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Morphological variation in the metatarsal bones of selected recent and pre-pastoral humans from South Africa

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CHAPTER 2 - MATERIALS AND METHODS

2.1 Introduction

Broadly, this study is divided into three parts:

- A preliminary morphometric study of the patterns of morphological variation present in selected hominoidea, namely extant humans, chimpanzees, gorillas and orangutans. In addition, the isolated SKX 5017 early hominin first metatarsal fossil is also included.
- A primary morphometric study of the patterns of morphological variation present in a spectrum of modern humans; both recent and ancient.
- A non-metric study of patterns of variation of morphological features and, osteogenic changes between them in the recent and ancient humans.

2.2 Materials – the hominoid preliminary study

The materials for the preliminary study, which aimed to show the large scale differences between selected hominoid species, comprised samples of the first, second and fifth metatarsal bones. These were considered sufficiently representative of the entire complex in order to show the patterns of variation within and between the selected hominoid species. In addition, four osteometric data-sets, as yet unpublished, were made available courtesy of Associate Professor R.S. Kidd, obtained from the following skeletal collections or remains:

Human:

Victorian-British	– 18 male; 18 female	The British Museum of Natural History *The Spitalfields collection*

Apes:

Chimpanzee	– 20 male; 20 female	The Powell-Cotton Museum
Gorilla	– 20 male; 20 female	The Powell-Cotton Museum
Orangutan	– 11 male; 16 female	The Smithsonian Institution

In addition, data was also collected from the following isolated early hominin fossil:

SKX 5017	- Left first metatarsal	Transvaal Museum *The Robert Broom collection*

2.3 Materials – the human study

The materials for the main human study may be divided into two parts, consisting of all five human metatarsal bones of both recent and ancient populations. These bones have been chosen as they represent the most significant portion of the forefoot and the structures in the forefoot most prone to pathological changes. Samples examined were:

- The metatarsals of recent humans from three contemporary human sub-groups.
- The sub-fossil metatarsals of pre-pastoral *Holocene*-aged human individuals.

An important component of this study is that complete units of the contemporary samples were used; this was to allow examination of any patterns of co-variation present in the groups under consideration. Accurate knowledge of the sex of the specimens is vital if patterns of sexual dimorphism are to be investigated. Regrettably, the sex of only a few of the pre-pastoral individuals was known with the remainder being uncertain or unknown. A suite of osteometric and non-metric data were obtained from the following skeletal collections or remains:

Recent human:

Zulu:	– 30 male; 30 female	University of the Witwatersrand
Sotho:	– 30 male; 30 female	University of the Witwatersrand
"European":	– 30 male; 30 female	University of the Witwatersrand
		The Raymond Dart Collection

Ancient humans of pre-pastoral archaeological context:

18 individuals		South African Museum – Cape Town
		Department of Archaeology
17 individuals		National Museum – Bloemfontein
		Florisbad Quaternary Research Station
(Total 35 individuals)	- 11 male; 10 female	
	- 14 of unknown sex	
KRM 6113B	Isolated first metatarsal	South African Museum – Cape Town
		Department of Archaeology

A list of these sub-fossil specimens, their date BP, and archaeological context may be found in Table 2.1.

There is no published evidence that one side has greater variation over the other (Steudal, 1984). Therefore where possible, the metatarsals of only the left feet were examined, and if the left was missing or damaged, the right side was used. The archaeological samples were classified according to their temporal context, in terms of their absolute and estimated dates. Undated samples were not used and even though not all samples were complete, an attempt was made to use as many complete and intact specimens as possible. As discussed in the previous chapter, these pre-pastoral individuals are presumed to have belonged to habitually unshod forager societies.

The Zulu and Sotho samples represent two different Bantu speaking groups, and the "European" sample a diverse South African group of European decent. These sub-groups are presumed to have been exposed to footwear, modern substrates and other environmental factors that could potentially influence foot morphology, function and dysfunction.

2.4 Methods – the hominoid preliminary study

In order to contextualize the patterns of variation between the morphology of humans and apes, a suite of linear data from selected extant hominoid metatarsals were utilized. In addition, linear data from the isolated first metatarsal of the SKX 5017 fossil were collected. Apart from the definitions of the linear dimensions, defined by Kidd (2000, pers. com.), the linear data were collected in a similar manner to the main

Table 2.1: Details of pre-pastoral individuals with metatarsal bones.

Collection Accession Number	Locality	Sex*	Date (B.P.)†	Metatarsals
SAM-AP 1443	Gordon's Bay	M	2,050 ± 50	Right
SAM-AP 4825	Coldstrea Cave, Humansdorp	F	2,060 ± 50	Left. 2 missing
SAM-AP 4305	Noordhoek	X	2,100 ± 45	Right
SAM-AP 4720	Kommetjie	X	2,195 ± 80	Left
NMB MSK2	Matjies River	(F)	2,200 ± 50	Left
SAM-AP 4824B	Tucker's Cave, Humansdorp	M	2,210 ± 50	Right
SAM-AP 1889	Prince Albert	M	2,310 ± 50	Left
SAM-AP 2440	Saldanha	X	2,440 ± 60	Right
SAM-AP 5075	Cape Point	X	2,530 ± 60	Left
SAM-AP 4943	Kommetjie	X	2,610 ± 50	Right
NMB-P 1639	Robberg	F	2,590 ± 60	Right 1 & 3 missing
NMB-C 1705	Plettenburg Bay	F	2,780 ± 60	Right 1 – 4 missing
NMB-C 1273	Matjies River	M	3,050 ± 60	Left 5 missing
SAM-AP 1145	Robberg	M	3,210 ± 70	Right
NMB 1241(B)	Matjies River	(F)	3,290 ± 90	Left
NMB MSK5	Matjies River	X	3,380 ± 60	Left
NMB-C 1271	Matjies River	(F)	3,570 ± 50	Right
SAM-AP 4931	Buffels River, Namaqualand	M	3,750 ± 60	Left
SAM-AP 4210(A)	Humansdorp	X	3,760 ± 60	Left
SAM-AP 4637	Gordon's Bay	X	3,880 ± 50	Left
NMB-P 1640	Robberg Cave	F	4,120 ± 60	Left
SAM-AP 4210(B)	Drury's Cave, Humansdorp	F	4,210 ± 70	Left
NMB-P 1437	Matjies River	M	4,940 ± 70	Left 2 missing
SAM-AP 6032	Cape St Francis	X	5,180 ± 65	Left 3 distal shaft missing
NMB SS3	Matjies River	(M)	5,390 ± 70	Left
SAM-AP 1163	Drury's Cave	(M)	9,290 ± 90	Right
SAM-AP 4208(B)	Drury's Cave	X	9,540 ± 120	Left
SAM-AP 4208(A)	Drury's Cave	X	9,720 ± 100	Right
NMB-P 1704	Plettenburg Bay	F	Presumed ≥ 2000	Left
NMB SS1	Matjies River	M	Presumed ≥ 2000	Left
NMB MSK5	Matjies River	F	Presumed ≥ 2000	Left
NMB MR5	Matjies River	X	Presumed ≥ 2000	Right 1 head lateral portion broken
NMB MR4	Matjies River	M	Est. 5,000 – 7,000	Right
NMB Unlisted	Matjies River	X	Est. 5,000 – 7,000	Left 2, 3 and 5 missing
NMB Unlisted	Matjies River	X	Est. 5,000 – 7,000	Right 2 – 5 missing
SAM 6113B	Klassies River Mouth (KRM1)	X	Est. 80 K – 90 K	Left first. Head, plantar medial portion broken

*Skeletons are identified as M or F if there is confidence of sex; (M) and (F) are probable males and females, and skeletons to which no sex could be attributed are marked X.

† Absolute dates were determined by ^{14}C and Stable Isotope dating techniques. Estimated dates were determined by the taphonomic context in which skeletons were found.

human study subgroups described in Chapter 2.5. Univariate descriptors of mean, standard deviation and coefficient of variation and multivariate morphometric analysis utilizing principal components analysis and canonical variates analysis were carried out to illustrate the scale of variation within and between the different species. This was done to contextualize the more subtle variation within and between the human sub-groups. These statistical methods are described under the human study in this chapter.

2.4.1 Problems in the choice of variables

The choice of measured variables in any morphometric study is of paramount importance as it may have significant effects upon the results. All dimensions have been chosen so as to reflect what are thought to be functionally important components. For the purpose of this preliminary study, a minimum number of variables thought to represent the general size and shape of the bones were utilized. The reasons for this are explored later in this chapter.

