Journal of Archaeological Science 37 (2010) 201–209

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Variability in bifacial technology at Elandsfontein, Western cape, South Africa: a geometric morphometric approach

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ARTICLE INFO

Article history:
Received 12 June 2009
Received in revised form
15 September 2009
Accepted 16 September 2009

Keywords:
Acheulean
Biface
Elandsfontein
Experimental archaeology
Middle Pleistocene
Lithic analysis

ABSTRACT

This study applies a new three-dimensional measurement technique to determine the major source of variation in the Acheulian bifacial tool collection from the Middle Pleistocene site of Elandsfontein, South Africa. This three-dimensional technique is compared with conventional two-dimensional methods to investigate which methods capture morphological variation in the assemblage most comprehensively. Additionally, a set of experimentally produced bifacial tools are incorporated into the analyses to isolate the behavioral pattern underpinning identified variation in the archaeological assemblage. The interpretative breadth of current models explaining morphological variation in bifacial tools is then tested against the pattern identified in the Elandsfontein assemblage. Variation appears to be related to the consistent application of a specific reduction strategy associated with the early stages of bifacial tool manufacture. The intensity with which this strategy was applied seems to have been mediated by the availability of raw material that was suitable for the production of large bifacial tools.

1. Introduction

Variation in tool morphology is the foundation upon which established descriptive and analytical frameworks in lithic studies are based. To understand the behavioral patterns that belie artifact variation it is necessary to build links between artifact form and hominin activities. Quantitative assessments and the interpretation of morphological variation in large bifacially flaked cutting tools has been the subject of many studies of Middle Pleistocene technology. In this regard, the seminal methods of Bordes (1961) and Roe (1964) provide the standard measurements upon which the majority of contemporary attempts to investigate these questions are based. Studies of large bifacially flaked cutting tool morphology are beginning to explore both new methods of capturing traditional measures of form (Grosman et al., 2008) and new approaches to the analysis of shape variability (Saragusti et al., 2005; Lycett et al., 2006; Lycett, 2007; Lycett and von Cramon-Taubadel, 2008). However, the majority of research on the form of large cutting tools relies on traditional measurements (e.g. Bordes, 1961; Roe, 1964; Isaac, 1977). Subsequently, the vast majority of variables that have been used to study variation in large bifacially flaked cutting tool assemblages are those that focus on aspects of two-dimensional morphological variation (e.g. McPherron, 2003; White, 1995, 1998; McNabb, 2004; Gowlett, 1996; Sharon, 2008; de la Torre et al., 2008).

Relying primarily on archaeological data, current explanatory models have spawned a range of factors 'driving' or providing an impetus for variation in Acheulian large cutting tools (here we will use the term large cutting tool or LCT to refer to large tools that have been bifacially flaked to produce two convex surfaces on either side of a bifacial equilibrium plane; Sharon, 2008; Inizan et al., 1999: 44). However, little agreement exists as to which measures most accurately capture the morphological variation upon which behavioral interpretations are based. Thus little consensus exists concerning (i) the optimal measurements that capture behaviorally significant morphological variation within and between LCT assemblages, and (ii) the principal behavioral and ecological factors that drive recognized variation in LCT form.

This study applies new three-dimensional techniques to a LCT collection from the Middle Pleistocene site of Elandsfontein (Singer and Wymer, 1968; Klein, 1978, 1982; Klein and Cruz-Uribe, 1991; Klein et al., 2007), on the west coast of South Africa to answer two related questions. First, can the major source of variation in LCT form be found in the classic two-dimensional measures of shape, or do three-dimensional measures isolate aspects of form variation that have previously been unaccounted for in behavioral models? Second, can either raw material characteristics or reduction intensity be identified as factors that directly explain LCT shape

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doi:10.1016/j.jas.2009.09.033

variation at Elandsfontein? In other words, is the interpretative breadth of current models of LCT variation (e.g. White, 1995, 1998; McPherron, 1994, 2003, 1999, 2000, 2006) wide enough to explain the situation at Elandsfontein?

This analysis employs a three-dimensional scaling technique to identify shape related features of LCT production in the Acheulean industry of Elandsfontein. Further, experimentally produced LCTs are used to document how shape variation is associated with a consistent pattern of large cutting tool production. Traditional two-dimensional measures of handaxe shape are not highly correlated with variation captured by size adjusted measures of three-dimensional shape. The major sources of three-dimensional variation appear to be linked to the early stages of LCT production. They also suggest that variation in LCT form reflects differing levels of intensity in the application of a single tool production strategy. Reduction intensity itself may have been mediated by raw material availability or other ecological variables. Interestingly these patterns of shape variation show little allometric scaling.

2. Background

Current behavioral explanations for LCT form variation are often extended to explain variation over broad geographic areas (e.g. (Lycett et al., 2006; Lycett and von Cramon-Taubadel, 2008)), and can be divided loosely into two interrelated groups. These are, (i) those that examine variation primarily in the context of techno-economic factors (e.g. Jones, 1979; Clark, 1980; McPherron, 1994; Ashton and McNabb, 1994; White, 1995, 1998; Sharon, 2008) such as raw-material availability, reduction intensity/strategy or a ‘mental construct’ (Ashton and White, 2003); and (ii) those that recognize variability in the social transmission (e.g. Gowlett, 1996; Lycett and Gowlett, 2008) as well as in the adoption and individual negotiation (McNabb et al., 2004) of tool-producing techniques in varied LCT morphologies. McNabb et al.’s (2004) ‘individualized memic construct’ concept of variability in the South African Acheulean is one example of the latter. McNabb et al. (2004) argue for *conceptual* standardization occurring amongst knappers in that all members of a group would have learned to knap generally by seeing LCTs being made. However, the individual *articulations* of a commonly shared idea or set of ideas in a specific context would result in variations in end products. This shared conceptual standardization, argues McNabb et al. (2004), explains regularities, for example, in initial forms destined for LCT production. The end result is a similarity in ‘practice’ but not necessarily in ‘end-product’ (McNabb et al., 2004: 667). Individuals were exposed to the same social context of learning, but the internalization and expression of the inherited concepts in the form of bifacial tools was a subjective process.

