# Size and shape of a human foot bone from Klasies River main site, South Africa

**Bernhard Zipfel[1*] & Robert S. Kidd[2]**

[1]*Bernard Price Institute for Palaeontological Research, University of the Witwatersrand, Private Bag 3, WITS, 2050 South Africa*

[2]*School of Biomedical and Health Sciences, University of Western Sydney, Cambelltown, NSW 2560, Australia*

Received 23 May 2007. Accepted 30 August 2007

Rightmire *et al.* (2006) recently described three human metatarsal bones of Middle Stone Age antiquity from Klasies River Mouth (KRM) main site, South Africa. One of these, a complete adult left first metatarsal is broadly similar to Late Stone Age (LSA) Holocene skeletons from the southern coastal margins of the Cape, and based on size, was suggested to be from a male. Our analysis subjected the KRM first metatarsal and comparative human samples to selected morphometric analyses, in an attempt to test the hypothesis regarding shape-associated sexual dimorphism as a means to estimate sex in the KRM individual. The results support earlier suggestions that it falls within the range of early Holocene variation, this being very narrow both in size and shape. The size-independent shape-associated morphology, however, suggests that the individual may be female. Even though these findings imply that the KRM individual may have been female based on sexually dimorphic shape-associated discrimination in LSA Holocene people, they are not conclusive and that this individual could probably be assigned to either sex.

**Keywords**: first metatarsal, Middle Stone Age, Klasies River Mouth, morphometrics, sexual dimorphism.

## INTRODUCTION

Rightmire *et al.*'s (2006) recent study of three late Pleistocene human metatarsal bones from Klasies River main site, situated on the southern coast of South Africa provides valuable insights into Middle Stone Age (MSA) occupation of these archaeologically informative deposits. Although there is still some debate on the age of the site (Parkington 1990; Wolpoff 1989), the general consensus is that the early Klasies River humans date between 80 000 and 100 000 years ago. One of these bones, a left first metatarsal (KRM 6113B), was recovered during the 1967–1968 excavations, originally thought to be from a non-human hominin, later regarded as indistinguishable from modern humans (Rightmire & Deacon 1991). Rightmire *et al.* (2006) describe this specimen as broadly comparable in size to that of Late Stone Age (LSA) San males drawn from Cape burials.

The univariate comparison of the dimensions of the Klasies River Mouth (KRM) first metatarsal reveal that the length, proximal and distal dimensions are slightly smaller than average black South Africans. Mid-shaft diameters are comparable to those of black females. All dimensions are close to the averages for early Holocene males from the western and southern Cape (Zipfel 2004; Rightmire *et al.* 2006). The appearance of the KRM specimen is therefore unremarkable and based upon size is suggested to be male. This is also supported by the stature estimates of Rightmire *et al.* (2006) based on the formula by Byers *et al.* (1989), who found significant correlations between metatarsal lengths and stature. Despite Rightmire *et al.*'s well justified hypothesis that the KRM first metatarsal probably belonged to a male based on size, the important question of shape remains unresolved. Shape-associated sexual dimorphism, or in some cases 'dimorphisms' have been reported in foot bones (e.g. Kidd 1995; Kidd & Oxnard 1997; Ferrari *et al.* 2004; Zipfel 2004) in which the intercorrelation between variables reveals more information than individual dimensions or indices on their own. Numerous studies have addressed sex estimation from the hands and feet with varying results (e.g. Robling & Uberlaker 1997; Case & Ross 2007) which require clear identification of the population being considered. Determining the sex of an isolated specimen such as a metatarsal from an extinct group of humans thus poses a challenge.

As late Pleistocene human postcranial remains are extremely scarce, further investigation of such remains are justified. The analysis presented here subjects the KRM first metatarsal and comparative human samples to selected morphometric analyses, in an attempt to test the hypothesis regarding shape associated sexual dimorphism as a means to estimate sex in the KRM individual.