2.4.2 The problem of analogy and homology

Kidd (1995), in a study of the hind-tarsus, addressed the problem of the comparison of comparable structures from different species that has the potential of problems associated with *analogy* and *homology.* Similarly, in a comparison of the metatarsus in different species, analogy and homology should be considered. Wilson (1975) defines analogy to be a resemblance in function, also often in appearance, between two structures, physiological processes or behaviours that is due to evolution rather than common ancestry. He defines homology to be a similarity between two structures that is

due to inheritance from a common ancestor. Examples such as the forelimbs of whales, dolphins or porpoises, and the paired fins of fish such as sharks, have the same function and are analogous, but not homologous (this is known as homoplasy). Whales, dolphins and porpoises are permanently aquatic marine mammals where the forelimbs have become paddlelike balancers with the phalanges embedded at the distal end (Kent, 1987). In sharks, the paired fins are braced against the corresponding girdle and are not true forelimbs but rather specifically designed aquatic appendages. An example that is less well defined is the forelimb structure of a whale and turtle; both involve the forelimb anatomy, but different regions having similar but different functions. In this example, the turtle, unlike the whale, can also use the forelimbs, in addition to swimming, for locomotion on land.

In the metatarsus analogy between the species was considered particularly in terms of the proximal and distal aspects of the bones as these represent the areas of articular function. Fortunately, unlike some of the hind-tarsal elements, the metatarsals of both humans and apes are similar enough not to present any serious problems in the identification of planes (orientation of bones) and definition of dimensions.

2.4.3 Definitions of the hominoid metatarsal dimensions

Kidd (2000, pers. com.), described a series of metatarsal dimensions that he used to collect linear metrical data from the first, second and fifth metatarsals of humans, African apes and orangutans. This study incorporates Kidd's definitions as follows:

2.4.3.1 Planar definitions

The first and second metatarsals

The long dimension of the base is considered to be coincident with the sagittal plane and the transverse plane to be at right angles to this.

The fifth metatarsal

The long dimension of the base is considered to be coincident with the transverse plane and the sagittal plane to be at right angles to this.

2.4.3.2 Variable definitions

Using these standard planes and definitions, the following linear variables are defined:

First and second metatarsals (Figures 2.1 and 2.2)

1) *Maximum length* is measured from the posterior articular surface to the extreme of the anterior articular surface.
2) *Height of base* is the maximum height measured from the most superior point on the base to the most inferior point on the base in the assumed sagittal plane.
3) *Breadth of base* is measured at right angles to 2) above.
4) *Height of head* is the maximum height measured from the most superior point on the distal articular surface to the most inferior point of the distal articular surface.
5) *Breadth of head* is the maximum bone span measured at right angles to 4) above.
6) *Height of shaft* is measured at the mid shaft in the sagittal plane.
7) *Breadth of shaft* is measured at right angles to 6) above.

Figure 2.1: First metatarsal dimensions 1 - 7. These are illustrated on the human metatarsal, but apply to all the selected hominoidea. See preceding page for definitions.

Figure 2.2: Second metatarsal dimensions 1 - 8. These are illustrated on the human metatarsal, but apply to all the selected hominoidea. See preceding pages for definitions. .See definitions on preceding page.

Fifth metatarsal (Figure 2.3)

1) *Length – A* is defined as the maximum dimension from the extreme of the anterior articular surface to the articular margin dividing the shaft and the styloid process.
2) *Length – B* is defined as the maximum length, including the styloid process.
3) *Height of base* is the maximum height measured from the most superior point on the base to the most inferior point on the base in the assumed sagittal plane.
4) *Breadth of base* is measured at right angles to 3) above.
5) *Height of head* is the maximum height measured from the most superior point on the distal articular surface to the most inferior point of the distal articular surface.
6) *Breadth of head* is the maximum bone span measured at right angles to 4) above.
7) *Height of shaft* is measured at mid shaft in the sagittal plane.
8) *Breadth of shaft* is measured at right angles to 7) above.

2.5 Methods – the human study

Three methods of data collection were undertaken in this study. First, a suite of linear data was obtained from the five metatarsal elements of the skeletal collections. Secondly, a series of non-metrical morphological features were identified. Thirdly, any obvious osseous modification was identified and described. The first of these may be considered as a method of quantifying biological form that rely on recognizable anatomical landmarks. The second and third rely on the recognition of previously described and classified morphological traits or features and manifestations.

The purpose of using these different methods, is that osteometric data gives an overall indication of size and shape of the bone, whereas some morphological traits,

Figure 2.3: Fifth metatarsal dimensions 1 - 8. These are illustrated on the human metatarsal, but apply to all the selected hominoidea. See preceding pages for definitions. .
See definitions on preceding page.

such as articular facets and manifestations, such as pathological changes, are better identified according to previously defined descriptions. Although the later two types of variants are to some extent captured within a morphometric analysis, much of this variation can only be noted by direct observation.

2.5.1 The choice of morphological variables

The choice of linear (metric) and non-metric variables in this study are of critical importance. In order to obtain as much information as possible regarding functional affinities and their possible correlation with modification of bone, it is important that the variables chosen are thought to be of functional significance. One problem with this is that the functional significance of many of these variables, both metric and non-metric, are as yet, not fully understood and these poorly understood variables are explored in this study.

2.5.2 The choice of landmarks and measured variables

Anatomical landmarks are defined as biologically meaningful loci that can be unambiguously defined and repeatedly located with a high degree of accuracy and precision (O'Higgins & Johnson, 1988; Richtsmeister *et al.*, 1995). Generally, landmarks may be of five types (O'Higgins & Johnson, 1988), three of which are of relevance in the study of metatarsal elements. One is a point of extent of a structure such as the outer margin of the bone or an articular facet, typified in the metatarsus by dimensions such as the metatarsal head height or the maximum height of the posterior articular surface. A second is a point on a highly curved region such as a metatarsal

head, typified in the metatarsus by a point on the most distal extreme of the metatarsal head. A third is a bony process, typified in the metatarsus by the styloid process. Illustrations of the linear dimensions are to be found in Figures 2.4 - 2.8.

A fourth and fifth type of bony landmark may be defined by the intersection of sutures of the skull, and foramina for neurovascular bundles. The later two are of no relevance in a pedal study of adult elements.

Particular landmarks are chosen based on prior knowledge that can help to identify features that have direct bearing on a research question (Valeri *et al.*, 1998). That is, the landmarks chosen for measurement and subsequent analysis must reflect structural and functional information.

An example of this is seen in the breadth of the metatarsal head; it is necessary not to obtain just one measurement, but a suite of measurements which reflect more accurately the actual shape. For example, in the first metatarsal head, the superior breadth of the head is usually slightly narrower than the inferior breadth of the head. This is an important feature, which when within normal limits, contributes to the stability of the first metatarsophalangeal joint during the propulsive phase of gait (Susman, 1983). A minimum of a superior and inferior measurement is required, therefore, to establish the degree of wedging.

Another example demonstrating the importance of obtaining a functionally significant dimension is that of metatarsal length. The posterior articular surface of the second, third and fourth metatarsals is usually angulated to all three planes, thus resulting in a medial, lateral and inferior length dimension of the metatarsal. Neither the "functional" length described by Martin & Saller (1957), nor the "morphological

length" used by Byers *et al.* (1989) are fully representative of the metatarsal length. Clearly, no single measurement would represent the "functional" length of these metatarsals as the proximal articular surface is angled to three planes.

2.5.3 The problem of homology in terms of ambiguity

In metatarsal elements, identifying completely unambiguous, homologous landmarks is neither obvious nor possible. An example of this may be landmarks involving the margin of an articular surface, which may be very clear in most specimens, but less clearly defined in others. For instance, in the fifth metatarsal, the medial margin of the proximal articular surface may be unclear as the medial articular surface for the fourth metatarsal often extends posteriorly, making the junction between the two surfaces unclear. This requires careful examination of the superior and inferior articular margins in order to identify the most obvious path of the articular margin into the ill-defined region.

Another example of a potentially ambiguous landmark, is where an inter-landmark distance on the metatarsal head is measured on a curved surface from the most supero-medial point on the distal articular surface to the most supero-lateral point on the distal articular surface. Again, these landmarks may be obvious in most specimens, but may be less obvious where the medial and lateral aspects of a metatarsal head are extremely curved resulting in a landmark that is not obviously the most superior medial or lateral point. By identifying the side with the most obvious landmark, the opposite side can be estimated resulting in a reasonable representation of the superior metatarsal head breadth.

Pathological changes may also result in the modification of some part of a bone, and thus alter morphology to such an extent, that landmarks are no longer identifiable. Although the presence of pathology is noted and is of importance to this study, samples with extreme osseous modification that may result in ambiguous landmarks, have been excluded.

