05 | IMAGE ANALYSIS

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3D Lithic Analysis

Abstract: Stone tools are palimpsests of ancient lifeways which otherwise left behind few material remains. They are the products of codified human behaviours which lithic analysts seek to understand by inferring the processes that lead to their design, production, usage and eventual discard. Traditional quantitative lithic analyses typically focus on describing stone tool morphology using discrete linear measurements and on examining their formal variability by descriptive statistics. This paper presents an alternative approach based on 3D modelling techniques and demonstrates its application in a case study of Middle Palaeolithic projectile points. Using 3D landmarks to quantify artefact morphology permits an objective comparison of artefact shape variations using Procrustes superimposition, a geometric morphometrics technique for studying the shape of organisms. This approach is particularly 'user-friendly' as the computed shape differences can be visualised directly to facilitate an intuitive understanding of the perceived variation.

Introduction

In the Middle Palaeolithic, medium-sized stone points approximately 4–7 cm long, morphologically suitable for tipping projectile hunting weapons, were recurrent stone tool forms (Gowlett 1992). The period also bridges the innovation of one-piece throwing spears in the Lower Palaeolithic, as evidenced by the Lehringen and Schöningen finds (Dennel 1997; Thieme 1997), and the proliferation of refined, bone-tipped projectile weapons in the Upper Palaeolithic (Rigaud 1989; Farmer 1994). It is logical to infer that prototyping and development of projectile point technology would have taken place within the Middle Palaeolithic. If projectile weapons are evaluated purely as practical tools to enhance survival, their design may be assessed with reference to essential, performance-related attributes, so as to yield insight on their functional potential and suitability for particular hunting strategies.

In order to study stone point design, it is necessary to use an objective framework for describing and comparing their 3D morphology. Morphology is a multivariate phenomenon which cannot be efficiently expressed or analysed by simply conflating a collection of discrete, one-dimensional measurements, as is commonly done in traditional lithic analyses. I present here a landmark-based approach to lithic analysis that is sensitive to 3D shape difference. I will begin by outlining the deficiencies of the conventional framework for quantitative lithic analysis, and then present an alternative approach employing 3D landmarks, before applying the methodology to study the functional design of two specific categories of projectile points: thrusting and throwing spearpoints. The case study is based on a chronologically structured sample of 301 stone points selected from four demographic centers of the Middle Palaeolithic Old World.

Why the Conventional Approach is not Enough

Artefact morphology or form is a major analytical unit in lithic study. Lithic archaeologists may be interested in examining the size and/or shape differences between artefacts from different contexts, such as geography or material culture. Size can generally be represented by some scaled measurements in the geometric dimension of the form.

Lengths, for instance, are size measures of dimension one (Slice et al. 1996). Describing shape, on the other hand, is more problematic. An object's shape is a function of the visible arrangements of its component parts relative to each other. It refers to the geometric properties of a configuration of points on the object that are invariant with respect to changes in position, orientation and scale. Terms such as straightness, elongation, squatness and symmetry are shape attributes that are particularly relevant to the study of projectile point design (see section "3D Analysis of Middle Palaeolithic Projectile Points").

The conventional method for capturing artefact morphology is to take linear measurements with calipers at fixed loci along an arbitrary line of maximum bilateral symmetry, generally defined as Length *(see Fig. 1)*. Any shape information is assembled indirectly using an external reference framework based on Length. Linear measurements, however, are absolute quantities reflecting only size. No geometric information is provided on the relative position of the various breadth and thickness measurements (Crompton 1995). Consequently, the variables sampled constitute an abstract collection of relative size measurements which only approximates the artefact's morphology (Klingenberg 1996). This problem is particularly acute with asymmetrical pieces and cannot be overcome simply by using an external reference framework. *Fig. 1* shows two stone points with the same absolute width dimensions along fixed Length intervals. Yet it is obvious that they have very different shapes. Furthermore, it can reasonably be expected that the asymmetrical point (B) would be highly unsuitable for tipping spears. Consequently, numerical analyses based solely on absolute linear dimensions will have limited utility due to the failure to capture shape information.