Two central models that put forward techno-economic explanations of variation in biface LCT form in European and Levantine assemblages are proposed by McPherron (1994, 2003, 1999, 2000, 2006) and White (1995, 1998). McPherron suggests that a large portion of variation within and between LCT assemblages is captured by Bordes’ (1961) and Roe’s (1964) measurement of elongation. McPherron (2000) explains this using a reduction sequence model wherein LCT form represents a specific stage of reduction at the point of tool discard. Consequently, the different modalities of shape within and between assemblages are not recognized as discrete mental constructs; rather they are considered to be variations on a dominant or modal form. Within McPherron’s model, LCTs start out narrow and pointed and are reduced through resharpening into ovate like forms.

Another perspective has been forwarded by White (1995, 1998), who suggests that constraints imposed by raw-material type and the initial form of the material are chief determinants of final LCT form. Therefore, the range of shapes attainable in manufacture at a specific location on the landscape is limited by the type of raw material available and the shape of blank selected. However, it is interesting that factors associated with reduction intensity are recognized by certain authors subscribing to the raw-material model (Ashton and McNabb, 1994) as constraining shape variation in the opposite way to which these influences work in McPherron’s (2000) model. That is, production phases aimed at thinning edges as well as resharpening, can inadvertently produce a more pointed tip or *increase* overall elongation (Ashton and McNabb, 1994) whereas in McPherron’s (1994, 2000) model reductive shape change *decreases* elongation. Sharon (2008) points out that neither of these – the raw-material model nor the reduction model – when applied alone can explain all of the variation in a number of assemblages comprehensively.

Here we report on an independent analysis of the Acheulean LCT collection from Elandsfontein, South Africa. In contrast to previous approaches to morphological variation in LCT form we adopt a geometric morphometric approach originally developed by Lycett and colleagues (Lycett et al., 2006).

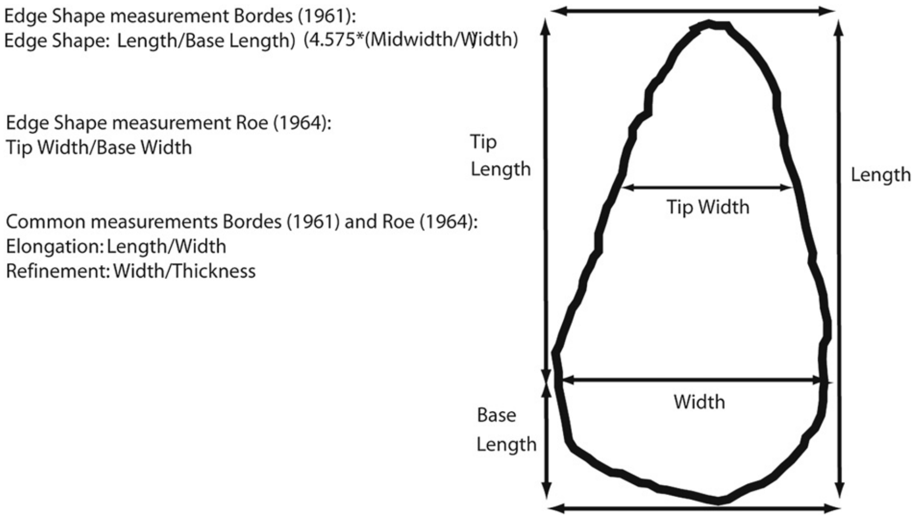

Fig. 1. Roe (1964, 1968) and Bordes (1961) illustrating conventional two-dimensional measurements of biface shape modified from McPherron (2003).

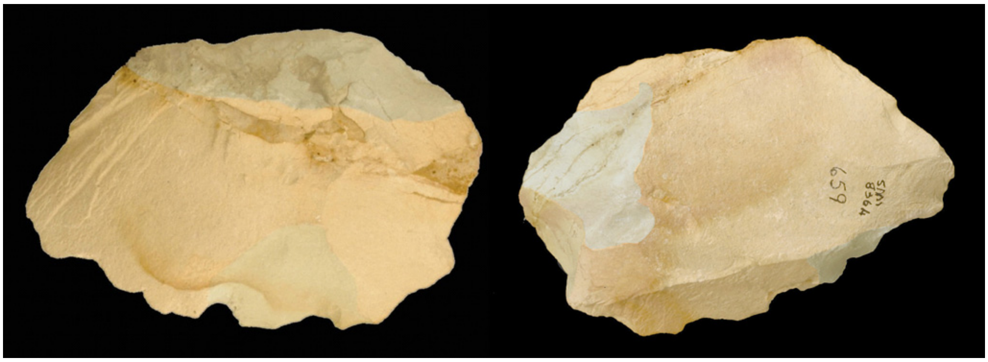

Fig. 2. A typical side struck flake from the cutting 10 collection.

3. Materials and methods

The site of Elandsfontein is an approximate 16 square kilometer outcrop of fossil and artifact-bearing Middle Pleistocene sediments. It is an open air locality, and recent analysis of the fauna associated with the artefacts suggests the site was formed between 600 thousand and 1 million years ago (Klein et al., 2007).