## MATERIALS AND METHODS

### *Materials*

In addition to the KRM specimen (South African Museum, Cape Town), the first metatarsal elements from both recent (Sotho, Zulu and European) and pre-pastoral Holocene (LSA) skeletal samples were examined for morphological variation. The three recent samples each comprised 30 males and 30 females and the LSA sample of ten males, nine females and 13 of uncertain sex. The recent human specimens were made available courtesy of the University of the Witwatersrand (Raymond Dart Collection, Johannesburg) and the ancient (LSA) specimens by the South African Museum, Cape Town and National Museum, Bloemfontein. The LSA humans were dated between 9720 and 2000 ($^{14}$C) years B.P. Until about 2000 years ago, all local inhabitants were hunter-gatherers (Hausman 1982; Roberts 1989; Sealy & Pfeiffer 2000; Stock & Pfeiffer 2001) and represent pre-pastoral people with habitual behaviours most closely associated with those of

*Author for correspondence. E-mail: bernhard.zipfel@wits.ac.za

the MSA. Where possible, dimensions were collected from the left side, previous studies demonstrating no significant difference in variation between sides (Steudal 1984; Kidd 1995).

*Methods*

Linear metatarsal dimensions were defined so as to reflect the general functional shape and size of the bone. These were loosely based on the definitions by Martin & Saller (1957), together with those of, for example, Susman & Brain (1988) and Byers *et al.* (1989). As both distal and proximal portions of the bone are partially damaged, an entirely precise data set is not possible. In this case, two options may be considered. The first, an estimated value for a missing or imprecise dimension could be used. This should be done with caution as an artificial or unrealistic value could easily affect the overall results. Second, the number of variables used in the analyses is reduced. This option, however, 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 analyses (Jollife 1972a,b).

Both these options were applied in defining dimensions. A preliminary principal components analysis (PCA) and canonical variates analysis (CVA) of the recent human groups excluding a dimension such as the proximal breadth or inferior distal breadth of the head dimension did not result in any significant change to the results; this was therefore considered an acceptable strategy. Any minor error in estimation, although imprecise, is very small, and the intercorrelation with the remaining variables, which are precise, validates the technique.

For the purpose of this study, eight linear variables were utilized. These were the articular length, proximal articular height and breadth, distal height, total and superior distal breadth and mid-shaft height and breadth. All linear data dimensions were obtained using standard digital sliding callipers. All readings were taken in millimetres and recorded to 0.01 mm. All measurements, except 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 bone vice at the mid-shaft with the proximal articular surface long dimension orientated in the sagittal plane.

Plots of means against their standard deviations revealed a clear positive regression; as a consequence, all data were subsequently transformed to their natural logarithms. The multivariate objective of the study was to establish patterns of morphological discrimination within and between the groups, initially using principal components analysis (PCA) (Blackith & Reyment 1971; Bryant & Yarnold 2001) and subsequently using canonical variates analysis (CVA) (Reyment *et al.* 1984; Albrecht 1980, 1992). Computations for both analyses were undertaken using PC SAS® 8.2 (2003).

Principal components analysis does not make any *a priori* definitions 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 therefore be used as a cluster finding tool including the KRM specimen within the overall structure. In the current study, the PCA served primarily as an exploratory exercise to validate the data for subsequent canonical variates analysis and to examine the relationship of the KRM specimen to the individuals from the other human sub-groups. As the sex of a number of the LSA individuals is uncertain, the PCA was useful to validate the small LSA sample in terms of determining if the LSA group could be discriminated from the recent human groups. No attempt was made to assign sex via the PCA as this would make the compositions of both males and females in the LSA sample potentially suspect.

Canonical variates analysis defines the maximum discrimination between groups, relative to the variation within the group (Reyment *et al.* 1984) and unlike PCA, requires *a priori* definition of the groups. Therefore, the LSA group was limited to the specimens of known sex only. In the CVA used in this study, the KRM specimen was entered directly as part of the overall canonical structure as a sample size of unity, rather than by interpolation into the matrix of the Holocene comparative samples. A weighted analysis was used. While there is much debate with regards to the relative merits of weighted and unweighted analyses (e.g. Albrecht 1980, 1992), they do serve to maximize the amount of discrimination held within early variates (Kidd 1995).