Whether one is using bivariate comparison or multivariate methods, with linear data, results are confined to the co-variance between pairs of variables. Shape is a multivariate phenomenon and should be analysed as such. In conventional morphometrics, analysis results are mostly communicated numerically and ordinated graphically to highlight discrete morphological groupings. It is difficult, though, to illustrate and interpret data with more than three dimensions (Baxter / Beardah 1995). Results from traditional multivariate analyses are typically projected down into lower dimensions and illustrated as bi- or tri-variate principal component (PC) plots. Consequently, some loss of information is unavoidable (Rohlf 1993). It should also be noted that variation in artefact shape is usually associated with artefact size, and most metric characters are highly intercorrelated. In conventional multivariate analysis, the factor of size often takes up a large fraction of the total variation in a data set. For this reason, the first PC is sometimes identified as a "size component" if all its co-efficients have the same sign (see Marcus 1990 for a discussion). More significantly, numerical findings from traditional techniques do not preserve geometric information and it is not possible to map the findings back on to the artefacts in 3D object space to facilitate interpretation. Consequently, conventional methods are not as powerful as landmark-based geometric morphometrics techniques for the study of morphology (see section "Procrustes Analysis").

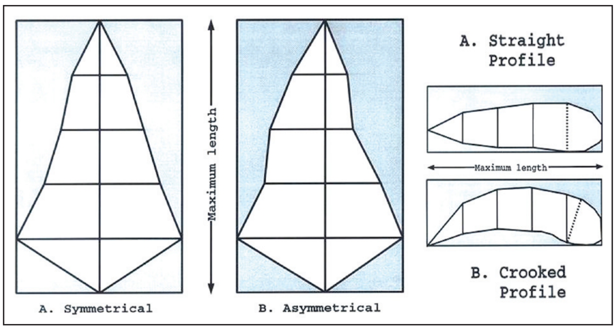

Fig. 1. Two stone points with different shapes but having the same absolute measurements.

A 3D Approach to Lithic Analyses

To provide a better framework for the objective study of projectile point morphology or design, I used an alternative analytical framework based on computer-aided technology (CAT) in conjunction with Procrustes superimposition techniques from the field of geometrics morphometrics. This approach emphasises the role of pictorial representations in aiding direct and intuitive interpretation of complex mathematical relationships.

3D Data Capture and Coordinate Landmarks

Instead of using calipers to measure the stone points, I captured their 3D morphology with a portable electronic digitiser, the Polhemus 3-Draw. The 3D point data are then "reverse-engineered" into 3D surface models using standard CAD-CAM tools, such as Imageware Surfacer (http://www.sdrc.com). A surface model is essentially a virtual geometric replica of the original stone point minus information on solid properties like density. The error statistics measuring the standard deviations of the computed surface from the digitised points are all less than 1 mm. This figure is much lower than the variation demonstrated between artefacts carrying the same typological label. A bonus of using digital models to quantify lithics is re-usability. Using computer visualisation software, these "virtual" models can be repeatedly inspected or manipulated in real-time to yield different datasets in various formats to cater to diverse types of analysis. In the projectile point study, 3D landmarks were extracted by standard CAD functionalities from the surface models for submission to the Procrustes analyses. Landmarks are 2D or 3D co-ordinates representing specific points located according to given rules on the sample. These loci must be unambiguously identifiable between samples in order for the superimposition to be meaningful (see also next section). In the case study, 11 landmarks are chosen to represent performance-related attributes (see section "3D Analysis of Middle Palaeolithic Projectile Points").

Procrustes Analysis

As traditional morphometric procedures applied to linear measurements are insensitive to shape, I have chosen to use the Procrustes superimposition procedure of the geometric morphometrics to compare stone point designs. Geometric morphometrics represents a synthesis of techniques from mathematical statistics, multivariate biometrics, non-Euclidean geometry and computer graphics (Bookstein 1996). They deal directly with landmark data rather than uni-linear or angle measurements. As coordinate data describe the relative position of the data points with respect to one another within a Cartesian framework and are invariant to rotation, scaling and translation, the artefact's overall geometry is preserved in the analyses. It is possible to project the statistical findings back into 3D object space and to visualise morphological differences using interactive computer graphics. This capability enables analysts to grasp mathematical relations intuitively without having to grapple with tables of numerical co-efficients which are standard output from conventional analyses.

