuring the length of the posterior projection of the cranial base (basion-sella).

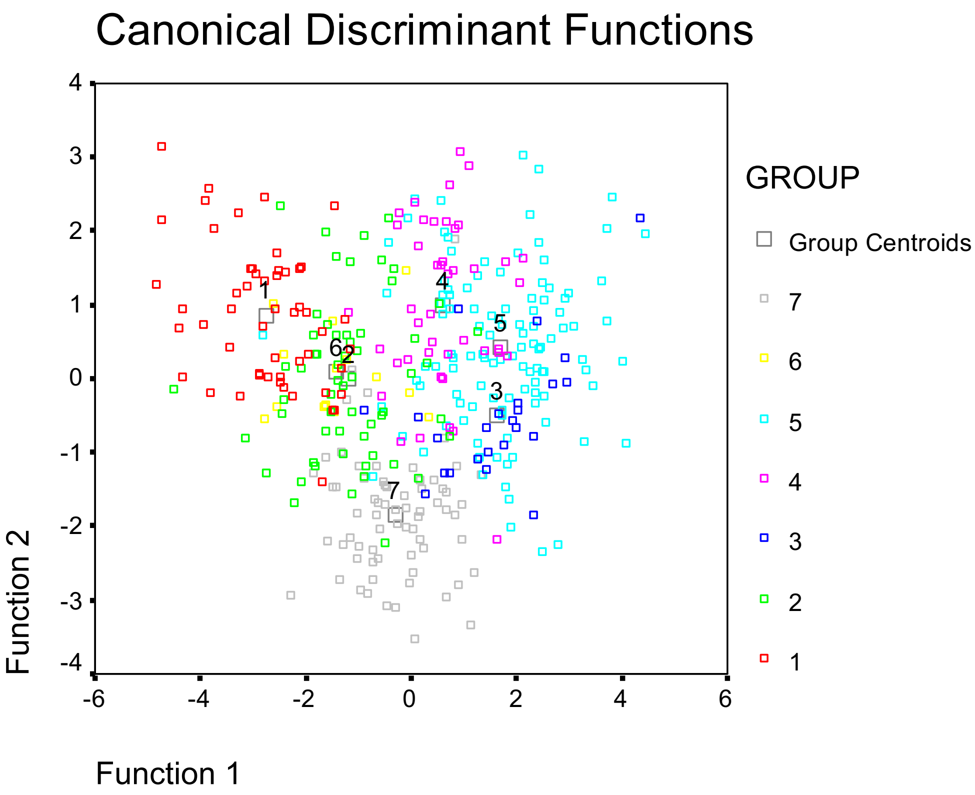


Figure 3.25: Scatter-plot for the first two discriminant functions, dimensions only. The group numbers represent the following: Group 1: Chinese (red), Group 2: American (green), Group 3: African K/S (blue), Group 4: Polynesian (magenta), Group 5: African S/X/Z turquoise), Group 6: Thai (yellow), Group 7: Australian (grey).

Principal Components Analysis was used to determine if there was a pattern in the data identifying a common factor of variation. The SPSS program was used for this analysis. Computation of results was undertaken using the following options in SPSS. All of the variables of the present study were entered into the Variables list. No selection variable was entered. The Principal Components Analysis method was selected from the Factor Analysis: Extraction option in SPSS and the number of factors requested was ten. No rotation was applied to the data.

The analysis, which was first conducted on the total sample (N = 414), found that over 85% of the variance was explained by the first five components (total cumulative percentage = 85.4%). The first component explained 47.7% of the total variance, the second component explained 20.2% and the third component explained 8.5%. The remaining components explained decreasing proportions of variance, all being less than 5%. Only the first three factors had Eigenvalues greater than 1.0 (Table 3.56).

Table 3.56: Results of the Principal Components Analysis for the first five components – Eigenvalues and percentage of variance for each component.

	Initial Eigenvalues		
Component	Total	% of Variance	Cumulative %
1	9.5	47.7	47.7
2	4.1	20.5	68.1
3	1.7	8.5	76.6
4	1.0	4.8	81.4
5	0.8	4.0	85.4

Examination of the component matrix for the variables with the highest correlation coefficients showed that the three variables with the best correlation with the first component were the angles basion-sella-nasion (0.947), basion-pituitary point/sella-nasion (0.929), and the clival plane-sella-nasion angle. The three variables with the highest correlation with the second component were all dimensions, specifically basion-sella (0.770), sella-nasion (0.706) and basion-nasion (0.683). The three variables with the highest correlation with the third component were the two dimensions measuring the height of the nose, nasion-ANS and nasion-A point (0.744 for both variables) along with the dimension sella-nasion (-0.378).

Table 3.57: Correlation coefficients between each variable and the first three Principal Components (in bold) for the total sample

				Component
Variable	Type	1	2	3
BA.S.N	Cranial base angle	**0.947**	-0.207	0.038
CLIV.SPH	Cranial base angle	0.761	-0.282	0.116
BA.PP.SP	Cranial base angle	0.727	-0.394	0.080
BA.PP.N	Cranial base angle	0.901	-0.311	0.029
CLIV.S.N	Cranial base angle	**0.910**	-0.153	0.054
ECP.S.N	Cranial base angle	0.889	-0.157	0.060
BA.SE.N	Cranial base angle	0.728	-0.228	0.131
O.B	Craniofacial angle	0.525	-0.423	-0.111
PALATE	Craniofacial angle	-0.814	0.181	0.365
S.N	Craniofacial angle	**0.929**	-0.277	0.032
PP.N	Craniofacial angle	0.909	-0.315	0.033
S.N	Dimension	0.411	**0.683**	**-0.378**
BA.S	Dimension	0.195	**0.770**	0.183
BA.N	Dimension	0.635	**0.706**	-0.129
BA.O	Dimension	0.359	0.501	-0.133
BA.PNS	Dimension	0.639	0.468	-0.289
PNS.ANS	Dimension	0.481	0.612	-0.189
PNS.A	Dimension	0.540	0.610	-0.250
N.ANS	Dimension	0.359	0.486	**0.744**
N.A	Dimension	0.379	0.471	**0.744**

Principal Components Analysis was also conducted on males and females separately. This was to find out if there was any sexual dimorphism in the variables contributing to craniofacial morphology. Results for each sex were similar to the results for the total sample, with over 85% of the variance explained by the first five components (Table 3.58). For both the male and the female samples, only the first three components had Eigenvalues over 1.0. For the females, the first three components had variance contributions of 47.8%, 21.2% and 8.1% respectively. Similar values were seen for males, with 48.8%, 17.4% and 9.8% respectively for the first three components.

Table 3.58: Correlation coefficients between each variable and the first three Principal Components for males and females

			Females			Males
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	9.6	47.8	47.8	9.8	48.8	48.8
2	4.2	21.2	69.0	3.5	17.4	66.2
3	1.6	8.1	77.1	2.0	9.8	75.9
4	1.0	5.0	82.1	1.0	5.1	81.1
5	0.8	4.2	86.3	0.8	4.2	85.2
6	0.7	3.4	89.7	0.7	3.5	88.8
7	0.5	2.5	92.1	0.7	3.4	92.2
8	0.4	2.0	94.1	0.5	2.3	94.5
9	0.3	1.7	95.8	0.3	1.7	96.2
10	0.2	1.2	96.9	0.2	1.1	97.3
11	0.2	0.9	97.8	0.2	0.8	98.1
12	0.1	0.7	98.6	0.1	0.6	98.7
13	0.1	0.5	99.0	0.1	0.3	99.0
14	0.1	0.3	99.3	0.0	0.2	99.2
15	0.0	0.2	99.5	0.0	0.2	99.4
16	0.0	0.1	99.7	0.0	0.2	99.6
17	0.0	0.1	99.8	0.0	0.2	99.8
18	0.0	0.1	99.9	0.0	0.1	99.9
19	0.0	0.1	100.0	0.0	0.1	100.0
20	0.0	0.0	100.0	0.0	0.0	100.0

With regard to correlations between the variables and the first three components, the following results were seen (Table 3.59). Among females, the three variables with the highest correlation with the first component were the angles basion-sella-nasion (0.945) and clival plane-sella-nasion (0.904), and the angle of orientation of the sella-nasion plane relative to the clivus (basion-opisthion) (0.917). For the second component, the three variables with the highest correlation in the female sample were all dimensions, being sella-nasion (0.753) basion-sella (0.704), and basion-nasion (0.689). For the third component, the variables were the two vertical dimensions of the nose, nasion-ANS and nasion-A point (0.725 and 0.732 respectively), and the angle of orientation of the hard palate relative to the clivus (0.368). For the male sample, the variables with the best correlation with the first component were the angle basion-sella-nasion (0.957), and the two angles measuring the orientation of the anterior cranial base with the clivus: sella-nasion (0.940) and pituitary point-nasion (0.921). For the second component, the three variables were the basion-sella dimension (0.774), the basion-nasion dimension (0.676) and the sella-nasion dimension (0.588). The variables with the highest correlation with the third component in males were the dimensions measuring the height of the nose, nasion-ANS and nasion-A point (0.799 and 0.797 respectively) and the sella-nasion dimension (-0.497).

Table 3.59: Correlation coefficients between each variable and the first three Principal Components (in bold) for the males and females

		Females			Males		
Variable	Type	Component			Component		
		1	2	3	1	2	3
BA.S.N	Cranial base angle	**0.945**	-0.204	0.019	**0.957**	-0.176	0.061
CLIV.SPH	Cranial base angle	0.757	-0.289	0.140	0.769	-0.255	0.104
BA.PP.SP	Cranial base angle	0.698	-0.439	0.085	0.749	-0.364	0.045
BA.PP.N	Cranial base angle	0.889	-0.350	-0.016	0.907	-0.293	0.027
CLIV.S.N	Cranial base angle	**0.904**	-0.119	0.048	**0.923**	-0.137	0.085
ECP.S.N	Cranial base angle	0.883	-0.153	0.048	0.899	-0.133	0.083
BA.SE.N	Cranial base angle	0.711	-0.258	0.094	0.736	-0.252	0.114
O.B	Craniofacial angle	0.489	-0.468	-0.246	0.573	-0.311	-0.018
PALATE	Craniofacial angle	-0.811	0.189	**0.368**	-0.819	0.146	0.362
S.N	Craniofacial angle	**0.917**	-0.339	-0.006	**0.940**	-0.215	0.048
PP.N	Craniofacial angle	0.888	-0.375	-0.018	0.921	-0.277	0.037
S.N	Dimension	0.407	**0.753**	-0.235	0.430	**0.588**	**-0.497**
BA.S	Dimension	0.339	**0.704**	0.171	0.086	**0.774**	0.208
BA.N	Dimension	0.670	**0.689**	-0.068	0.647	**0.676**	-0.183
BA.O	Dimension	0.393	0.579	-0.088	0.338	0.464	-0.099
BA.PNS	Dimension	0.671	0.462	-0.173	0.626	0.451	-0.366
PNS.ANS	Dimension	0.412	0.661	-0.284	0.544	0.535	-0.098
PNS.A	Dimension	0.531	0.615	-0.341	0.558	0.582	-0.164
N.ANS	Dimension	0.437	0.381	**0.725**	0.314	0.437	**0.799**
N.A	Dimension	0.454	0.376	**0.732**	0.333	0.425	**0.797**

Examination of the results for Principal Components for the total sample and for males and females separately shows that there is a similar pattern for the first three components contributing to variation in the cranial base and craniofacial morphology. The first point worth noting is that in each case, most of the variation can be attributed to the first three components, with the remaining components contributing less than 5% of variation. The first component appears to represent variables such as cranial base flexion and orientation of the facial skeleton, in particular the angle of orientation of the anterior cranial base relative to the clivus. The second component contributing a large amount (about 20%) of variance to the face in the current study is represented by the variables measuring the size of the cranial base itself, specifically, the dimensions sella-nasion, basion-sella and basion-nasion. The third component, responsible for about 8 to 10% of variation, is made up of the variables measuring the height of the nose, or mid-face height, and also either the dimension sella-nasion (a negative correlation) in the case of the total sample and the males of the sample, or the orientation of the hard palate relative to the clivus in the case of the females of the sample (also a negative correlation).

Conclusion of correlations and multivariate analyses

The results of the multivariate comparisons have revealed a number of interesting points about craniofacial variation. The Discriminant Function Analysis found that about 83% of individuals were correctly classified into their original group when all variables were included. However, when only angles were included in the analysis, less than 50% were correctly classified. A similar result was obtained when only the craniofacial angles were examined. However, when dimension variables alone were examined, 77% of individuals were correctly classified according to their original group. These findings suggest that, among the variables included in the present investigation, the main discriminating functions between individuals of the present sample are attributable to size differences (dimensions).

The findings of the multivariate analyses are of interest since they add to the findings of the descriptive statistics of previous sections, specifically that the variables of the present study do not show distinct differences between samples. This confirms well-established findings for other characters that no discrete boundaries exist for attributing individuals to a particular group. This is the biological justification for rejecting the concept of "race" (Brace, 2005). The finding of dimension variables being more discriminating than angular variables is likely to be a result of regional adaptation in general size. The apparent clustering of groups using Discriminant Function Analysis (Figure 3.22) with all variables included can be attributed to size differences in the dimensions of the face, which would be most likely a result of regional gene pools. A further point worth mentioning is that detailed descriptions of specific group differences are beyond the scope of the present study. Since the aim of the study was to describe the amount of variation present in cranial base and craniofacial variables, singling out particular samples for their specific facial types would detract from the general argument of the importance of individual differences.

Individual variation

One of the aims of the current work was to determine the extent of individual variation in numerous cranial base and facial measurements. Typically, averages are presented in the literature; however, as shown in the following section, the average may not be the most informative statistic to describe variation in craniofacial morphology.

Of the seven angles used to measure cranial base flexion, the following statistics were found in the total sample: mean, standard deviation, minimum and maximum. These results are shown in Table 3.60, along with the difference between minimum and maximum values for each angle. Here it can be seen that the difference between the largest and smallest measurements (range) was large, varying between 36.5 and 46.5 degrees, depending on the angle measured. The variable with the smallest range was basion-sella-nasion, while the variable with the largest range was the angle between the clival plane and the sphenoidal plane.

With regard to cranial base flexion and craniofacial morphology, the most common statistics presented in the literature are values of mean and standard deviation. For most variables of the present study, the standard deviation is about 7 or 8 degrees. This would suggest that an individual with values outside three standard deviations above or below the mean would be a person of abnormal craniofacial morphology. However, a different presentation of results is one that describes the range of variation present in people of non-pathological craniofacial appearance, such as those of the present study. This shows that a range of variation of around 40 degrees (20 degrees to each side of the mean), which, while being the same as three standard deviations to each side of the mean, still encompasses individuals of normal facial appearance. This is in contrast to studies in the literature, where an individual with a cranial base flexion (measured from basion-sella-nasion) of 115 degrees or 152 degrees is considered to be outside the normal, modern human range.

Table 3.60: Range of variation for cranial base angles

	Mean (degrees)	Std. Deviation	Minimum	Maximum	Difference between Minimum & Maximum
Basion-sella-nasion	132.5	7.1	115.5	152.0	36.5
Clivus-sphenoidal plane	108.0	8.4	86.0	132.5	46.5
Basion-pituitary point-sphenoidal plane	121.9	7.7	103.5	145.0	41.5
Basion-pituitary point-nasion	134.4	7.2	117.0	153.0	36.0
Clival plane-sella-nasion	124.3	7.5	104.0	145.5	41.5
Endocranial clival plane-sella-nasion	127.8	7.9	106.5	150.0	43.5
Basion-SE-nasion	147.5	7.0	129.0	167.0	38.0

The range of variation for craniofacial angles has not been extensively studied. In the current sample, the five angles measured showed considerable differences between minimum and maximum values. The difference between minimum and maximum values was around 35 to 40 degrees, depending on the variable studied. The basion-pituitary point-sphenoidal plane angle had the largest range, of 41.5 degrees, while the orientation of the hard palate relative to the clivus (basion-pituitary point) had the smallest range, which was 32.5 degrees (Table 3.61).

Table 3.61: Range of variation for the craniofacial angles (measured relative to the basion-pituitary point plane).

	Mean (degrees)	Std. Deviation	Minimum	Maximum	Difference between Minimum & Maximum
opisthion-basion	135.0	7.4	117.0	157.0	40.0
palate	50.3	5.7	33.5	66.0	32.5
sella-nasion	138.3	6.6	122.0	156.0	34.0
pituitary point-nasion	134.6	7.2	116.0	153.5	37.5
pituitary point-sphenoidal plane	121.9	7.7	103.5	145.0	41.5

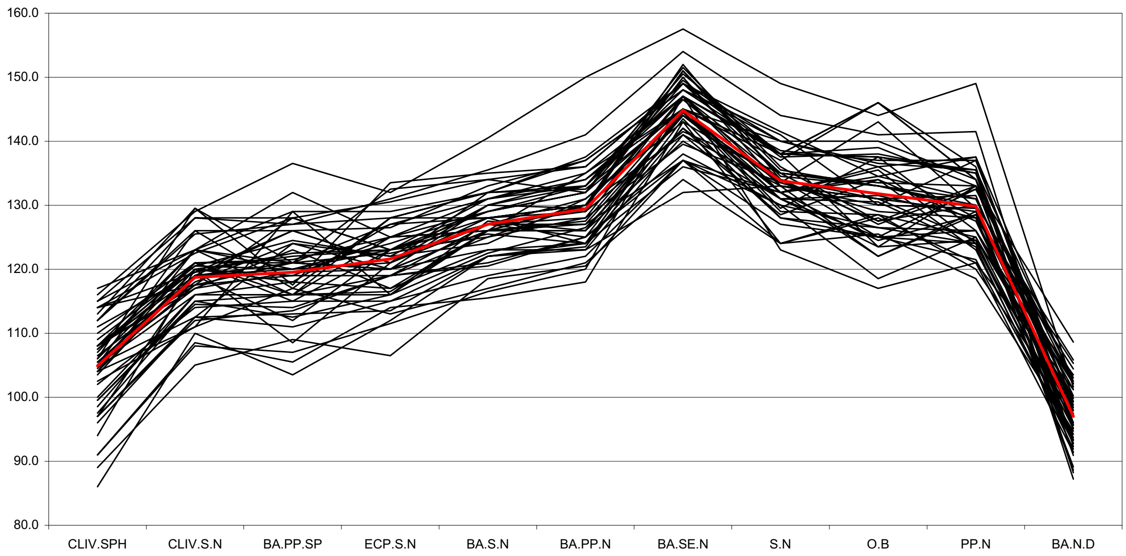
The range of variation in dimensions was also examined. This showed that the difference between minimum and maximum values for the various dimensions of the cranial base and face ranged between 21.2 mm for the distance between nasion and the ANS, and 50.1 mm for the dimension of facial projection (basion-PNS combined with PNS-ANS) (Table 3.62).

Table 3.62: Range of variation of dimensions:

Dimension	Mean (mm)	Std. Deviation	Minimum	Maximum	Difference between Minimum & Maximum
sella-nasion	68.9	4.9	56.1	81.9	25.8
basion-sella	45.5	4.0	35.8	59.7	23.9
basion-nasion	104.6	7.6	86.0	128.1	42.1
basion-opisthion	35.7	5.1	23.8	53.4	29.6
basion-pns	47.3	5.6	28.2	64.0	35.8
pns-ans	51.6	4.3	40.4	64.5	24.1
pns-a point	49.6	4.5	37.6	64.0	26.4
nasion-ans	52.0	4.2	41.9	63.1	21.2
nasion-a point	56.4	4.6	44.6	70.4	25.8
projection	98.9	8.4	73.6	123.7	50.1

The large range seen in the total sample for all of these variables shows, to some extent, the individual variation present in the cranial base and face, which is generally about five or six times the standard deviation. However, individual variation cannot be effectively described using basic statistics. More complex measures must be used in order to determine the relationships between these variables in different people.

A number of figures have been prepared to highlight the extent of individual variation in the craniofacial skeleton. These show the results of individuals compared to their sample average. Figures 3.26 to 3.32 show the raw data for each sample with the sample average shown in red. The variables were divided into two groups so that the range of variation was better displayed. In each figure, the top part represents the larger variables, including all of the angles of cranial base flexion, all craniofacial angles except the palatal plane, and the basion-nasion dimension. The lower part shows all the variables with smaller values, including most of the dimension variables and the palatal plane of orientation.



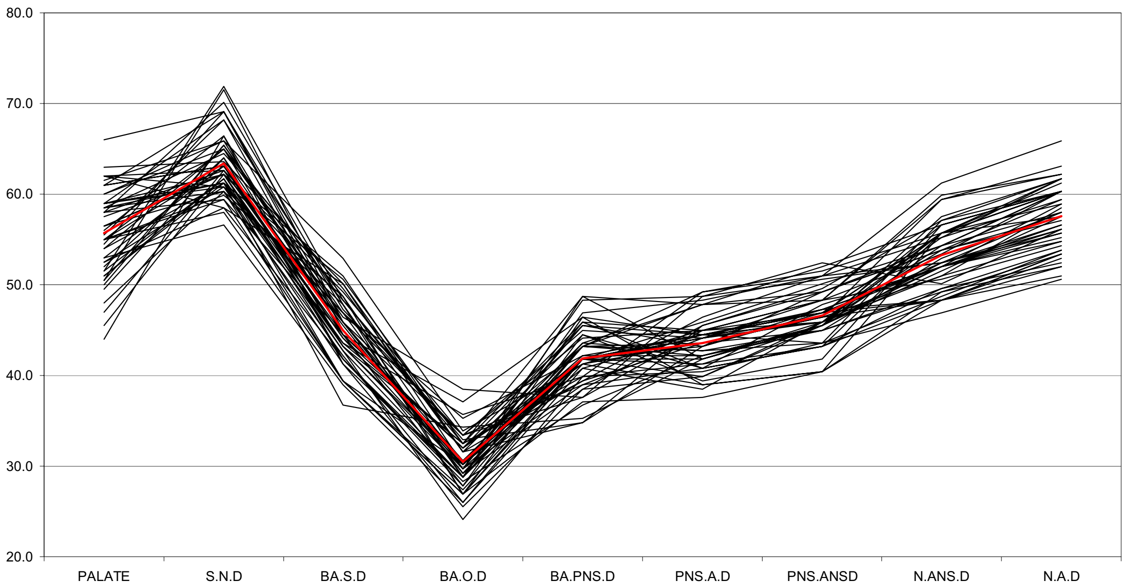


Figure 3.26: Results for the Chinese sample, showing individuals scores in black and the sample average in red.

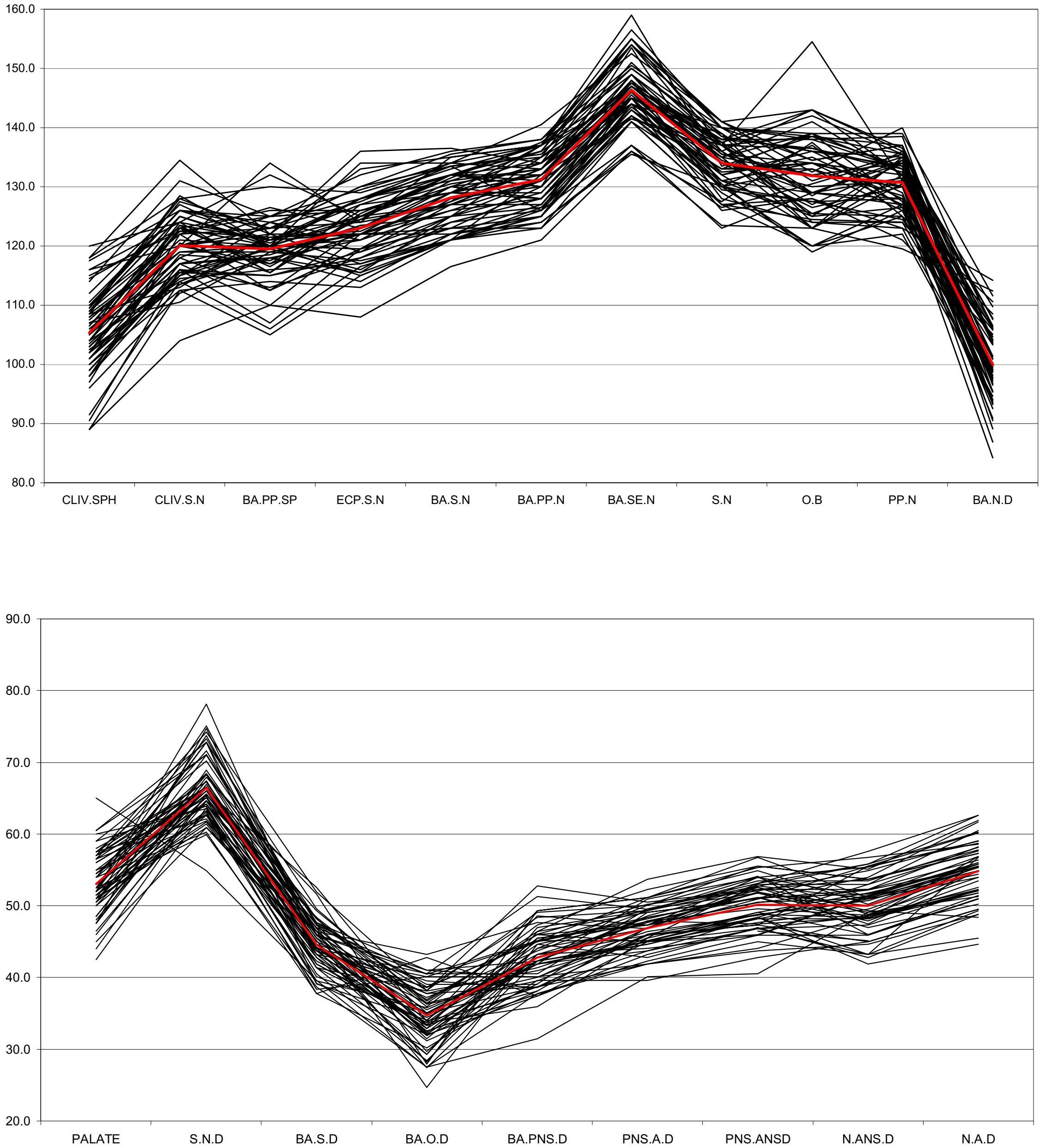
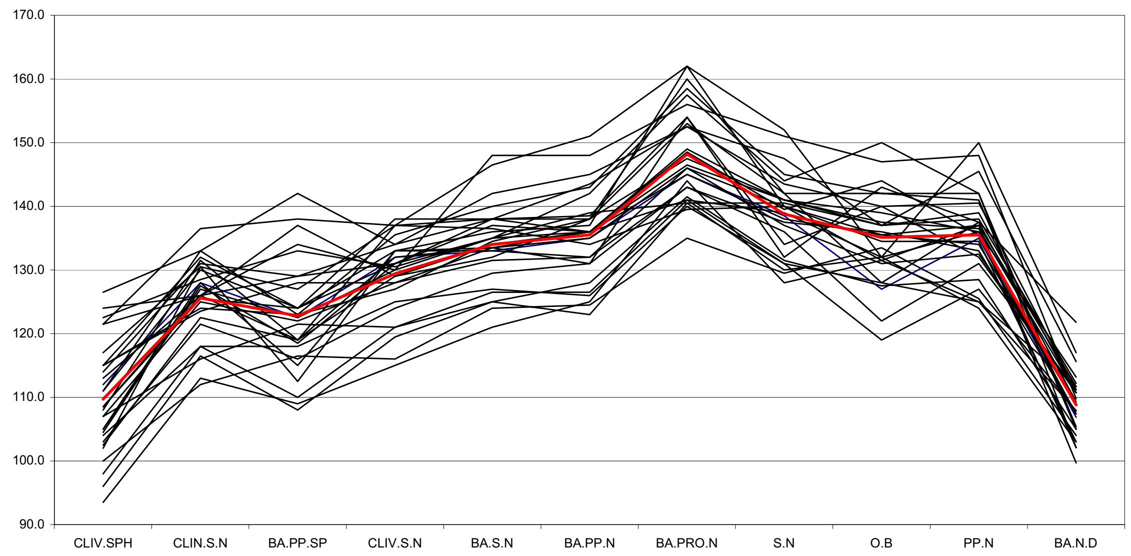


Figure 3.27: Results for the American sample, showing individuals scores in black and the sample average in red.