## RESULTS

### Principal components analysis

The majority of the variation lies within the first two principal components, together accounting for just over 83% of the total variation. The eigenvectors from the first principal component, are all of positive sign and broadly similar in magnitudes; this suggests that most of the variance contained within this component is associated with size and size-related shape (Jolicoeur 1963) (Table 1). On the second principal component, containing 11.87% of the total variation, the eigenvectors are of both positive and negative sign indicating a large component of size-independent shape content (Table 1).

Even though the variation within the first two principal components does not entirely discriminate any of the groups, the Sotho, Zulu and European groups occupy a

**Table 1**. The eigenvalues, percentages of variance and eigenvectors for the principle components analysis of the first metatarsal from the five human groups and the KRM first metatarsal.

| | | PRIN 1 | PRIN 2 |
|---|---|---|---|
| Eigenvalue: | | 0.067 | 0.012 |
| % of variance: | | 70.50 | 12.52 |
| Eigenvectors | VAR 1: Articular length | 0.272 | 0.126 |
| | VAR 2: Proximal art. height | 0.296 | 0.175 |
| | VAR 3: Proximal art. breadth | 0.386 | –0.573 |
| | VAR 4: Distal height | 0.357 | 0.370 |
| | VAR 5: Total distal breadth | 0.387 | 0.306 |
| | VAR 6: Superior distal breadth | 0.385 | –0.347 |
| | VAR 7: Mid-shaft height | 0.348 | –0.182 |
| | VAR 8: Mid-shaft breadth | 0.377 | –0.491 |

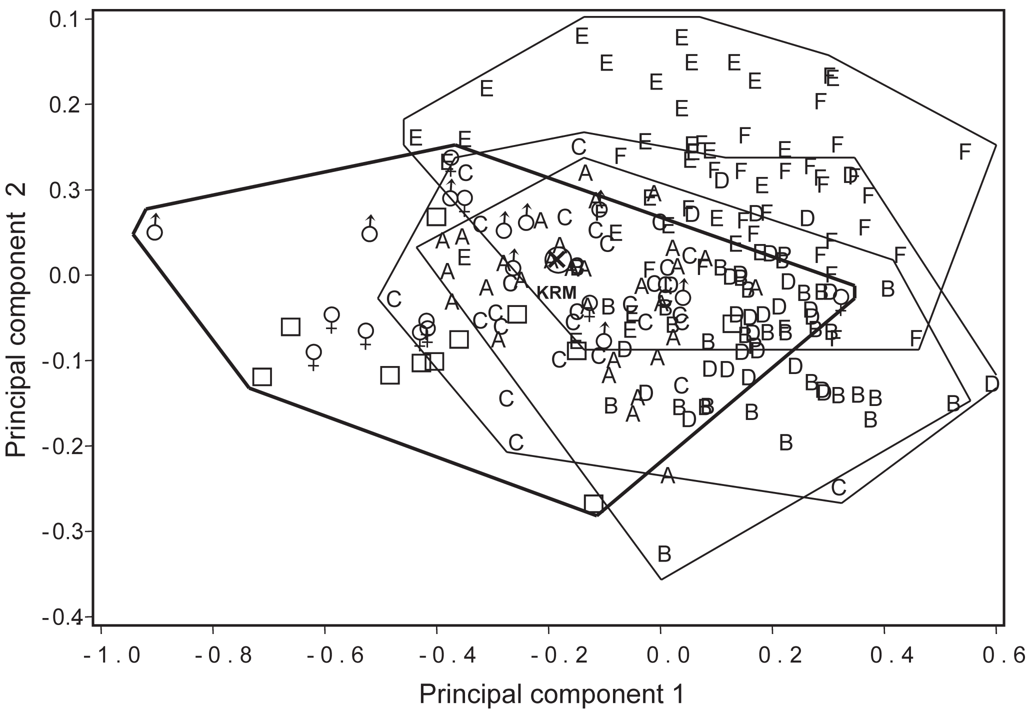


**Figure 1**. First metatarsal bivariate plot of principal components one and two of log-transformed dimensions including the Holocene human groups and KRM fossil X. **Key**: A = Sotho female; B = Sotho male; C = Zulu female; D = Zulu male; E = European female; F = European male; ♀ = LSA female; ♂ = LSA male; □ = LSA sex indeterminate.