In a Procrustes analysis, shape differences between the samples are demonstrated by superimposing the landmark configurations according to some criteria or by making them coincide

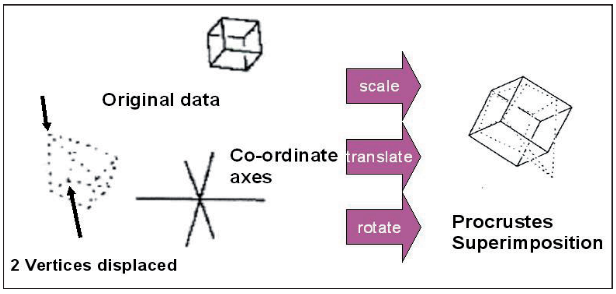

Fig. 2. Procrustes superimposition of two objects with eight 3D landmarks.

(Slice 1994). This is analogous to scaling and rotating photographic negatives of the samples as represented by the landmarks and superimposing their corresponding landmarks to obtain an overall best fit *(Fig. 2)*. After fitting the landmark configurations to the computed mean shape, the shape differences are recorded as residuals from this mean shape. Procrustes superimposition provides a way to transform configurations of landmarks into individual points within Kendall's shape space, and from there onto tangent space, where multivariate analyses can be carried out (Bookstein 1991). Kendall's shape spaces are very general statistical constructs which can accommodate any k-dimensional configuration of p points. As the spatial relationships of the landmark configurations are preserved by using co-ordinate data, outputs from these multivariate analyses can be projected back into 3D object space for visual inspection.

3D Analysis of Middle Palaeolithic Projectile Points

This section gives a walkthrough of an analysis of Middle Palaeolithic stone points using this 3D landmark-based approach. The objective is to demonstrate its utility in quantitative lithic analysis, highlighting in particular the capability for visualising numerical findings in object space to facilitate the analytical process. To explore the shape-related differences in functional aspects of the 301 stone points, I carried out different Procrustes superimpositions between all the samples against the computed mean shape as well as between discrete typological and spatio-temporal groups of points against their respective group mean shapes. The investigation presented here relates mainly to the shape analysis of all 301 samples.

Projectile Point Landmarks

As described in the section "3D Data Capture and Coordinate Landmarks", 11 landmarks were selected to describe attributes which affect stone points usefulness as throwing or thrusting spearpoints. While at a pinch, the two weapons can be used interchangeably, they are very different in design (Mears 1990). Thrusting spears are intended as close-range slash and cut weapons in an ambush hunting situation. Throwing spears, on the other hand, are longrange weapons that operate as puncturing, surgical weapons in an encounter hunting situation. Their specific functional differences require the optimisation of different elements of the projectile weapons (Christenson 1986), many of which are directly related to the working end, i.e. the stone point.

A thrusting spearpoint is likely to be squat and short with a wide tip angle. This design combines relatively long cutting edges with a short blade and a relatively wide base suitable for hafting with a strong, robust shaft. A throwing spearpoint, in contrast, needs to optimise the requirements for aerodynamics, killing power and accuracy. A slim, elongated point combines mass with a relatively acute tip angle and a small presentation area and base. A smaller base means that a smaller shaft can be used and this leads to a lower overall weapon mass. According to Newtonian mechanics, a lighter missile can be launched at a higher velocity with a flatter trajectory resulting in a faster, more powerful projectile weapon. *Fig. 3* illustrates the 11 landmarks chosen to represent these functional attributes of projectile points, irrespective of their typological designation.