2.5.4 The problem of homology in terms of planar orientation

Unlike for example the calcaneus and talus, the metatarsus cannot be positioned by resting on a surface giving a consistent orientation. Human metatarsals also have a degree of torsion in the shaft resulting in the metatarsal head being angled in the coronal plane in relation to the base. This creates a problem in terms of taking measurements in a consistent plane throughout the bone. An example of this is the mid-shaft height and breadth dimensions of a metatarsal. Taking the maximum height and breadth measurements may appear to be the most logical approach, but metatarsals have a variable mid-shaft geometry. This may result in the maximum height, for instance, in one bone, to represent the actual height of the bone, but in another bone maximum mid-shaft height may lie in another plane altogether. To deal with this problem, the planes of the metatarsus were defined, and utilized to define some of the dimensions. This may not necessarily give the "true" dimension in for example the mid-shaft, but does ensure consistency in measurement from one bone to another.

2.5.5 The problem of unknown sex and sex estimation

When presented with a sample of skeletons, physical anthropologists usually attempt to identify the sex of each individual represented. In view of the mostly incomplete and fragmentary condition of the pre-pastoral sample in the current study, the sex of only a few could be accurately determined. In such cases, estimating sex can be problematic. If the skull and pelvis are absent, sex estimation can be especially difficult (Phenice, 1969; Lovell, 1989). Robling & Uberlaker (1997) presented a sex-estimation method based on osteometric data from metatarsals utilizing discriminant-function analysis. As with other discriminant functions, these are population specific and may require adjustments if applied to other populations. In the current study, this technique of sex estimation could not be reliably applied for two reasons. Firstly, no samples of significant size with known sex exist to test this hypothesis, and secondly, the sample consisted of presumably "Khoisan" people, of which the Khoikhoi and San differentiation is somewhat ambiguous. Khoikhoi are generally of larger stature than San (Sealy & Pfeifer 2000). This may be exaggerated, considering that these populations lived over a period of 8,000 years with cultural and geographical barriers being influenced by time and space.

However, an attempt was made to determine any obvious pattern of sexual dimorphism. A principal components analysis was undertaken on the first metatarsal component of the sub-fossil sample utilizing the dimensions described in 2.5.6. This presented a subtle albeit ambiguous clustering to the left and right on the first principal component representing primarily variation in size. Subsequently, the individuals to the left were hypothetically assigned as females, and to the right as males. The seventeen

individuals (nine male and eight female) of known and presumed sex were included in the group. The PCA with these hypothetically assigned individuals produced results that placed a few known males onto the female side and a known female onto the male side. Tentative results suggested that the extent of sexual dimorphism in this sample was relatively small. As a result, no further attempt was made to determine the sex of these specimens and the individuals in the sample were assigned as either unknown sex, male or female according to their official collection allocation.

2.5.6 Definitions of metatarsal dimensions

Martin (1928) and Martin & Saller (1957), described a series of metatarsal dimensions that are neither comprehensive nor precisely defined. Loosely based on these definitions, together with those of, for example, Susman & Brain (1988), Byers *et al.* (1989), novel metatarsal dimensions were developed in greater detail for the purpose of this study.

2.5.6.1 Planar definitions

The variables used in this study are defined using the standard reference planes below (after Kidd 2000, pers. comm.):

The first to fourth metatarsals

The long dimension of the base is considered to be coincident with the sagittal plane and the transverse plane to be at right angles to this.

The fifth metatarsal

The long dimension of the base is considered to be coincident to the transverse plane and the sagittal plane to be at right angles to this.

2.5.6.2 Variable definitions

Using these standard planes and definitions, the following linear variables are defined:

First metatarsal (Figure 2.4)

1) *Interarticular length* is measured from the most distal point on the upper part of proximal articular surface to the most distal point on the distal articular surface. This dimension was adapted from the definition according to Martin (1928).
2) *Height of the proximal articular surface* is the maximum height, measured from the most superior point on the proximal articular surface to the most inferior point on the proximal articular surface in the assumed sagittal plane. This dimension was adapted from Susman and Brain (1988).
3) *Breadth of the proximal articular surface* is the maximum breadth, measured from the most medial point on the proximal articular surface to the most lateral point on the proximal articular surface at right angles to the assumed sagittal plane. This dimension was adapted from Susman and Brain (1988).

Figure 2.4: First metatarsal dimensions 1 - 9. See definitions for the first metatarsal.

4) *Height of the head* is measured from the most superior point on the metatarsal head to the most inferior point on the metatarsal head. This dimension was adapted from the definitions according to Martin (1928).

5) *Breadth of the head* is the maximum bone span measured from the most medial point on the metatarsal head to the most lateral point on the metatarsal head at right angles to the *height of the head.* This dimension was adapted from the definitions according to Martin (1928).

6) *Superior breadth of the head* is measured from the most supero-medial point on the distal articular surface to the most supero-lateral point of the distal articular surface. Dimension according to Susman and Brain (1988).

7) *Inferior breadth of the head* is measured from the most infero-medial point on the distal articular surface to the most inferor-lateral point on the distal articular surface. Dimension according to Susman and Brain (1988).

8) *Height of the mid-shaft* is measured at a point mid-way between the most distal point on the proximal articular surface to the most distal point on the distal articular surface in the assumed sagittal plane.

9) *Breadth of the mid-shaft* is measured at a point mid-way between the most distal point on the proximal articular surface to most distal point on the distal articular surface at right angles to the assumed sagittal plane.

Second, third and fourth metatarsals (Figures 2.5 – 2.7)

1) *Lateral interarticular length* is measured from the most supero-lateral point on the posterior articular surface to the most distal point on the distal articular surface.
2) *Medial interarticular length* is measured from the most supero-medial point on the posterior articular surface to the most distal point on the distal articular surface.
3) *Inferior interarticular length* is measured from the most inferior point on the posterior articular surface to the most distal point on the distal articular surface.
4) *Height of the proximal articular surface* is the maximum height, measured from the most superior point on the proximal articular surface to the most inferior point on the proximal articular surface in the assumed sagittal plane.
5) *Breadth of the proximal articular surface* is the maximum breadth, measured from the most medial point on the proximal articular surface to the most lateral point on the proximal articular surface at right angles to the assumed sagittal plane.
6) *Height of the head* is measured from the most superior point on the metatarsal head to the most inferior point on the metatarsal head. This dimension was adapted from the definitions according to Martin (1928).
7) *Breadth of the head* is the maximum bone span measured from the most medial point on the metatarsal head to the most lateral point on the metatarsal head at right angles to the *height of the head.* This dimension was adapted from the definitions according to Martin (1928).

Figure 2.5 : Second metatarsal dimensions 1 - 11. See definitions for second, third and fourth metatarsals.

Figure 2.6 : Third metatarsal dimensions 1 - 11. See definitions for second, third and fourth metatarsals.

Figure 2.7 : Fourth metatarsal dimensions 1 - 11. See definitions for second, third and fourth metatarsals.

8) *Superior breadth of the head* is measured from the most supero-medial point on the distal articular surface to the most supero-lateral point of the distal articular surface.

9) *Inferior breadth of the head* is measured from the most infero-medial point on the distal articular surface to the most infero-lateral point on the distal articular surface.

10) *Height of the mid- shaft* is measured at a point mid-way between the most supero-medial point of the proximal articular surface to the most distal point of the distal articular surface in the assumed sagittal plane.

11) *Breadth of the mid-shaft* is measured at a point mid-way between the most supero-medial point of the proximal articular surface to the most distal point of the distal articular surface at right angles to the assumed sagittal plane.

Fifth metatarsal (Figure 2.8)

1.) *Maximum length* is measured from the most proximal point on the metatarsal, to the most distal point on the distal articular surface.

2.) *Lateral interarticular length* is measured from the most lateral point on the proximal articular surface to the most distal point of the distal articular surface.

3.) *Medial interarticular length* is measured from the most supero-medial point on proximal articular surface to the most distal point on the distal articular surface.

4.) *Height of the proximal articular surface* is the maximum height, measured from the most superior point on the proximal articular surface to the most inferior point on the proximal articular surface at right angles to the assumed transverse plane.

Figure 2.8 : Fifth metatarsal dimensions 1 - 12. See definitions for the fifth metatarsals.

5.) *Breadth of the proximal articular surface* is the maximum breadth, measured from the most supero-medial point on the proximal articular surface to the most lateral point on the proximal articular surface in the assumed transverse plane.

6.) *Maximum breadth of the base* is the maximum breadth of the base measured from the most medial point on the posterior articular surface to the most lateral point on the lateral extreme of the styloid process measured in the assumed transverse plane.