more positive position than the LSA group on the first principal component, with a considerable overlap between all of them (Fig. 1). The spread of males and females in the Sotho, Zulu and European groups are broadly similar. In these groups, on the first principal component, males generally lie more positively than females with a small degree of overlap. There is obvious discrimination by sex in these three groups. In the LSA group, however, there is no clear discrimination between the individuals of known sex. A number of these, including a few of unknown sex lie more negatively than any of the other groups and the most positive portion of the LSA group lies about halfway within the spread of the other three groups.

The KRM specimen lies centrally on the first component, positively within the spread of the LSA group. On the second principal component, the fossil also lies centrally within the entire sample and positively within the LSA group. On this component, of the LSA sample, three females and six males lie positively and six females and three males lie negatively from the KRM specimen (Fig. 1). Both males and females of the LSA group therefore fall within the broad morphology of the KRM first metatarsal. A subsequent canonical variates analysis was thus essential in order to maximize any differences within and between the groups.

## Canonical variates analysis

In the analysis of the KRM specimen together with the Holocene human groups, the majority of the discrimination lies within the first two variates, together accounting for almost 90% of the total discrimination. Subsequent variates contain considerably less variation. The third variate contains 6.25% of the total discrimination and the fourth variate 2.59%. The group mean scores along the first, second and third canonical variates are given in Table 2 and Mahalonobis' distance matrix in Table 3.

On the first canonical variate, the group centroids are spread over approximately 4.25 standard deviation units (SDU) with the LSA females on the negative extreme and the European males on the positive extreme. The European centroids lie most positively and the LSA centroids most

**Table 2**. First metatarsal group means along canonical variates 1, 2 and 3.

| Group | Sex | CAN 1 | CAN 2 | CAN3 |
|---|---|---|---|---|
| % Total discrimination | | 50.29 | 37.34 | 6.25 |
| KRM | | –2.28 | –0.57 | 2.35 |
| Sotho | F | –0.87 | –0.10 | –0.33 |
| Sotho | M | 0.34 | 1.53 | 0.12 |
| Zulu | F | –1.10 | 0.22 | –0.59 |
| Zulu | M | 0.55 | 1.02 | 0.43 |
| European | F | 0.72 | –1.61 | 0.20 |
| European | M | 1.79 | –0.51 | –0.25 |
| LSA | F | –2.43 | –0.64 | 0.48 |
| LSA | M | –1.84 | –1.12 | 0.61 |

**Table 3**. Mahalanobis $D^2$ distances from the KRM first metatarsal to group centroids of the first metatarsal.

| Group | Sex | $D^2$ |
|---|---|---|
| KRM | | 0 |
| Sotho | F | 16.01 |
| Sotho | M | 23.45 |
| Zulu | F | 18.21 |
| Zulu | M | 22.39 |
| European | F | 22.99 |
| European | M | 29.50 |
| LSA | F | 10.71 |
| LSA | M | 11.78 |