Our initial analysis was confined to 66 LCTs from the Elandsfontein Cutting 10 collection excavated in 1966 from *in situ* Middle Pleistocene deposits (Singer and Wymer, 1968; Klein et al., 2007). Samples of specific raw materials that were underrepresented in the Cutting 10 collection were augmented with material from the Elandsfontein Main Site (Deacon, 1998). All of the LCT forms in this analysis conform to a technological and typological definition of a biface in that they are all core tools produced by the removal of bifacial thinning flakes from two surfaces of a nodule, flake or cobble (Debenath and Dibble, 1993: 130). A substantial proportion of the perimeter of these tools has been bifacially worked and the cross-section of these tools is generally lenticular but can also be triangular forming at least two distinct convex removal planes (Bordes, 1961: 49; Tavoso, 1978; Tyldesley, 1987; Inizan et al., 1999: 40). None of the LCTs in this analysis conform to the broad definition of cleaver, which are made exclusively on large flakes and generally have a transverse cutting edge on the distal end of the piece which has not been bificially flaked (Debenath and Dibble, 1993: 130).

Table 1
The experimental and archaeological assemblages incorporated into the present analysis. Raw material categories are based on hand sample identification.

Raw material category	Description	Distance to source (Braun et al., 2008)	Archaeological specimens (N)	Experimental specimens (N)
1	Coarse grained siliceous volcanic rock.	>25 kilometers	29	0
2	Pedogenic, porphyritic silcrete. Wide range of crystal size.	>10 kilometers	19	5
3	Grey, fine grained silcrete with dark grey, black crystals. Small crystal size range.	>10 kilometers	5	5
4	White, fine grained silcrete with few crystals in the matrix.	>10 kilometers	7	5
5	Ground water silcrete.	> 10 kilometers	10	5
6	Vein quartz: non-local.	Unknown	6	0
7	Fine grained West Coast Quartzite	Unknown	0	5

The Elandsfontein collection is suited to investigate questions about LCT shape mentioned above for three central reasons. Firstly, the collection comprises an unusually wide range of raw materials in comparison with other assemblages (e.g. Sharon, 2008). Secondly, the raw material sources are located at relatively large distances away from their final discard location (Deacon, 1998). Recent analysis shows that primary outcrops of raw materials found at Elandsfontein were only available in areas upwards of 10 kilometers from the site itself (Braun et al., 2008). The great distance over which raw materials must have travelled suggests these LCTs will display a broad range of reduction.

Thirdly, there is recognizable variation in the initial blank forms [here we use the term blank to define any raw material form that is sufficiently large enough to have been flaked and is likely to have been intended for shaping (Inizan et al., 1999: 131; Debenath and Dibble, 1993:10)] selected for LCT production. There is evidence for this in (i) recognizable features of large side struck flakes on the analyzed LCTs (i.e. remnants of bulbar scars as well as platforms, and other attributes of ventral surfaces such as points of percussion); as well as (ii) characteristics of certain raw-material sources sampled, such as the presence of weathered cortex characteristic of

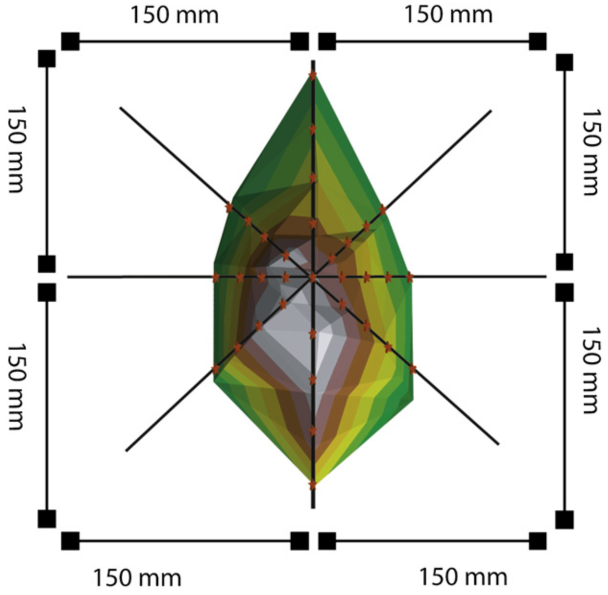

Fig. 3. A tin model displaying the 33 point semi-landmark system, displayed here as a series of red stars, taken with a microscribe along 4 axes on one of the archaeological bifaces in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

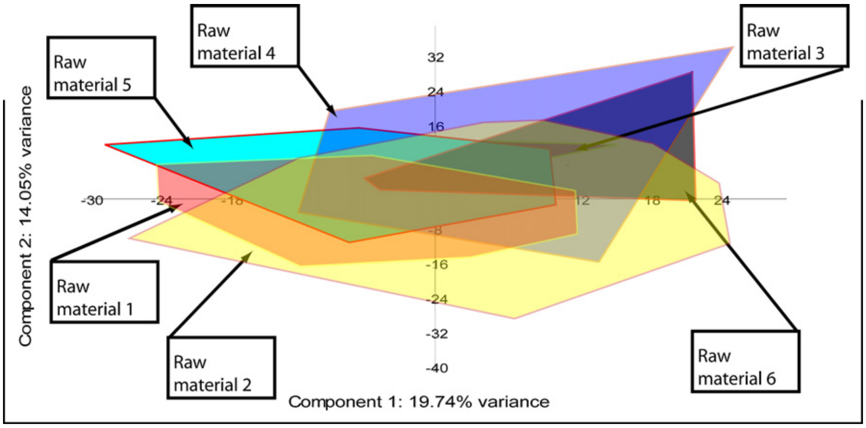

Fig. 4. Convex hulls representing variation in form along principal components 1 and 2 for the bifaces within each raw-material group.