7.) *Height of the head* is measured from the most superior point on the metatarsal head to the most inferior point on the metatarsal head. This dimension was adapted from the definitions according to Martin (1928).

8.) *Breadth of the head* is the maximum bone span measured from the most medial point on the metatarsal head to the most lateral point on the metatarsal head at right angles to the *height of the head.* This dimension was adapted from the definitions according to Martin (1928).

9) *Superior breadth of the head* is measured from the most supero-medial point on the distal articular surface to the most supero-lateral point of the distal articular surface.

10) *Inferior breadth of the head* is measured from the most infero-medial point on the distal articular surface to the most inferor-lateral point on the distal articular surface.

11) *Height of the mid-shaft* is measured at a point mid-way between the most medial point on the proximal articular surface to the most distal point of the distal articular surface at right angles to the assumed transverse plane.

12) *Breadth of the mid-shaft* is measured at a point mid-way between the most medial point on the proximal articular surface to the most distal point of the distal articular surface in the assumed transverse plane.

2.5.7 Methods employed in obtaining osteometric data

All linear data dimensions were obtained using standard digital sliding calipers. All readings were taken in millimeters and recorded to 0.01mm. Data were collected directly into a computer spread sheet at the site of measurement. *Microsoft Excel*® was used for this purpose. This removed any sources of error associated with data transportation at a later date. All measurements, excepting the mid-shaft dimensions, were taken with the bone held and orientated by hand. For the mid-shaft measurements, the metatarsal was placed in a custom built bone vice (see Figure 2.9) at the mid-shaft with the proximal articular surface orientated in the sagittal plane for metatarsals one to four and transverse plane for metatarsal five. This was achieved by orientating the long dimension of the proximal articular surfaces of the first to fourth metatarsals, and short dimension of the proximal articular surface of the fifth metatarsal with a perpendicular aluminum reference "square" held behind the bone. It was in these planes that the measurements were taken. This ensured that all measurements were taken in the same orientation.

2.5.8 Evaluation of error

When taking measurements on bones, every attempt to eliminate error should be made. However, there is an inevitable component of error when measuring bone

Figure 2.9 : Bone vice used for mid-shaft height and width measurements orthogonal to each other..

utilizing landmarks that may not be equally clear in all specimens. The problem of systematic error has been eliminated to a high degree because (a), planar reference positions and measured variables were carefully defined and (b), all data was collected personally. Random error is difficult to estimate, and therefore quantify. However, so long as random error associated with a variable is small compared to the natural variability in that dimension between individuals and groups, it is acceptable as the actual measurement will still be meaningful (Sokal & Rohlf, 1981).

In order to test whether the amount of error associated with any variable was greater or less than the natural variation in the variable, a reproducibility study was undertaken. Six specimens of each of the five metatarsal elements were measured on six different occasions. Thus, for each dimension, a six by six matrix was constructed as suggested by Sokal and Rohlf (1981). For this exercise, dissecting-room specimens were utilized that were visually similar in appearance in order to avoid measurer bias.

A two way analysis of variance (ANOVA) without replication was undertaken (Sokal & Rohlf, 1981) to establish the degree of variation between the replicates for each bone, in which the variability resulting from the replicate measurments of the same bone was compared with the variability in that dimension between different bones. In all dimensions obtained, there was a far greater variation between the specimens than was found in the replicate measurements. Therefore for each dimension, the error associated with replicate measurements was found to be significantly less than the actual variation between bones ($P < 0.01$).

2.5.9 Analytical methods for metric data

2.5.9.1 Univariate analysis

Regardless of the complexity of any intended statistical analyses, the analysis of data must start with simple univariate analysis. There are several reasons for this. First, they are useful in identifying erroneously recorded data. Second, they are a useful method for obtaining a broad comparison of the size and variance of each variable in different groups. Third, they are essential in the interpretation of subsequent multivariate analysis.

Data from the groups being compared were examined in terms of the standard univariate descriptors of mean, standard deviation and coefficient of variation.

2.5.9.1.A Method used to compare the mean values

A series of two sided Student's *t-tests* was undertaken to investigate any significance of differences of means within the groups between males and females. *SAS® 6.12* was used to undertake this analysis. This programme undertakes two t-tests simultaneously, one with a pooled standard deviation, and one using separate standard deviations and gives P values for both (Crockett, 1988) . In addition, an F ratio and its associated P value is produced; this is a test for similarity of variance and P values of less than 0.05 indicate that there is sufficient evidence to show that variances are not equal. When there is sufficient evidence of variances being equal, the P value (related to the means) generated using separate standard deviations was used. The t-tests were

presented as the P value being less than 0.05 and less than 0.01. The F-tests were presented as the P value being less the 0.05.

A comparison of mean values does indicate significant differences in any particular measured dimension. However it does not give any indication of the degree of differences between males and females. A number of univariate estimates of sexual dimorphism have been proposed (Green, 1989; Marini *et al.*, 1999) and intrasexual variability has received some consideration (La Velle, 1993; Plavcan, 1994; Marini *et al.*, 1999). One of the univariate indices of dimorphism widely used in the anthropological literature is the mean distance index (*MDI*). This is a simple but effective way of estimating the degree of sexual dimorphism in the metatarsals by calculating the percentage difference in each dimension. This was undertaken based upon the distance between male and female means (Tobias, 1975; Hall, 1982):

$$MDI = \frac{\text{male mean value} - \text{female mean value}}{\text{male mean value}} \times 100$$

2.5.9.1.B The standard deviation

The standard deviation (*SD*) is the spread of data around their mean and is expressed by the formula:

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

Where: x = variable value

m = mean value of all variables in the sample

n = number of specimens in the sample

$\sum$ = the sum of

The standard deviation is the square root of the variance. The reason for using the $n - 1$ instead of n in the standard deviation is complex. However, for the purpose of the current study, $n - 1$ in the denominator produces a more accurate estimate of the true population standard deviation and has desirable mathematical properties for statistical inferences (Dawson & Trapp, 2001). This is more important in small sample sizes where differences show a greater magnitude in variance.

2.5.9.1.C Testing for normality of distribution

Any meaningful interpretation of patterns of morphological variation in a sample such as bone dimensions can only be made when it is assumed that the distribution shape described by individual dimensions are approximately normal. If the sample from which data to be analyzed were to violate one or more of the normality test assumptions, the results of the analysis may be incorrect or misleading. For example, if the assumption of mutual independence of the sampled values is violated, then the normality test results will not be reliable. If outliers, perhaps as a result of erroneous recording of data are present, then the normality test may reject the null hypothesis assuming normality, even when the remainder of the data do in fact come from a normal distribution. Often, the effect of an assumption violation on the normality test result depends on the extent of the violation. Some small violations may have little practical effect on the analysis, while other violations may render data incorrect or

uninterpretable. This is important, as in biological components such as pedal bones, occasional radical variants that may result in an abnormal distribution, but may be biologically relevant, should remain within the data set. However, this only applies when the deviations from the normal distribution or dissimilar standard deviations are not marked. In order to validate the data used in the current study, it must be assumed that the data is approximately normally distributed. This does not mean that data that are not normally distributed are not useful. Rather, in this instance, results can be interpreted while taking the distribution into consideration.

In order to test for normal distribution in the three bones of the hominoid preliminary study and five bones of the human metrical study, a Shapiro-Wilk statistic was generated for each dimension in each sex of every subgroup. This test for normality, developed by Shapiro and Wilk (1965), has been found to be the most powerful test in most situations and generates a *W* statistic. It is the ratio of two estimates of the variance of a normal distribution based on a random sample of n observations. The numerator is proportional to the square of the best linear estimator of the standard deviation. The denominator is the sum of squares of the observations about the sample mean. *W* is roughly a measure of the straightness of the quantile-quantile plot. *W* must be greater than zero and less than or equal to one. Hence, the closer *W* is to one, the more normal the sample is. It should be noted that this statistic does not demonstrate normality of the distribution shape. Normality is assumed unless there is sufficient evidence to reject the null hypothesis proposing that distribution is normal. When the p-value is greater than 0.05, normality can be assumed.

2.5.9.1.D The coefficient of variation

The coefficient of variation (*CV*) is a useful measure of relative spread in data and is used frequently in the biologic sciences. When considering the standard deviation, the same units of measurement are being used, but the variance associated with the dimension tends to increase with increasing magnitude of the dimension.