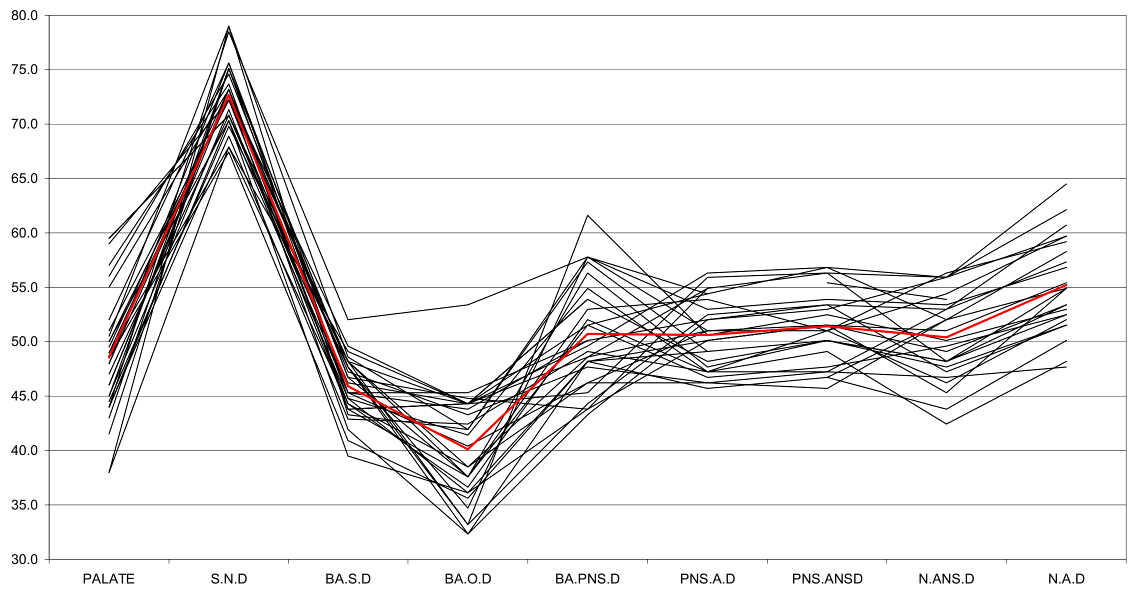
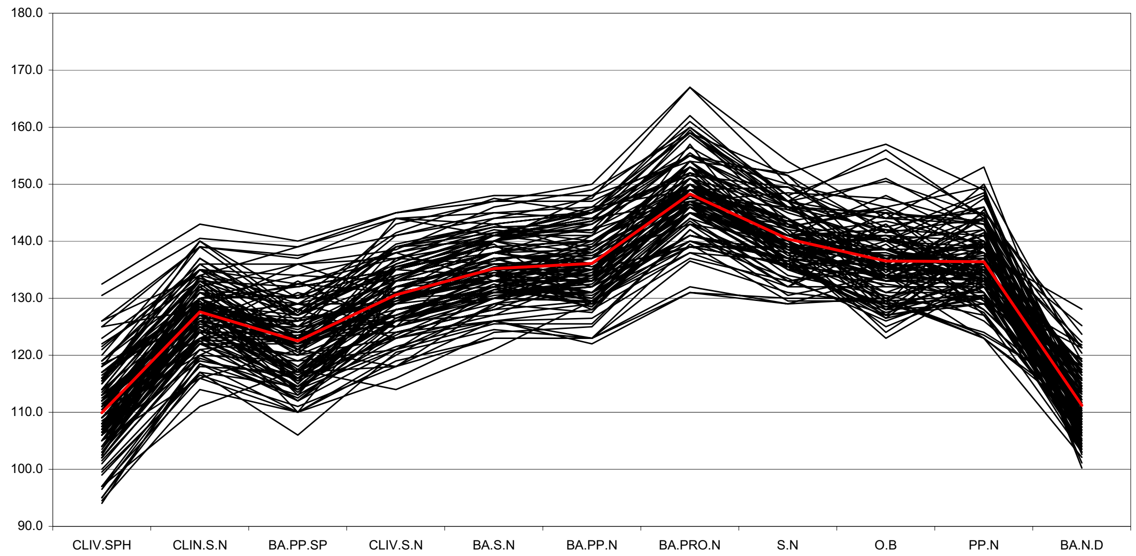


Figure 3.28: Results for the African K/S sample, showing individuals scores in black and the sample average in red.



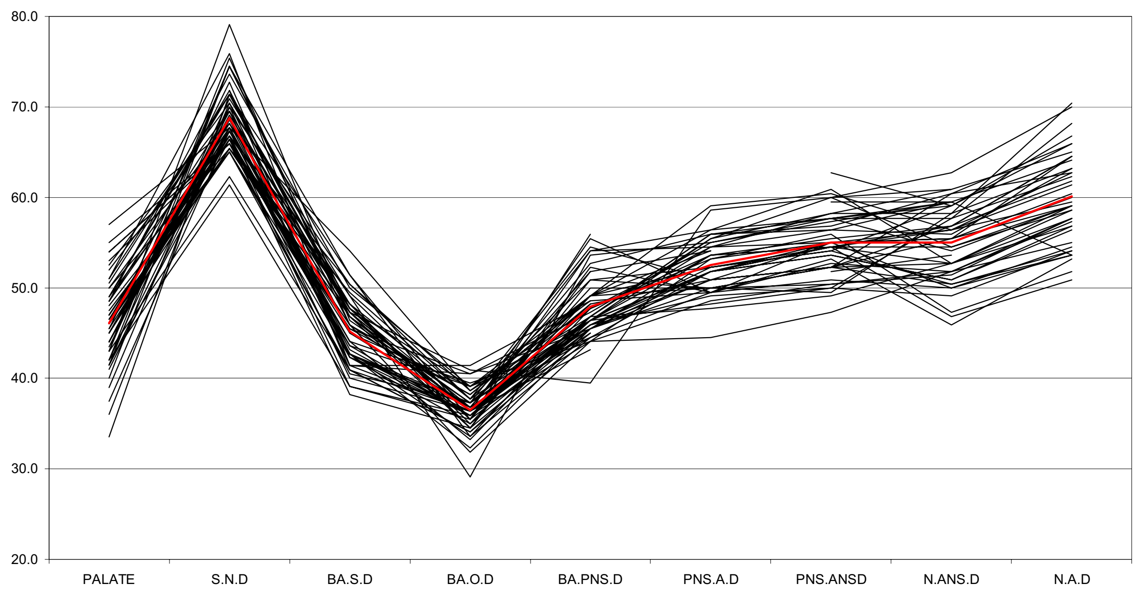


Figure 3.29: Results for the African S/X/Z sample, showing individuals scores in black and the sample average in red.

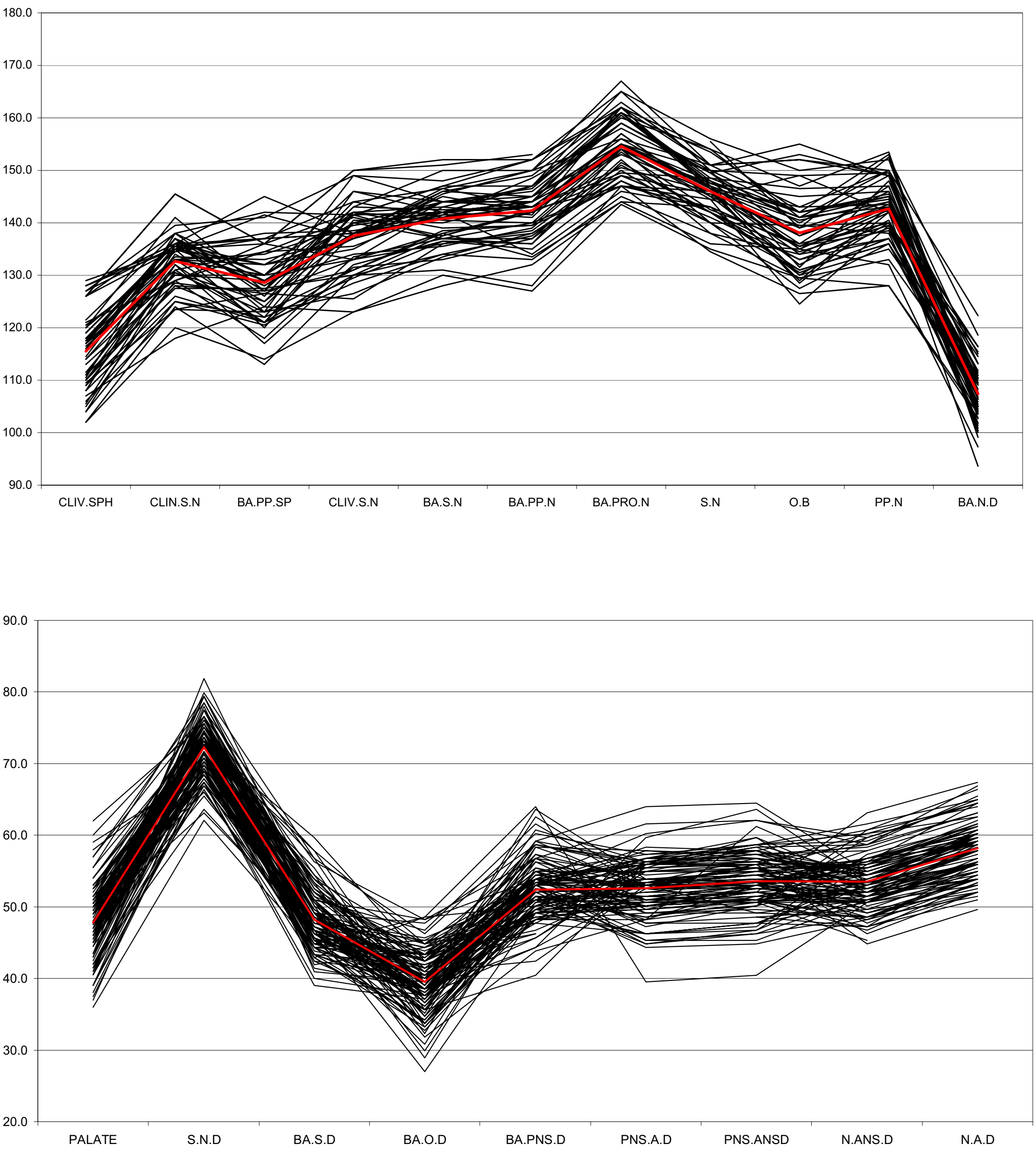
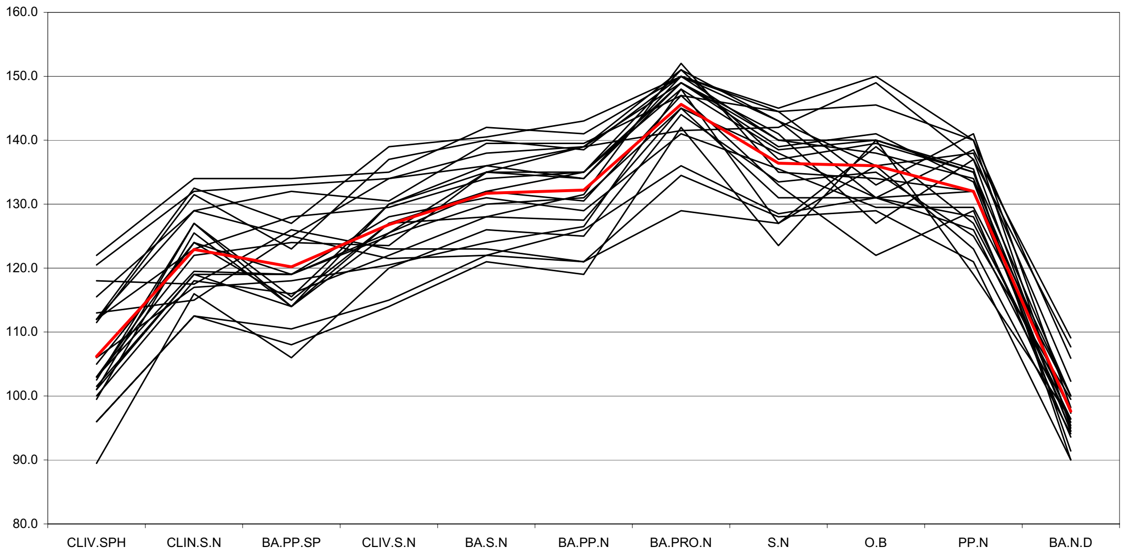


Figure 3.30: Results for the Polynesian sample, showing individuals scores in black and the sample average in red



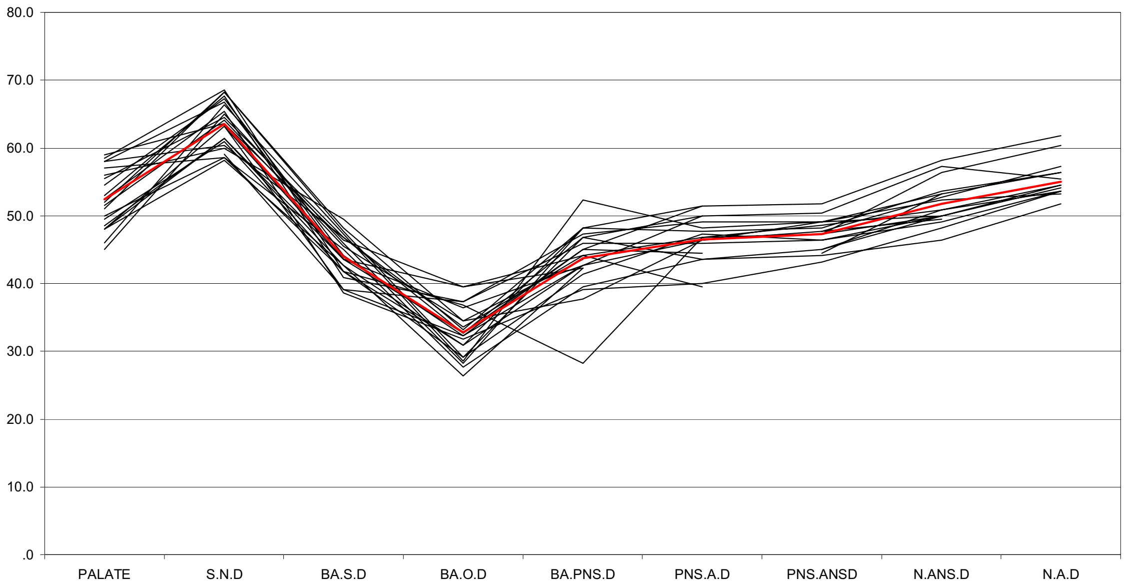
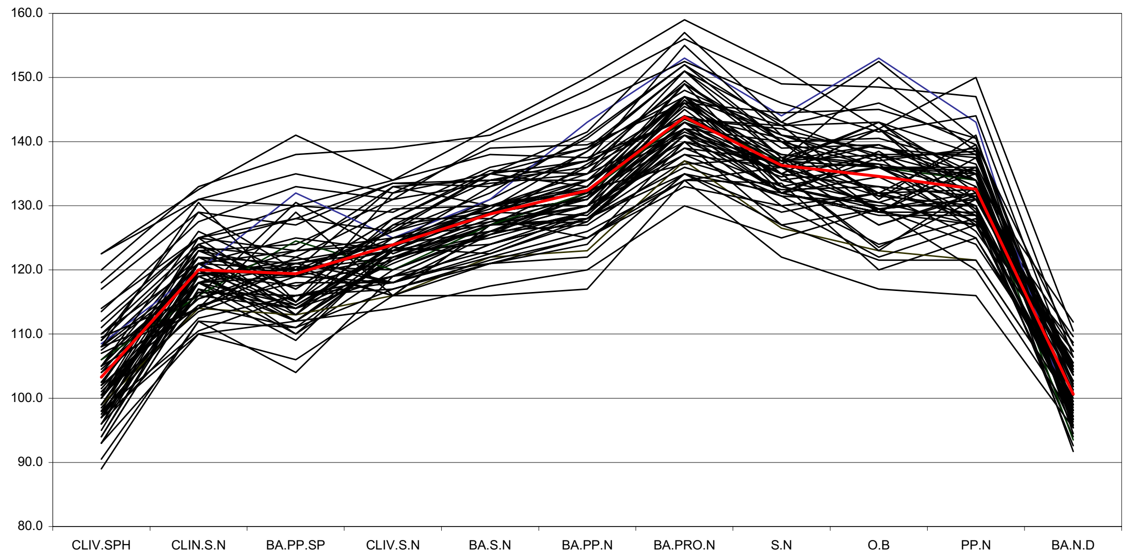


Figure 3.31: Results for the Thai sample, showing individuals scores in black and the sample average in red.



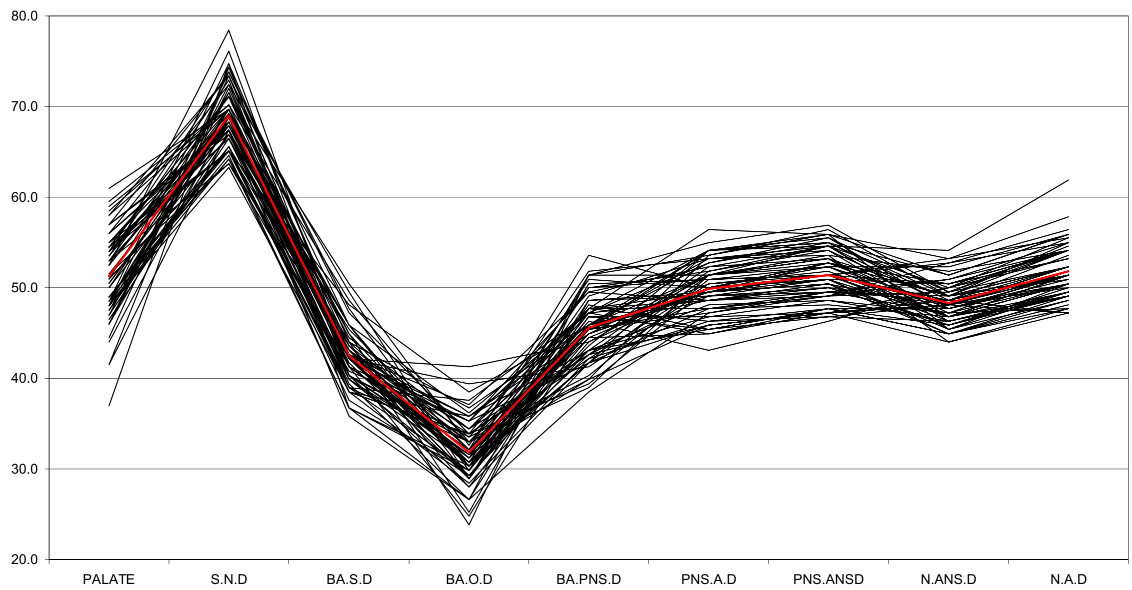
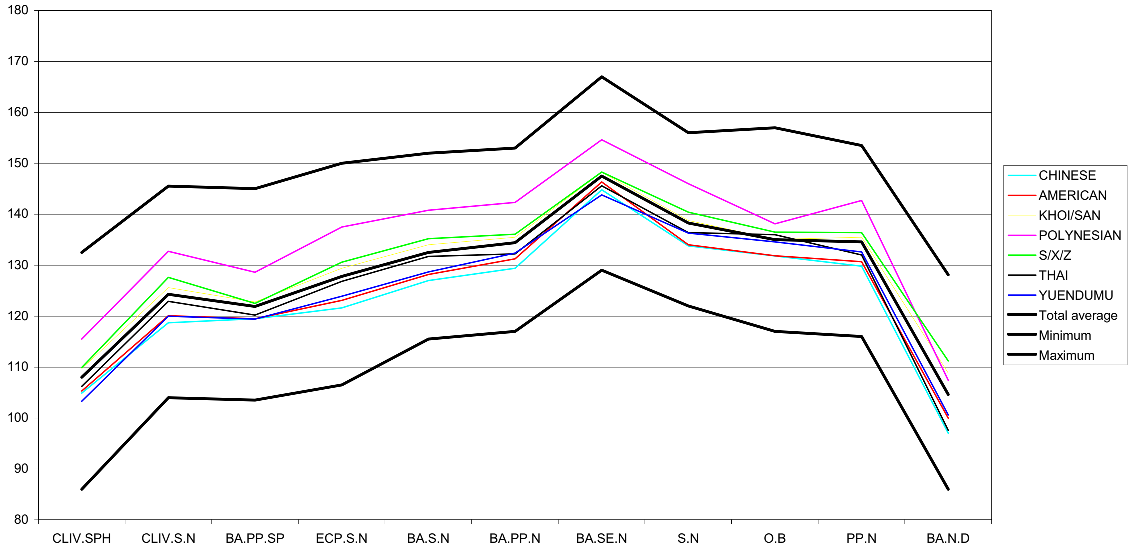


Figure 3.32: Results for the Australian sample, showing individuals scores in black and the sample average in red.

In each of the preceding figures (Figures 3.26 to 3.32), the individual variation is clearly shown. Most individuals appear to follow the general pattern shown by the sample average; however, some deviations from the average are also evident in the various samples. Some samples, for example the African K/S and Thai samples, appear to show greater amounts of variation (more heterogeneous). However this is most likely to be a visual effect of the smaller sample sizes of these two samples compared to the others.

Figure 3.33 shows the results for each sample superimposed on the total sample average, as well as the minimum and maximum values for each variable. The Polynesian sample is clearly identified in the upper part of the figure (most angles and the basion-nasion dimension), with average values for each variable lying well above the other sample means. However, in the lower part of the figure, the largest average dimensions are seen in the African S/X/Z sample, with the average values for the Polynesian sample being closer to the total sample average. The other samples are variously placed around the total sample mean. However, the close similarity between the Chinese and American groups can be seen in the position of their average values relative to each other, particularly in the upper part of the figure (most angles and the basion-nasion dimension).



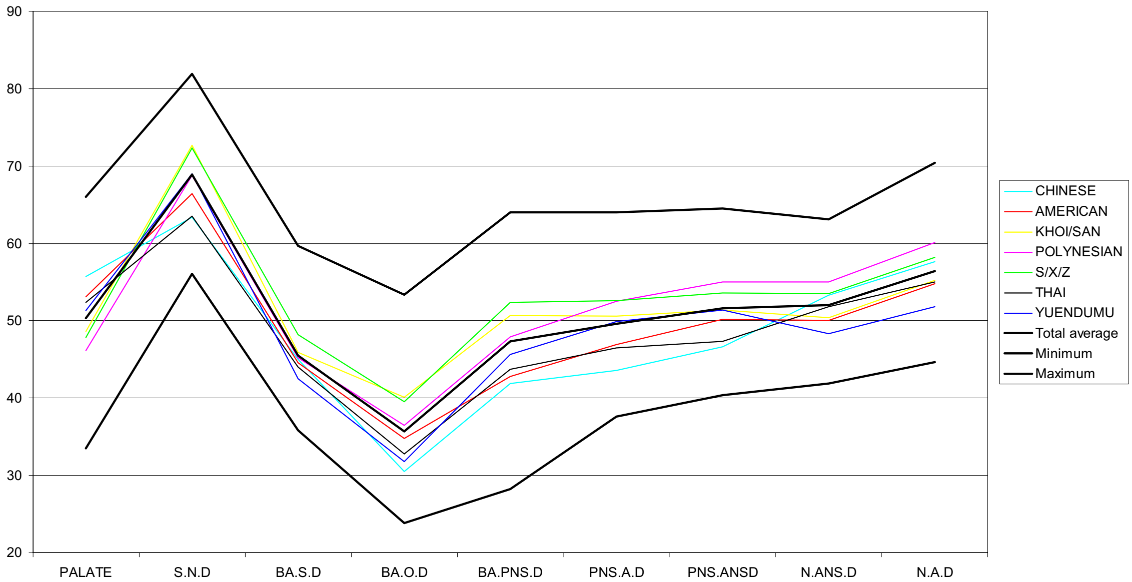


Figure 3.33: Average values for all samples, in addition to the extreme (minimum and maximum) values for each variable.

Individual variation has been explored in other sections in the form of correlation coefficients and multivariate statistics in an attempt to better describe the interaction between cranial base angles and facial morphology. In addition, the modal face for each sub-sample was determined using methods of z-score comparisons. At the same time, the variation present among individuals has been presented by the measurements of individuals most different from the average face. Results showed considerable fluctuation in the measurements of an individual above and below the values of the sample average.

Modal faces – Z score comparison

The aim of this part of the study was to find the individual faces most similar to the sample averages for overall facial morphology. These are referred to as the modal faces for each sample. The purpose of this was to present a visual example of the most typical face/craniofacial complex from each sample. Average values of sample craniofacial morphology have been discussed in previous parts of this chapter. The modal faces for each sample, and the modal male and female individual from each sample, were identified using a method of z-score comparison, the procedure for which is described below. These modal faces can be used as a visual reference for the differences between samples described earlier. The method used to determine the modal face for each sample is similar to that of Penrose in the reconciliation of numerous variables representing both size and shape in biological data (Penrose, 1954).

The following procedure was used to determine the modal face for each sample, based on the cranial base and facial variables of the study. Each sample was analysed separately. For each individual, z-scores of each variable were calculated using the mean and standard deviation of their sample. The z-scores of each individual were then added together to produce a "cumulative z-score" for that person (Table 3.63). For each sample, the individual with the cumulative z-score closest to zero was the individual with the smallest difference from the sample average when all variables were included.

Table 3.63: Results of cumulative z-scores for 20 variables, each sample examined separately. The left and right columns show the individuals who are the most different from the sample average, while the central column identifies the individuals who most resemble the average values for the sample. Italic font indicates identification numbers of individuals.