primary outcrops known to be found within the Cape Granite Suite where many blanks are likely to have been quarried from (Braun et al., 2008); and (iii) the presence of these different blank forms, in their unworked state, in the archaeological assemblage (see Fig. 2). There are both secondary and primary sources of raw material available in the region. At certain sources there is evidence that certain core reduction techniques were used to produce specific blank morphologies for LCT production. Issues concerning the standardized production of specific blank morphologies for LCT manufacture have been discussed in recent literature (McNabb, 2001; Sharon and Beaumont, 2006; Madsen and Goren-Inbar, 2004; Goren-Inbar et al., 2008; de la Torre et al., 2008) and will be addressed briefly here in relation to the Elandsfontein assemblage.

There are 6 raw-material groups represented in the Cutting 10 collection (Table 1). The raw-material distinctions applied to the archaeological assemblage were initially based on visual criteria, but subsequent sample collection and analysis suggests that our recognized raw-material groupings are also underpinned by geochemical differences (Braun et al., 2008). Raw material group 1 is most likely representative of the Cape Granite suite. Artifacts from this raw material group display cortical surfaces that are characteristic of outcrops of igneous rock suggesting large flakes were quarried from outcrops of the sub-volcanic granites and micrograntes of the Vredenburg region (Scheepers and Poujol, 2002). Cortical surfaces on artifacts from raw material group 2 exhibit angular cortical surfaces suggesting this material was collected from the numerous outcrops of silcrete in the Darling/Hopefield region. Comprehensive surveys of silcrete sources in this region suggest these primary outcrops were available for Middle Pleistocene hominins (Roberts, 2003). Cortical features of the artifacts produced on raw material groups 3 through 7 suggest these rock types were collected from secondary source contexts (e.g. ancient riverbeds or marine beach deposits). Initial review of secondary raw material sources in the region suggest that cobbles large enough to produce large side struck flake blanks were not available (Braun et al., 2008).Thus blanks procured from raw material groups 1 and 2 are likely to have been large side struck flakes. LCTs made from raw material groups 3–7 were most likely produced on cobbles.

3.1. *Methods: archaeological material*

To assess the efficacy of three-dimensional LCT variation measures in comparison with conventional two-dimensional ones we calculated Bordes' (1961) and Roe's (1964) measures of LCT shape on all specimens in this analysis (Fig. 1). The geometric morphometric analysis is based upon a methodology that has already been extensively used amongst biologists (Richtsmeier et al., 2002). The application of this approach to stone artifact analysis (specifically bifacial tools) has been outlined by Lycett et al (Lycett et al., 2006; Lycett, 2007; Lycett and von Cramon-Taubadel, 2008) and applied in several studies of Early and Middle Pleistocene core forms.

The geometric morphometric approach capitalizes on the ability of certain algorithms to identify relative shape difference, irrespective of variance in size. The vast majority of these techniques rely on homologous landmarks to investigate relative shape change through the variation in distances between these landmarks (Jungers et al., 1995). Clearly, homologous features do not exist on LCTs. Instead, the method we employed uses a series of 33 semi-landmarks. These semi-landmarks were captured using a MicroScribe Immersion 3D digitizer at evenly spaced intervals along four axes. The axes along which the measurements are taken are angled at 45 degrees to one another and these measurements are based on the intersection between the two largest perpendicular dimensions on an LCT. These two dimensions are often referred to as "maximum length" and "maximum width" in traditional measurement schemes (Fig. 3).

To position the LCTs prior to the measurements being taken we used Lycett et al.'s (2006) co-ordinate system grid. The placement of semi-landmark measurements were measured out manually along the four axes on each LCT before they were positioned on the grid (Fig. 3). The intersection of maximum length and maximum width was placed directly over the centre point of the grid. Each LCT was secured in position to prevent any movement.

To insure the accuracy of this measurement system we took each individual set of semi-landmark measurements three times and then averaged the separate coordinates of each point. Replication of measurements was done on separate days to determine if placement of the LCT affected the subsequent analysis. The limited variance in centroid values within replicated sets indicated that this technique allowed for an accurate and replicable assessment of LCT form. Subsequent analyses of variance between LCTs were conducted separately using the different replicated sets of measurements to determine the replicability of this measurement technique. All three of the measurement sets of a single LCT consistently produced invariant results.

Gowlett (1996, 2006) has suggested allometric shape change is an important factor in LCT morphological variation. Consequently, size related factors may often account for a significant proportion of variation within an assemblage unless measurements are somehow standardized or size-adjusted. Some earlier attempts at size-adjustment in LCT analysis (Wynn and Tierson, 1990) have received criticism (McPherron, 1999, 2000) because of the specific methodological application of size adjustment. However, an understanding of the interplay between size and shape is a necessary part of the analysis of LCT morphological variation. Fortunately specific morphometric transformations (e.g. Procrustes) are designed to investigate shape variation irrespective of size. Using PAST statistical software version 1.92 (Harper, 1999), each set of three-dimensional semi-landmarks was size-adjusted using a Procrustes transformation that removes position, size and rotation using algorithms described by Mardia and Dryden (1989). This allowed relative shape to be investigated as an independent variable to size variation. This process scales the individual geometric LCT measurements to each other's centroids, effectively equalizing their volumes while preserving their original shape information (Jungers et al., 1995). We also investigate the relationship between shape variables and absolute size captured by traditional measurement systems and the three-dimensional centroid of each LCT.