The coefficient of variation adjusts the scales so that a sensible comparison can be made (Dawson & Trapp, 2001). However, it should be noted that this adjustment of scales in terms of "size" and "shape" is not entirely satisfactory, and therefore is limited in terms of interpretation of results. The coefficient of variation is defined as the standard deviation divided by the mean multiplied by 100. It produces a measure of relative variation; variation that is relative to the mean. The formula is expressed as follows:

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

Where: SD = standard deviation

x = mean

Although the coefficient of variation value is not absolute, a value of four to ten, typically five or six , may be expected in the majority of observations. Below four may suggest that the sample size was inadequately small to exhibit genuine variability, and values in excess of ten may indicate that the sample contains specimens from a

mixed population (Simpson *et al.*, 1960). These values should however only be used as a guide, and are not absolute.

2.5.9.1.E A further analysis: robusticity

Although robusticity is often used to describe the relative size of articulations, muscular attachments, or diaphyseal cortical thickness, it is more accurately defined as the strength or rigidity of a structure relative to the mechanically relevant measure of body size (Ruff, *et al.*, 1993). In this context robusticity is an important consideration in the functional interpretation of morphological differences since between-sample differences in robusticity (beyond genetically determined minimum requirements) reflect the adaptation to differing levels of mechanical loading (Niewoehner *et al.*, 1997). For the metatarsals, relative dominance in robusticity, being an important feature of bipedalism, may reflect variation in function between different human groups. In contrast, the broad patterns of relative robusticity between humans and apes have been established (Archibald *et al.*, 1972) and were therefore not carried out in the current hominoid preliminary study. With this in mind, robusticity indices for the human samples were computed based on the following simple formula, adapted to accommodate the different bones:

First metatarsal:

$([\text{mid-shaft width} + \text{mid-shaft height}]^{1/2} / \text{inter-articular length} \times 100)$

Second to fourth metatarsal:

([mid-shaft width + mid-shaft height]$^{1/2}$ / lateral inter-articular length x 100)

Fifth metatarsal:

([mid-shaft width + mid-shaft height]$^{1/2}$ / maximum length x 100)

The mean robusticity for each of the five metatarsals and each sub-group were computed, and ranges and standard deviations determined. Relative robusticity formulae could then be examined and differences, if any, between the sub-groups determined.

2.5.9.2 Multivariate analysis

Although there are a number of alternate morphometric methods (Rohlf, 2000), a multivariate morphometric approach was chosen for the current study. The fairly simple characterization of bone shape by means of a number of measurements can be refined by utilizing techniques that make allowance for differing sizes of specimens and take into account correlation among characters within individuals and groups of individuals (Oxnard, 1973). Such multivariate techniques are capable of providing discriminations relating to many variables taken on many individuals within single or multiple groups. No matter what data set has been collected, to look at it in a traditional "univariate" manner is revealing, but limited. Much information concerning shape is not held by one dimension or another, but is dependant upon the manner in which they vary with respect of each other (Kidd, 1995). By utilizing a series of measurements, the

shape of each specimen can be described and often shows that an apparently complex, multidimentional space may be reduced to a simpler, few-dimensional domain with loss of very little information (Oxnard, 1973). The multivariate objective of the study was to establish patterns of morphological discrimination within the group using principal components analysis (Blackith & Reyment, 1971; Bryant & Yarnold, 2001) and between the groups using canonical variates analysis (Reyment *et al.*, 1984; Albrecht, 1980; 1992).

Multivariate analysis, which examine suites of data simultaneously, are also affected by the proportional relationship between the mean and standard deviation. A more appropriate approach in this circumstance, is to transform the data to an exponent, frequently their logarithms (Kidd, 1995). For this reason, it is important that the raw data is approximately normally distributed. As the current primary human study involved only one species, with size remaining an important component of variation, transformation of the data to their natural logarithm was undertaken, and utilized in both the principal components and canonical variates analyses. The multivariate analyses were undertaken utilizing *SAS® 6.12* version *7*.

2.5.9.2.A Principal components analysis

Even though biological specimens may appear similar to a greater or lesser extent, it is unlikely that two specimens are exactly the same. This means that a suite of measurements obtained from a group of related organisms would by virtue of their dimensions being to some extent correlated, form an ellipsoid or cigar shaped data cloud (Blackith & Reymont, 1971; Oxnard, 1973; Bryant & Yarnold, 2001). Each

specimen may be imagined to occupy a unique position in the multidimensional data space (Oxnard, 1973). Principal components analysis is an analytical system in which the multidimensional cloud of points formed by each individual organism or specimen, is summarized by "principal components". The first principal component is the long dimension of this data cloud and describes the maximum quantity of morphological variation within the data. The second and subsequent principal components are orthogonal to the first and describe successively less information. The procedure yields a number of components equal to the number of measured variables; but as the major part of the information is contained in the earlier components, it may be possible to drop the later components as having little content (Oxnard, 1973; Bryant & Yarnold, 2001). Typically, the first principal component will contain about 85% of the total morphological information and the second about 5 to 10%. Thus, about 90% of the total morphological information may be contained in a simple bivariate plot, regardless of how many original dimensions were utilized; it is to some extent, a dimension reducing technique (Blackwith & Reyment, 1971; Mardia *et al.*, 1979; Chatfield & Collins, 1986). Thus, the primary objective in principal components analysis is to account for as much of the total variance, in as few components as possible, as most of the biologically relevant information will be contained in the earlier principal components (Oxnard, 1973). The first principal component will, in general, be an indicator of overall size, and the subsequent principal components an indicator of overall shape. This is perhaps an oversimplified explanation, as size and shape cannot actually be entirely separated. Formally, the linear function, or principal component, is referred to as an *eigenvector*. Also, the amount of the total variance that is explained by an

eigenvector is known as the *eigenvalue*. There is therefore an eigenvector for every corresponding variable and principal component. What value of a factor loading coefficient is required for a variable to be considered a constituent of a given eigenvector? Typically, researchers consider variables with factor loading coefficients of at least .30 in absolute value as "loading on the eigenvector" and thus worthy of consideration in interpreting the meaning of the eigenvector (Bryant & Yarnold, 2001). Variables with negative factor loading coefficients are negatively correlated with the eigenvector; eigenvectors that have variables with positive factor loadings as well as variables with negative factor loadings are called *bipolar eigenvectors*. A factor loading of .30 implies that the variable and the eigenvector share $(.30)^2$ x 100%, or 9%, of their variance.

The principal components analysis is of particular value in the current study as it requires no *a priori* patterns of interrelationship such as sex differences or the identification of a particular group or groups. It thus shows the distribution shape of the pooled group of organisms and can thus be used as a cluster finding tool. In the hominoid preliminary study, the PCA served primarily as an exploratory exercise to validate the data for subsequent canonical variates analysis. In this instance, where samples from different species are examined, it is to be expected that clear clustering of the groups occurs. In contrast, in the human study, involving a single species, the discrimination is expected to be much more subtle. In the hominoid preliminary study, a principal components analysis was undertaken in which eight classes were identified. They were human males and females, chimpanzee males and females, gorilla males and females and orangutan males and females. In the primary human study, a principal

components analysis was undertaken in which nine classes were identified. They were Zulu males and females, Sotho males and females, European males and females, pre-pastoral males and females and a group of pre-pastoral individuals of unknown sex. The distribution shapes could then be scrutinized to determine the patterns of discrimination within and between the groups.

There are however, several caveats that should be considered in the use of principal components analysis:

The number of dimensions used

Each measurement is regarded as new information that contributes to the overall morphological picture. Any dimension that does not represent a new aspect of morphology merely repeats the information contained in a similar or identical dimension. An analogy for "surplus" dimensions may be explained by the example of dimensions used to describe a perfect cube (Figure 2.10a). In this example, measurement of any one of the sides describes all eight dimensions as they are all the same. Using the example of a rectangular box (Figure 2.10b) where the sides are not all the same, three dimensions of the eight adequately describe its size and shape. Morphology can thus be described by surprisingly few dimensions. Jolliffe (1972) notes that PCAs' are undertaken with a large number of variables, usually ten or more, but the result remains largely unchanged when a smaller subset of variables is used as they are correlated. In the main human study; for the first metatarsal, nine variables, for the second to fourth, eleven variables and for the fifth, twelve variables were used. Although the numbers used are acceptable, there are variables that probably do not

Figure 2.10: The perfect cube (a) on the left may be represented by one variable, which is representative of each dimension that can be measured. In contrast, the rectangular structure (b) on the right requires three dimensions that would represent overall morphology.

contribute additional morphological information. The overriding question is, which should be discarded? However, dimensions chosen are of potential functional value, and in view of the findings by Joliffe (1972, 1973), have been retained. Another consideration is the weighting of the eigenvectors, which when too many variables are used, it becomes more difficult to identify the variables that are primarily responsible for variation. For this reason, the relatively few dimensions used in the hominoid preliminary study are justifiable as to emphasize the scale of variation between the different species. In contrast, more dimensions were used in the primary human study as variation within a single species is much more subtle and requires greater refinement so that variation, where present may be identified.