Sample	Negative z-score		z-score closest to 0		Positive z-score	
	Male	Female	Male	Female	Male	Female
Chinese	-18.3	-16.5	1.6	0.1	18.5	29.9
	77	*112*	*88*	*20*	*52*	*2*
American	-14.7	-21.4	0.1	-0.1	19.0	18.9
	F26	*F25*	*D532*	*D12*	*F78*	*F193*
African K/S	-17.7	-17.6	0.5	-1.0	23.8	16.2
	S26	*S199*	*S334*	*S30*	*S34*	*S319*
Polynesian	-22.0	-17.7	-0.2	-0.6	18.9	19.4
	SM22	*SM212*	*NM374*	*NM124*	*Mo34*	*Mo211*
African S/X/Z	-25.0	19.6	0.2	0.0	20.9	24.8
	S507	*X2858*	*S765*	*X2314*	*S209*	*S752*
Thai	-17.0	-23.4	0.7	0.0	19.6	15.0
	30	*45*	*74*	*64 & 73_b*	*93_a*	*77*
Australian	-19.7	-23.6	-0.1	-0.2	28.1	18.6
	98	*63*	*533*	*229 & 294*	*182*	*71*

This calculation is limited, as the sum of the cumulative z-score refers to differences in size, and does not take into account any variations in shape. These variations in shape affect the contribution of the z-score of each variable to the cumulative z-score. For example, the cumulative z-scores of two individuals from the Australian sample were both –0.1 (Male 542 and Female 66) (Table 3.64) (not all cranial base flexion angles were included in this comparison due to the close relationships between them). When sums of z-scores for different elements of the face were examined, for example the angles of cranial base flexion compared to the craniofacial angles, Individual 542 had a z-score of –4.3 for the angles of cranial base flexion and 0.3 for the craniofacial angles, while Individual 66 had cumulative z-scores of –0.5 and 0.6 for the same variables. When the z-scores of the dimensions were examined, Individual 54 had cumulative z-scores of 3.6, while Individual 66 had cumulative z-scores of –0.2. Despite these differences, the end product of each person's cumulative z-scores was the same.

Table 3.64: Example of cumulative z-scores of two individuals from the Australian sample

VARIABLE		**Z-SCORE**
	542 (MALE)	**66 (FEMALE)**
Basion-sella-nasion	-1.2	0.1
Clival plane-sphenoidal plane	-0.4	-0.6
Basion-pituitary point-sphenoidal plane	-0.1	-0.7
Basion-pituitary point-nasion	-1.0	0.3
Basion-SE-nasion	-1.6	0.5
CRANIAL BASE ANGLES TOTAL	**-4.3**	**-0.5**
Opisthion-basion	0.3	0.4
ANS-PNS	1.2	-0.2
Sella-nasion	-0.1	0.1
Pituitary point-nasion	-1.1	0.2
CRANIOFACIAL ANGLES TOTAL	**0.3**	**0.6**
Sella-nasion	0.7	0.0
Basion-sella	1.1	-0.8
Basion-nasion	1.0	-0.3
Basion-opisthion	1.3	-0.7
Basion-PNS	0.5	-0.5
PNS-ANS	-0.8	0.4
PNS-A point	-0.4	0.0
Nasion- ANS	0.5	0.9
Nasion-A point	0.2	0.8
DIMENSIONS TOTAL	**3.6**	**-0.2**
SUM	**-0.1**	**-0.1**
AVERAGE	**0.0**	**0.0**
ST. DEVIATION	**0.9**	**0.5**

A further calculation of the standard deviation of the cumulative z-scores was, therefore, performed to identify similarities and variations in shape. The standard deviation of the cumulative, or total z-score value was calculated as the standard deviation of the cumulative z-score for all variables in each individual (calculation of z-scores for all variables, followed by calculation of mean and standard deviation of this value). This identifies the individual whose variables are most similar to the sample average with regard to shape, with all variables taken into consideration. Using the same example outlined above, that of the Australian aboriginal individuals Male 542 and Female 66, the standard deviations of the cumulative z-scores were 0.9 and 0.5 respectively (Table 3.64). Thus, Individual 66 is more representative of the average for the whole sample (having a lower standard deviation) than Individual 542.

Calculation of the standard deviation z-score statistics made it possible for the individuals from each sample with the smallest difference in shape from the sample average to be identified. The male and female from each sample with the lowest standard deviation of the cumulative z-score, along with the sample average, are shown in Table 3.65.

Table 3.65: Individuals of each sample with the lowest standard deviation of cumulative z-score (individual identification number shown in italics)

Sample	Standard deviation of cumulative z-score			
	Male	ID	Female	ID
Chinese	0.5	*60*	0.5	*105*
American	0.5	*D533*	0.4	*F185*
African K/S	0.5	*S658*	0.4	*S321*
Polynesian	0.5	*SM175*	0.4	*M102*
African S/X/Z	0.4	*S2431*	0.3	*Z1301*
Thai	0.6	*24*	0.5	*73_b*
Australian	0.5	*487*	0.5	*264*

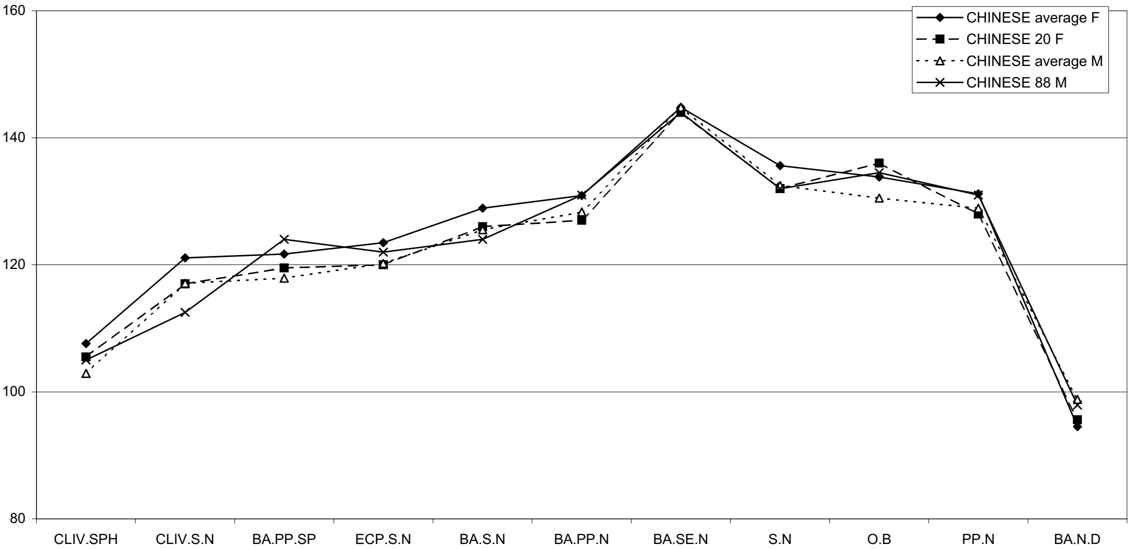
The individuals who best resembled their sample average (males and females) were identified as the ones with the lowest values for cumulative z-score, average of cumulative z-score, and standard deviation of cumulative z-score. This was verified by comparing raw values for all the measurements with the sample average. These individuals are listed in Table 3.66. Line graphs illustrating the sample average, the average values for males and females and the modal face are shown below (Figures 3.34 to 3.40).

Table 3.66: Individuals (males and females) most similar to sample averages

Sample	Sex	ID	Sum of z-scores	Average of z-scores	Standard deviation of z-scores
Chinese	F	*20*	0.1	0.0	0.6
	M	*88*	1.6	0.1	0.7
American	F	*D12*	-0.1	0.0	0.6
	M	*F216*	0.5	0.0	0.6
African K/S	F	*S30*	-1.0	-0.1	0.5
	M	*S334*	-0.5	0.0	0.9
Polynesian	F	*NM124*	-0.6	0.0	0.8
	M	*Mo25*	-0.7	0.0	0.6
African S/X/Z	F	*S2101*	0.6	0.0	0.5
	M	*S556*	-0.5	0.0	0.5
Thai	F	*73-B*	0.0	0.0	0.5
	M	*74*	0.7	0.0	0.7
Australian	F	*294*	-0.2	0.0	0.6
	M	533	0.1	0.0	0.7

Comparison of modal face to the average

The figures of the z-scores of each variable for the sample average and the individual with the lowest cumulative z-score standard deviation show that some fluctuation of the values of the modal face relative to the sample average exists. However, when the values of the two individuals who are the most different from the sample average are examined, the fit between the average and the typical face becomes more convincing. These figures have been prepared for each sample separately. Determining the individuals with the largest and smallest cumulative z-scores identified the individuals showing the most extreme variation relative to the sample average.



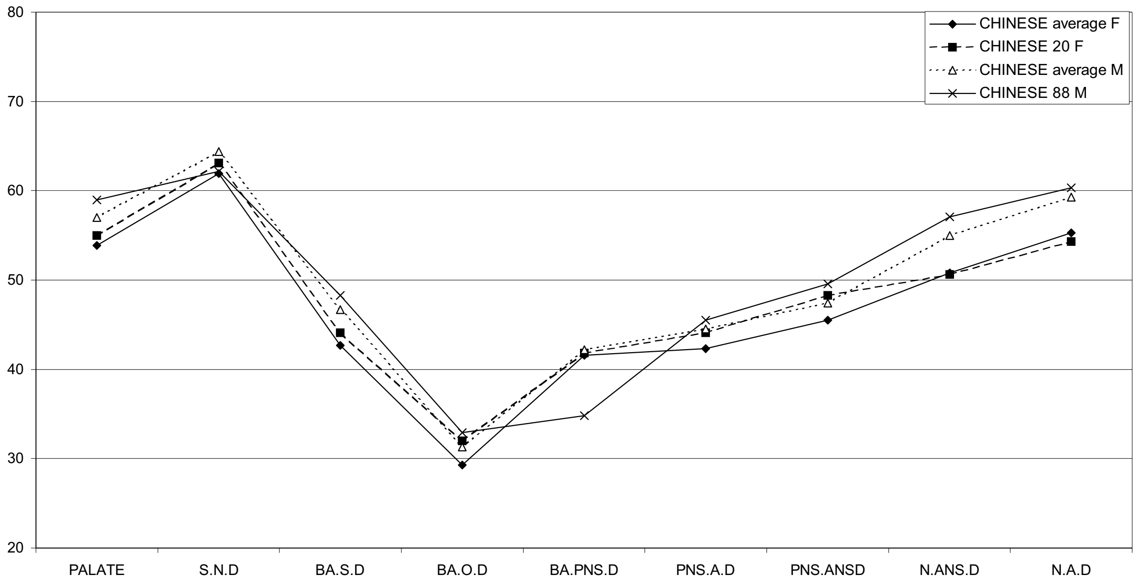
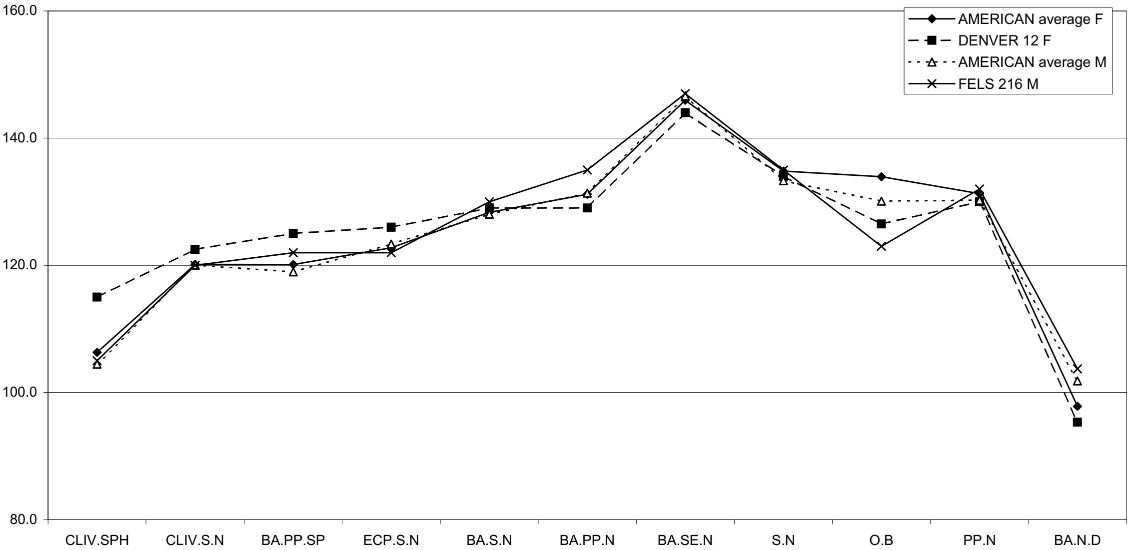


Figure 3.34: Comparison between average values for males and females and modal faces of each sex – Chinese sample.



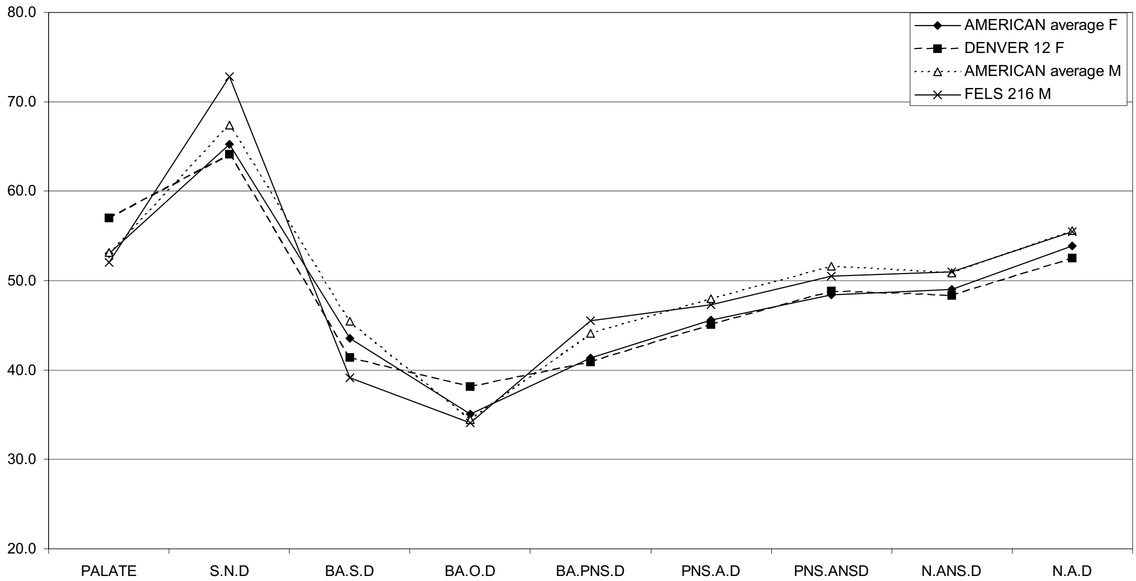


Figure 3.35: Comparison between average values for males and females and modal faces of each sex – American sample.

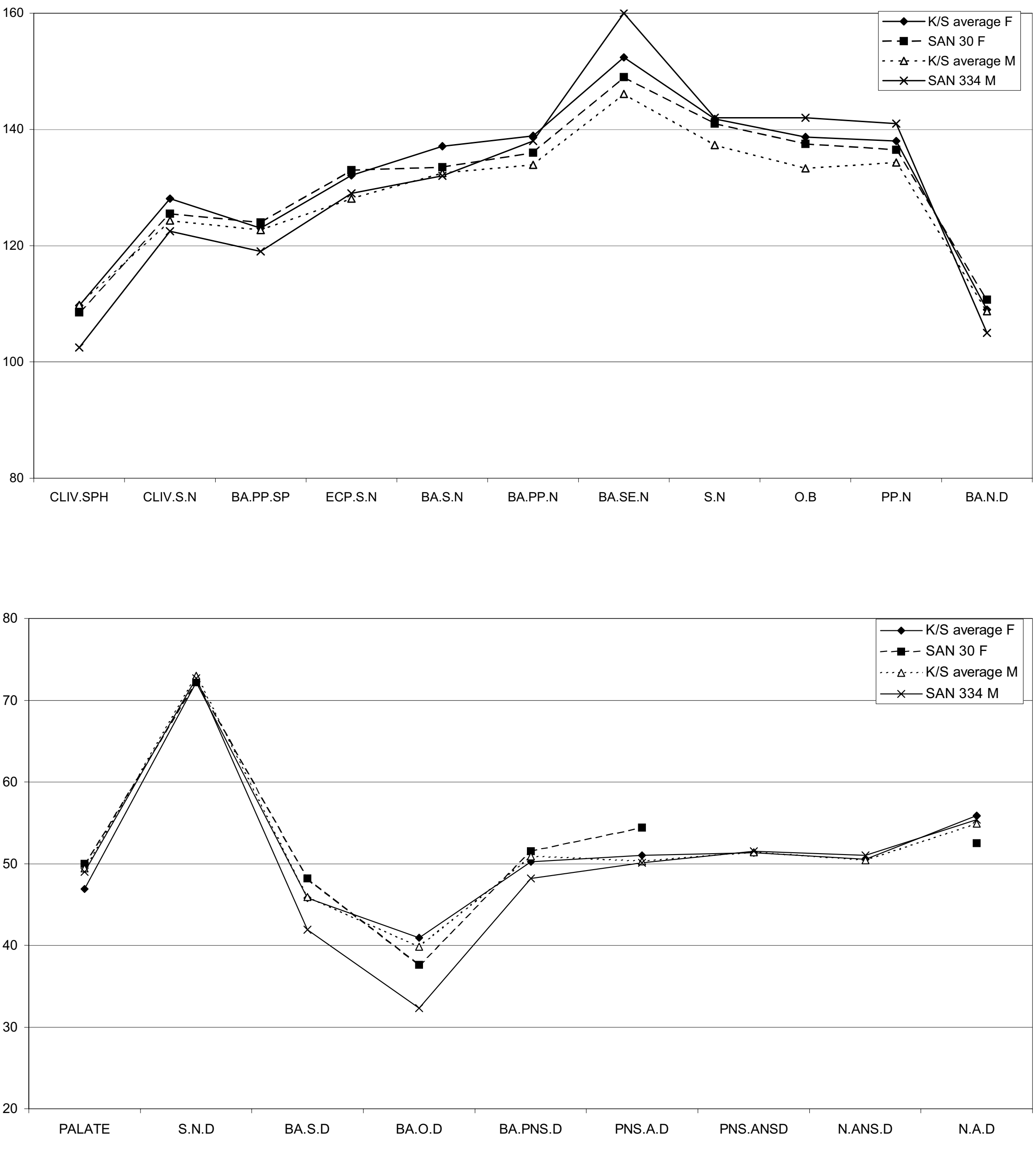
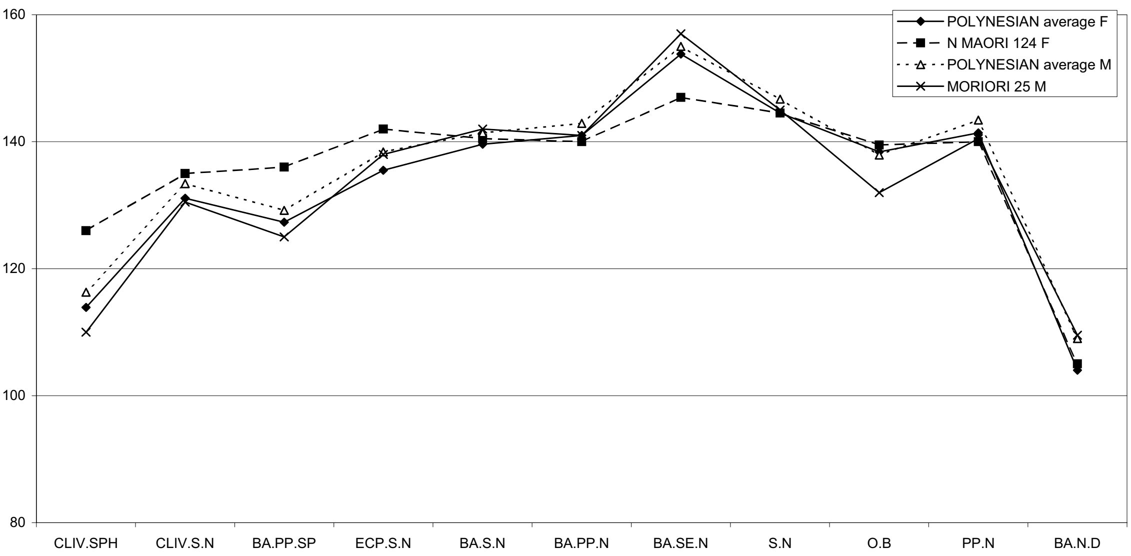


Figure 3.36: Comparison between average values for males and females and modal faces of each sex – African K/S sample.



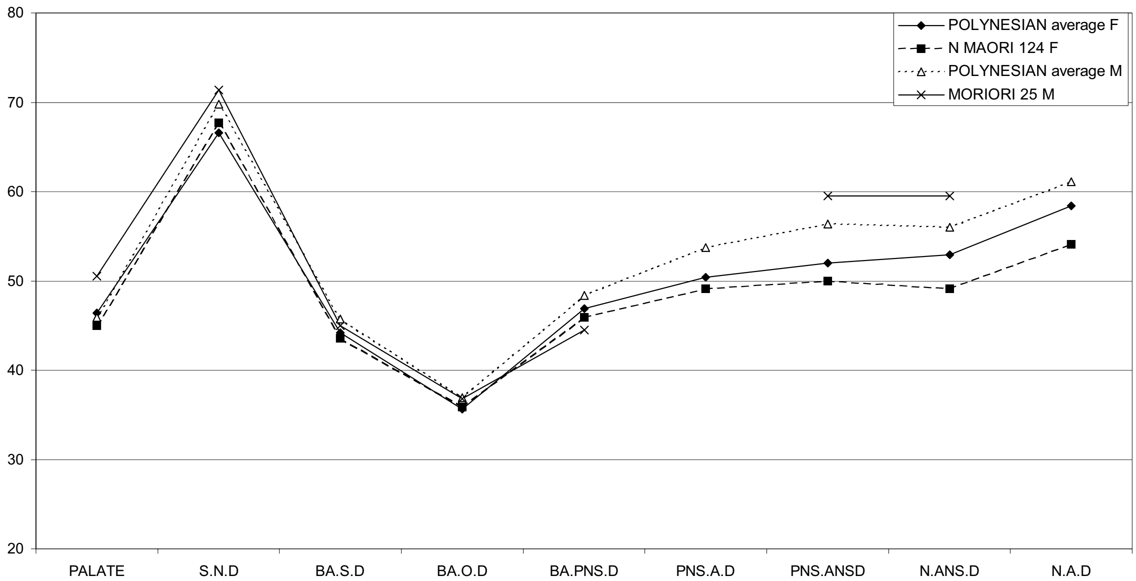


Figure 3.37: Comparison between average values for males and females and modal faces of each sex – Polynesian sample.

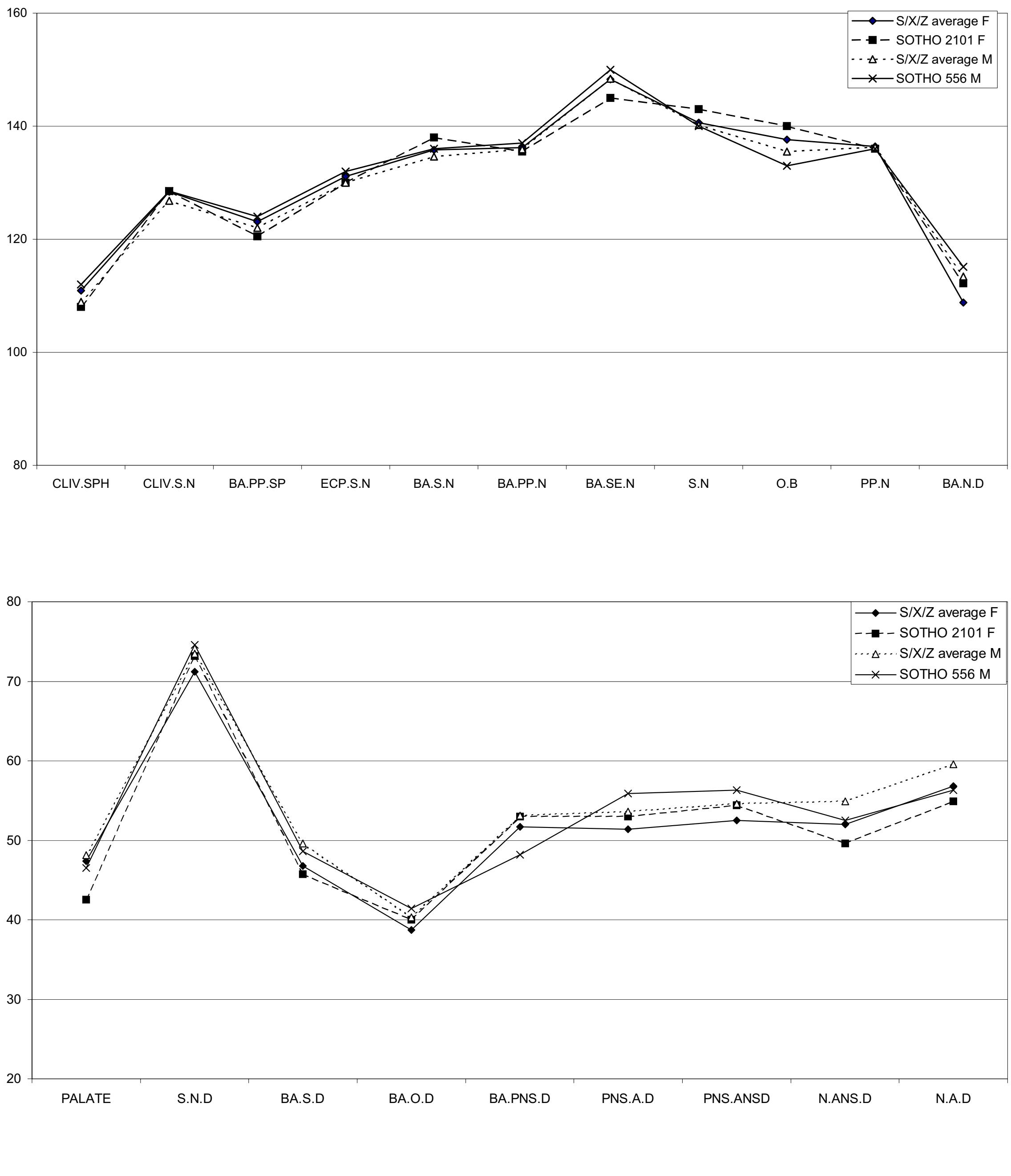
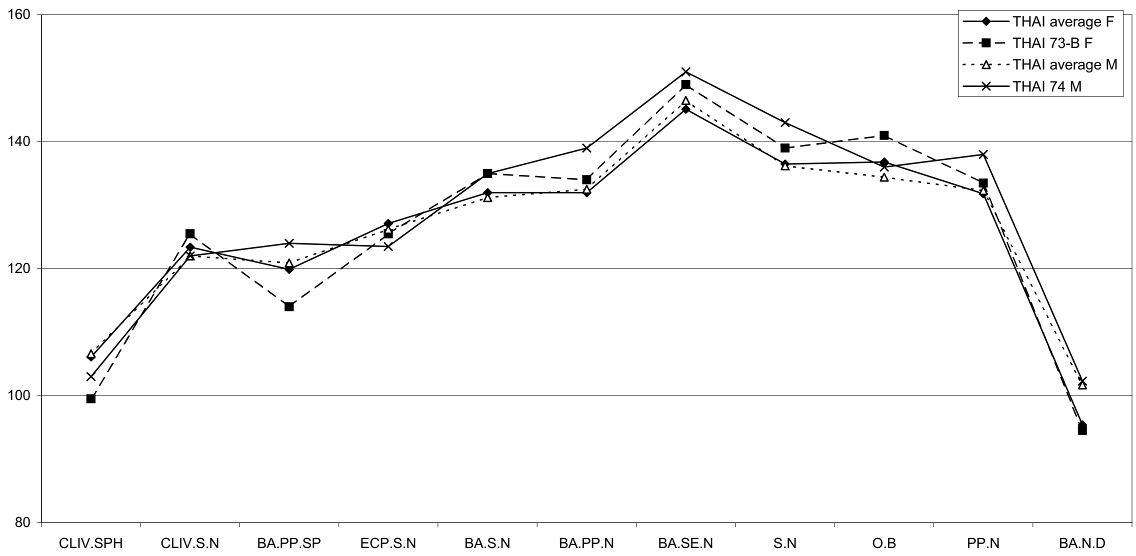


Figure 3.38: Comparison between average values for males and females and modal faces of each sex – African S/X/Z sample.