Procrustes transformed semi-landmark data were interrogated using a Principal Components Analysis (hereafter a 'PCA') using PAST statistical software (Harper, 1999) to determine which aspects of shape represent the major source of morphological variation in the LCT collection from Elandsfontein.

3.2. Methods: experimental material

This study incorporates data from 25 experimentally replicated LCTs produced from raw material types and initial forms recognizable within the Elandsfontein collection. The experimental set of LCTs was produced by a knapper that was initially unaware of the objectives behind the replication exercise (i.e. the quantitative capture of reductive shape change through the production process). These experimentally produced LCTs are particularly useful because they allow the systematic investigation of shape change associated with the LCT production process. Although it is possible to recognize archaeological collections as representative of differing levels of reduction, experimental replication allows for shape variation to be associated with a specific degree of reductive shape change.

Excluding the initial phase of blank acquisition in the bifacial tool *chaîne opératoire* the replication sequence followed two basic phases recognized in experimental and archaeological investigations of LCT manufacture (Inizan et al., 1992). The experimental LCT preforms were first shaped through a system of *faconnage* (Inizan et al., 1992:146–147), using a direct hard-hammer technique on the blank then thinned and finally sharpened using the soft hammer production technique. The initial phase, sometimes referred to as "*ébauchage*" focuses on producing an initial bifacial symmetry. The second and final phase known as "*finition*" regularizes final bilateral symmetry on the piece. This is an oversimplification of a more complex process but represents the overall outline of LCT production. As is the case with all artifact production there may be variation in accordance with, amongst other factors, the three-dimensional morpho-functional requirements of the knapper (i.e. whether a particularly thin or pointed tip is required or not). Similar schematic production phases have been recognized in other recent LCT replication studies (Goren-Inbar and Sharon, 2006; Newcomer, 1971; Bradley and Sampson, 1986; Sharon and Goren-Inbar, 1999; Wenban-Smith, 1999; Sharon and Goring-Morris, 2004) and are recognizable in the bifacial waste in the Elandsfontein assemblage.

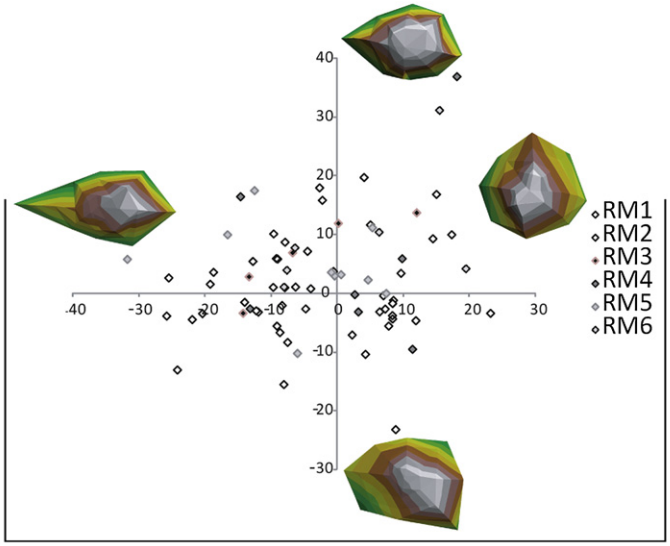

Fig. 5. Three-dimensional models of archaeological bifaces plotted at either end of the two major axes of variation, principal components 1 and 2.

Table 2
R-squared values for correlations between two-dimensional measurements of shape and principal components 1, 2 and 3.

Traditional measurements	Principal component 1	Principal component 2	Principal component 3
Elongation	.508 ($p < .001$)	.184 ($p = .001$)	.019 ($p = .237$)
Pointedness	.049 ($p = .055$)	.013 ($p = .326$)	.000 ($p = .931$)
Refinement	.049 ($p = .055$)	.343 ($p < .001$)	.012 ($p = .348$)
Roundness	.152 ($p = .005$)	.000 ($p = .931$)	.004 ($p = .589$)

We measured artifact morphology at several defined stages of reduction and used a 10% increase in number of removals as an indication of a change in 'stage of reduction'. The experimentally produced LCTs were ultimately incorporated in the PCA along with the archaeological specimens. One concern in this analysis is that the extensive variation in the experimental assemblage would unduly influence the PCA. As PCA is an ordination technique it is possible that the inclusion of the experimental LCTs may orient the maximum amount of variation between *experimentally* produced LCTs instead of isolating the variation in *archaeological* specimens. To reduce the influence of the experimental assemblage on the PCA, we added the individual experimental LCTs sequentially into separate analyses. After the inclusion of each successive experimental LCT we checked the impact the inclusion of that specific LCT had on the initial pattern of variation in the previous principal component analyses that were restricted to archaeological specimens. Experimental LCTs were removed from the PCA if they fell *outside* the distribution of archaeological LCTs in a plot of factor scores for principle components 1 and 2. Furthermore, an experimental LCT was excluded from the analysis if the position and *direction* of the eigenvector loadings in relation to one another on the initial PCA (i.e. without the experimental LCTs) was affected by the contribution of the experimental specimens.

Table 3
R-squared values for correlations between centroid size with both principal components 1 and 2 as well as with the traditional two-dimensional measures of shape.