The problem of scale

A second caveat is the problem of scale (Chatfield & Collins, 1986). If the standard deviation of one variable is notably greater than that of the others, the variable may be represented far more by the first principal component than it would otherwise have been. By using transformed data, rather than raw linear data, this problem is largely avoided (Chatfield & Collins, 1986). Therefore, in the current study, the data were transformed to their natural logarithm. Another important issue is the use of the *covariance matrix* as opposed to the *correlation matrix.* The *correlation matrix* is a tabular procedure for summarizing all possible correlations between a set of variables and dimensions are scaled to have unit variance. The *covariance matrix* measures the tendency of two features to vary together, i.e. to co-vary, but is not scaled as in *correlation matrix*. This results in those variables of greatest variance being more

heavily represented i.e. being larger, particularly with respect to the earlier components and therefore produces output that may be biologically more meaningful. The correlation matrix may also be thought of as making all dimensions "equally important". This may not be the case, rendering biologically important variances less relevant. The *covariance matrix* was therefore considered appropriate in the current study.

A third caveat, that of using different dimension types, for example linear data and angular data in a single data set. This does not apply to the current study, as all measurements are linear, presented in millimeters.

2.5.9.2.B Canonical variates analysis

Canonical variates are commonly used in comparative studies of the morphology of different groups or organisms. Unlike PCA, in which the first principal component defines the maximum variation within a group, canonical variates analysis (CVA), defines the maximum discrimination between groups, relative to the variation within the group (Reyment *et al*., 1984). Though closely related to PCA, it does require an *a priori* definition of the groups. Like PCA, though computationally complex, the mean or centroid of each group is simply represented on a two-dimensional plot. The first canonical variate affords the maximum separation or discrimination between the groups. The second canonical variate maximally discriminates between the groups after the first has been removed, the third after the second and so on (Chatfield & Collins, 1986). Like PCA, the vast majority of information can be displayed in the first two or three variates, thus it is also a dimension

reducing technique (Blackwith & Reyment, 1971; Mardia *et al.*, 1979; Chatfield & Collins, 1986). The number of canonical axes or variates produced depends upon the number of variables and number of groups used in the analysis. Since CVA maximizes between group distances, in contrast to within group variance as in PCA, the maximum number of variates obtained can only equal n-1 where *n* is the number of groups. However if there are fewer variables than groups, then there will only be p axes, where *p* is the number of variables. Awareness of the relationship between axes, variables and groups is important when carrying out a CVA analysis and is considered again below.

The eigenvalues for each variate are a measure of the between group variance contained within the axis. Typically, the majority of the morphological information is represented by the first three axes, later axes containing largely redundant information. If for example, canonical variate two appears to contain redundant information, usually canonical variate three may be meaningful. In order to allow meaningful interpretation of the results, it is important that both the abscissa and ordinate use the same scale (Albrecht, 1980).

Regrettably, in the current study, a large number of the pre-pastoral subgroup individuals are of unknown sex. This poses a problem when a species such as humans potentially presents with considerable sexual dimorphism. It is important that this discrimination is shown within a group as well as between different groups. Nevertheless the pre-pastoral individuals of known sex were considered to be representative of the larger group. As CVA is useful for plotting isolated fossil specimens against extant groups, both the isolated human and extinct hominin fossils were introduced as separate samples. This is further explained later. However, the

results for these should be interpreted with caution as it is uncertain whether the isolated specimen represents mean values for a group or species, or is a unique individual, not representative of a group.

Interpretation of Canonical Coefficients

Canonical coefficient, also called the *canonical function coefficient* or the *canonical* weight; the canonical coefficients are the weights in the linear equation of variables which creates the canonical variables. The contribution of the original (untransformed) variables to the position of the centroid on each canonical axis may be found by inspection of the canonical coefficients. This is similar to the eigenvectors in PCA. The statistical programme used in this study (*SAS*®), produces three types of coefficients. These are the raw canonical coefficients, the total sample standardized canonical coefficients and the pooled within-class standardized canonical coefficients. The question arises as to which should be used? Reymont *et al.* (1984) state that the pooled within-class standardized canonical coefficients are often used to indicate which variables contribute the most to a particular axis. They suggest that those characters with the smallest absolute values of standardized canonical coefficients generally contribute the least to discrimination contained within that axis. Reymont *et al.* (1984) caution that when there is a high within-group correlation between variables, misleading results can be obtained. In keeping with the suggestion by Reyment *et al.* (1984), the pooled within-class standardized coefficients are used for the interpretation of results in this study. The canonical coefficients are standardized coefficients and their magnitudes can be compared; some researchers simply note variables with the highest coefficients

to determine which variables are associated with which canonical correlations and use this as the basis for inducing the meaning of the dimension represented by the canonical correlation. However, Levine (1977) argues against the procedure above on the ground that the canonical coefficients may be subject to multicollinearity, leading to incorrect judgments. With this in mind, interpretation of canonical coefficients should be done with caution and where necessary with reference to the univariate results so that interpretation remains biologically meaningful.

The influence of sample sizes

The standard application of canonical variates analysis, uses sample sizes as a weighting factor in the derivation of the among groups covariance matrix (Albrecht, 1992). This may, with unequal sample sizes, distort the results of the canonical analysis. An important consideration is the effect that disparate sample sizes have on the distribution of canonical discrimination between the axes. In most cases, canonical axes beyond the third or fourth are disregarded as they contain largely redundant information. Where groups are of disparate sizes, the group with the smaller sample size will frequently emphasize the greater proportion of variation on higher-numbered canonical variates, the groups with the larger sample size being stressed on the first few axes (Albrecht, 1992). This is of particular importance when isolated fossils are to be included. In the current study, there are groups of disparate sample size, particularly the pre-pastoral group where the sample of individuals of known sex are relatively small when compared to the other groups and represent a little under a third of the other sample sizes. In this instance, higher axes were carefully examined as they may contain

important information pertaining to the group of smaller size. A useful exercise was to perform several exploratory analyses excluding the smaller group, then comparing results excluding the smaller sample to those analyses where the smaller sample is included.

The number of variables used was considered in the section on PCA where Jolliffe (1972, 1973) noted that the use of smaller or larger numbers of variables frequently give similar results. This means that even if unnesasary or superfoulous variables are included in PCA, would not distort the result. This does not nessasarily apply to canonical variates analysis. As explained earlier, there are n-1 canonical axes if the number of variables, p, is more than n. If the number of variables exceed the sample size there will only be the number of variable axes. Albrecht (1992) explaines that, if the number of variables equals or exeed the number of groups, the total variance contained within the original measurement variables is not contained within the n-1 canonical axes normally considered. For this reason, it has been recommended that the number of variables used should not exceed n-1, which would avoid complicating the analysis with higher within-group axes.

The inclusion of isolated fossils

Canonical variates analysis is frequently used for assessing the comparative morphology of living and fossil primates. Albrecht (1992) draws attention to some of the common pitfalls of this method when used to analyze fossil specimens; (1) ignoring the possibility that a fossil belongs to a group other than one of the predefined reference samples, (2) misinterpreting probabilities of group membership and (3) failing

to understand how sample sizes influence multivariate ordination in trying to effectively illustrate the morphometric affinities of a fossil. The last point is of particular importance as this represents the most extreme situation of unequal sample sizes.

One method, is to undertake a canonical variates analysis of the relevant species or groups. This results in the isolated fossil being interpolated into the resultant matrix of extant species or groups. The fossil is thus interpolated indirectly, not contributing to the overall canonical structure and therefore its own position in relation to the other groups. Examples of interpolation of isolated fossils into the matrix of extant species were carried out by Day (1967), Day and Napier (1969) and Day and Wood (1968, 1969). This has received considerable criticism from Oxnard (1972) and later Albrecht (1992). However, a counter argument was reported by Day (1974). A more meaningful approach is to include the fossil as a group on its own with a sample size of one, which allows it to become part of the overall canonical structure. However, a within class covariance matrix cannot be established for an isolated specimen and the *SAS* programme gives a warning to this effect. Albrecht (1992), recognizes the advantages of the direct over the indirect (interpolation) method, but states that considerable distortion of the results may occur due to the dramatically differing sample sizes. This has been discussed above, although the situation here is even more pertinent as there is only a single specimen being included. Albrecht (1992), addresses this by recommending that in addition to a direct approach in contrast to an indirect interpolation, an unweighted analysis is undertaken. He stated that this would not distort the results of the higher-numbered canonical axes, so that major differences, if any, are revealed in the earlier axes.