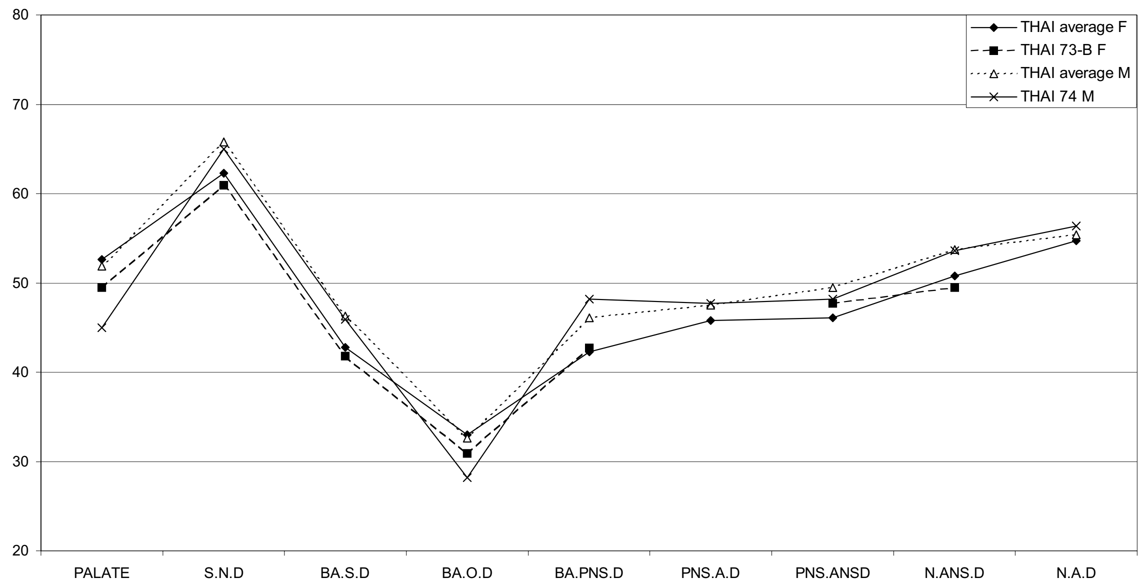
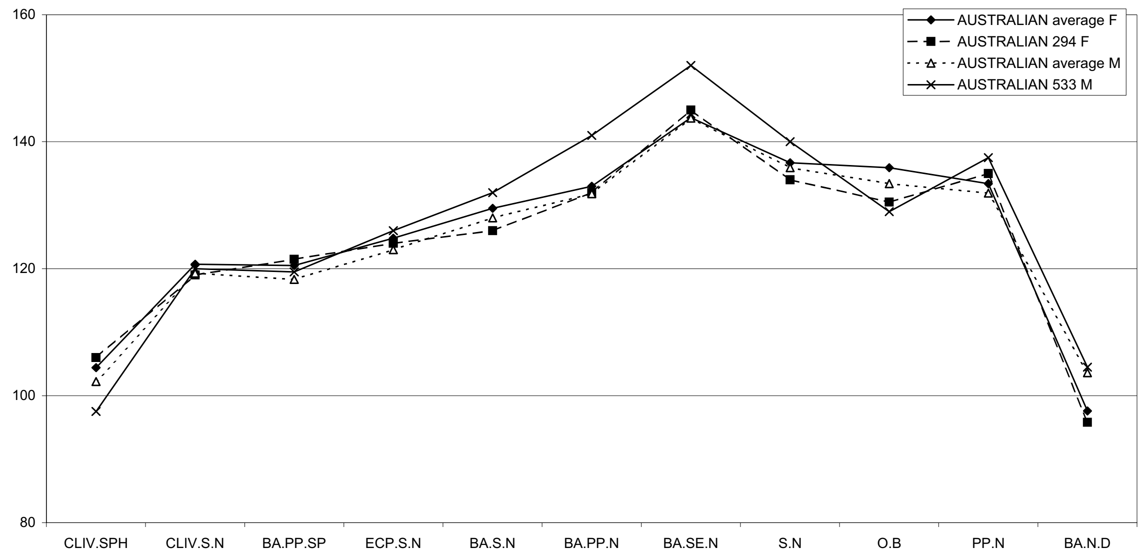


Figure 3.39: Comparison between average values for males and females and modal faces of each sex – Thai sample.



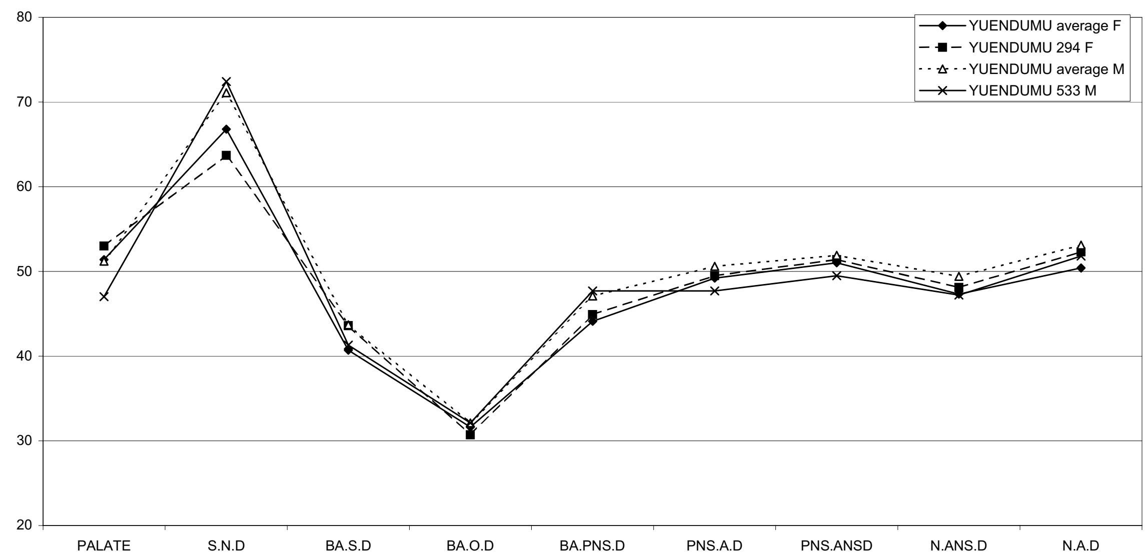


Figure 3.40: Comparison between average values for males and females and modal faces of each sex – Australian sample.

The male and female modal face of each sample is shown below in Figure 3.41. This provides a visual reference of the actual face as traced from the radiograph to compare with the values in the tables and the figures. The tracing of each modal face has been oriented so that the basion-opisthion plane is horizontal. When examining the figures, it should be remembered that each tracing had a different radiographic enlargement that has not been corrected in this figure (despite the reduced size of each tracing). Therefore, while comparisons of shape and proportion between the individuals can be made, comparisons of size in this instance are inappropriate. When examining the modal faces, it can be seen that overall the faces appear quite similar, especially when the shape of the vault is excluded. The cranial base in the Polynesians appears less flexed compared to the other samples. The orientation of the hard palate (ANS-PNS) also appears to vary somewhat between samples, for example, being oriented slightly inferiorly in the Chinese sample. Some sexual dimorphism is apparent in some samples, but in others it is quite difficult to distinguish male and female modal faces.

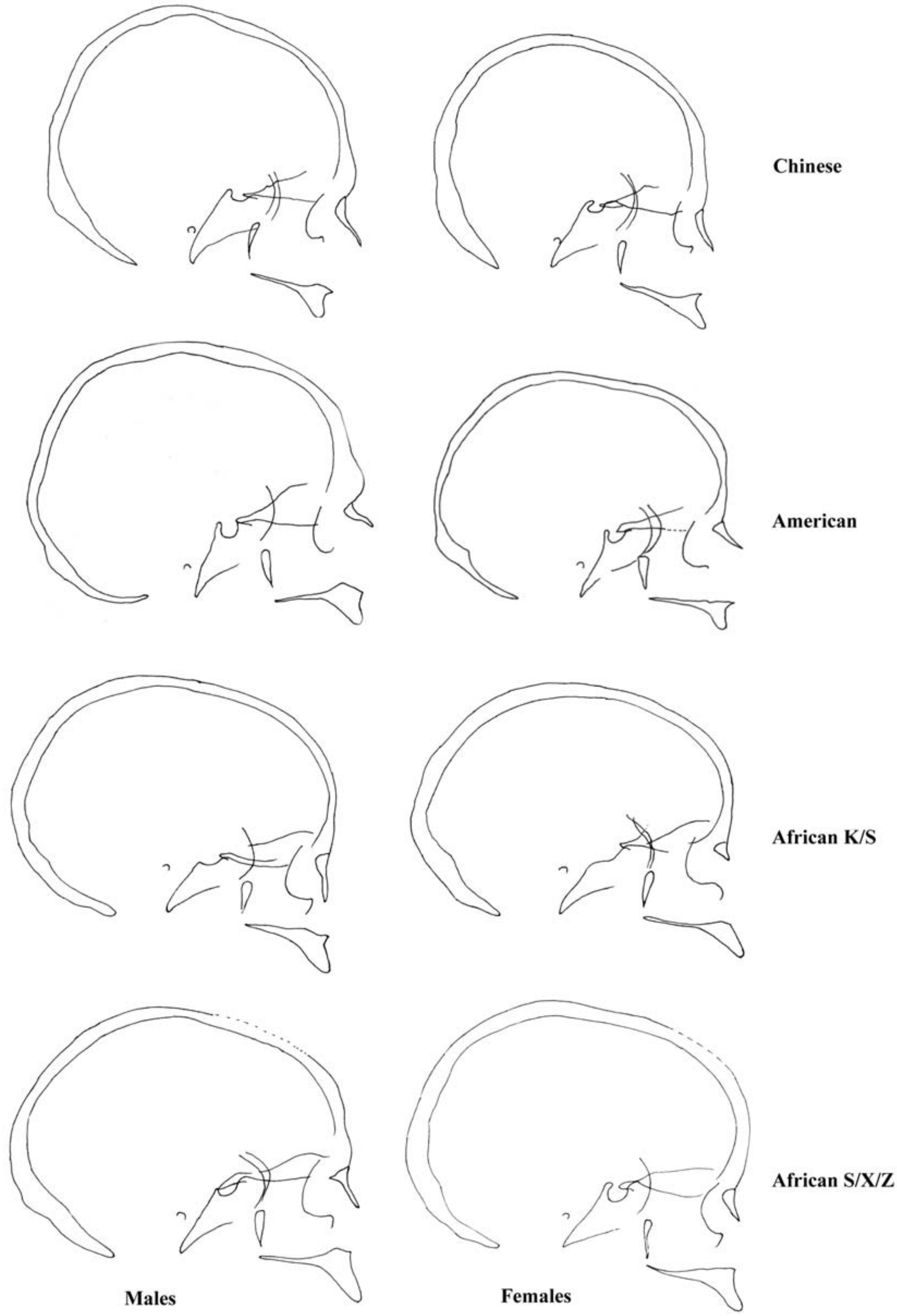


Figure 3.41: Modal faces of each sample, generated through comparison of cumulative z-scores (males on the left, females on the right)(continued next page)

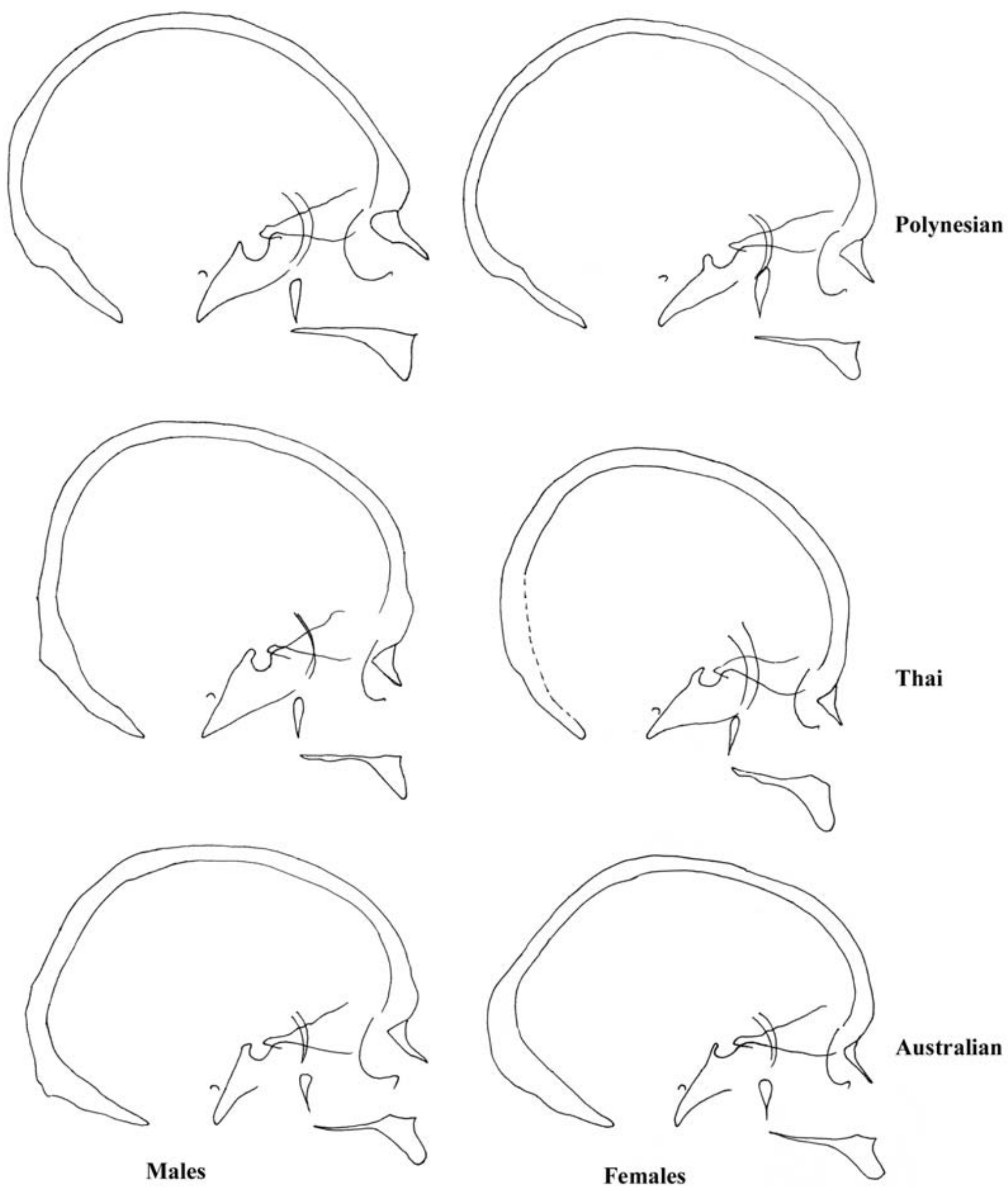


Figure 3.41 continued from previous page: Modal faces of each sample, generated through comparison of cumulative z-scores (males on the left, females on the right)

An examination of individual variation in the cranial base and craniofacial skeleton would be incomplete without also examining the craniofacial variation present in the individuals who differed the most from the sample mean, as well as the individuals who are the most similar (modal faces). The individuals with the values most different from the sample average were identified using the following method. First, the individuals of each sample with the highest and lowest values for cumulative z-scores, in conjunction with large standard deviations of z-scores were located in the data. If multiple individuals for each extreme (above and below the sample average) were present, their z-scores were plotted on a graph, and the ones which differed the most from the sample average on visual inspection were selected. Males and females from each sample were selected in this way. The individuals displaying the greatest variation from the average with regard to shape are listed in Table 3.67.

Table 3.67: Individuals varying the most from sample averages.

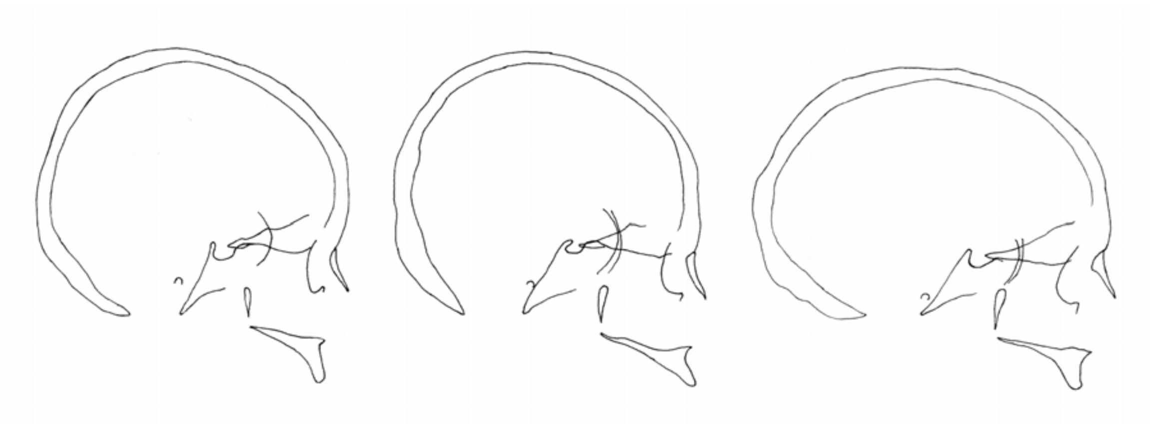
Sample	Sex	ID	Sum of z-scores	Average of z-scores	Standard deviation of z-scores
Chinese	F	*2*	29.9	1.4	1.2
	F	*112*	-16.5	-0.8	0.8
	M	*52*	18.5	0.9	0.9
	M	*77*	-18.3	-0.9	1.1
American	F	*F193*	18.9	1.0	0.7
	F	*F25*	-21.4	-1.1	1.0
	M	*F78*	19.0	1.0	0.6
	M	*F26*	-14.7	-0.7	1.0
African K/S	F	*S319*	16.2	0.8	1.1
	F	*S199*	-17.6	-0.8	1.2
	M	*S34*	23.8	1.1	1.2
	M	*K171*	-5.7	-0.3	1.3
Polynesian	F	*SM362*	15.9	0.8	1.3
	F	*SM74*	-14.3	-0.7	1.2
	M	*SM23*	17.8	0.8	1.2
	M	*SM22*	-22.0	-1.0	1.6
African S/X/Z	F	*X3590*	15.8	0.8	1.3
	F	*Z3817*	-13.3	-0.6	1.6
	M	*S1459*	17.4	0.8	1.2
	M	*X3159*	-19.8	-0.9	1.2

Table 3.67 continued

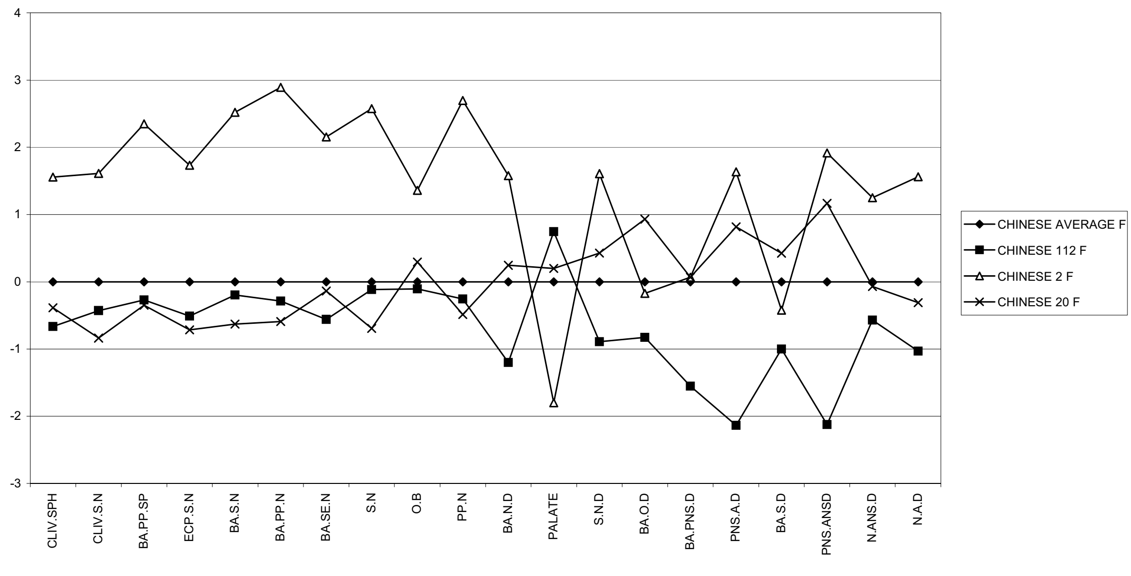
Sample	Sex	ID	Sum of z-scores	Average of z-scores	Standard deviation of z-scores
Thai	F	*18-A*	9.4	0.5	1.0
	F	*61*	-3.9	-0.2	1.3
	M	*93-A*	19.6	0.9	0.6
	M	*44*	-9.2	-0.5	1.0
Australian	F	*71*	18.6	0.9	1.0
	F	*63*	-23.6	-1.1	1.4
	M	*10(B)*	19.5	0.9	1.7
	M	*98*	-19.7	-0.9	1.1

The information shown in Table 3.67 shows that there were some individuals who appeared to differ quite dramatically from the sample average when z-scores and associated statistics were calculated. For each sample, the male and female individual who differed the most from the sample average could be identified. An examination of the z-score statistics showed that some individual's cumulative z-scores were up to 30 units away from the sample average in some samples (with average cumulative z-scores around 1.0.

Line graphs comparing the sample average, the modal face and the two most extreme individuals are shown in Figures 3.42 to 3.55 below. These show the sample average with a z-score of zero and the other series with their relative z-scores. The z-score results of the modal face for each sex of sample are also displayed on each figure, to enable comparisons to be made between the modal face and the individuals found to be the most different from the sample average. Males and females are shown separately.



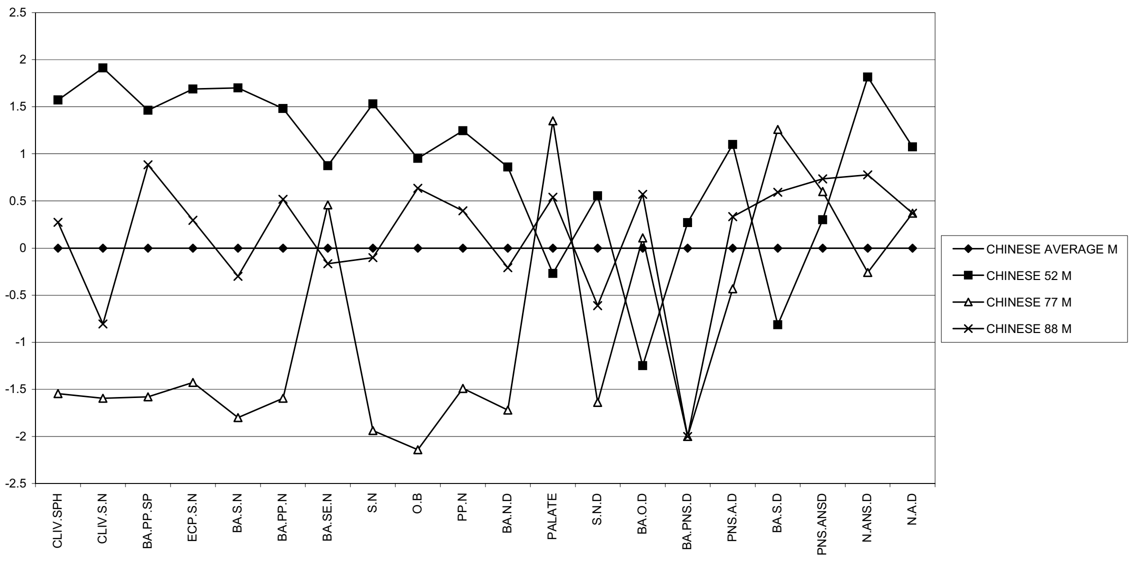
(a)



(b)

Figure 3.42: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Chinese female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Chinese female sample showing modal face and the two most extreme individuals with the sample average at zero.

(a)



(b)

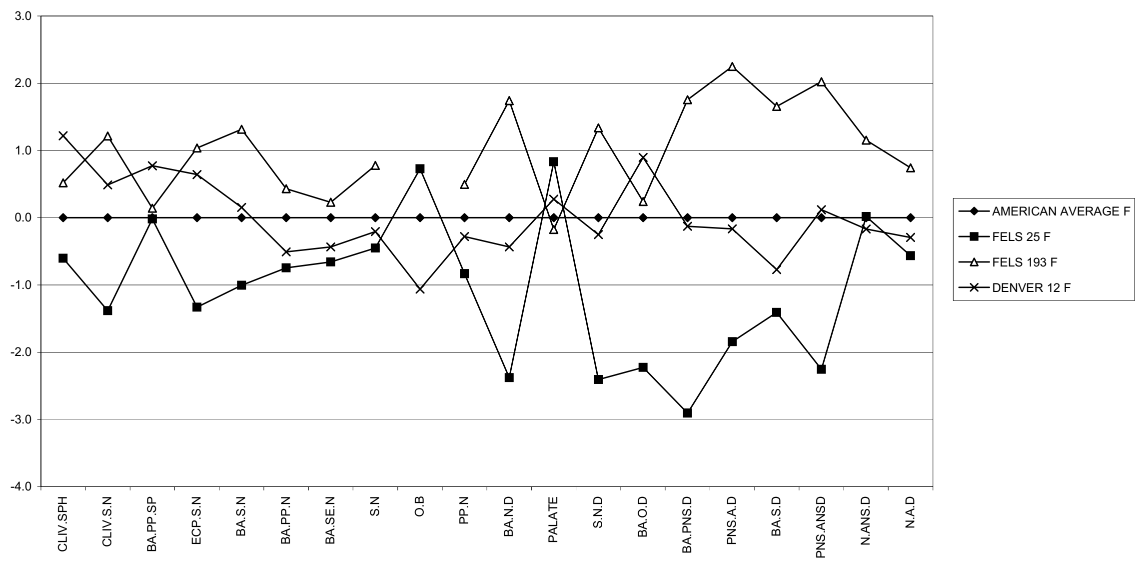
Figure 3.43: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Chinese male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Chinese male sample showing modal face and the two most extreme individuals with the sample average at zero.