Correlations	r	r^2	p
Elongation vs Centroid size	0.3847	0.148	.006
Pointedness vs Centroid size	0.1048	0.011	.371
Roundness vs Centroid size	0.0316	0.001	.786
Refinement vs Centroid size	0.2408	0.058	.036
PC1 vs Centroid size	−0.4348	0.1891	<.001
PC2 vs Centroid size	−0.0748	0.0056	.525

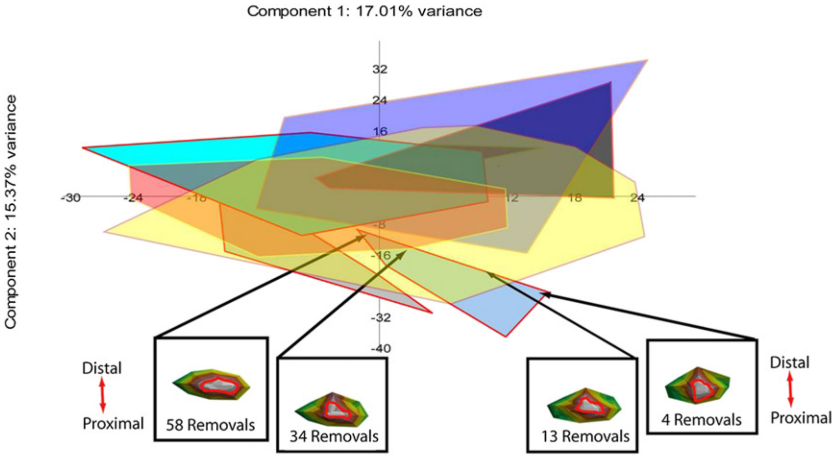

Fig. 6. Three-dimensional models of the resultant forms of each documented step in the biface production method. The red lines on each model circulate the maximum thickness on each model in an attempt to show the uniform direction in which it moves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4. Results

4.1. Results: archaeological data

Results of the PCA were visualized using a bivariate plot of factor scores for principal component 1 and principal component 2. Initial analyses that are restricted to the archaeological specimens are displayed in Fig. 4. The convex hulls (different colored polygons on the plot) represent the variation of form along principal components 1 and 2 for the LCTs within each raw-material group in this study. This plot illustrates that the LCTs manufactured on different raw-materials have relatively similar shapes.

To visualize the variation in artifact form we have plotted three-dimensional representations of procrustes transformed data and highlighted their position along the two principal components (Fig. 5). Principal components 1 and 2 account for 19.75% and 14.058% of the variation respectively (Table 4). These low amounts of variation are to be expected in an analysis where variation that is introduced through size related differences have been removed through Procrustes transformation (Harper, 1999).

Table 2 shows that elongation has the highest correlation with component scores for principal component 1 ($r = -0.712$; $p = 0.001$). However, elongation accounts only for approximately 51% of variation on the component scores for principal component 1 (hereafter PC1). An investigation of the three-dimensional representations of LCT form at different points along PC1 shows that the location of maximum thickness is also related to the major axis of morphological variation. Further, that the location of maximum thickness changes in a uniform manner as PC1 values decrease. Although other traditional measures are significantly correlated with PC1, they account for a very low percentage of the variation (<15%). PC2 is correlated with both elongation ($r = 0.42$; $p = 0.001$) and refinement ($r = 0.58$; $p = 0.009$). However, refinement only accounts for a relatively small amount of variation on PC2 (34%).

4.2. Results: experimental data

The incorporation of the experimentally replicated LCT data into the principal components analysis allowed for an investigation of LCT shape change during the production process. This shows a relationship between principal component 1 and LCT production. As the number of removals increases, PC 1 values decrease. Non-parametric measures of association show that component scores on PC1 and numbers of removals are highly correlated (Kendall's $\text{Tau}_b = -.851$, $p < .001$, $n = 21$).

4.2.1. Testing for allometry

Centroid size is a measure of size that is correlated with shape only when size and shape change together or when shape does not

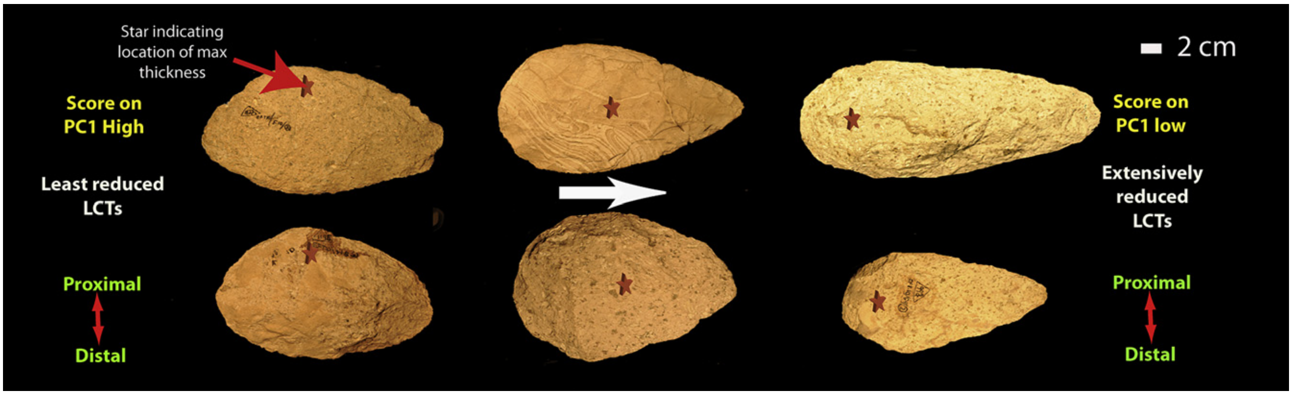

Fig. 7. A sequence of archaeological bifaces at different stages of reduction from least reduced (left) to most reduced (right) forms. The red stars show the direction of movement of maximum thickness as PC1 scores decrease. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