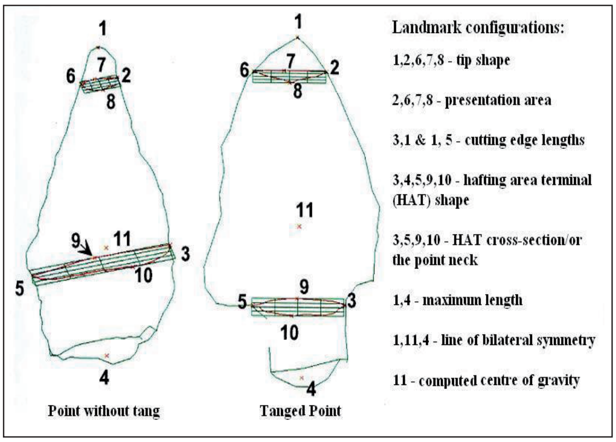

Fig. 3. 11 landmarks chosen to represent the functional attributes of stone points.

The Morphometric Analysis

A morphometric analysis typically involves performing different types of statistical procedures and then co-relating the different outputs to form interpretation. In the all sample superimposition, a PCA was carried out on the Procrustes residuals (see section "Procrustes Analysis") to obtain ordination plots in order to illustrate shape similarity patterns between samples regardless of their typological designations. Unlike conventional PCA, the eigenvector associated with each PC can be graphically examined with regard to the shape being studied. *Fig. 4* shows the first eigenvector scaled up by a factor of 2 and illustrated as vectors (bold lines) superimposed on the 11 landmarks of the overall mean configuration (in grey). In interactive mode, the outputs can be manipulated dynamically to provide optimal viewpoints. Here, four different perspectives are shown for both the negative and positive trends of PC1 to illustrate the orientation of these vectors. In general, the pattern of displacements in the 11 landmarks indicates that PC1 loads high on the ratios of both relative Breadth and Thickness to Length. The first eigenvector, in the negative direction, is found to have a significant influence on the relative elongation of the stone point geometry. This indicates that artefacts with negative PC1 scores would display a comparatively slim and elongated shape – an optimal shape for penetration. It is not surprising to find the group of Aterian points sharing similarly low PC1 scores. A Moroccan Point *(Fig. 4, top right)*, a typological variant of Aterian Points, has the lowest PC1 score. Its antithesis, a Pseudo-Levallois Point *(Fig. 4, bottom right)* is found to have the highest PC1 score.

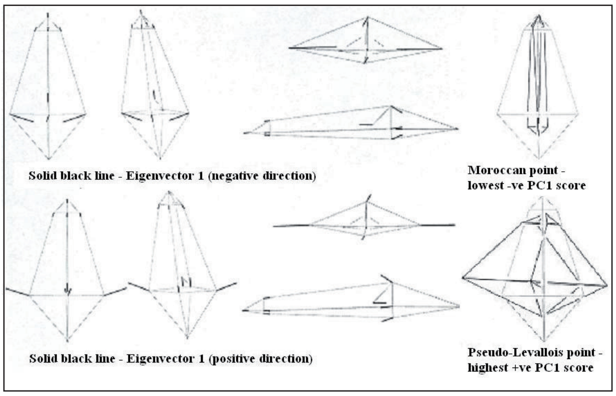

Fig. 4. Plots of the first eigenvector shown as vectors (solid black lines) loaded by a factor of 2 superimposed on landmarks in the overall mean configuration (grey lines) from a PCA of the residuals from all 301 samples.

By iterating the process of cross-referencing the various PCs ordination and eigenvector plots, a better resolution and understanding can be achieved of the quantitative variation in projectile point design. *Fig. 5* summarises the principal shape tendencies observed from the analysis. The physical location of each type of stone point is based on a PCA of the residuals from a group mean superimposition. The diagram suggests three distinct design trajectories within the collection. When examined within the context of the functional attributes proposed in the section "Projectile Point Landmarks", these trajec–tories may be described as representing distinct design trends towards:

- Trend 1: Acute, elongated, light-weight throwing spearpoints with a robust cross-section
- Trend 2: Broad, squat, robust thrusting spear-points
- Trend 3: Acute, elongated points with a lenticular cross-section (coupled with a large blade element) which are akin to spearpoint-cum-knife implements