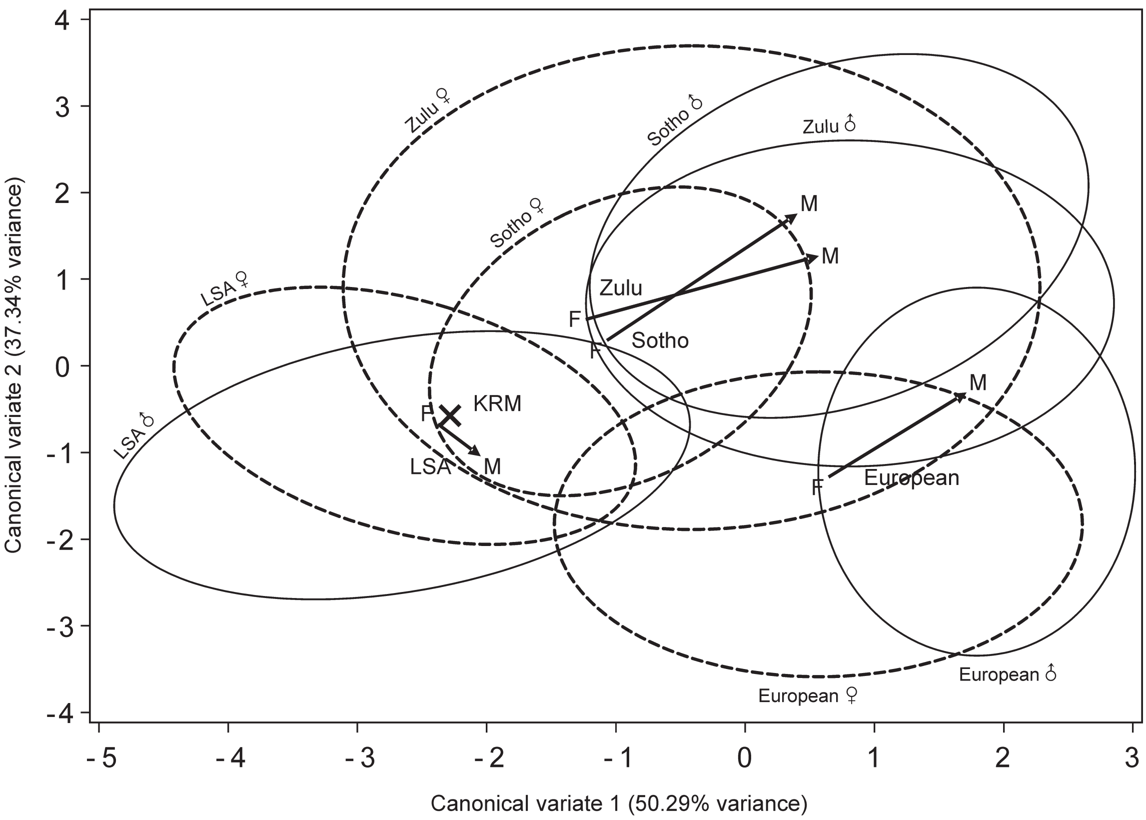


**Figure 2**. First metatarsal bivariate plot of canonical means and dispersions along canonical variates one and two of log-transformed dimensions including the human fossil KRM. Both the axes are in standard deviation units. F = female. M = male.

negatively with the Bantu-speakers (Sotho and Zulu) between them. On the first canonical variate, the KRM specimen lies well within the spread of the LSA closest to the female centroid (Fig. 2).

On the second canonical variate the group centroids are spread over approximately 3 SDU. The Sotho and Zulu male centroids lie most positively and the European females and LSA males most negatively. The KRM specimen lies closest to the female LSA centroid which lies about halfway between the European males and females (Fig. 2). The KRM specimen is thus not unique and has the greatest affinity with the LSA females. This is also borne out by the Mahalanobis' distance, although the difference in distance between the males and females is only 1.07 (Table 3). The dispersion ellipses, however, show an overlap with LSA males and females as well as Zulu and Sotho females. On the third canonical variate, the KRM specimen lies almost 2 SDU positively to the closest Holocene human centroid (Fig. 3).

## DISCUSSION

Based on size only, this is a relatively large human metatarsal, certainly within the range of early Holocene San males. This is not unique among southern African MSA specimens as evidenced by the relatively large, nearly complete right metatarsals IV and V from Border Cave (Morris 1992). Notwithstanding, in the LSA sample, percentage differences between the sexes indicate relatively little size-associated dimorphism (Zipfel 2004). The initial PCA, however, reveals that two of the LSA females are 'larger' than the KRM specimen. The size-independent shape content does not clearly place the fossil within either the LSA male or female morphology as there is no clear discrimination.