The raw values of the individuals representing the modal face and extreme negative and positive faces of the Chinese sample are shown in Table 3.68. Examination of the results presented in Figures 3.42 and 3.43 and Table 3.68 reveals some interesting features about the modal and extreme faces of the Chinese sample. For example, cranial base flexion in the extreme positive faces is considerably greater (less flexed) than the modal face and extreme negative face in both sexes. In the Chinese females, the craniofacial angles (anterior cranial base and foramen magnum) in the extreme positive face is much greater (less flexed) compared to the extreme negative face. This represents a more stretched out "z" shape. The orientation of the palatal plane relative to the clivus in the extreme positive female is 44.0 degrees, which is less than the average face, modal face and extreme negative faces. In contrast, the extreme negative Chinese female face has smaller angles between most of the craniofacial angles relative to the clivus (anterior cranial base and foramen magnum), resulting in a more compact "z" shape, while the orientation of the palatal plane relative to the clivus is more extreme, with a value of 58 degrees, meaning that the ANS is located inferiorly compared to the PNS. Regarding the craniofacial and cranial base dimensions in the female sample, all dimensions are greater in the extreme positive face compared to the extreme negative face. In particular, the length of the mid-face (nasion-ANS/nasion-A point) is greater in the extreme positive individual. Combined with the smaller angle of orientation between the palate and the clivus, this suggests a more inferior location of the PNS, rather than the ANS. In the Chinese male sample, similar relationships are seen, with the individual representing the extreme positive face having less cranial base flexion, greater craniofacial angles relative to the clivus (elongated "z"), and larger dimensions. In both sexes the diameter of the foramen magnum (basion-opsithion) did not have a distinct pattern of variation according to the three facial types. Finally, it is interesting that on visual inspection of the extreme negative and extreme positive faces shown in Figures 3.42a and 3.43a, the extreme negative face appears more dolicocephalic and the extreme positive face appears to be more brachycephalic. However, since measurements were not undertaken on the cranial vault these impressions cannot be verified using the data of the present study.

Table 3.68: Comparison between average values, modal face and extreme negative and positive faces for the Chinese sample.

Chinese		Females				Males			
	ID	average	modal face 20	extreme positive 2	extreme negative 112	average	modal face 88	extreme positive 52	extreme negative 77
Cranial base flexion angles	CLIV.SPH	107.6	105.5	116.0	104.0	102.9	105.0	115.0	91.0
	CLIV.S.N	121.1	117.0	129.0	119.0	117.1	112.5	128.0	108.0
	BA.PP.SP	121.7	119.5	136.5	120.0	117.9	124.0	128.0	107.0
	ECP.S.N	123.5	120.0	132.0	121.0	120.2	122.0	130.5	111.5
	BA.S.N	128.9	126.0	140.5	128.0	125.5	124.0	134.0	116.5
	BA.PP.N	130.9	127.0	150.0	129.0	128.3	131.0	136.0	120.0
	BA.SE.N	144.8	144.0	157.5	141.5	144.8	144.0	149.0	147.0
Craniofacial angles	S.N	135.6	132.0	149.0	135.0	132.5	132.0	140.0	123.0
	O.B	133.8	136.0	144.0	133.0	130.5	134.5	136.5	117.0
	PP.N	131.2	128.0	149.0	129.5	128.9	131.0	135.5	121.0
	PALATE	53.9	55.0	44.0	58.0	57.0	59.0	56.0	62.0
Dimensions	BA.O	29.3	32.0	28.8	26.9	31.3	32.9	27.8	31.6
	BA.PNS	41.6	41.8	41.8	37.1	42.2	34.8	43.2	34.8
	PNS.A	42.3	44.1	45.9	37.6	44.5	45.5	47.8	43.2
	BA.S	42.7	44.1	41.3	39.4	46.7	48.3	44.5	50.1
	PNS.ANS	45.5	48.3	50.1	40.4	47.4	49.6	48.3	49.2
	N.ANS	50.8	50.6	54.3	49.2	55.0	57.1	59.9	54.3
	N.A.D	55.3	54.3	60.3	52.0	59.3	60.3	62.2	60.3
	S.N	61.9	63.1	66.4	59.4	64.4	62.2	66.4	58.5
	BA.N	94.5	95.6	101.6	89.1	98.8	97.9	102.5	91.4

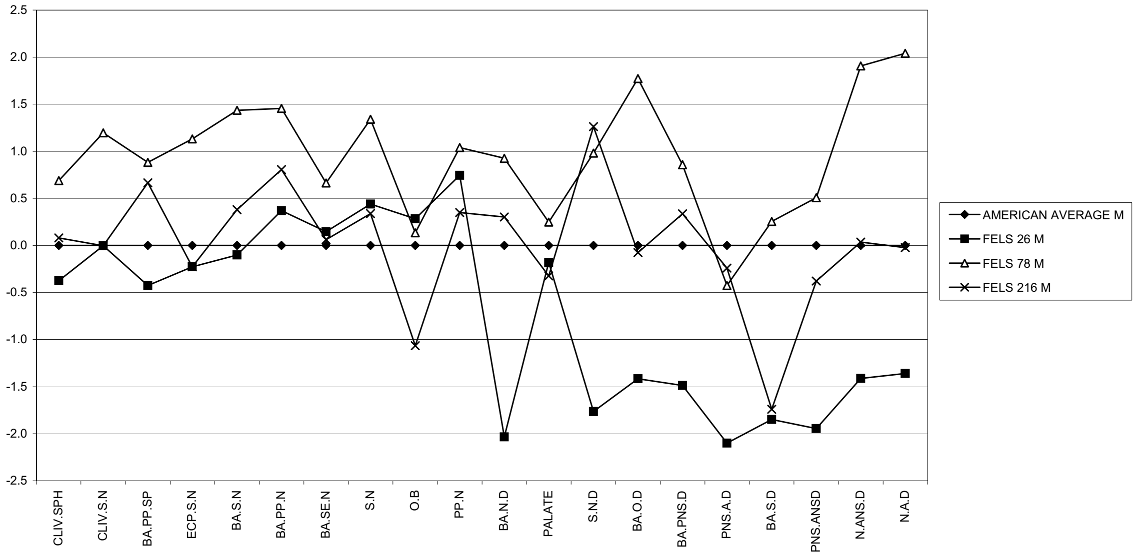
(a)



(b)

Figure 3.44: (a) Line diagrams of modal face (centre) with the two most extreme faces from the American female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of American female sample showing modal face and the two most extreme individuals with the sample average at zero.

(a)



(b)

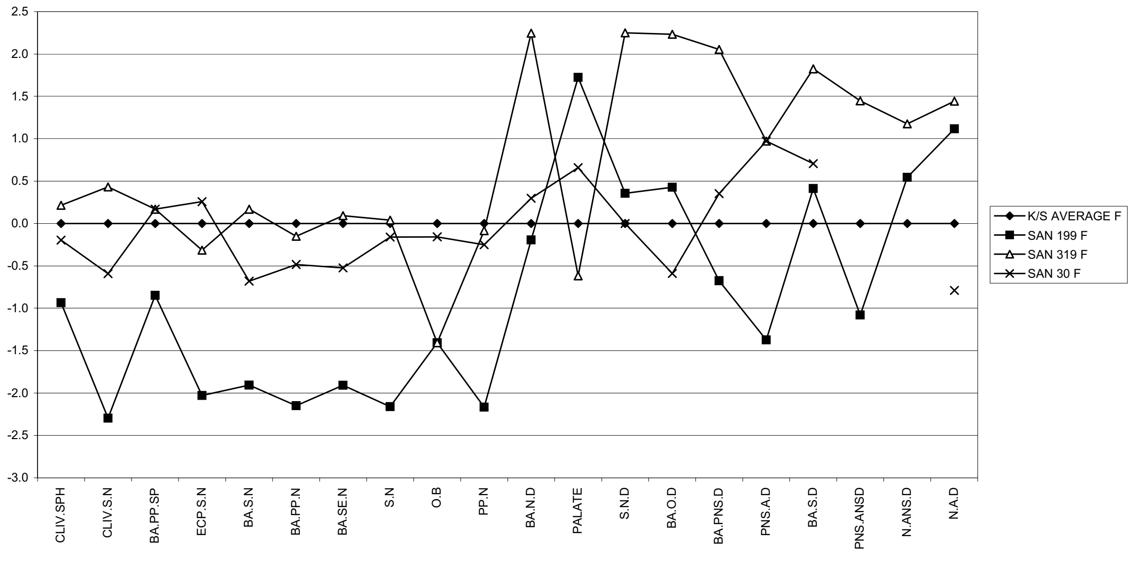
Figure 3.45: (a) Line diagrams of modal face (centre) with the two most extreme faces from the American male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of American male sample showing modal face and the two most extreme individuals with the sample average at zero.

The results of the American samples shown in Figure 3.44 and 3.45 and Table 3.69 are similar to those of the Chinese sample, in terms of the relationships between cranial base flexion and craniofacial angles. In both males and females, the cranial base is less flexed in the extreme positive face, while the orientation of the palatal plane (relative to the clivus) is reduced. In addition, the extreme positive individuals appear to have an elongated "z" shape (between the foramen magnum, clivus and anterior cranial base, while the extreme negative individuals have the opposite relationship (more compact "z"). There are some differences in the dimensions of the cranial base and craniofacial skeleton. While the American females follow the pattern seen in both male and female Chinese individuals, with larger dimensions in the extreme positive individuals, the American males show a different pattern. In particular, all dimensions of the extreme positive individual are smaller than those of the extreme positive face. Examining the raw values of dimensions of the sample average, modal face, extreme negative and extreme positive, it becomes apparent that the variation seen in the extreme positive individual in this instance is most likely to be the result of individual variation. Furthermore, the differences between the extreme negative and positive faces are relatively small, suggesting that the sample may be fairly homogeneous, which may also account for the smaller dimensions in the extreme positive face. This is apparent when comparing the male faces shown in Figure 3.45a, where it can be seen that they are all quite similar in proportion. In contrast, the female faces in Figure 3.44a appear quite disparate, with the extreme negative face appearing brachycephalic, whereas the extreme positive face, while the vault appears very large in comparison to the modal face and extreme negative, also appears relatively dolicocephalic.

Table 3.69: Comparison between average values, modal face and extreme negative and positive faces for the American sample.

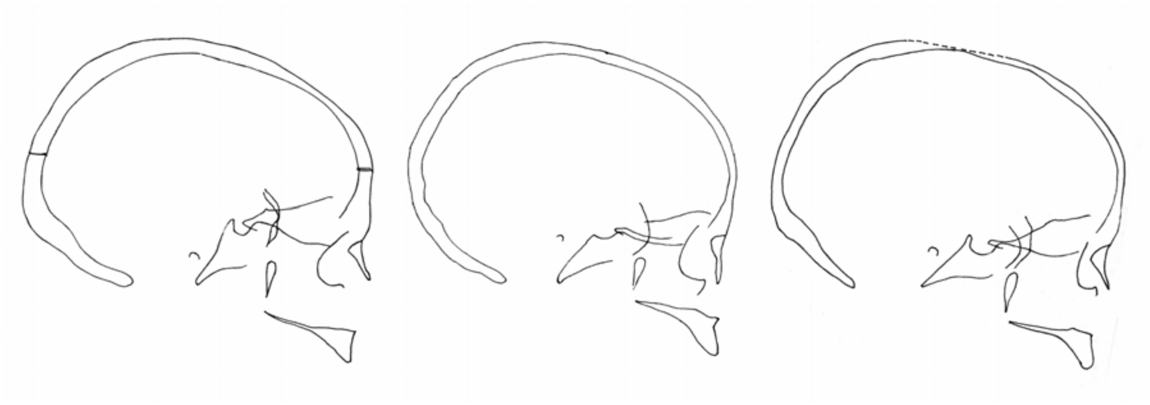
American		Females				Males			
		average	modal face	extreme positive	extreme negative	average	modal face	extreme positive	extreme negative
	ID		D12	F193	F25		F216	F78	F26
Cranial base flexion angles	CLIV.SPH	106.3	115.0	110.0	102.0	104.5	105.0	109.0	102.0
	CLIV.S.N	120.2	122.5	126.0	113.5	120.0	120.0	127.5	120.0
	BA.PP.SP	120.1	125.0	121.0	120.0	119.0	122.0	123.0	117.0
	ECP.S.N	122.8	126.0	128.0	116.0	123.3	122.0	130.0	122.0
	BA.S.N	128.3	129.0	134.0	124.0	128.0	130.0	135.5	127.5
	BA.PP.N	131.2	129.0	133.0	128.0	131.3	135.0	138.0	133.0
	BA.SE.N	146.0	144.0	147.0	143.0	146.6	147.0	150.5	147.5
Craniofacial angles	S.N	134.8	134.0	138.0	133.0	133.3	135.0	140.0	135.5
	O.B	133.9	126.5		139.0	130.1	123.0	131.0	132.0
	PP.N	131.3	130.0	133.5	127.5	130.2	132.0	135.5	134.0
	PALATE	53.0	57.0	50.5	65.0	53.1	52.0	54.0	52.5
Dimensions	BA.O	35.1	41.0		28.2	34.5	28.7	32.4	39.8
	BA.PNS	41.4	44.0	46.7	32.4	44.1	47.2	45.3	48.0
	PNS.A	45.6	48.5	45.8	41.2	48.0	50.0	48.1	52.8
	BA.S	43.6	44.5	49.0	40.7	45.5	44.9	46.7	49.0
	PNS.ANS	48.4	52.5	46.7	41.6	51.6	51.8	52.3	56.6
	N.ANS	49.0	52.0	52.3	50.4	50.9	53.2	55.5	57.4
	N.A.D	53.9	56.5	57.8	52.7	55.6	57.4	63.4	64.3
	S.N	65.3	69.0	66.6	56.4	67.4	74.0	68.5	72.2
	BA.N	97.8	102.5	105.9	86.5	101.8	107.8	106.8	108.7

(a)

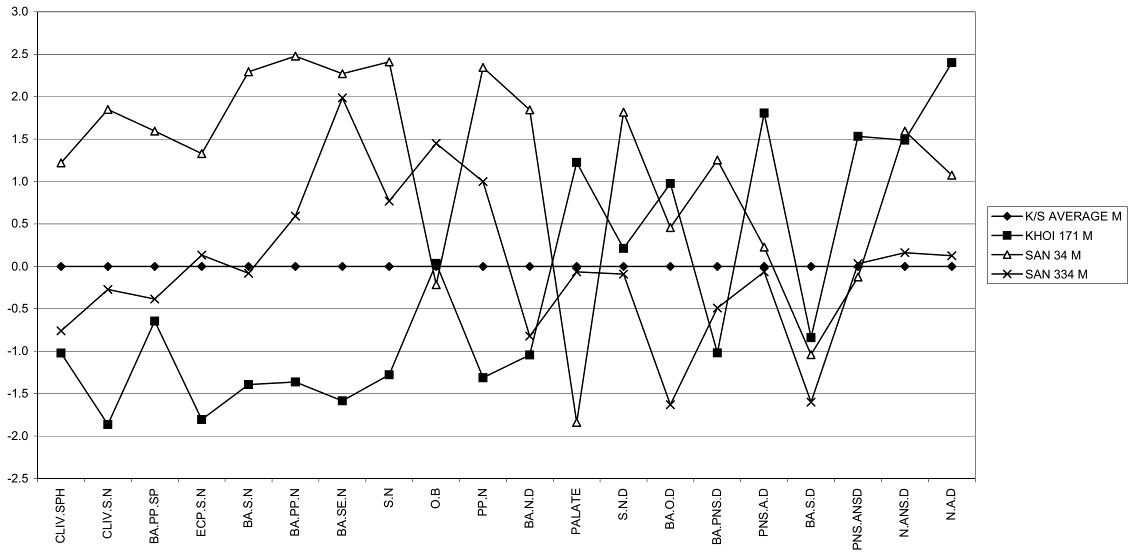


(b)

Figure 3.46: (a) Line diagrams of modal face (centre) with the two most extreme faces from the African K/S female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of African K/S female sample showing modal face and the two most extreme individuals with the sample average at zero.



(a)



(b)

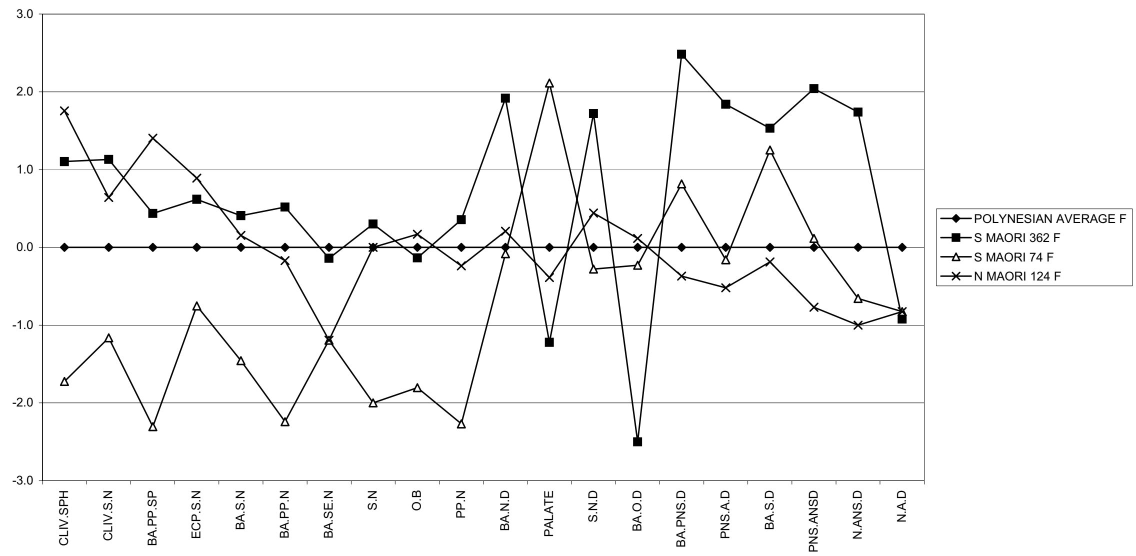
Figure 3.47: (a) Line diagrams of modal face (centre) with the two most extreme faces from the African K/S male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of African K/S male sample showing modal face and the two most extreme individuals with the sample average at zero.

The extreme faces of the African K/S sample are shown in Figures 3.46 and 3.47 along with the modal and average faces. The extreme positive face for both sexes has reduced cranial base flexion, a more elongated "z" shape, and a smaller angle of orientation between the clivus and the palate. However, the dimension data show varied results (Table 3.70). For females, all dimensions are larger in the extreme positive face. For the males, the dimensions basion-PNS, nasion-ANS, sella-nasion and basion-nasion are larger in the extreme positive face, while the dimensions basion-opisthion, basion-sella, PNS-ANS, PNS-A point and nasion-A point are larger in the extreme negative face (although only minimally for the dimensions basion-sella and nasion-ANS). The differences in size of the face are relatively small and do not detract from the consistent pattern of variation seen in the angular and "z" results.

Table 3.70: Comparison between average values, modal face and extreme negative and positive faces for the African K/S sample.

African K/S		Females				Males			
	ID	average	modal face S30	extreme positive S319	extreme negative S199	average	modal face S334	extreme positive S34	extreme negative K171
Cranial base flexion angles	CLIV.SPH	109.7	108.5	111.0	104.0	109.8	102.5	121.5	100.0
	CLIV.S.N	128.1	125.5	130.0	118.0	124.3	122.5	136.5	112.0
	BA.PP.SP	123.0	124.0	124.0	118.0	122.7	119.0	138.0	116.5
	ECP.S.N	132.1	133.0	131.0	125.0	128.1	129.0	137.0	116.0
	BA.S.N	137.1	133.5	138.0	127.0	132.5	132.0	146.5	124.0
	BA.PP.N	138.9	136.0	138.0	126.0	133.9	138.0	151.0	124.5
	BA.SE.N	152.4	149.0	153.0	140.0	146.1	160.0	162.0	135.0
Craniofacial angles	S.N	141.8	141.0	142.0	131.0	137.3	142.0	152.0	129.5
	O.B	138.7	137.5	128.0	128.0	133.3	142.0	132.0	133.5
	PP.N	138.0	136.5	137.5	125.0	134.3	141.0	150.0	125.5
	PALATE	46.9	50.0	44.0	55.0	49.4	49.0	38.0	57.0
Dimensions	BA.O	40.9	37.6	53.4	43.3	39.8	32.3	41.9	44.3
	BA.PNS	50.2	51.5	57.8	47.7	50.9	48.2	57.8	45.3
	PNS.A	51.0	54.4	54.4	46.2	50.3	50.1	51.0	55.9
	BA.S	45.8	48.2	52.0	47.2	45.9	41.9	43.3	43.8
	PNS.ANS	51.3		56.8	47.2	51.4	51.5	51.0	56.3
	N.ANS	50.5		55.9	53.0	50.4	51.0	56.3	55.9
	N.A.D	55.9	52.5	62.1	60.7	54.9	55.4	59.2	64.5
	S.N	72.2	72.2	78.5	73.2	73.0	72.7	79.0	73.7
	BA.N	109.0	110.7	121.8	107.9	108.7	105.0	117.0	104.0

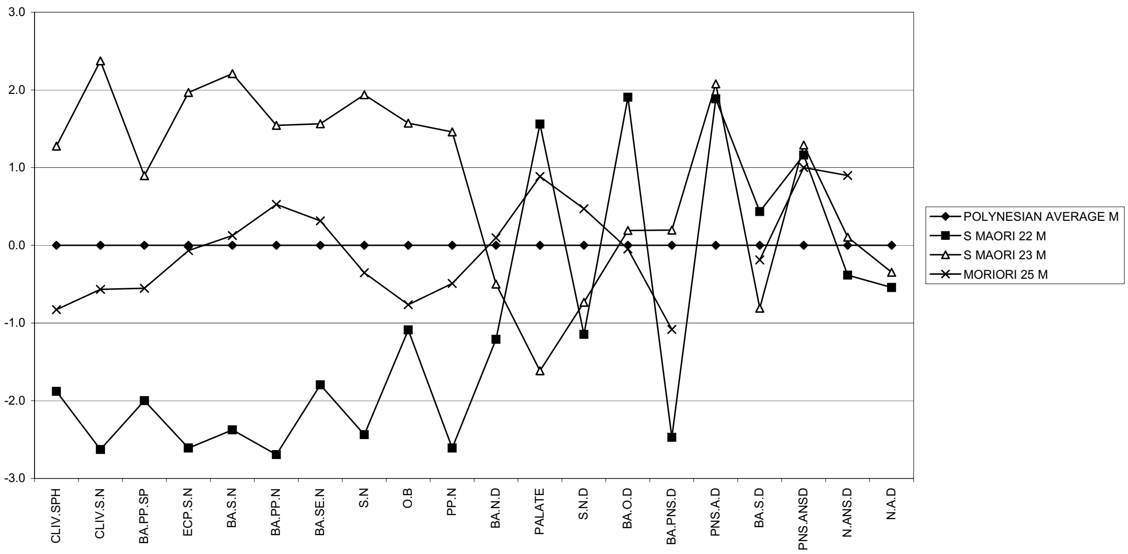
(a)



(b)

Figure 3.48: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Polynesian female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Polynesian female sample showing modal face and the two most extreme individuals with the sample average at zero.

(a)



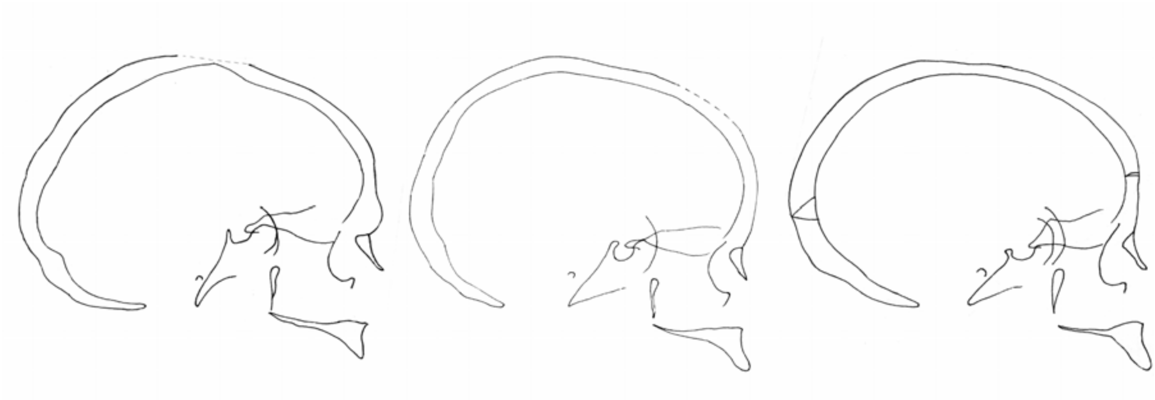
(b)

Figure 3.49: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Polynesian male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Polynesian male sample showing modal face and the two most extreme individuals with the sample average at zero.

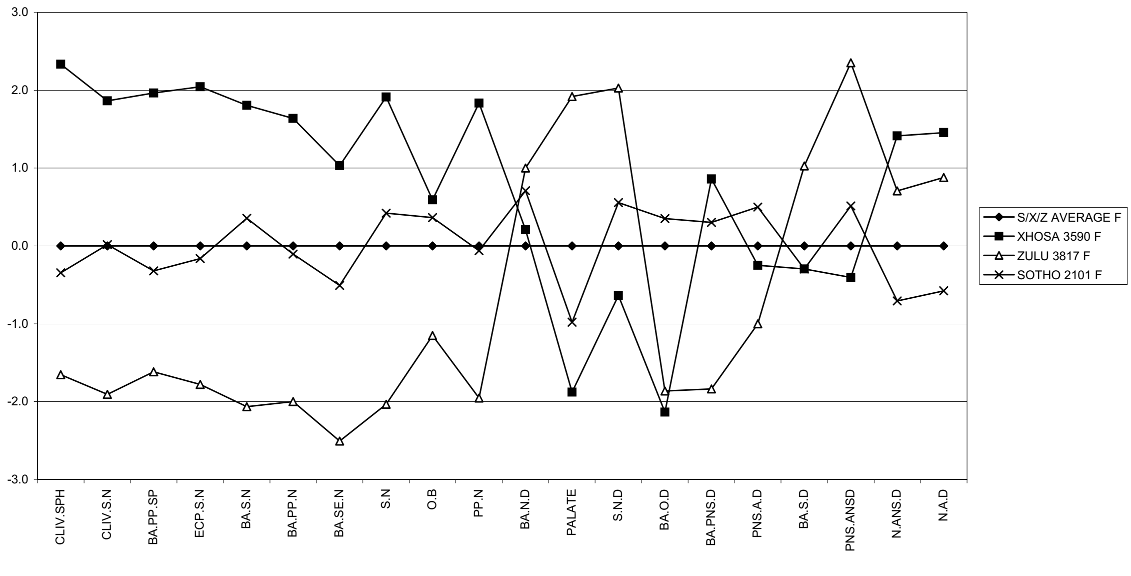
The extreme positive and negative representatives of the Polynesian samples tend to follow the same pattern observed in the previously described samples. This is true for the variables of cranial base flexion and craniofacial angles relative to the clivus ("z" formation and palate orientation). All dimensions are larger in the extreme positive females except for basion-opisthion. Among males, dimensions tend to be larger in the extreme positive males (except for the variables basion-sella and basion-opisthion).