Although the suggestion by Albrecht (1992) may be valid, Kidd (1995) draws attention to a potential problem. Although the amount of total proportion of information contained within a particular higher canonical variate may be very small, for example 1%, it is of importance as it may represent a difference between one group (or specimen) and all the other groups. The use of an unweighted analysis in examining an isolated specimen in this instance may in fact defeat the purpose of the canonical variates analysis; that of determining where the variation lies. A small degree of variation that would ordinarily have been revealed in the higher axes, is now "disguised" in the earlier axes of an unweighted analysis.

Missing variables

Although only complete specimens were examined in the three recent human samples, the archeological material presented with a number of specimens with missing variables or data points. This occurred to some extent in all five metatarsals due to either early *post mortum* degredation, or later breakage. This was a problem with all five bones. It was therefore not possible to obtain a complete data set on several of the specimens from the archaeological context. Where a complete data set is not available, a number of options may be considered:

a.) The specimens with an incomplete data set could be discarded from the analysis. This is probably the most appropriate option.

b.) An estimated value for a missing dimension could be used. This should be done with caution as an artificial or unrealistic value could affect the overall results. However, an acceptable value can be obtained where both left and right

specimens are available, allowing the investigator to obtain a reliable value when the specimen used is considered representative of the one with a missing data point.

c.) The third option is to include the specimen with missing variables; the remainder of the samples excluding those variables. In this instance, the number of variables used in the analysis are reduced. However, this option is only acceptable when due consideration is given to possible distortion of the results. This depends largely on the type of variable, and the amount of information it contributes to the analysis.

The first option was applied to the pre-pastoral sample in this study, therefore only complete specimens were included. For this reason, sample sizes for the pre-pastoral subgroup vary in each of the five bones. However, the human left first metatarsal fossil, KRM 6113B, although complete, has sustained some damage to the plantar aspect of the medial side of the head (Rightmire & Deacon, 1991). As this late Pleistocene fossil was a single specimen, important because of its archaeological context, it was included. A preliminary CVA excluding the inferior breadth of the head dimension did not result in any detectable change to the results; this was therefore considered acceptable.

Mahalanobis D^2 Distances

The Generalized Distance D^2, is historically a popular statistic of physical anthropologists (e.g. Bronowski & Long, 1952) and incorporates Fischer's linear discriminant function, Mahalanobis' D^2, and Hotelling's T^2 statistics which together

with other related techniques are algebraically similar (Corruccini, 1975). Mahalanobis D^2 is a distance measure based on correlations between the variables and by which different patterns could be identified and analyzed with respect to a base or reference point (Taguchi & Jugulum, 2002). It is frequently considered to be the most appropriate measure of multivariate relationships when data are normally distributed. It is also useful if this is not quite true. It is difficult to find a measure for heterogeneous cases and for other distributions; the generalized distance (its other name) seems to be informative. Mahalanobis Distance is a very useful way of determining the ”similarity” of a set of values from an ”unknown” sample or specimen to a set of values measured from a collection of ”known” samples. This is more than just one canonical variate plotted against another, but represents the combined information from all the canonical variates. It is superior to Euclidean distance because it takes distribution of the points (correlations) into account. Mahalonobis D^2 distances are therefore examined in this study where generalised distances from isolated specimens are of value.

2.5.10 The choice of non-metric variables

Broadly, the observed variables are divided into two types:

a.) A series of epigenetic morphological features that have been identified as being variable or potentially variable.

b.) Obvious peri-mortum modification (pathology) to bone.

These features were selected as they are thought to be of functional significance.

2.5.10.1 Definition and classification of non-metric features

One of the first and most important observations that can be made is that every human metatarsal is different from another human metatarsal and can be differentiated in terms of size, shape, various bumps, grooves and surface textures. Much of this variation may be partitioned according to factors responsible for it; age, gender and pathology (White, 1991). However, much of this variation is idiosyncratic and some of it is attributable to ancestry. The afore mentioned importance of functional affinities can to a great extent be addressed by identifying two types of non-metrical features. Firstly, defining epigenetic variation of articular facets, being obvious functional traits associated with joints. Secondly, defining pathology, associated with a change in the health of bone and the individual.

2.5.10.1.A Epigenetic variants

These selected morphological features were defined and classified according to the descriptions by Singh (1960), Sarrafian (1983) and Gudas (1992):

1. *First metatarsal head shape* is described according to Gudas (1992), Landers (1992) and La Porta *et al.* (1994) and describes the general shape of the distal articular surface in the transverse plane:

   Variation 1: Round.

   Variation 2: Square.

   Variation 3: Square with a central ridge.

Illustrations of these variations are to be found in Figure 2.11.

2. *Shape of the first metatarsal proximal articular surface* is described according to Singh (1960), *Ajmani et al.* (1984), Draves (1986) and Aiello & Dean (1990):

Variation 1: Kidney or Reniform (common morphology)

Variation 2: Partially divided

Variation 3: Completely divided (bipartite)

Illustrations of these variations are to be found in Figure 2.12.

3. *Lateral facet of the first metatarsal* classified according to the observations by Singh (1960) and illustrations by Sarrafian (1983):

Variation 1: Smooth facet with well defined margins for the second metatarsal.

Variation 2: Smooth area with indefinite margins.

Variation 3: No indication of an area for the second metatarsal.

4. *Variation of the medial basal facet of the second metatarsal* described by Singh (1960) and classified according to the illustrations by Sarrafian (1983):

Variation 1: Facet on the superior part for the medial cuneiform bone. This facet is very variable in size. The proximal part of the facet is either flat or slightly

Figure 2.11: Variation in the first metatarsal head shape

Figure 2.12: Variation in the first metatarsal proximal articular surface

convex. More inferiorly and distally, an elevated area, often rough is present.

Variation 2: Facet on the superior part for the medial cuneiform extents distally, and is gently concave.

Variation 3: The superior facet is partially or completely cut off from the proximal articular margin by a non-articular notch. More inferiorly and distally, a definite smooth facet is shown, with well defined margins for contact with the first metatarsal.

Variation 4: No indication of contact with the medial cuneiform or first metatarsal.

5. *Variation of the lateral basal facet of the second metatarsal* described by Singh (1960) and classified according to the illustrations by Sarrafian (1983):

Variation 1: Two, superior and inferior, facets separated by a non-articular area. The proximal parts of both facets are beveled off. The distal areas for the third metatarsal are always larger and better defined than the proximal areas, for the lateral cuneiform, the later being generally small.

Variation 2: The inferior facet is not beveled off and articulates only with the third metatarsal.

Variation 3: The proximal beveled part of the inferior facet only, there being no inferior facet for the third metatarsal.

Variation 4: The entire inferior facet is absent.

Variation 5: The proximal part of the superior facet is absent, a non-articular strip taking the place of the latter.

Variation 6: The proximal beveled parts of both inferior and superior facets are absent. The inferior facet reaches the proximal margin of the base to become continuous with the area for the intermediate cuneiform, but the superior facet is separated from the latter by a non-articular area.

Variation 7: The inferior facet is similar to that described in *variation 6* above, but the entire superior facet is missing.

Variation 8: The superior and inferior areas for the lateral cuneiform are continuous with one another, those for the metatarsal remaining separate.

Variation 9: The proximal part of the superior facet is absent, a non-articular strip taking the place of the latter as in *variation 5*. The entire inferior facet is absent.

6. *Variation of the medial basal facets of the third metatarsal* described by Singh (1960) and classified according to the illustrations by Sarrafian (1983):

Variation 1: Two flat facets, superior and inferior, for the base of the second metatarsal. The facets reach the proximal margin to become continuous with the proximal articular surface for the lateral cuneiform. The superior facet is always the larger of the two. The inferior facet is at times barely perseptable.

Variation 2: The inferior facet is absent.

Variation 3: The inferior facet is absent and the superior facet does not reach the margin of the proximal articular surface from which it is separated by a non-articular strip.

Variation 4: Both the superior and inferior facets are absent.

7. *Variation of the lateral basal facets of the third metatarsal* described by Singh (1960) and classified according to the illustrations by Sarrafian (1983):

   Variation 1: Oval facet on the superior part and does not reach the proximal articular margin.

   Variation 2: Facet on the superior part reaches the proximal articular margin to become confluent with the area of the lateral cuneiform, and has the appearance of an oval with its proximal part cut off. The facet is usually concave but is sometimes flat.