Examining the patterns of variation within and between the different groups with canonical variate 2 and canonical variate 1 together, the groups clearly present three areas of discrimination (Fig. 2). One for the European group, one for the Sotho and Zulu groups together, and one for the LSA group. This suggests that the greatest proportion (over 88%) of discrimination may best be described as largely 'genetic'. There are three distinct groups of people, European (Caucasoid) on the one hand, LSA (Khoisanoid) on the other with Bantu-speakers (Zulu and Sotho) between them. The KRM fossil clearly falls within the parameters of the LSA group, close to the LSA female centroid essentially in agreement with the proposed genetic discrimination between the three main human groups (Fig. 2). This suggests, both from the canonical variates plots and to a lesser extent, Mahalonobis' distances, that this individual may have been female, this discrimination being primarily shape-associated. This should however, be considered with the caveat that the range of variation in sexual dimorphism in the LSA sample is very narrow when compared to the other groups. On canonical variates 1 and 2 together, the dispersion ellipses show a distinct overlap of the KRM specimen with male and female LSA and Zulu and Sotho female groups. The fossil could therefore fall into any of these groups at this level of discrimination.

Canonical variates 3 and 1 together present a line of discrimination between the LSA group on the one hand and the recent groups on the other (Fig. 3). This may suggest a largely functional or life-style based discrimina-

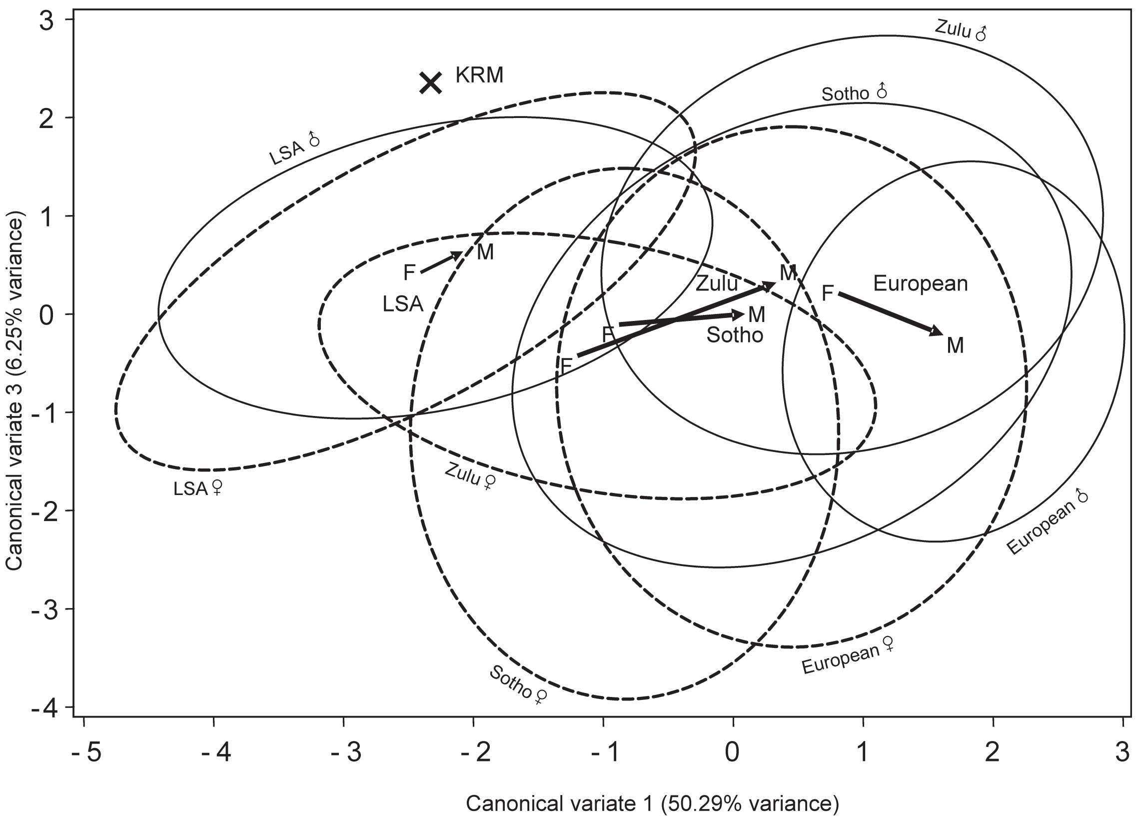


**Figure 3**. First metatarsal bivariate plot of canonical means and dispersions along canonical variates one and three of log-transformed dimensions including the KRM human fossil. Both the axes are in standard deviation units. F = female. M = male.