Table 3.71: Comparison between average values, modal face and extreme negative and positive faces for the Polynesian sample.

Polynesian		Females				Males			
	ID	average	modal face NM124	extreme positive SM362	extreme negative SM74	average	modal face MO25	extreme positive SM23	extreme negative SM22
Cranial base flexion angles	CLIV.SPH	113.9	126.0	121.5	102.0	116.3	110.0	126.0	102.0
	CLIV.S.N	131.1	135.0	138.0	124.0	133.4	130.5	145.5	120.0
	BA.PP.SP	127.3	136.0	130.0	113.0	129.2	125.0	136.0	114.0
	ECP.S.N	135.5	142.0	140.0	130.0	138.4	138.0	150.0	123.0
	BA.S.N	139.6	140.5	142.0	131.0	141.4	142.0	152.0	130.0
	BA.PP.N	141.0	140.0	144.0	128.0	142.9	146.0	152.0	127.0
	BA.SE.N	153.8	147.0	153.0	147.0	155.0	157.0	165.0	143.5
Craniofacial angles	S.N	144.5	144.5	146.0	134.5	146.7	145.0	156.0	135.0
	O.B	138.4	139.5	137.5	126.5	137.9	132.0	150.0	129.5
	PP.N	141.4	140.0	143.5	128.0	143.4	140.5	152.0	128.0
	PALATE	46.4	45.0	42.0	54.0	45.9	50.5	37.5	54.0
Dimensions	BA.O	35.6	35.9	29.1	35.0	36.9	36.8	37.3	40.9
	BA.PNS	46.9	45.9	53.6	49.1	48.4	44.5	49.1	39.5
	PNS.A	50.4	49.1	55.0	50.0	53.7		59.1	58.6
	BA.S	44.2	43.6	49.1	48.2	45.7	45.0	42.7	47.3
	PNS.ANS	52.0	50.0	57.3	52.3	56.4	59.5	60.4	60.0
	N.ANS	52.9	49.1	59.5	50.4	56.0	59.5	56.4	54.5
	N.A.D	58.4	54.1	53.6	54.1	61.1		59.5	58.6
	S.N	66.6	67.7	70.9	65.9	69.8	71.4	67.3	65.9
	BA.N	104.0	105.0	113.2	103.6	109.0	109.5	106.4	102.7

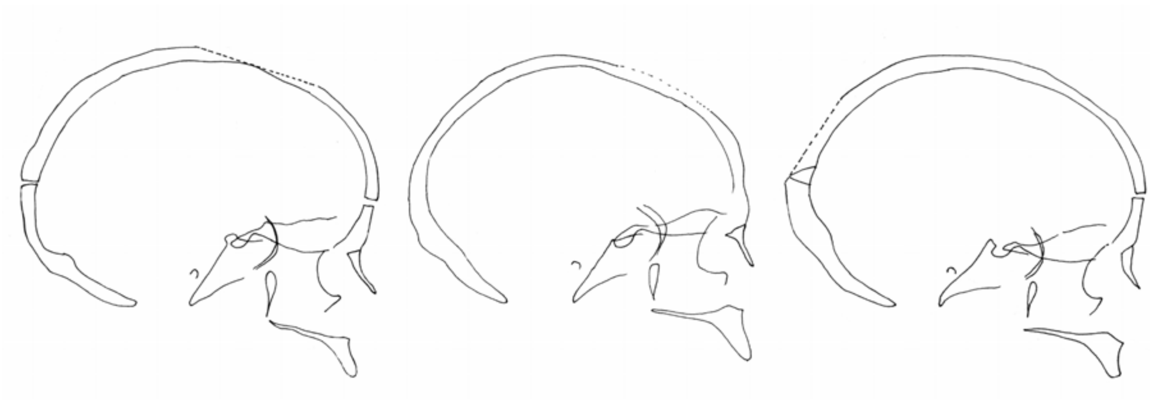


(a)

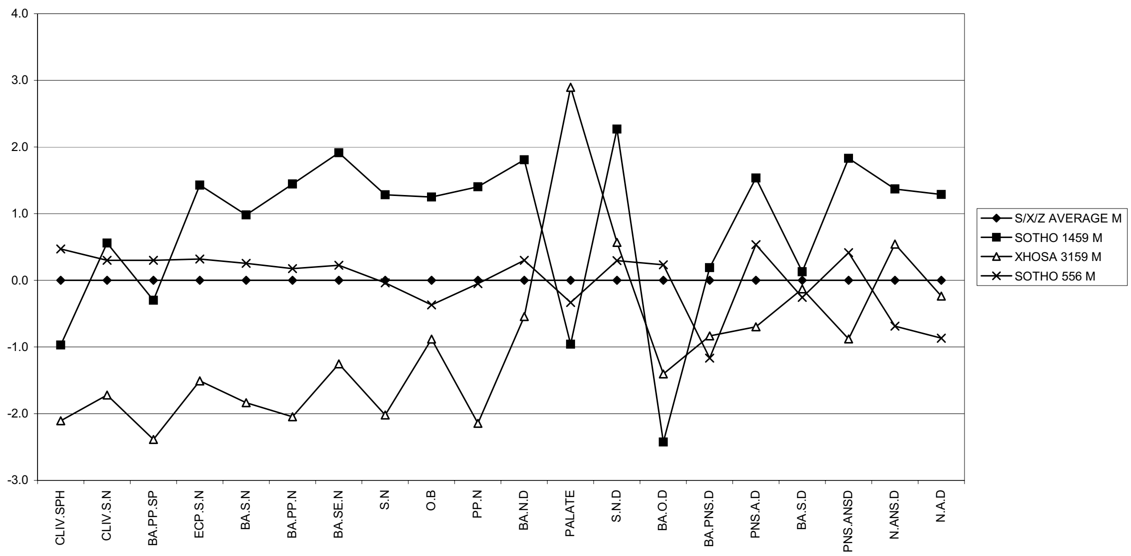


(b)

Figure 3.50: (a) Line diagrams of modal face (centre) with the two most extreme faces from the African S/X/Z female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of African S/X/Z female sample showing modal face and the two most extreme individuals with the sample average at zero.



(a)



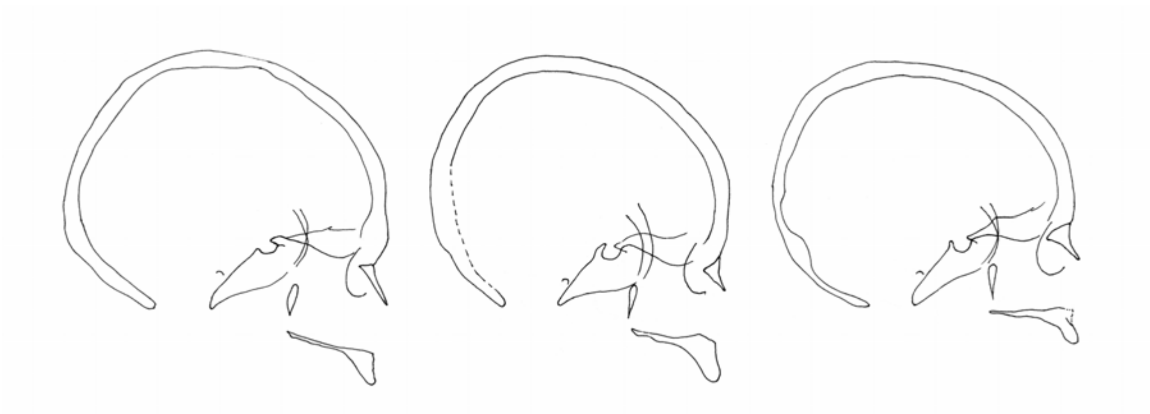
(b)

Figure 3.51: (a) Line diagrams of modal face (centre) with the two most extreme faces from the African S/X/Z male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of African S/X/Z male sample showing modal face and the two most extreme individuals with the sample average at zero.

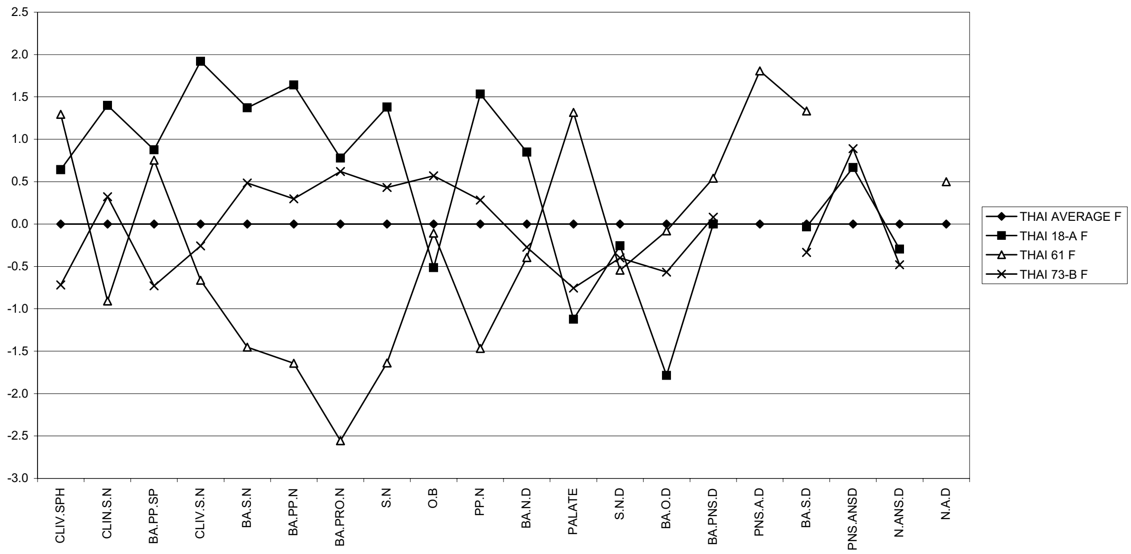
The extreme positive and negative faces for the African S/X/Z sample follow the pattern observed in other samples (Figures 3.50, 3.52 and Table 3.72). The cranial base is more flexed in the extreme negative faces of both males and females. The orientation of the anterior cranial base and foramen magnum planes relative to the clivus are less flexed in the extreme positive group, resulting in an elongated "z" shape. The craniofacial angle between the palate and the clivus is greater in the extreme negative group. In both sexes this is associated with a smaller mid-face height (nasion-ANS and nasion-A point), suggesting a difference in the location of the PNS landmark. In males, all dimensions are larger in the extreme negative face. In females, the extreme negative face has larger dimensions for basion-opisthion, basion-sella, PNS-ANS, sella-nasion and basion-nasion. There does not seem to be a clear pattern of apparent brachycephaly or dolichocephaly in this sample.

Table 3.72: Comparison between average values, modal face and extreme negative and positive faces for the African S/X/Z sample.

African S/X/Z		Females				Males			
	ID	average	modal face S2101	extreme positive X3590	extreme negative Z3817	average	modal face S556	extreme positive S1459	extreme negative X3159
Cranial base flexion angles	CLIV.SPH	110.9	108.0	130.5	97.0	108.9	112.0	102.5	95.0
	CLIV.S.N	128.4	128.5	140.5	116.0	126.8	128.5	130.0	117.0
	BA.PP.SP	123.1	120.5	139.0	110.0	122.0	124.0	120.0	106.0
	ECP.S.N	131.1	130.0	145.0	119.0	130.0	132.0	139.0	120.5
	BA.S.N	135.8	138.0	147.0	123.0	134.6	136.0	140.0	124.5
	BA.PP.N	136.2	135.5	147.0	123.0	135.9	137.0	145.0	123.0
	BA.SE.N	148.3	145.0	155.0	132.0	148.4	150.0	162.0	139.5
Craniofacial angles	S.N	140.6	143.0	151.5	129.0	140.2	140.0	147.0	129.5
	O.B	137.6	140.0	141.5	130.0	135.5	133.0	144.0	129.5
	PP.N	136.4	136.0	148.5	123.5	136.3	136.0	145.0	123.0
	PALATE	47.4	42.5	38.0	57.0	48.1	46.5	43.5	62.0
Dimensions	BA.O	38.7	40.0	30.8	31.8	40.3	41.4	28.9	33.7
	BA.PNS	51.7	53.0	55.4	43.8	53.1	48.2	53.9	49.6
	PNS.A	51.4	53.0	50.6	48.2	53.6	55.9	60.2	50.6
	BA.S	46.8	45.7	45.7	50.6	49.6	48.6	50.1	49.1
	PNS.ANS	52.5	54.4	51.0	61.2	54.6	56.3	62.1	51.0
	N.ANS	52.0	49.6	56.8	54.4	54.9	52.5	59.7	56.8
	N.A.D	56.8	54.9	61.6	59.7	59.6	56.3	64.5	58.7
	S.N	71.2	73.2	68.9	78.5	73.5	74.6	81.9	75.6
	BA.N	108.8	112.2	109.8	113.6	113.4	115.1	123.7	110.3



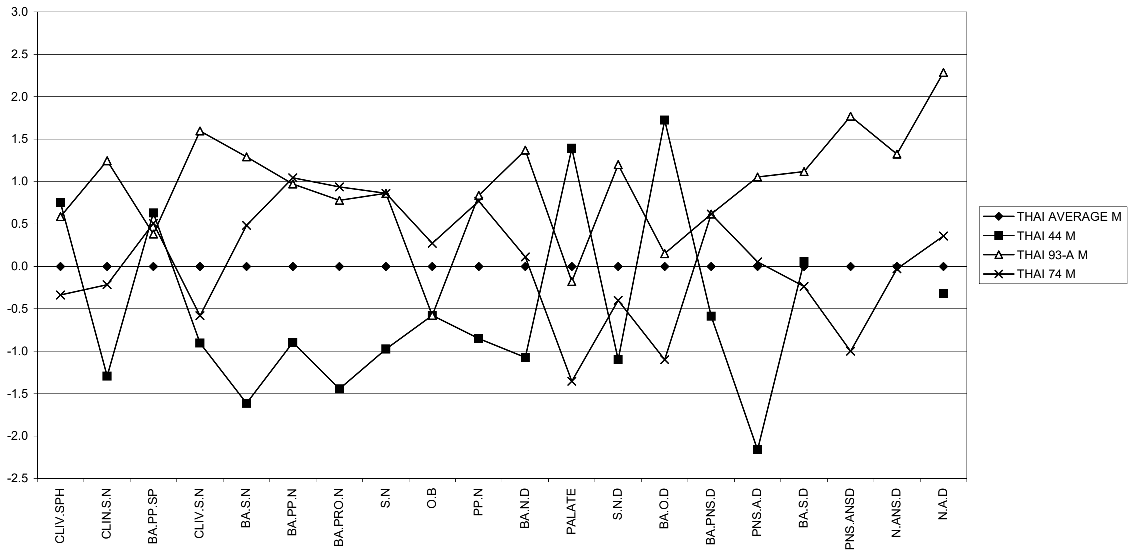
(a)



(b)

Figure 3.52: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Thai female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Thai female sample showing modal face and the two most extreme individuals with the sample average at zero.

(a)



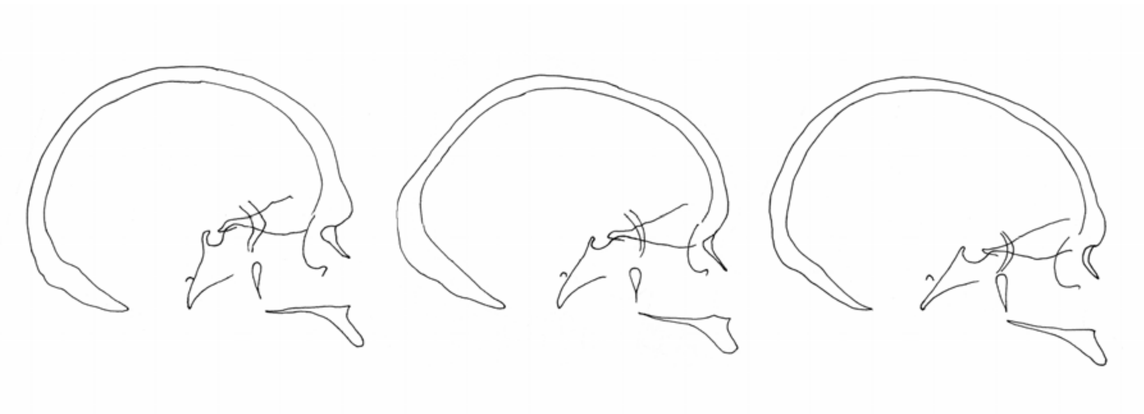
(b)

Figure 3.53: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Thai male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Thai male sample showing modal face and the two most extreme individuals with the sample average at zero.

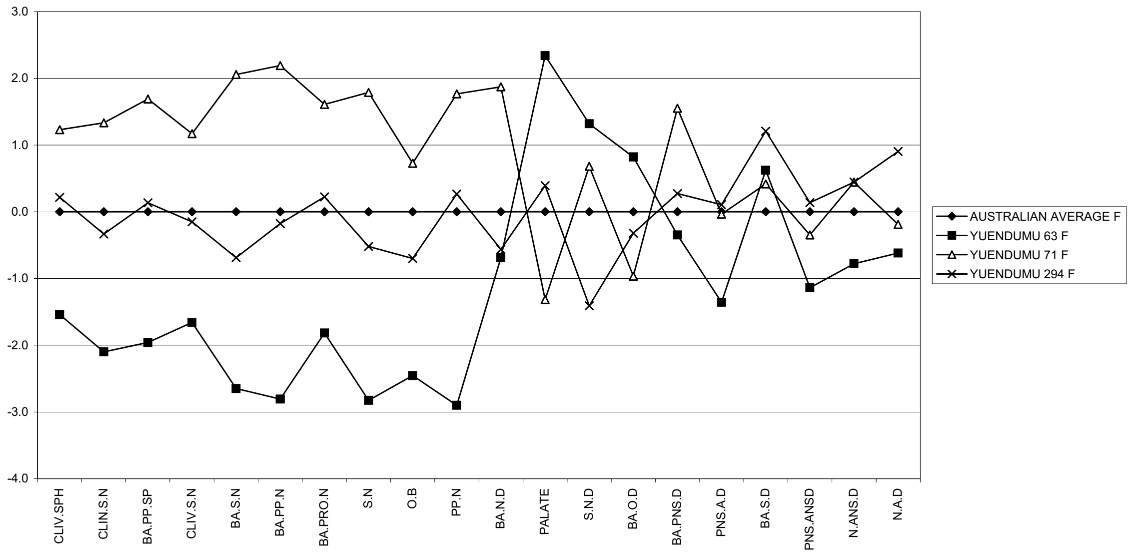
Results for the Thai sample are shown in Figures 3.52, 3.53 and Table 3.73. These show the similar pattern of a more flexed cranial base in the extreme negative faces of each sex, associated with a compacted "z" shape made up of the angles between the foramen magnum, clivus and anterior cranial base variables. The angle of orientation between the palatal plane and the clivus is greater in the extreme negative face of each sex. Despite a number of missing variables, dimensions tend to be larger in the extreme positive face of males, while there does not seem to be a clear pattern regarding size for females. The faces shown in Figures 3.52 and 3.53 appear to be brachycephalic in overall shape.

Table 3.73: Comparison between average values, modal face and extreme negative and positive faces for the Thai sample.

Thai		Females				Males			
	ID	average	modal face 73-B	extreme positive 18-A	extreme negative 61	average	modal face 74	extreme positive 93-A	extreme negative 44
Cranial base flexion angles	CLIV.SPH	106.1	99.5	112.0	118.0	106.6	103.0	111.5	113.0
	CLIV.S.N	123.4	125.5	132.5	117.5	122.0	122.0	131.5	115.0
	BA.PP.SP	119.9	114.0	127.0	126.0	120.9	124.0	123.0	125.0
	ECP.S.N	127.1	125.5	139.0	123.0	126.2	123.5	137.0	121.5
	BA.S.N	132.0	135.0	140.5	123.0	131.2	135.0	140.0	122.0
	BA.PP.N	132.0	134.0	143.0	121.0	132.5	139.0	138.5	126.0
	BA.SE.N	145.1	149.0	150.0	129.0	146.5	151.0	150.0	136.0
Craniofacial angles	S.N	136.5	139.0	144.5	127.0	136.2	143.0	143.0	128.5
	O.B	136.8	141.0	133.0	136.0	134.4	136.0	131.0	131.0
	PP.N	131.8	133.5	141.0	123.0	132.3	138.0	138.5	126.0
	PALATE	52.6	49.5	48.0	58.0	51.9	45.0	51.0	59.0
Dimensions	BA.O	33.0	30.9	26.4	32.7	32.6	28.2	33.2	39.5
	BA.PNS	42.3	42.7	42.3	45.0	46.1	48.2	48.2	44.1
	PNS.A	45.8			51.4	47.5	47.7	51.4	39.5
	BA.S	42.8	41.8	42.7	46.8	46.3	45.9	48.2	46.4
	PNS.ANS	46.1	47.7	47.3		49.5	48.2	51.8	
	N.ANS	50.8	49.5	50.0		53.7	53.6	58.2	
	N.A.D	54.7			55.9	55.4	56.4	61.8	54.5
	S.N	62.3	60.9	61.4	60.4	65.8	65.0	68.2	63.6
	BA.N	95.4	94.5	98.2	94.1	101.7	102.3	109.1	95.9

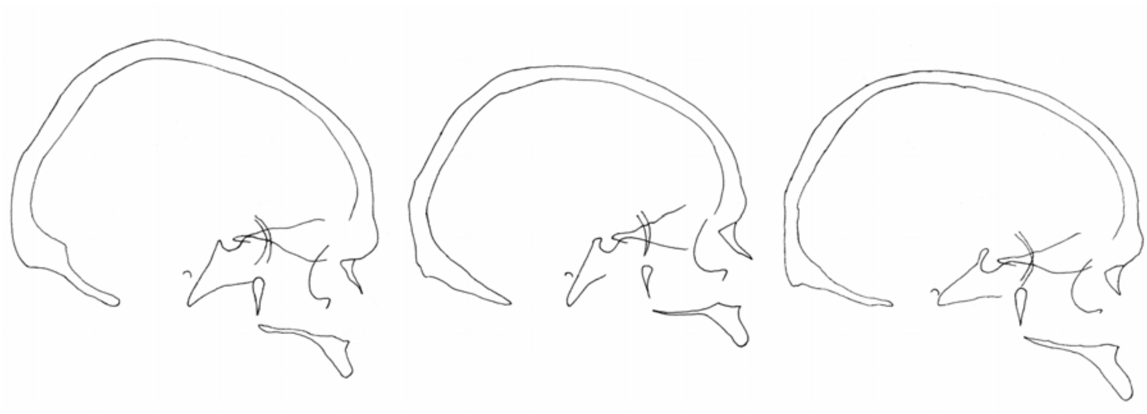


(a)

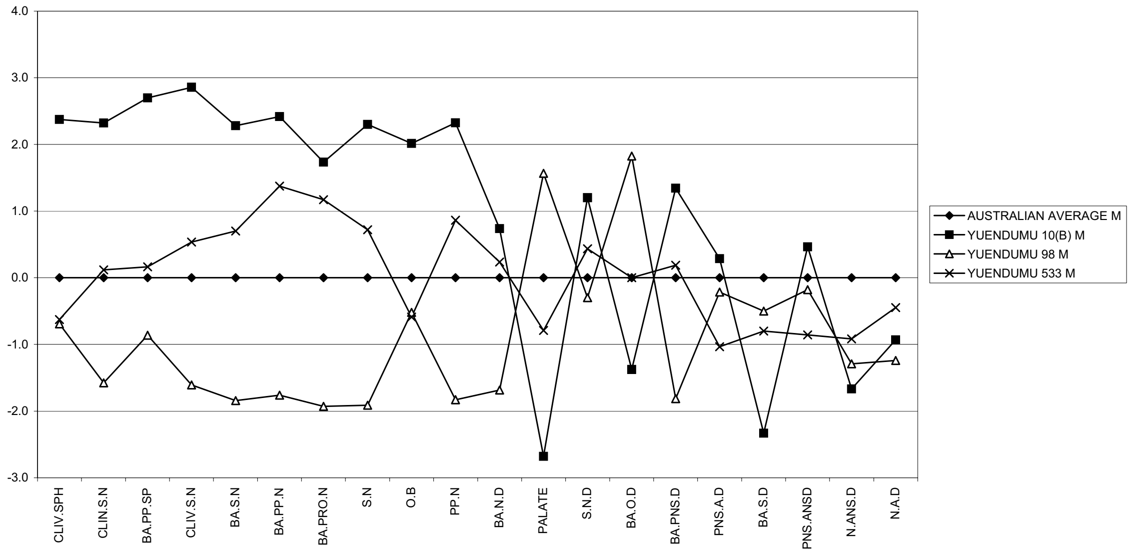


(b)

Figure 3.54: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Australian female sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Australian female sample showing modal face and the two most extreme individuals with the sample average at zero.



(a)



(b)

Figure 3.55: (a) Line diagrams of modal face (centre) with the two most extreme faces from the Australian male sample (left = extreme negative, right = extreme positive). (b) Z-score comparison of Australian male sample showing modal face and the two most extreme individuals with the sample average at zero.

Figures 3.54 and 3.55 show the results for the sample average, modal face and extreme negative and positive faces for each sex in the Australian sample. Raw values are presented in Table 3.74. The extreme positive face has the characteristics of a less flexed cranial base and greater craniofacial angles, apart from the palatal plane, which is reduced in its orientation with the clivus. In Australian individuals the length of the mid-face (nasion-ANS and nasion-A point) does not differ much between the extreme positive and extreme negative faces of either sex. Differences in the orientation of the hard palate relative to the clivus are most likely a result of a change in the position of the PNS. In females, the extreme negative face appears to be more brachycephalic, while the extreme positive face appears more dolichocephalic. In males, all three faces shown (modal face, extreme negative and extreme positive), all appear dolichocephalic.

Table 3.74: Comparison between average values, modal face and extreme negative and positive faces for the Australian sample.