8. *Variation of the medial basal facet of the fourth metatarsal d*escribed by Singh (1960) and classified according to the illustrations by Sarrafian (1983):

   Variation 1: Oval facet not reaching the proximal articular margin and not subdivided into two parts. The entire facet is for the third metatarsal, there being no facet for the cuneiform.

   Variation 2: Oval facet, not reaching the proximal articular margin, but subdivided into a proximal and distal part.

   Variation 3: The superior facet reaches the proximal articular margin to become continuous with the articular area for the cuboid. It is subdivided into proximal and distal parts. The proximal part of the facet, when present, is generally small.

*9. The lateral basal facet of the fourth metatarsal d*escribed by Singh (1960):

A concave somewhat triangular facet. It is always present and varies only slightly in size and shape. A deep notch is present in front of it.

10. The medial basal facet of the fifth metatarsal described by Singh (1960):

The facets for the fourth metatarsal and cuboid are constant in shape.

Illustrations of variation in the basal facets are to be found in Figure 2.13.

2.5.10.1.B Pathological features

Obvious pathological features or lesions are identified then associated with a suspected pathology or function where possible. Unusual or ill-defined manifestations would be described when not consistent with the existing descriptions and definitions.

Relevant photographs were taken when indicated for comparison and future reference. Care was taken to distinguish ante mortum modification from peri and post mortum modification. Table 2.2 contains a summary of osseous modifications, pathomechanical implications and literature sources.

2.5.11 Methods employed in obtaining non-metric data

A template with illustrations of the previously described epigenetic variants was used to identify observed variations in each bone. Obvious pathological changes were identified according to their typical descriptions (Table 2.2). Systematic examination of

Figure 2.13: Variation of the basal facets of the metatarsals. After Singh (1960). Illustrations after Sarraffian (1983).

Table 2.2: Summary of osseous changes of the metatarsal bones and their pathological manifestations as found in contemporary literature.

Following 3 pages

each bone was done, first comparing the selected features with the illustrations on a "template" followed by the identification and description of any obvious pathological modification. Data were collected directly into the same computer spread sheet as for the metrical data. A number was allocated to each epigenetic variant which corresponded with the illustrations in Figures 2.11 - 2.13. Any variant that was not previously described was noted and described as a "new variant". Other features such as pathological changes were described in terms of their appearance, and where appropriate or obvious, their possible significance.

2.5.11.1 The problem of subjectivity

When attempting to differentiate between non-metrical traits, especially in large samples, there is a degree of subjectivity as to the classification or description of the variables under scrutiny. The epigenetic variables in terms of articular facet morphology can be relatively objectively classified when accurate and clear definitions are applied. However, when attempting to identify and describe pathological changes, the criteria are somewhat ambiguous. This still poses a challenge, as with any morphologically variable organism, the differentiation between what constitutes a "normal" variant and what is pathological is not clear. What may be considered pathological to an osteologist or physical anthropologist, may be of no clinical significance to a clinician or forensic pathologist. The line between, atypical and abnormal is often blurred, as a "blend" between these may occur. In skeletal material in most instances it is unknown whether a particular change in bony morphology had any obviously practical implications for the individual. For this reason, only "obvious"

pathological changes were identified. Unfortunately, few diseases leave signatures of any kind on the human skeleton, and those that do may cause very similar skeletal reactions (White, 1991). This is particularly true when a study of bony pathology is limited to macroscopic examination. There is no indication as to what has happened on a histological or radiological level. The present study of pathology is also at a distinct disadvantage in that only metatarsals are considered; a comprehensive review of the entire skeleton is required in order to draw broader conclusions on the practical implications of pathology on an individual's quality of life (Ortner, 2003a). Two main criteria were applied; firstly, the identification of obvious and unambiguous pathological changes according to the descriptions in Table 2.2, and secondly, any obvious changes in bone that are not seen in most other specimens.

Although the definition and classification of pathological morphology is not entirely satisfactory, the systematic scrutiny of each bone allowed for relatively consistent data collection. The descriptions in Table 2.2 were drawn from literature that describes skeletal pathological conditions primarily in their clinically relevant context.

2.5.12 Methods for the analysis of non-metric data

Frequencies of observed epigenetic and pathological features were expressed in percentages. These frequencies were contextualized in terms of variation between the groups or sexes being studied. Subsequently the frequencies of variation in morphological features were compared with the frequencies of pathological features in each individual to determine if there was any obvious pattern and therefore correlation

between the two. By scrutinizing the percentile variation within and between groups, general trends in variation could be determined.

2.5.12.1 Methods used to compare frequencies of morphological features

2.5.12.1.A Determining trends in variation

The frequency of morphological features were presented in frequency Tables and simple histograms. This allowed the data to be visually compared for obvious trends within and between the groups.

2.5.12.1.B Chi-Square statistic for comparison of frequencies

The chi-square test was used to test the differences between two independent proportions. This allowed for each group to be tested against the other in terms of variance in each feature; for example the variance of the lateral side of the second metatarsal base (with frequencies for nine variations) of one group versus the same features in another group. The chi-square statistic is expressed by the formula:

$$x^{2}_{(df)} = \sum \frac{(O - E)^{2}}{E}$$

Where: x^2 = chi-square

(df) = degrees of freedom

$\sum$ = sum of

O = observed frequency

E = expected frequency

Each group was thus tested against the other; Zulu versus Sotho, Pre-pastoral versus Zulu and Pre-pastoral versus Sotho, European versus Zulu, European versus Sotho, pre-pastoral versus European. A *p*-value was generated for the collective variation in each area of the metatarsal. The differences were expressed as similar ($p>0.05$), different ($p<0.05$) or significantly different ($p<0.01$).

2.5.12.1.C Method used for the analysis of skeletal lesions

The first decision to be made in studying skeletal material for evidence of disease is whether there is any observable evidence of abnormality present in the bones. This initially involves the macroscopic study of the bone, and requires the observer to have a good grasp of the normal anatomy of the skeleton at all stages of growth and development. Variation from normal anatomy provides the initial evidence of disease. Ortner (2003b) expresses this skeletal disease as (1) abnormal bone formation, (2) abnormal bone destruction, (3) abnormal bone density, (4) abnormal bone size, and (5) abnormal bone shape. Each of these expressions of disease can occur as the only manifestation of disease in a skeleton or in combination with one or more of the other expressions.

Abnormal bone formation is always as a result of an antemortum pathological process (Ortner, 2003b). Destructive processes are usually as a result of disease or injury, however, occasionally abnormal manifestations may be as a result of postmortem changes. This is particularly important in the context of archaeological

material and has the potential of causing difficulty in differentiating between antemortum and postmortem changes. Postmortum changes are known as pseudopathologies (Ortner, 2003b), and are the result of two basic conditions: (1) the immediate burial environment and (2) problems during or after excavation. This problem was largely overcome by: (1) examination of the archaeological specimens after experience was gained in examining dissection room specimens and (2) referring to the archaeological context in which the skeletons were found.

Four further caveats particular to the current study were identified: (1) only gross analysis of the bones was possible, (2) the metatarsals were examined without serious consideration of the remainder of the skeleton where present, (3) only bones suitable for metrical analysis were examined and (4) identification of pathology may increase as more specimens are examined. The first caveat is unavoidable, as identification of pathological conditions are only one part of morphological variation. The second and third pose a challenge; any pathological changes identified are considered primarily in the context of the mechanical changes taking place in the bone. However, wherever possible, when changes suggest systemic involvement, for example in rheumatoid arthritis, brief examination of other skeletal components was conducted and noted. Only metatarsals where landmarks for metrical mensuration were identifiable were included, which resulted in the exclusion of any severe bony pathology. For this reason the frequency of pathological lesions do not represent the total pathological manifestations in any of the samples under investigation. This was considered within the context of the "reconciliation" between metric and non-metric data. Finally, the fourth caveat is easily dealt with, in which the examiner (BZ), after

collecting all data from all four human subgroups, revisited the first subgroup (Zulu) and re-examined all specimens for comparison with observations made on the first examination. In the current study, after re-examination of this subgroup, there appeared to be no obvious change in bias as examination of specimens progressed.

The frequency of pathological features were presented in tables and simple bar graphs. This allowed for the visual comparison between the sexes and groups. The differences in frequency of osseous changes between the bones in order to determine dominance of metatarsal bone pathology are important. In this instance determining trends rather than statistical significance were of greater importance and value.

2.5.12.1.D Correlation of non-metric data

The nominal data of variation in morphological features of each individual of each group were entered onto a spreadsheet with a summary of pathological lesions where present. The pathological feature in each individual was then compared to the epigenetic morphological feature associated with that part of the metatarsal to determine if any patterns of association emerge.