tion; habitually unshod LSA individuals walking on natural substrates and shod contemporary people walking on variable substrates. It is, however, possible that canonical variate three reflects residual genetic variation that is not reflected in canonical variate two. With the exception of the European males, the dispersions around the centroids of the other groups overlap to varying degrees (Fig. 3). The KRM fossil, however, lies in a unique position positively on the third canonical variate, clearly discriminated from the other four groups. The canonical coefficients on the third canonical variate including the KRM specimen, have a particularly heavily weighted total distal breadth dimension when compared to the analysis excluding the fossil. There was no indication of macroscopic pathology in this specimen, therefore this is excluded as a reason for this discrimination. There is also no evidence to suggest that the late Pleistocene human populations had life-styles or behaviours that were much different from those of the early Holocene (Hausman 1982). The proportion of discrimination, however, is relatively small representing just over 6% of the total discrimination. It describes in the broadest sense, differences between the KRM specimen on one hand from all other groups on the other. Reasons for this are beyond the scope of this paper. Nevertheless, the majority of the morphological information (87.62%) falls within the range of South African LSA Holocene morphology.

## CONCLUSION

All four group samples present with different patterns of sexual dimorphism to some extent, obviously in size, and more subtly in shape. In the LSA group, unlike the recent humans, the first metatarsal shows a size-related dimorphism in which some of the male bones are 'smaller' than those of the females. Therefore, estimating sex based on size alone is not entirely satisfactory. Equally problematic is the relatively small shape-associated sexual dimorphism within the LSA sample. Even though these findings suggest that the KRM individual may have been female based on sexually dimorphic shape-associated discrimination in LSA Holocene people, they are not conclusive. In view of these conflicting, yet equally valid arguments, we suggest that this individual could probably be assigned to either sex.

Our grateful thanks go to G. Avery at the Iziko South African Museum, Cape Town, J. Brink at the National Museum, Bloemfontein, and K.L. Kuykendall, E. Mofokeng and L.R. Berger at the University of the Witwatersrand, Johannesburg, for facilitating access to the skeletal collections. We also wish to acknowledge the reviewers, C. Groves and A. Morris for their helpful comments and suggestions. This work was supported by the Palaeontogical Scientific Trust (PAST).

## REFERENCES

ALBRECHT, G. 1980. Multivariate analysis and the study of form, with special reference to canonical variates analysis. *American Zoologist* **20**, 679–693.

ALBRECHT, G. 1992. Assessing the affinities of fossils using canonical variates and generalized distances. *Journal of Human Evolution* **7**, 49–69.

BLACKITH, R.E. & REYMENT, R.A. 1971. *Multivariate Morphometrics.* London and New York, Academic Press.

BRYANT, F.B. & YARNOLD, P.R. 2001. Principal-components analysis and exploratory and confirmatory factor analysis. **In**: Grimm, L.G. & Yarnold, P.R. (eds), *Reading and Understanding Multivariate Statistics,* 99–108. Washington, American Psychological Association.

BYERS, S., AKOSHIMA, K. & CURRAN, B. 1989. Determination of adult stature from metatarsal length. *American Journal of Physical Anthropology* **79**, 275–279.

CASE D.T. & ROSS A.H. 2007. Sex determination from hand and foot bone lengths. *Journal of Forensic Sciences* **52**, 264–270.

FERRARI, J., HOPKINSON, D.A. & LINNEY, A.D. 2004. Size and shape differences between male and female foot bones. *Journal of the American Podiatric Medical Association* **94**, 434–452.

HAUSMAN, A.J. 1982. The biocultural evolution of Khoisan populations of southern Africa. *American Journal of Physical Anthropology* **58**, 315–330.

JOLICOEUR, P. 1963. The Multivariate generalisation of the allometry equation. *Biometrics* **19**, 497–499.

JOLLIFE, I.T., 1972a. Discarding variables in principle components analysis I: artificial data. *Applied Statistics* **21**, 160–173.

JOLLIFE, I.T. 1972b. Discarding variables in principle components analysis II: real data. *Applied Statistics* **22**, 21–31.