Strictly speaking, a fourth trend may be defined which loosely covers a collection of pointed artefacts. In general, though, the analyses demonstrated that these artefacts tend to have an asymmetrical shape and a chunky hafting area (HAT), both being attributes deemed undesirable in projectile point function. Thus, this fourth group may simply reflect passable but not efficient designs. Given that other types of stone points with more suitable morphology occurred alongside such types (e.g. pointed flakes), it is unlikely that they would be preferentially chosen to tip spears. On this basis, it is questionable that this collection of "crude" stone points represents a conscious (let alone refined) projectile point design. A detailed discussion of the analyses and a conceptual model of the pathways to the acquisition of projectile weapon technology in the Middle Palaeolithic is given in (CROMPTON 1997).

Conclusion

The 3D landmark-based approach presented in this study is potentially useful for many areas of lithic metrics. Given appropriate landmarks, the technique is capable of objective and visual quantification of both technological and morphological attributes. This highly visual approach offers a "user-friendly" framework, grounded in statistics, for lithic analysts to objectively study lithic variability as a consequence of mediated human actions. In addition, artefacts archived as digital models could be reused to yield different data for diverse types of study, thereby adding value to the approach.

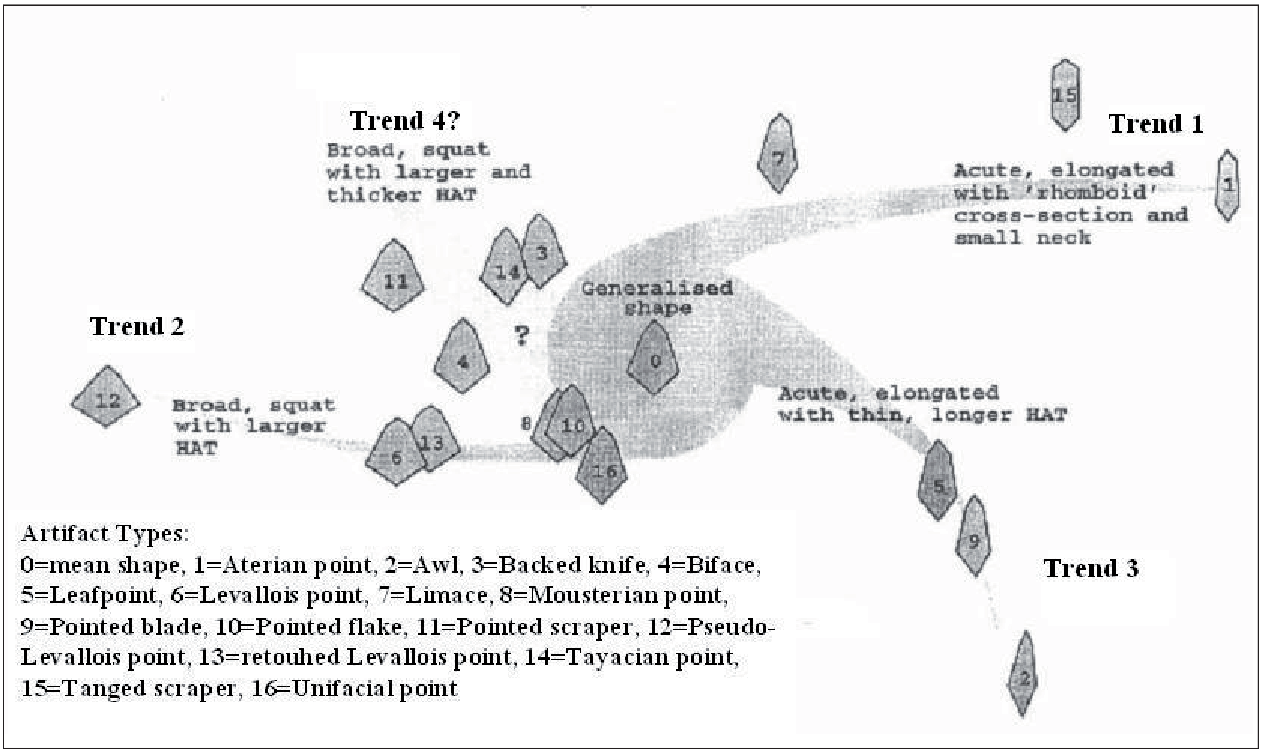

Fig. 5. Simplified model of the shape trends observed in the sample of 301 Middle Palaeolithic stone points.