Australian		Females				Males			
		average	modal face	extreme positive	extreme negative	average	modal face	extreme positive	extreme negative
	ID		294	71	63		533	10(B)	98
Cranial base flexion angles	CLIV.SPH	104.4	106.0	113.5	93.0	102.2	97.5	120.0	97.0
	CLIV.S.N	120.7	119.0	127.5	110.0	119.3	120.0	133.0	110.0
	BA.PP.SP	120.5	121.5	133.0	106.0	118.3	119.5	138.0	112.0
	ECP.S.N	124.8	124.0	131.0	116.0	123.0	126.0	139.0	114.0
	BA.S.N	129.5	126.0	140.0	116.0	128.0	132.0	141.0	117.5
	BA.PP.N	133.0	132.0	145.5	117.0	131.8	141.0	148.0	120.0
	BA.SE.N	143.8	145.0	152.5	134.0	143.7	152.0	156.0	130.0
Craniofacial angles	S.N	136.7	134.0	146.0	122.0	135.9	140.0	149.0	125.0
	O.B	135.9	130.5	141.5	117.0	133.4	129.0	148.5	129.5
	PP.N	133.4	135.0	144.0	116.0	131.9	137.5	147.0	120.0
	PALATE	51.4	53.0	46.0	61.0	51.2	47.0	37.0	59.5
Dimensions	BA.O	31.6	30.7	28.9	33.9	32.1	32.1	26.6	39.4
	BA.PNS	44.1	44.9	48.6	43.1	47.1	47.7	51.4	41.3
	PNS.A	49.2	49.5	49.1	45.4	50.6	47.7	51.4	50.0
	BA.S	40.7	43.6	41.7	42.2	43.7	41.3	36.7	42.2
	PNS.ANS	51.0	51.4	50.0	47.7	51.9	49.5	53.2	51.4
	N.ANS	47.3	48.1	48.1	45.9	49.4	47.2	45.4	46.3
	N.A.D	50.4	52.3	50.0	49.1	53.1	51.8	50.4	49.5
	S.N	66.8	63.7	68.3	69.7	71.1	72.4	74.7	70.2
	BA.N	97.6	95.8	103.6	95.4	103.6	104.5	106.4	97.2

The results of the preceding section on variation in the craniofacial complex have revealed a consistent pattern of variation between extreme individuals of each sample in the present study. This relates to the flexion of the cranial base, the relationship between the craniofacial angles and the relative size of different cranial base and facial dimensions. The emerging pattern is one of increased cranial base flexion in individuals with cumulative z-score values at the extreme negative end of the scale, and increased flexion in individuals whose cumulative z-scores were at the extreme positive end of the scale, compared to the modal face. In addition, the extreme positive faces had an elongated "z" shape between the foramen magnum, clival and anterior cranial base planes. These individuals also had less flexion between the palate and the clivus, which, when interpreted relative to the length of the mid-face, suggested a change in the location of the PNS, since the distance between nasion and the anterior part of the palate (nasion-ANS and nasion-A point) was usually reduced in these individuals. These findings add weight to the assertion of the importance of the "z" shape in the craniofacial complex. Further to this, the appearance of the faces (while limited to the mid-sagittal plane), could be seen as tending towards dolichocephaly (extreme positive) or brachycephaly (extreme negative), which, if found to be constant in future investigations, may prove to be another important aspect of assessing craniofacial morphology relative to the "z" shape identified in the present study.

Chapter 4: General discussion

The results of the present study offer new insight into the understanding of cranial base flexion and craniofacial variation. As well as contributing to the general body of knowledge pertaining to the cranial base, they also suggest new directions for research into the relationship of this anatomical structure with other elements of the craniofacial skeleton. There were three main aims of this investigation: (i) to discover the range of variation of cranial base flexion and craniofacial morphology in a sample of normal individuals, (ii) to investigate population differences in cranial base flexion with the null hypothesis that no differences exist between populations, and (iii) to explore the relationship between cranial base flexion and craniofacial morphology with regard to a postural theory of basicranial flexion. In this section, the results presented in the preceding chapter will be discussed and interpreted with regard to these aims.

Variation in cranial base flexion was assessed using seven angles of cranial base flexion. The results of this analysis generated average values of cranial base flexion for a large sample of individuals with normal craniofacial anatomy, representing various samples around the world. The average angle of cranial base flexion, measured as the angle basion-sella-nasion was 132.5 degrees, with a range from 115 to 152 degrees. This shows a broad range of individual variation usually not acknowledged by other studies in the literature. The other cranial base angles showed similar ranges of variation. An important finding of the study was that variation within groups was greater than variation between groups for all angles of flexion. Most angles showed about 60% to 80% variation within groups, compared to between 20% and 40% variation between groups. Furthermore, sexual dimorphism in cranial base flexion was not a significant source of variation at all. There were no significant differences between male and female averages. This shows that individual variation contributes a substantial amount to the total variation in the total sample, which has largely been overlooked by previous studies investigating the cranial base and craniofacial skeleton. In 2001 Nevell found significant variation in basicranial morphology in a sample of 120 adults and, as a consequence, argues against evolutionary conservatism of the cranial base. However, the results of Nevell's study cannot be interpreted with regard to those of the present study, as the results were published in abstract form and little information was available (Nevell, 2001). Table 4.1 shows a comparison between published values of the basion-sella-nasion angle and the results of the present study. It is evident that there is considerable variation in cranial base flexion in these average values. The Polynesians clearly stand out as having values of cranial base flexion that are around 140 degrees. Other samples, such as the Americans measured by Ursi (1993), have average values around 125 degrees. When considering results such as those displayed below, it is easy to see how cranial base flexion has been used as a basis for comparison between samples. However, the present study found that the variation between samples was considerably less than the variation within samples, for all of the angles of cranial base flexion measured. While the ANOVA results showed significant differences on average between some samples for the various cranial base angles, the only clear pattern of variation was that the average value for the Polynesian sample was usually greater (less flexed) than the remaining samples.

Table 4.1: Comparison of mean adult values for basion-sella-nasion angle in the literature:

Population/sample	Composition	Basion-sella-nasion mean	St.dev	Study
Scandinavia	102 males	129.6	5.2	(Solow, 1966)
Scandinavia	243 males	131.6	4.5	(Björk, 1955)
Scandinavia	34 males	131.2	4.8	(Stramrud, 1959)
African Ibo	26 males/ 22 females	135.5	3.8	(Kuroe et al., 2004)
Japanese Ainu	16 males/ 8 females	138.1	4.4	(Kuroe et al., 2004)
English	36 males/ 36 females	135.2	5.1	(Kuroe et al., 2004)
Moriori	20*	143.6	4.8	(Kieser et al., 1999)
South Island Maori	21*	138.4	6.3	(Kieser et al., 1999)
North Island Maori	19*	138.8	3.7	(Kieser et al., 1999)
Modern Indians	26*	132.2	6.1	(Kieser et al., 1999)
Archaic Indians	8*	129.9	6.2	(Kieser et al., 1999)
New Zealand caucasoids	21 males	127.8	5.5	(Kieser et al., 1999)
New Zealand caucasoids	23 females	130.9	5.3	(Kieser et al., 1999)
Japanese (modern)	46 males	134.0	5.3	(Kasai et al., 1995)
Peruvian Indian	45*	132.9	4.9	(Anton, 1989)
American whites	16 males	125.4	5.7	(Ursi et al., 1993)
American whites	16 females	125.8	4.3	(Ursi et al., 1993)
American blacks	42 males	131.6	5.8	(D'Aloisio and Pangrazio-Kulbersh, 1992)
American blacks	58 females	132.5	6.3	(D'Aloisio and Pangrazio-Kulbersh, 1992)
New Zealand Polynesians	60 male	140.3	5.6	(Kean and Houghton, 1982)
Chinese	31 males/ 22 females	127.0	5.1	Present study
American	34 males/ 30 females	128.0	4.8	Present study
African K/S	20 males/ 10 females	134.0	6.2	Present study
African S/X/Z	60 males/ 60 females	135.2	5.9	Present study
Polynesian	38 males/ 18 females	140.8	7.4	Present study
Australian	34 males/ 34 females	128.7	5.4	Present study
Thai	8 males/ 15 females	131.7	6.5	Present study
Total sample	225 males/ 189 females	132.5	7.1	Present study

* no sample numbers of males or females provided in the paper

This part of the study contributed new averages of variables describing cranial base flexion in several samples of modern humans. However, in the context of the present study it is the variation in flexion in the modern human sample that is of interest. This is because most studies that report average cranial base flexion in their study samples present statistics of central tendency only, without exploring other aspects of the results such as the extent of variation. While this variation is implicit in the reporting of mean and standard deviation statistics (an estimate of the range can easily be obtained by adding three standard deviations to each side of the average), reporting of these values in isolation encourages a focus on averages and steers interpretation away from the variation present. For example, since cranial base flexion is often used as a basis for interpretation of craniofacial abnormalities, understanding of the range of variation present in a normal sample of modern humans is needed to properly interpret the effect of the dismorphologies. Kreiborg and colleagues report on the basion-sella-nasion angle in a sample of adults with cleidocranial dysostosis, a congenital craniofacial disorder involving the cranial vault, facial skeleton and dentition (Kreiborg et al., 1981). In their study a sample of 17 adults with cleidocranial dysostosis had an average flexion of 125.6 degrees, with a variance of 27.4, while their control sample of 153 adults had average basion-sella-nasion angles of 130.5 and a variance of 27.47. Statistical testing revealed significant differences between these samples. However, when these results are viewed alongside the results of the present study and the averages of other samples reported in Table 4.1, it can be seen that there are quite a few samples with average cranial base flexion of around 126 degrees. In addition, with the total sample of the present study having a range of variation for this angle between 115 and 152 degrees, it can be concluded that cranial base flexion of around 126 degrees is not particularly abnormal. In contrast, a study by Peterson-Falzone and Figueroa (1989) on a sample of individuals with mandibulofacial dysostosis (also known as Treacher-Collins syndrome) found that average flexion was less than those of normal controls, and often became more flexed during life. However a closer look at the results shows that some individuals in their study had cranial base flexion that was still within the normal range (according to the results of Riolo as between about 120 and 140 degrees, equivalent to two standard deviations above and below the mean). What can be concluded from these results is that basicranial flexion alone is not a good indicator of abnormal craniofacial morphology, but should be assessed in conjunction with other parameters specific to the various syndromes.

In order to put the findings of the present study into context, the results were compared to published studies on primate and fossil hominin cranial base flexion. Among the studies measuring cranial base flexion in non-human primates and fossil hominins, none were identified that used the conventional flexion angle of basion-sella-nasion. Instead, the majority of studies focussed on cranial base flexion as the angle between basion-sella-foramen caecum, or used the angle between the clival and sphenoidal planes. The foramen caecum landmark defining the anterior extension of the anterior cranial base was not used in this study, due to difficulties with landmark location. Scott (1958) comments that the relationship between nasion and the foramen caecum varies throughout life, but no studies have been identified comparing the relationships between the basion-sella-nasion angle and the basion-sella-foramen caecum angle. Consequently, the conclusions drawn from the results of the present study relating to evidence from the fossil record are limited to a consideration of the clival plane-sphenoidal plane angle, which was measured in the present study. Measurement of cranial base flexion on fossils has inherent problems, such as the fact that the cranial base is often broken and requires reconstruction before measurements of flexion can be taken. For example, the paper by Ross and Henneberg (1995) includes estimations of cranial base flexion on the OH 9 *Homo erectus* skull. The cranial base of this skull had required reconstruction prior to measurement (Maier and Nkini's reconstruction, 1984).

The authors included in their results an estimation of the cranial base flexion (clival plane-sphenoidal plane) as 99 degrees, along with estimates of the upper and lower limits possible for the orientation of the clival plane (92 to 104 degrees).

There have been a number of studies conducted comparing modern human cranial base flexion to that seen in fossil hominins and non-human primates. Cramer (1977), Ross and Ravosa (1993), Ross and Henneberg (1995), Spoor (1997), Koppe (1999) and McCarthy (2001), among others, measured cranial base flexion in numerous primates including modern humans, and found that the modern human sample had angles considerably more flexed than the anthropoid and non-anthropoid primates (Table 4.2). The anthropoid primates (gorillas, chimpanzees and orang-utans had angles that were moderately flexed, while the non-anthropoid primates had angles that were even less flexed. Cramer (1977) found similar average results and also commented that there was considerable overlap of ranges between samples of modern humans and chimpanzees.

Table 4.2 presents the findings of the studies investigating cranial base flexion in non-human primates, using two angles of flexion: basion-sella-foramen caecum, and clival plane-sphenoidal plane. In the present study, the clival plane-sphenoidal plane angle ranged between 86 degrees and 133 degrees. The primate samples shown in Table 4.2 had average values of clival plane-sphenoidal plane ranging between 129 to 148 degrees, which overlaps the modern human range at the lower end. It should be remembered that these non-human primate samples usually consist of less than ten individuals (apart from the data of Cramer, whose samples of *Pan paniscus* and *Pan troglodytes* consist of about 60 individuals each), and there appears to be considerable variation between samples. For example the studies including chimpanzee samples report averages of between 135 and 152 degrees, while the results for studies including gorilla samples have averages between 135 and 148 degrees. For the angle basion-sella-foramen caecum, of which no results were available for the present study, similar differences between samples are seen, with results for chimpanzees ranging between 135 and 156 degrees. For the most part, it can be concluded that there are some differences in cranial base flexion between modern humans and other primates, with overlap of ranges at the lower end of the primate range/higher end of the modern human range.

Table 4.2: A comparison of cranial base flexion in primates and modern hominins, showing results of previous research and of the present study.

Taxon	Angle	Degrees	Study
H. sapiens	Basion-sella-foramen caecum	136	(McCarthy, 2001)
P. paniscus	Basion-sella-foramen caecum	140	(Cramer, 1977)
P. paniscus	Basion-sella-foramen caecum	148	(McCarthy, 2001)
P. troglodytes	Basion-sella-foramen caecum	135	(Cramer, 1977)
P. troglodytes	Basion-sella-foramen caecum	156	(McCarthy, 2001)
P. pygmaeus	Basion-sella-foramen caecum	150	(McCarthy, 2001)
G. gorilla	Basion-sella-foramen caecum	154	(McCarthy, 2001)
Primate range	Basion-sella-foramen caecum	148-185	(Spoor, 1997)
H. sapiens range	Clival plane-sphenoidal plane	86-133	Present study
H. sapiens	Clival plane sphenoidal plane	108	Present study
H. sapiens	Clival plane-sphenoidal plane	111	(McCarthy, 2001)
H. sapiens	Clival plane-sphenoidal plane	112	(Ross and Henneberg, 1995)
P. paniscus	Clival plane-sphenoidal plane	135	(McCarthy, 2001)
P. troglodytes	Clival plane-sphenoidal plane	149	(McCarthy, 2001)
Pan	Clival plane-sphenoidal plane	134	(Koppe et al., 1999)
Pan	Clival plane-sphenoidal plane	152	(Ross and Henneberg, 1995)
P. pygmaeus	Clival plane-sphenoidal plane	129	(Koppe et al., 1999)
P. pygmaeus	Clival plane-sphenoidal plane	134	(McCarthy, 2001)
P. pygmaeus	Clival plane-sphenoidal plane	135	(Ross and Henneberg, 1995)
G. gorilla	Clival plane-sphenoidal plane	135	(Koppe et al., 1999)
G. gorilla	Clival plane-sphenoidal plane	146	(McCarthy, 2001)
G. gorilla	Clival plane-sphenoidal plane	148	(Ross and Henneberg, 1995)

With regard to estimations of cranial base flexion in fossil hominins, most researchers have concluded that the cranial base flexion of fossil hominins lies within the human range (Ross and Henneberg, 1995; Baba and colleagues, 2003). However, Spoor

(1997) found that the Sts 5 and KNM-WT 17000 skulls had angles that were significantly different from modern humans, and resembled great ape values, while the Sangiran 17 and OH 5 skulls were not significantly different from modern humans in cranial base flexion. In the study by Ross and Henneberg (1995), with a sample of 99 individuals, the range was found to be 92 to 135 degrees. In the present sample of over 400 individuals the range was between 86 and 133 degrees. Apart from a two-degree difference between these samples at the upper end of the range, the results of Ross and Henneberg (1995) lie within the range of the present study. The increased variation seen in cranial base flexion of the present study can be attributed to its larger sample size. This also makes the finding of Ross and Henneberg (1995) of 99 degrees for clival plane-sphenoidal plane flexion in the OH 9 individual well within the modern human range. This is also true for most of the other fossil hominins, with all individuals lying within the range of the present study for the clival plane-sphenoidal plane angle.

Table 4.3: A comparison of cranial base flexion in various fossil and modern hominins showing results of previous research and of the present study.

Specimen	Taxon	Angle	Degrees	Study
Sts 5	*A. africanus*	Basion-sella-foramen caecum	147	(Spoor, 1997)
OH 9	*A. boisei*	Basion-sella-foramen caecum	135	(Spoor, 1997)
KNM-WT 17000	*A. boisei/ aethiopicus*	Basion-sella-foramen caecum	156	(Spoor, 1997)
Sm 4	*H. erectus*	Basion-sella-foramen caecum	141	(Baba et al., 2003)
Sangiran 17	*H. erectus*	Basion-sella-foramen caecum	129	(Spoor, 1997)
Modern homo	H. sapiens	Basion-sella-foramen caecum	136	(Baba et al., 2003)
Modern homo	*H. sapiens*	Basion-sella-foramen caecum	138	(Spoor, 1997)
Modern homo	*H. sapiens*	Basion-sella-foramen caecum	138	(McCarthy, 2001)
Sts 5	*A. africanus*	Clival plane-sphenoidal plane	114	(Ross and Henneberg, 1995)
MLD 37/38	*A. africanus*	Clival plane-sphenoidal plane	111	(Ross and Henneberg, 1995)
Sm 4	*H. erectus*	Clival plane-sphenoidal plane	97	(Baba et al., 2003)
OH9	*H. erectus*	Clival plane-sphenoidal plane	99	(Ross and Henneberg, 1995)
Kabwe	*H. sapiens*	Clival plane-sphenoidal plane	128	(Ross and Henneberg, 1995)
Modern homo	*H. sapiens*	Clival plane-sphenoidal plane	112	(Ross and Henneberg, 1995)
Modern homo	*H. sapiens*	Clival plane-sphenoidal plane	108	Present study
Modern homo range	*H. sapiens*	Clival plane-sphenoidal plane	86-133	Present study

Table 4.3 shows the results of basicranial flexion in fossil hominins compared to modern humans. The range of the angle between the clival and sphenoidal planes measured in the present study lay between 86 and 133 degrees, and it is clear that all fossil hominins shown here have values within that range. There does not seem to be any evidence of a consistent pattern of increasing flexion between representatives of *A. africanus* and modern *H. sapiens*. For example the flexion of Sts 5, measured by Ross and Henneberg (1995), is 114 degrees, while the flexion of MLD 37/38 is 111 degrees. The average of the present study was 108 degrees. Furthermore, if there were a pattern of increasing flexion over time, it would be expected that the values of *H. erectus* individuals would lie between the *A. africanus* and *H. sapiens* values. Such a pattern is not observed here, with both *H. erectus* individuals having values of 97 and 99 degrees. While this does lie well within the range of modern humans, these values are at least ten degrees less flexed than those observed in *A. africanus* individuals.

The relationship between cranial base flexion and craniofacial angles was also explored in the present study. The significant and positive correlation coefficients between the anterior cranial base angles relative to the orientation of the clivus can be explained by topographical associations. However, the significant correlations between these angles and the orientation of the hard palate and foramen magnum relative to the clivus are much more informative about the true relationships between these elements of craniofacial morphology, since, apart from basion, there are no shared landmarks between these planes. The overall relationship between the angles was the presence of positive correlations between the orientation of the foramen magnum relative to the clivus and the anterior cranial base planes, and negative correlations between the orientation of the hard palate and the other planes. Furthermore, the average angle of the orientation of the opisthion-basion plane relative to the clivus was 135.0 degrees, while the average angle of orientation of the pituitary point-nasion line was 134.6 degrees. This implies a parallel configuration between these two planes, strengthened by the significant (but moderate) correlation coefficient of 0.6. While a t-test revealed a significant difference in the angle of orientation of the foramen magnum relative to the clivus (134 degrees in males compared to 136 degrees in females), the other craniofacial angles did not show any differences between males and females. The parallel relationship between the basion-opisthion and pituitary point-nasion planes was also evident in both males and females of the total sample, although there were some differences within individual samples. The parallel relationship between the pituitary point-nasion and opisthion-basion planes persisted when all samples were investigated independently – the absolute difference between the orientation of the basion-opisthion plane and the pituitary point-nasion plane (relative to the clivus) was never more than 2.6 degrees, except in the Polynesian male sample, where the difference was 5.5 degrees. Analysis of variance revealed significant differences between the samples for the five planes for the samples studied. However, examination of the contributions of within and between sample variation revealed a significant finding: that most of the variation present could be attributed to variation within the samples. The within sample variance ranged between 64% and 91%, while the variation between groups was calculated as ranging between 9% and 36%. The variable with the largest amount of variation within the samples (and the least amount of variation between the samples) was the orientation of the opisthion-basion plane relative to the clivus. The variable with the smallest amount of variation within the samples (and the largest amount of between group variation) was the orientation of the sella-nasion plane relative to the basion-pituitary point plane, but the within group variation was still more than 60% of the total variation.

There are two studies that have been found that measured the orientation of the foramen magnum plane relative to the clivus in fossil hominins (Baba et al., 2003; Spoor, 1997). Baba and colleagues (2003) found that the basion-sella-foramen magnum angle was 141 degrees in the *Homo erectus* skull Sm 4 from Java. While this is a slightly different angle from that measured in the present study (pituitary point-basion-foramen magnum), some comparisons can still be made. Bearing in mind that the angle using sella will be smaller than that using the pituitary point, the range of the present study for the pituitary point –basion-foramen magnum angle was 117 to 157 degrees. Therefore, the angle of 141 degrees seen in the *H. erectus* skull is still within the range of the modern human sample of the present study. The other study investigating the orientation of the foramen magnum in modern humans and fossil hominins was that of Spoor (1997). Spoor's landmarks consisted of the orientation of the foramen magnum and petrosal pyramids in relation to the orientation of the anterior cranial base (sella-foramen caecum). Spoor's results are interesting as they are similar to the parallel relationship between the foramen magnum and pituitary point-nasion planes observed in the present study, even though in Spoor's work an alternative cranial base plane was used. However, it shows that in general, most fossil hominins have similar results to modern humans, while primates tend to differ. Spoor concluded that the Sts 5, *Australopithecus africanus* specimen seems to follow a non-human primate pattern, resembling chimpanzees, while the other fossil hominins had a foramen magnum more inferiorly rotated than was predicted by regression analysis. This suggests that factors other than brain-size are influential on cranial base in these individuals, such as adaptations to bipedalism and the resulting postural alterations.

With regard to dimensions of the cranial base and facial skeleton, significant differences were observed between males and females for the total sample, with males having larger dimensions in every variable studied except the dimension basion-opisthion. This pattern of sexual dimorphism was observed when samples were examined individually, with some samples showing more differences than others. Correlation coefficients between dimension variables were all significant when the whole sample was examined. When correlation coefficients for males and females were examined separately, it was found that the female sample had significant correlations between all variables. The male sample had significant correlation coefficients between all variables, apart from some correlations with the basion-PNS dimension that were not significant. The variables that were not significantly correlated with basion-PNS in males were the ones measuring the vertical height of the nose, or mid-face (nasion-ANS, nasion-A point). Between and within group variation was calculated, and ranged between about 50% to 75% variation within groups, compared to between 25% and 50% of variation occurring between groups.

When the dimension results of each sample were examined for differences between them, significant differences were found between the samples. However, the pattern of differences varied according to the dimension measured. This suggests an allometric relationship in craniofacial variation, rather than an isometric one. For example the Chinese sample was similar to the Thai sample for most dimensions, and had the smallest average values for the dimensions nasion-sella, basion-nasion, basion-opisthion, basion-PNS, PNS-ANS and PNS-A point. The Australian sample had the smallest dimensions for the remaining variables of basion-sella and the two variables measuring the height of the nose/mid-face (nasion-ANS and nasion-A point). Regarding the samples with the largest dimensions, it was usually either the African K/S or African S/X/Z sample, apart from some dimensions of the palate and nose, where the Polynesian sample had the largest dimensions (PNS-ANS, nasion-ANS, nasion-A point). The African K/S sample had the largest dimensions for the dimensions nasion-sella and basion-opisthion, while the African S/X/Z sample had the largest dimensions for basion-sella, basion-nasion, basion-PNS, and PNS-A point. The Chinese and Thai pattern had a long anterior cranial base and nose, but the reduced length of the other measurements resulted in a small face tucked under the anterior cranial base. Compared to the other groups, however, the anterior cranial base was short, resulting in a smaller face than the others. At the other extreme, the pattern seen in the two African groups was one of greater size, combined with a longer anterior cranial base and shorter nose than the Chinese pattern. The palatal measurements were the same size as the nose height, compared to a much shorter palatal length in the Chinese people. One interesting feature that has emerged from these between-sample comparisons is the fact that the Polynesian data often fall at the extreme ends of a range. In addition, the Polynesian sample differed from the others in that the average angles of cranial base flexion were greater (less flexed) in males than in females (this difference was not significant, however). In the other six samples the females were characterised by a less flexed cranial base. The different features of the Polynesian sample is not a novel finding: in a study examining the craniofacial variation of a number of samples, including Polynesians, it was found that the majority of the Polynesian samples (including Maori and Moriori) form a group distinct from other

Asian/circum-Pacific samples in the analysis (Hanihara, 1997). This relatively distinct facial morphology has most likely developed through the maintenance of a small gene pool through isolation from other groups for a significant time.

The present study has found that variation within samples is considerable, while variation between samples contributes only a small amount to the total variation. While this appears to be a novel conclusion in the literature on cranial base flexion, in the field of biological anthropology, this is not a new finding. Henneberg (1990) reports that for measurements of brain size and body weight, over 50% of the variation is due to individual variation, that is, variation among individuals of the same sex and from the same population. Sexual dimorphism and between-sample variation each contribute about 25% to the total variation in *Homo sapiens* (Henneberg, 1990). Interpreted with regard to the literature on cranial base flexion and other craniofacial variables, this finding of significantly greater within- than between-sample variation warrants further discussion. For example, it highlights that so-called "racial" differences in cranial base flexion are minimal. Comparisons between samples for this purpose will only account for a small amount of the possible variation in these characters. The cranial base and craniofacial variables measured here show the same pattern of variation as other biological variables, with considerable overlap between samples. While some differences between samples at the extreme ends of the range are apparent, for example between the Polynesian and Chinese samples, for the most part there are no clear borders between the samples measured. This biological approach of analysis and interpretation demonstrates the importance of investigating variation in addition to reporting average values for these variables.