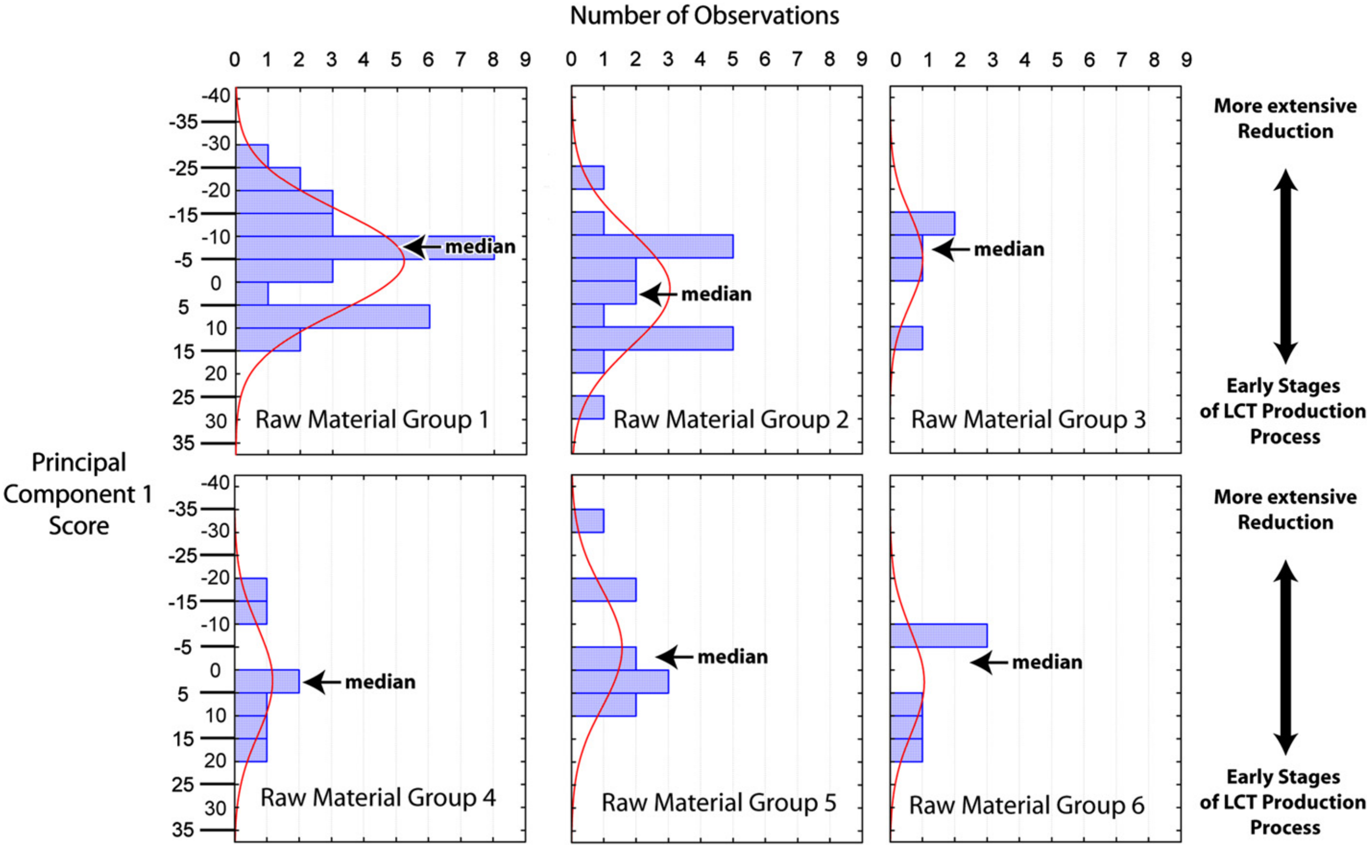

Fig. 8. Histograms showing the percentage of LCTs made on each raw-material in different stages reduction.

change *isometrically*. Thus centroid size and LCT shape should be correlated only when allometry is present in the dataset. In the context of this study, if LCT shape variation *is* related to allometric adjustments, as Gowlett (2006, 1996) has suggested for some East African assemblages, then one would expect centroid size to be correlated with component scores for PC1, which is the major axis of morphological variation in this study.

Centroid size was measured on the untransformed semi-landmark measurements of each LCT. PC1 scores are correlated with centroid size, which indicates that allometric changes are related to the major axis of shape variation in this study (Table 3). However, although PC1 is related to allometry, these allometric adjustments only account for 18% of the variation on PC1 (Table 3). Additionally, of the traditional measurements of LCT shape (Bordes, 1961; Roe, 1964), three-dimensional centroid size is only significantly correlated with elongation. However, elongation accounts for a small proportion of variation in centroid size (about 14%: Table 3).

Table 4
Results of principal components analysis of (A) archaeological specimens only, (B) and a combined archaeological and experimental dataset.

Principal component	Eigenvalue	% variance
A		
1	161.533	19.746
2	115.02	14.058
3	63.880	7.808
B		
1	151.07	17.01
2	116.59	15.371
3	74.64	8.399

5. Discussion and conclusions

When the principal component analysis is viewed with both the experimental and archaeological data it is clear that the majority of shape variation in this dataset is determined by morphological changes that occur during bifacial tool reduction. Furthermore, the shape change that occurs is suggestive of a specific reduction trajectory associated with initial manufacture rather than with tool maintenance or re-sharpening.