Acknowledgements

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References

BAXTER / BEARDAH 1995
M. J. BAXTER / C. C. BEARDAH, Graphical Presentation of Results from Principal Component Analysis. In: J. HUGGETT / N. RYAN (EDS.), Computer Applications and Quantitative Methods in Archaeology 1994 (Oxford 1995) 63–68.

BOOKSTEIN 1991
F. L. BOOKSTEIN, Morphometric Tools for Landmark Data: Geometry and Biology (Cambridge 1991).

BOOKSTEIN 1996
F. L. BOOKSTEIN, Biometrics, Biomathematics and the Morphometric Synthesis. Bulletin of Mathematical Biology 58:2, 1996, 313–365.

CHRISTENSON 1986
A. L. CHRISTENSON, Projectile Point Size and Projectile Aerodynamics: An Exploratory Study. Plains Anthropologist 31, 1986, 109–128.

CROMPTON 1995
S. Y. CROMPTON, The Third Measure: 3-D Data, Data Capture Systems and Accuracy. Archaeological Computing Newsletter 44, 1995, 5–11.

CROMPTON 1997
S. Y. CROMPTON, Essential Points: A Functional Evaluation of Middle Palaeolithic Stone Points (Liverpool 1997).

DENNEL 1997
R. DENNEL, The World's Oldest Spears. Nature 385, 1997, 767–777.

FARMER 1994
M. F. FARMER, The Origins of Weapon Systems. Current Anthropology 35, 1994, 679–681.

GOWLETT 1992
J. A. J. GOWLETT, Ascent to Civilisation: The Archaeology of Early Humans (New York 1992).

KLINGENBERG 1996
C. P. KLINGENBERG, Multivariate Allometry. In: L. F. MARCUS / M. CORTI / A. L. GAVIN / J. P. NAYLOR / D. E. SLICE (EDS.), Advances in Morphometrics (New York 1996) 23–50.

MARCUS 1990
L. F. MARCUS, Traditional Morphometrics. In: Proceedings of the Michigan Morphometrics Workshop (Ann Arbor 1990).

MEARS 1990
R. MEARS, The Survival Handbook (Oxford 1990).

RIGAUD 1989
J.-P. RIGAUD, From the Middle to the Upper Paleolithic: Transition or Convergence? In: E. TRINKAUS (ED.), The Emergence of Modern Humans: Biocultural Adaptations in the Later Pleistocene (Cambridge 1989) 142–153.

ROHLF 1993
J. ROHLF, Relative Warp Analysis and an Example of its Application to Mosquito Wings. In: L. F. MARCUS / E. BELLO / A. GARCIA-VALDECASAS (EDS.), Contributions to Morphometrics. Monografias del Museo Nacional de Ciencias Naturales 8 (Madrid 1993) 131–159.

SLICE 1994
D. E. SLICE, GRF-nd: Generalised Rotational Fitting of N-dimensional Data. Public Domain Software Available at http://life.bio.sunysb.edu/morph/morph.html [31 Dec 2007].

SLICE ET AL. 1996
D. E. SLICE / F. L. BOOKSTEIN / L. F. MARCUS / F. J. ROHLF, A Glossary for Geometric Morphometrics. In: L. F. MARCUS / M. CORTI / A. L. GAVIN / J. P. NAYLOR / D. E. SLICE (EDS.), Advances in Morphometrics (New York 1996) 531–551.

THIEME 1997
H. THIEME, Lower Palaeolithic Hunting Spears from Germany. Nature 385, 1997, 807–810.

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