Since the purpose of the present study was to explore variation in cranial base and craniofacial morphology, the separate results for each of the seven samples have not been discussed in detail here. However, during the course of the investigation it became apparent that previous researchers have not extensively studied the cranial base flexion and craniofacial morphology of the African K/S and Thai samples. This was evident in the lack of reference samples available to compare to the data of the present study. The findings of the present study on the morphology of the cranial base and craniofacial skeleton of these samples will, therefore, be useful to researchers who are interested in specific features of these samples. For example, despite the historic separation of African K/S and African S/X/Z people, the results of the present study show that these two samples appear more similar to each other than to the other samples studied. This is not surprising due to the geographical proximity of the samples. However, it is interesting that the differences between them appear to be mainly in the dimensions of the mid-face, such as the height of the nasal aperture (nasion-ANS, nasion-A point) and length of the hard palate (nasion-ANS, nasion-A point). It was also found that the African K/S sample had no sexual dimorphism in any of the dimensions measured, but did show differences between males and females in the orientation of the foramen magnum relative to the clivus, and two of the cranial base flexion angles measured, ECP-sella-nasion, and basion-SE-nasion. These and other relationships displayed by the various samples are interesting and warrant further work, but were not investigated fully here due to the principal aim to study variation in the total sample, rather than in sub-samples.

Multivariate analyses were used to investigate the second aim of the study, that there are no sample differences in cranial base flexion. This was undertaken in two ways. Discriminant Function Analysis showed that about 83% of individuals could be assigned to their original sample when all variables were included. However, further investigation of the results showed that the major contributing factors to the analysis were the dimension variables, which accounted for size differences between individuals. When angles of cranial base flexion or orientation were used separately in the analysis, less than 50% of individuals could be assigned correctly, and when dimensions were included separately, only 77% of individuals could be correctly assigned. Examination of the Discriminant Function results using all variables showed that the first function explained variation in size of the anterior cranial base, foramen magnum and palate. The second function explained variation in mid-face height (nasion-ANS variable), as well as differences in the length of the clivus. An interesting feature of this analysis is that the dimensions included in the first function were all measurements in the horizontal dimension of the cranial base and face, whereas the variables of the second function were all in the vertical dimensions of the cranial base and face. This relationship between the horizontal dimensions compared to the vertical dimensions is not new, and was investigated in detail by Enlow (1990). However, it is reinforced by the results of the present study in the finding that the two sets of variables emerge as distinct groups in Discriminant Function Analysis. The Discriminant Function Analysis showed that variation in cranial base flexion is insufficient to distinguish individuals from various samples. It only becomes more discriminating when dimension results and craniofacial angles are also included in the analysis, and even then only correctly assigns 83% of individuals to their correct sample.

The results of the Principal Components Analysis were used to complement the results of the Discriminant Function Analysis. Having already determined that cranial base flexion was highly variable across the total sample, it was not surprising to find that the first component extracted three angles that explained most of the variance in the total sample. These were: the cranial base angle basion-sella-nasion, the craniofacial angle basion-pituitary point/sella-nasion, and the cranial base angle endocranial clival plane-sella-nasion. This component contributed over 47% to the total variance. An interesting finding of this analysis was the inclusion of the basion-sella-nasion angle as highly variable, since it is used as a standard reference for numerous studies on craniofacial variation (see Table 4.1). In addition, the three angles for this first component all shared the sella-nasion plane as their anterior chord, which is the most frequently chosen reference plane in orthodontic studies and other comparative analyses. The second component contributed 20% to the total variance in the sample, and was highly correlated with dimension variables, including basion-sella, basion-nasion and sella-nasion. Interestingly, these were all dimensions of the cranial base, again reinforcing the argument that cranial base morphology is highly variable. The variables with high correlations with the third component were nasion-ANS and nasion-A point, with a moderate contribution from the sella-nasion dimension. This component accounted for about 8% of the total variance. The nasion-ANS and nasion-A point dimensions represent the height of the mid-face, and the inclusion of them as the third component suggests that they are moderately variable with regard to variation in craniofacial morphology.

The purpose of multivariate cluster analysis is to let groups emerge from the data based on their relationships with other variables, rather than prescribe relatively arbitrary groups that may not be based on biologically meaningful data (Hirschfeld et al., 1973). In the present investigation, the results of the multivariate analyses (Discriminant Function Analysis and Principal Components Analysis) revealed two features about variation in cranial base flexion and craniofacial morphology. The first feature was that dimension variables were the most effective in distinguishing between groups in the data, unless all variables were included, resulting in a correct placing of 83% of individuals. It also revealed that the most effective discriminant variables were horizontal dimensions, with the next group being made up of vertical dimensions. Principal Components Analysis established that among all individuals in the sample, angles of cranial base flexion accounted for about 47% of the variation, while dimensions accounted for nearly 30% (20% for the second component and 8% for the third component.

The following part of the discussion focuses on the final aim of the study, which was to explore the inter-relationships between the cranial base and craniofacial variables in relation to the postural theory of cranial base flexion. In particular, it is an interpretation of craniofacial morphology based on the flexion of the cranial base and the orientation of the foramen magnum. This relationship has been investigated to some extent by other researchers, but the interpretation to date has been based on pre-existing beliefs that the principal reference line for interpreting cranial base flexion and facial morphology was the sella-nasion line of the anterior cranial base. However, the results of the present investigation offer a new interpretation of the flexion of the cranial base and associated variations in the facial skeleton, with the reference line being the plane of the foramen magnum. The results of this study show that the angle of orientation of the foramen magnum relative to the clivus differs least between the samples. In addition, it also showed a parallel relationship with the orientation of the anterior cranial base (measured from pituitary point-nasion). Furthermore, a positive correlation was found between the flexion of the cranial base and the orientation of the foramen magnum. This latter relationship has been recognised previously, and has been interpreted as a posterior rotation of the foramen magnum associated with increases in the angle of cranial base flexion (Slice et al., 2001; Smahel and Skvarilova, 1988a; Smahel and Skvarilova, 1988b). In 1988 Smahel and Skvarilova found a positive correlation between the angles sella-basion-opisthion and basion-sella-nasion in a sample of 50 males from former Czechoslovakia (Smahel and Skvarilova, 1988a). In this and a later investigation, they were able to conclude that increased flexion of the cranial base led to posterior rotation of the neurocranium, when results were interpreted relative to the sella-nasion line (Smahel and Skvarilova, 1988a; Smahel and Skvarilova, 1988b). As they stated in their first paper, "…the angle that the foramen magnum formed with the clivus plane…increased or decreased parallel to the increase or decrease of the angle of the cranial base" (Smahel and Skvarilova, 1988a, p. 305). They went on to conclude that increased flexion of the cranial base was also related to an anterior inclination of the palatal plane, which led to anterior rotation of the face. These results agree with the findings of the present study, with a positive correlation between the cranial base flexion and orientation of the foramen magnum relative to the clivus, and a negative correlation between these angles and the hard palate. While Smahel and Skvarilova studied the orientation of the sella-nasion line only as the anterior projection of the cranial base, in the present study similar correlations were observed in the pituitary point-nasion and sphenoidal planes, with the highest correlation between the foramen magnum plane and pituitary point-nasion plane. Figure 4.1 shows the differing relationships between the "z" shape and the three anterior cranial base planes – pituitary point-nasion, sella-nasion and the sphenoidal plane. All of these angles have been superimposed on the basion-opisthion plane. It can be seen that the orientation of the pituitary point-nasion plane is approximately parallel to the orientation of the basion-opisthion plane, whereas the sella-nasion plane tends to slope superiorly, and the sphenoidal plane tends to slope inferiorly.

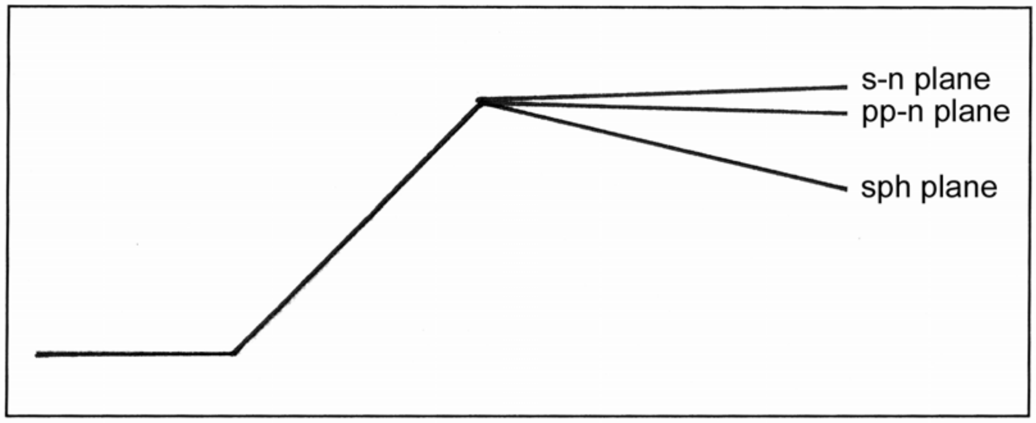


Figure 4.1: A comparison between the orientation of the three anterior cranial base planes relative to the clivus and the orientation of the foramen magnum, using angles based on averages for the total sample (note that this is a schematic diagram and normally the sella-nasion and pituitary point-nasion planes would end at the same anterior point).

In a study on dry skulls of individuals from geographically distant modern human populations, including Austrians, Khoi-San, Australian aborigines and New Guineans, Slice and colleagues found that European samples showed rotation of the foramen magnum. They concluded that most of the variation could be attributed to differences between dolichocephalic compared to brachycephalic skull shapes (Slice et al., 2001). However, since the results were published in abstract form only, it is unclear what direction of rotation was measured, and to what other structures it was interpreted. A review of the literature on cranial base flexion and craniofacial morphology has not revealed any further investigations into the relationship between the rotation of the foramen magnum and other aspects of the cranial base. This is significant, as one of the findings of the present study was the parallel association between the plane of the foramen magnum and the anterior cranial base measured from the pituitary point to nasion. This relationship appears to be consistent across samples from geographically distinct areas, and between males and females. Coupled with the finding of positive correlations between the flexion of the cranial base and the orientation of the foramen magnum, the resulting "z" shape depicts an explanation of craniofacial form that has not been explored previously. This relationship warrants further investigation on other samples in order to establish a causal relationship between these elements, as the current investigation could only explore the relationship through association, due to the cross-sectional nature of the sample. For example, investigation of the "z" shape in a longitudinal series would help to establish the developmental relationship between the angles. Additional information on craniofacial morphology would also aid interpretation of the relationship, such as an investigation into the "z" shape in representatives of the Angle classes of occlusion, and incorporating other potentially significant variables such as natural head posture and the orientation of the orbital plane.

As well as reporting on the average values for the orientation of the opisthion-basion and pituitary point-nasion planes relative to the clivus, the individuals with the most extreme values were also identified. Figure 4.2 shows the range of variation for the orientation of these two lines plotted as three standard deviations to each side of the total sample average. The individual with the smallest angle of orientation of the foramen magnum plane relative to the clivus and the smallest angle of orientation of the pituitary point-nasion plane relative to the clivus was an Australian aboriginal female (ID number 63), whose measurements were 117 degrees for the opisthion-basion plane and 116 degrees for the pituitary point-nasion plane (note once again that these two angles are nearly parallel, despite being more than 15 degrees below the total sample average of 135 degrees). The individual with the largest angle of orientation of the opisthion-basion plane relative to the clivus was a Zulu female, whose measurement for this angle was 157 degrees (ID number 3703). This individual also had a large measurement for the pituitary point-nasion plane relative to the clivus of 149 degrees, which is only 4.5 degrees smaller than the largest measurement of 153.5 degrees, measured in a Moriori female (ID number 211), whose measurement of the opisthion-basion plane was 147 degrees. These extreme values reflect the nature of the positive correlations between these two craniofacial angles (measured relative to the clivus)

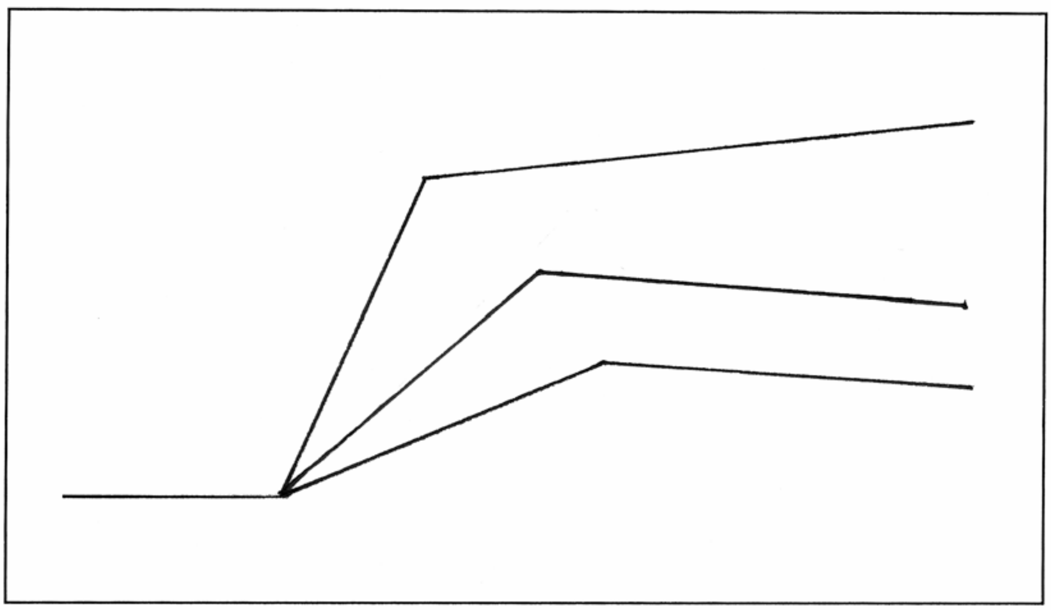


Figure 4.2: The range of variation present in the opisthion-basion-pituitary point-nasion angles, superimposed on the opisthion-basion reference line. The central line

represents the total sample average, while the upper and lower lines represent three standard deviations above and below the average. (Note that this is a schematic diagram only and the clival lengths have been approximated at 45 mm, which means that lines may not show the parallel relationship noted in the results.)

According to general principles of craniofacial growth, the facial skeleton, suspended from the anterior cranial base, grows in a "forwards and downwards" direction (Enlow, 1990). When serial cephalometric images are superimposed on the anterior cranial base (usually sella-nasion), this pattern of growth is readily apparent. However, it may be that this interpretation of the direction of overall growth is an artefact of the simple fact that the serial tracings are superimposed on the anterior cranial base. An alternative superimposition of the tracings on the plane of the foramen magnum creates a picture of growth occurring in the anterosuperior direction. This does not in any way contradict the extensive research on the growth of the craniofacial complex; instead, it is a proposal for an alternative location for superimposition that produces an alternative interpretation of growth that incorporates evolutionary changes, functional growth and variation in the facial skeleton. The results of the present investigation suggest that this interpretation of craniofacial variation is plausible, when the orientation of the foramen magnum is taken into consideration. When tracings of lateral radiographs are superimposed on the anterior cranial base, the resultant posterior rotation of the foramen magnum is evident. However, it is difficult to understand the growth changes that would have to occur in the cranial base to produce this posterior rotation, as well as the simultaneous encroachment of the facial skeleton on the pharyngeal space. As an alternative, superimposition on the plane of the foramen magnum shows an antero-superior rotation of the anterior cranial base, with corresponding projection of the craniofacial skeleton and widening of the pharynx. It is suggested here that the plane of the foramen magnum may be a more anatomically and functionally valid reference plane than the anterior cranial base.

There are several elements of the data that support this theory. First, there is the finding of little variation between samples for the basion-opisthion angle relative to the clivus, which suggests that this feature may be an evolutionarily conservative part of the structure. While this is a preliminary finding, as the present study only examined modern humans, in the context of biological variation the finding of little difference between samples suggests that there is no selection pressure on that structure, and therefore it is likely to be an evolutionarily "primitive" feature. This needs to be investigated further with data from primate and fossil hominins, however. Discriminant function analysis of all variables in the study showed that basion-opisthion was the "least discriminating" function between groups. This angle correlates with the fourth function with a low value of -0.158. There is also the parallel relationship between the pituitary point-nasion line and the foramen magnum. This suggests a functional relationship between these two structures, and it is suggested here that a primary cause for this relationship may be maintaining the orientation of the orbital axis with head balance. The postural theory of basicranial flexion is based on the premise that the development of erect bipedalism in humans caused flexion in the cranial base to allow for head balance over the vertebral column and retain the orbital axis, or line of vision, perpendicular to gravity (Strait and Ross, 1999). This is consistent with the findings of the present investigation that there is little variation in the orientation of the foramen magnum relative to the clivus between samples, and the parallel relationship between the orientation of the foramen magnum and the pituitary point-nasion plane. Postural hypotheses relating to the development of cranial base flexion in humans focus on the change in centre of mass with the adaptation to bipedalism, which required a re-orientation of the foramen magnum and consequently alterations in cranial base flexion. This is based on the observations that the location of the foramen magnum varies in different primate species. For example, in arboreal primates it is located at the rear of the skull, in chimpanzees it is positioned more ventrally, and in hominin fossils and modern humans it is located under the skull (Ashton, 1957; Bolk, 1915). The reorientation of the foramen magnum occurred through a bending of the posterior cranial base relative to the anterior cranial base, which remained in a horizontal position to preserve rostral orientation of the orbits (Dabelow, 1929; Weidenreich, 1924). At the same time, the masticatory apparatus maintained a parallel relationship with the line of vision. This is suggested to be due to the line of vision and the occlusal plane maintaining a functional relationship that requires them to remain perpendicular to the force of gravity. In association with the orbital and occlusal planes, the anterior cranial base would have remained relatively perpendicular to the force of gravity, and consequently parallel to the horizon. An alternative interpretation is that the orbital axis and palate maintain their covarying relationship due to developmental constraints or other non-functional influences (Ross and Henneberg, 1995).In humans, the relationship between the occipital condyles of the skull and the first and subsequent cervical vertebrae is important for head balance. The balancing of the head on the neck in erect bipedal posture is unique to humans. Humans are not the only vertebrates with bipedal posture. Birds, kangaroos, koalas and some primates, for example, also display a tendency towards bipedalism, or at least an upright posture during habitual activity. However, examination of the spine in these animals shows that flexion (allowing orientation of the line of vision with the horizon) occurs at locations other than the cranial base, since the foramen magnum in these species is located posteriorly on the skull, rather than inferiorly (Kardong, 1995). This was confirmed by the author's own observations on numerous mammalian skeletons in the Abbie Centre for Teaching and Research in Anatomy at the University of Adelaide. These showed that flexion occurs at various levels in the cervical vertebral column. The development of erect bipedal posture is generally accepted as a fundamental characteristic of human evolution. Early research on hominin skulls describes the location and position of the foramen magnum, as this is interpreted to establish the presence or absence of bipedalism in the individual. For these reasons, the orientation of the foramen magnum is important in interpreting characteristics of human and/or hominin skulls. It is possible that the rotation of the foramen magnum occurred simultaneously with flexion of the cranial base from the flattened primate type to the shape observed in modern humans. Information that is available on the development of the cranial base links these bones closely to the occipital bone, which adds further weight to this theory (Kjaer, 1990; Kjaer et al., 1993). In addition, in the study on humans conducted by Zuckerman (1955), the angle between basion and opisthion and basion-sella (referred to by Zuckerman as the foramino-basal angle), was found to be smallest at birth, increasing in conjunction with the size of the basion-opisthion diameter, and then decreasing again. Therefore, this increase (once foramen magnum diameter is stable) can only occur by growth in clival length. Changes in this angle will possibly affect its relationships with more anterior structures in the head. More work is clearly needed to assess the developmental relationship between the orientation of the foramen magnum relative to the clivus, as well as the relationships with other craniofacial structures and cranial base flexion. In addition the "z" shape of the foramen magnum, clivus and anterior cranial base adds another dimension to existing work on the relationships between craniofacial structures. For example, Enlow and colleagues (Enlow, 1990; Enlow et al., 1971a; Enlow et al., 1971b) found a consistent pattern of variation between the planes of the anterior cranial base, maxilla, occlusal plane, clivus and mid-face, and constructed schematic diagrams representing various face types. Due to differences of study design, the results of the present study cannot be directly compared to those of Enlow, however, it is hoped that future research will be able to include the orientation of the foramen magnum and incorporate the "z" shape into Enlow's original concepts. Further work will also determine the relationship of the "z" shape during growth and in samples of individuals of various face types.

Head posture is difficult to assess accurately because of limitations with data collection, such as the possibility of unnatural head posture of individuals when data are collected. As a result of the problems associated with the study of head posture, it is not surprising that relatively little work has been undertaken to determine its role as a causative factor in the development of cranial base flexion in modern humans. A similar problem has been encountered in the present study, as the study material included dry skulls and living subjects who were not radiographed in natural head posture. For this reason, the conclusions of this study regarding head posture must at this stage be considered preliminary. Further work is anticipated to better explore this relationship using radiographs of individuals in natural head posture. In 1976 Solow conducted a study on the effect of head posture on craniofacial morphology. Two sets of lateral cephalometric radiographs were taken on a sample of 120 Danish males aged between 22 and 30 years. The first set was taken with the individuals standing with their natural head posture, and the second set was taken with the subjects looking at themselves in a mirror. Solow found a number of correlations between head posture (in both head positions). The overall findings of the study were that extension of the head in relation to the cervical spine was associated with large anterior and small posterior facial heights, small antero-posterior craniofacial dimensions, a greater angle of inclination of the mandible relative to the anterior cranial base (resulting in facial retrognathism), a large cranial base angle, a backward upward slope of the foramen magnum in relation to the cranial base, and a small nasopharyngeal space. In contrast, flexion of the head in relation to the cervical spine was associated with small anterior and large posterior facial heights, large antero-posterior craniofacial dimensions (resulting in facial prognathism), a smaller inclination of the mandible relative to the anterior cranial base, a small cranial base angle, a backward downward slope of the foramen magnum relative to the cranial base, and a large nasopharyngeal space (Solow and Tallgren, 1976). As a result of the problems associated with the study of head posture, it is not surprising that relatively little work has been undertaken to determine its role as a causative factor in the development of cranial base flexion in modern humans. A similar problem was encountered in the present study, as the study material included dry skulls and living subjects who were not radiographed in natural head posture. For this reason, the conclusions of this study regarding head posture must at this stage be considered preliminary. Further work is anticipated to better explore this relationship using radiographs of individuals in natural head posture.

Concluding remarks

The conclusions drawn from the results of this study suggest that use of the basion-opisthion plane may be a new method to interpret variation, evolution and growth of the craniofacial complex. It is situated on the top of the vertebral column, with the force of gravity passing through the occipital condyles. Growth of the craniofacial structures interpreted relative to the basion-opisthion line is thus in the upward and forward directions, rather than in the downward and forward directions as observed when superimposition of serial tracings is performed on the nasion-sella line (Enlow, 1990). Orientation of tracings on the basion-opisthion line makes interpretation of later growth changes in the nasomaxillary area logical, with the resulting upward and forward growth allowing space for the developing jaws under the face, without compromising the airway. However, this warrants extensive additional research, as there are some inherent limitations to the method. The first is that in the present investigation it has been studied in two dimensions only, whereas the craniofacial complex is a three dimensional structure. In addition, the basion-opisthion line may be difficult to locate accurately and reliably on a radiograph, as the landmark opisthion is often obscured by the bony structures around it. In the present study the test-retest reliability for the orientation of the basion-opisthion plane relative to the clivus was 3.0 degrees, or 2.2% of the average, which is well within acceptable limits of measurement error; however, the test-retest of the basion-opisthion dimension was considerably higher, being 3.5 mm, or nearly 10% of the average. This difference in error estimations of these variables, which share similar landmarks, helps to demonstrate the problems associated with the location of these landmarks, which may need to be addressed when planning additional research in this area.

This work has documented the variation present in cranial base flexion and craniofacial morphology in a sample of modern humans, and has found that the variation is considerable, with individual variation contributing between 60% to 80% of the total variation. It has established that there is no sexual dimorphism in the cranial base flexion or most of the craniofacial angles studied. The one craniofacial angle showing significant differences between males and females was the orientation of the foramen magnum relative to the clivus in the total sample, however since this then varied in the sub-samples it is of uncertain significance. Sexual dimorphism, therefore, appears to be largely due to differences in the size of dimensions of the cranial base and craniofacial skeleton. Differences between samples in cranial base flexion and craniofacial angles are minimal, whereas most differences between samples are in the dimensions of the cranial base and facial skeleton. Furthermore, the craniofacial angles have revealed a previously unrecognised parallel relationship between the orientation of the foramen magnum and the anterior cranial base (measured from basion to the pituitary point), which together with the clivus form a "z" shape that can be used to interpret differences between face types. The parallel relationship between the foramen magnum, clivus and anterior cranial base is possibly due to an adaptation to bipedal posture in modern humans, associated with a re-orientation of the foramen magnum while maintaining the orientation of the anterior cranial base plane perpendicular to the force of gravity.

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Appendix

Summary of variables:

Landmark	Abbr.	Definition
Anterior nasal spine	ANS	the most anterior point on the maxillary body at the level of the nasal floor
A-point	A	the most posterior point on the curvature of the anterior surface of the maxilla
Basion	Ba	the most postero-inferior point on the clivus
Clival plane	Cliv	the line between basion and the SOS, representing the orientation of the clivus
Endocranial Clival Plane	ECP	the line representing the endocranial border of the clivus
Nasion	Na	the anterior end of the frontonasal suture, in the median sagittal plane
Opisthion	Op	the point at which the external and internal surfaces of the occipital bone meet on the posterior margin of the foramen magnum in its median plane
Orbitale	Or	the margin of the orbit at the most inferior point of curvature
Pituitary point	pp	the anterior edge of the groove for the optic chiasma, just in front of the pituitary fossa
Planum sphenoideum point		the superior-most point on the sloping surface of the pit in which the cribriform plate is set
Porion	Po	the superior point of the external auditory meatus
Posterior nasal spine	PNS	the most posterior point of the maxillary body at the level of the nasal floor at the articulation of the hard and soft palates
Sella	S	the centre of the sella turcica (hypophyseal fossa), independent of the clinoid processes
Spheno-ethmoid	SE	the point where the margin of the greater wing of the sphenoid bone intersects with the planum sphenoidale or cribriform plate
Spheno-occipital synchondrosis	SOS	located on the endocranial border of the spheno-occipital synchondrosis
Sphenoidal plane/ planum sphenoidale	Sph	the line representing the superior plane of the sphenoid bone, between planum sphenoidale point and SE.

Abbreviations of angles, planes and dimensions:

Abbreviation	Alternative abbreviations	type
ba-s-n		Angle of flexion
ba-pp-n		Angle of flexion
ba-pp-sph		Angle of flexion
cliv-sph		Angle of flexion
cliv-s-n		Angle of flexion
ECP-s-n		Angle of flexion
ba-se-n		Angle of flexion
ba-pp/s-n	s-n	Craniofacial angle
ba-pp/pp-n	pp-n	Craniofacial angle
ba-pp/pp-sph	pp-sph	Craniofacial angle
ba-pp/ANS-PNS	ANS-PNS	Craniofacial angle
ba-pp/o-b	o-b	Craniofacial angle
s-n	s.n.d	Dimension
ba-s	ba.s.d	Dimension
ba-n	ba.n.d	Dimension
o-b	o.b.d	Dimension
ba-PNS	ba.PNS.d	Dimension
ANS-PNS	ANS.PNS.d	Dimension
PNS-A	PNS.A.d	Dimension
n-ANS	n.ANS.d	Dimension
n-A	n.A.d	Dimension