When reviewing shape change at different points along the major axis of variation it is possible to relate production processes to changes in PC1 values (this is visually represented in the equivalent three-dimensional models represented in Fig. 6). It is clear from this study that shape change occurred during LCT reduction in the Elandsfontein assemblage. In this regard, a sequence of reductive shape change *stages* is visible. This has implications for the dominant bifacial tool production strategy followed, as well as for the extent to which raw-material availability may have contextualized the use of this strategy at Elandsfontein.

The least reduced bifaces are at the extreme positive terminus on PC1. As PC1 values decrease the degree of reduction increases (Fig. 6). Hence the most reduced LCT forms have the lowest PC1 scores. Therefore, reductive shape change characterizes movement from the positive to the negative extremes of PC1. By viewing the experimentally produced LCTs along this axis it is also possible to track the nature of this change.

A general characteristic of shape change that occurs with the initial sequence of removals is that the location of maximum thickness moves from the lateral margin of the LCT – the proximal end or platform of the initial side-struck flake – towards the centre of the piece. This is largely a result of the thinning and removal of the platform and bulb on the initial side-struck flake. A hard hammer flaking technique is applied for this purpose. Once the location of maximum thickness has been centralized, a general bifacial symmetry is visible on the piece. Finally, the application of a soft hammer technique regularizes both edges. Reduction resulting from further 'thinning' results in the location of maximum thickness moving towards the base of the piece (Fig. 7).

Initial blank morphology and flaking strategy are clearly interrelated factors that influence LCT morphological variation at Elandsfontein. This study indicates that a specific blank morphology was selected for LCT production. Once a side-struck flake was obtained, its form necessitated the application of a specific reduction strategy to transform it into an LCT. This strategy was employed consistently but to varying degrees of intensity, as is clear from the range of forms present in the Elandsfontein assemblage.

The reduction strategy in use resulted in the maximum length axis of the final bifacial product being perpendicular to the technological length axis (Debenath and Dibble, 1993: 17) on the initial side-struck flake blank. Reduction is traceable in the dual movement of maximum thickness from the proximal end of the initial side-struck flake to its centre, and from the centre of the bifacial piece towards the base of the final product (Fig. 7). Consequently, the range of bifacial forms at Elandsfontein falls on a continuum within which modalities of shape are not discrete but instead blend into one another. This range of forms can be seen in almost all of the raw material groups.

It is interesting to note that the igneous raw material (raw material group 1) that makes up the majority of the tools at the Elandsfontein Cutting 10 collection has a higher percentage of LCTs in the later stages of reduction (Fig. 8) although this difference is not statistically significant (Kruskal-Wallis ANOVA by ranks $H = 4.95$; $p = .421$). However, despite the fact that LCTs in raw material group 1 were more often found in the later stages of reduction they are significantly larger than LCTs in the other raw material groups (centroid size; Kruskal-Wallis ANOVA by ranks $H = 21.9$; $p < .001$). In other words even though LCTs in raw material group 1 were overall larger (centroid size) than their counterparts in other raw material groups they were actually more reduced. This suggests the blanks selected for the production of LCTs in raw material group 1 were substantially larger than the blanks selected from the other raw material sources. This patterning of raw material mediated blank selection could not have been undertaken without a three-dimensional understanding of the LCT production process.

It is important to note with regard to White's (1995, 1998) model that the implications to be drawn from Fig. 4 are not that raw-material plays *no* role in driving LCT shape variation in the Elandsfontein assemblage. Rather, the plot illustrates that raw-material type viewed independently cannot account for a considerable proportion of variation compared to factors appearing to drive variation on principal components 1 and 2. This conclusion could also not have been observed without the investigation of size independent measures of three-dimensional form.

In conclusion, our approach to measuring LCT shape by using three-dimensional semi-landmark data has captured a portion of shape variation that conventional measures could not. Predictably, specific aspects of both McPherron (1994, 2003, 1999, 2000, 2006) and White's (1995, 1998) models are recognizable in the assemblage analyzed here. Further Gowlett's (2006, 1996) observations regarding allometric variation in East African bifacial tools are also partially supported by the Elandsfontein data. Although the assemblage of LCTs from Elandsfontein reflects certain aspects of recent studies of LCT morphological variation no *single* model can account for the pattern found in the Elandsfontein collection. Combining the morphometric approach with experimentally generated data provides an explanation of three-dimensional variation that could not be achieved by using traditional measures of LCT morphology.

Application of the dominant reduction strategy at Elandsfontein results in a uniform trajectory of change in LCT shape. Morphological change associated with artifact reduction is related to the procurement and selection of large side struck flakes as the dominant blank form. This study emphasizes the need to consider economic context in the interrogation of LCT morphological variation at the assemblage level. Models that interpret morphological variation in terms of a single explanatory factor can not explain the full spectrum of variability at Elandsfontein. This study has shown that while several different factors influence LCT morphology (e.g. reduction strategy and intensity, raw material type and form), none in isolation can fully explain the variation captured using a morphometric approach.

Acknowledgements

Thanks to, Professor Pierre-Jean Texier and Dr. Guillaume Porraz of the Diepkloof Rockshelter Project, Professor Judy Sealy, Dr S.Wurz, Petro Keene, and all other members of the Iziko museum staff for facilitating our analysis of the collection, as well as Arie Dempers for allowing us to do field-work on Elandsfontein Private Nature Reserve land. Funding for this research was provided by the National Research Foundation Focus Area Program Grant, Paleontological Scientific Trust; the University of Cape Town Emerging Researchers Program; and the Fox Fellowship Program at Yale University.

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