KIDD, R. 1995. *An investigation into the patterns of morphological variation in the proximal tarsus of selected human groups, apes and fossils: a morphometric analysis.* Unpublished Ph.D. thesis, University of Western Australia.

KIDD, R.S. & OXNARD, C.E. 1995. Patterns of morphological discrimination in the human talus: a consideration of the case of negative function. **In**: Henneberg, M. & Freedman, L. (eds), *Perspectives in Human Biology,* 57–69. Perth, Centre for Human Biology; World Scientific Publishing.

LISOWSKI, F.P., ALBRECHT, G.H. & OXNARD, C.E. 1974. The form of the talus in some higher primates: a multivariate study. *American Journal of Physical Anthropology* **41**, 191–216.

MARTIN, R. & SALLER, K. 1957. *Lehrbuch Der Anthropologie in Systematischer Darschtellung mit besonderer Berucksichtigung der anthropologischen Methoden* (3rd edn). Stuttgart, Gustav Fischer Verlag.

MORRIS, A.G. 1992. Biological relationships between Upper Pleistocene and Holocene populations in southern Africa. **In**: Bräuer, G. & Smith, F.H. (Eds), *Continuity or Replacement: Controversies in Homo sapiens evolution,* 131–143. Rotterdam, AA Balkema.

PARKINGTON, J. 1990. A critique of the consensus view on the age of Howiesons Poort assemblages in South Africa. **In**: Mellars, P. (ed.), *The Emergence of Modern Humans,* 34–55. Edinburgh, University of Edinburgh Press.

REYMENT, R.A., BLACKITH, R.E. & CAMPELL, N.A. 1984. *Multivariate Morphometrics.* London, Academic Press.

RIGHTMIRE, G.P. & DEACON, H.J. 1991. Comparative studies of late Pleistocene human remains from Klasies River Mouth, South Africa. *American Journal of Physical Anthropology* **20**, 131–156.

RIGHTMIRE, G.P., DEACON, H.J., SCHWARTZ, H. & TATTERSALL, I. 2006. Human foot bones from Klasies River Mouth, South Africa. *Journal of Human Evolution* **50**, 96–103.

ROBERTS, N. 1989. *The Holocene – An Environmental History.* Oxford, Basil Blackwell.

ROBLING, A.G. & UBERLAKER, D.H. 1997. Sex estimation from the metatarsals. *Journal of Forensic Sciences* **42**, 1062–1069.

SINGH, I. 1960. Variations in the Metatarsal Bones. *Journal of Anatomy* **94**, 345–350.

STEUDAL, K. 1984. Limb bone allometry in primates: a test of the elastic similarity model. *American Journal of Physical Anthropology* **65**, 323–328.

STOCK, J. & PFEIFFER, S. 2001. Linking structural variability in long bone diaphyses to habitual behaviors: Foragers from the southern African Later Stone Age and the Andaman Islands. *American Journal of Physical Anthropology* **115**, 337–348.

SUSMAN, R.L. & BRAIN, T.M. 1988. New first metatarsal (SKX 5017) from Swartkrans and the gait of *Paranthropus robustus. American Journal of Physical Anthropology* **77**, 7–15.

SEALY, J. & PFEIFER, S. 2000. Diet, body size, and landscape use among Holocene people in the southern Cape, South Africa. *Current Anthropology* **41**, 642–655.

WOLPOFF, M.H. 1989. Multilingual evolution: The fossil alternative to Eden. **In**: Mellars, P. & Stringer, C.B. (eds), *The Human Revolution: Behavioural and Biological Perspectives on the Origins of Modern Humans,* 62–108. Edinburgh, University of Edinburgh Press.

ZIPFEL, B. 2004. *Morphological variation in the metatarsal bones of selected recent and pre-pastoral humans from South Africa.* Unpublished Ph.D. thesis, University of the Witwatersrand.

ZIPFEL, B., KIDD, R. & BERGER, L. 2003. Morphological variation in the metatarsus of selected modern and ancient Holocene people from South Africa [abstract]. *American Journal of Physical Anthropology* Supplement **36**, 231.