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A new method for 3D geometric morphometric shape analysis: The case study of handaxe knapping skill

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A B S T R A C T

The following study presents a novel method for computerized 3D geometric morphometric shape analysis of archaeological artifacts. It consists of a newly developed tool for automated positioning of 3D digital models and the following placement of 3D homologous landmarks for geometric morphometric analysis. It provides a quick and easy method for acquiring high-resolution 3D landmark coordinate data. This tool is applicable to a wide range of objects which have two opposed faces of relatively similar size and can be consistently positioned along their maximal length in planform view. The acquired data can be subjected to common multivariate statistical procedures for the quantitative description and analysis of shape variability in an assemblage. The method is applied here to a case study of experimentally produced assemblages of Acheulian handaxe replicas made by six knappers of differing skill levels. An analysis is performed to test whether the shapes of the handaxes can be used to classify them according to their knapper's skill level. Generalized Procrustes analysis (GPA), principal component analysis (PCA) and discriminant analysis (DA) are applied to the landmarks' coordinates. The results indicate that applying DA to PC scores allows a reliable classification of artifacts according to the skill level of their knappers, with a minimal misclassification rate. Thus, this method demonstrates that application of high-resolution 3D geometric morphometric methods can be used for the quantitative differentiation of skill levels based on tool morphology.

1. Introduction

Shape is generally recognized as one of the most important aspects of archaeological objects in general, and of formal tool types in particular. In a holistic sense, the shape of an object incorporates all its various subsets such as edge properties, outline, refinement, symmetry etc. It is commonly accepted that the shape of tools retrieved from the archaeological record, especially stone tools, is of utmost importance with respect to their various possible functions, whether utilitarian, social, cultural or symbolic (Sackett, 1982). Furthermore, the shapes of formal tool types have been viewed as significant factors in understanding various phenomena such as early human cognitive development, cultural transmission processes and dispersions (Mithen, 1994; Lycett and von Cramon-Taubadel, 2008; Hodgson, 2015).

The description and analysis of stone tool shapes is in many ways problematic. Stone tools are complex and irregular objects, and their shape is inherently three-dimensional and cannot be quantitatively described using a monovalent unidimensional variable such as volume or length. This difficulty is dealt with through a number of approaches. One relatively straightforward approach is that of subjective description, using geometrical adjectives such as pointed, oval, triangular, convex, and so on (e.g. Doronichev and Golovanova, 2010; Moncel et al., 2015). This approach is normally adopted only for general descriptions or when small assemblages are discussed, due to its subjectivity and lack of analytical power. A different and more common approach includes the use of metric distances and their ratios to describe and analyze specific aspects of tool morphology. Generally, the maximal distances of the three dimensions are recorded in accordance with common positioning, i.e., the maximal length, width and thickness (Andrefsky, 2005). While these measurements provide direct information regarding the size of the artifact, they only provide a very simplified representation of the tool's shape.

The analytical approach of distance ratios has been extended to allow a higher-resolution description of specific tool types such as Acheulian handaxes (Bordes, 1961; Roe, 1964, 1969, Isaac, 1977) by introducing additional distance measurements and calculated ratios (e.g., maximum width at half length, length to maximum width, etc.). These are subsequently used to classify tools into different typological

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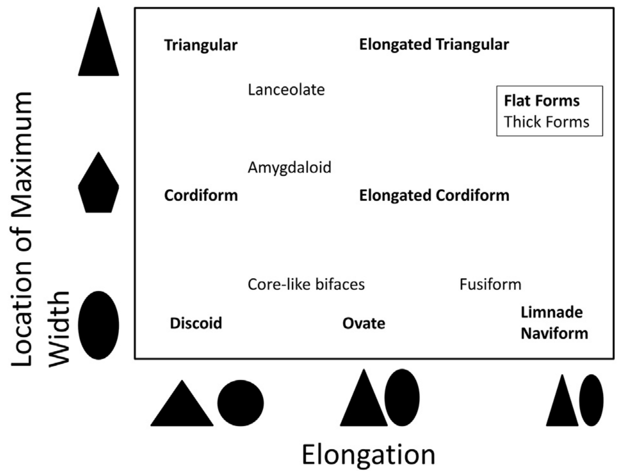

Fig. 1. Bordes' typological classification of handaxe morphologies. (Modified after Debénath and Dibble, 1994).

categories and allow graphic representation of inter- and intra-assemblage variability (Fig. 1). While this method provides a somewhat better description of the tool's shape, it is still highly constrained by its low resolution which masks much of the complexities and irregularities of these tools. Much of the existing variability is obscured, and important patterns that could be of significance in relation to various aspects of human behavior may be overlooked. Furthermore, in some cases non-metrical morphological observations are incorporated in the classification. Examples of this are the "shark's tooth" – a triangular handaxe with markedly concave edges – and the "sub-cordiform" – a cordiform handaxe that is thicker and retains a significant amount of cortex on its butt (Bordes, 1961). While non-metrical observations are regularly used to describe technological traits, their incorporation into such a method undermines its main goal, which is to provide an objective quantitative description of the tool's shape. In addition, this method was designed for Acheulian handaxes and while similar methods were developed for additional formal tool types such as arrowheads (Andrefsky, 2005), many still lack similar analytical methods. Consequently, different analytical methods for 2D and 3D datasets have been developed to study various aspects of tools, such as their degree of symmetry (Saragusti et al., 2005) or the location of their center of mass (Grosman, 2016).

A different approach to shape analysis of stone tools is taken by geometric morphometrics. This method has been well established over several decades in the biological sciences (Bookstein, 1978; Bookstein et al., 1985) and in recent years has also been increasingly adopted in the field of archaeology (Lycett et al., 2006). The method consists of the positioning of homologous landmarks on the surface of an artifact and the subsequent multivariate statistical analysis of the Cartesian coordinates of an assemblage of artifacts. The method provides a quantitative and objective description of shape variability between different objects (Dryden and Mardia, 1998).

While this approach presents a number of substantial advantages over the approaches described above, its application entails some intrinsic technical difficulties. These difficulties relate to the initial stage of data acquisition, mainly the positioning of landmarks and extraction of coordinates. The first major difficulty is that, in contrast to natural objects or formal geometric shapes, stone tools lack readily identifiable homologous points that can serve as landmarks. The second difficulty relates to the way in which the coordinates of the landmarks are actually recorded (Lycett and Chauhan, 2010). The recording of 2D landmarks can be carried out relatively quickly and easily using numerous computer programs. However, the third dimension is not represented causing a substantial loss of shape-related information. On the other hand, the manual recording of 3D landmarks is an extremely time-consuming process, limiting both the resolution and the number of artifacts that can be recorded, and highly prone to inaccuracies.

These difficulties are clearly reflected in the numerous studies that applied the geometric morphometric method to stone tools in the past two decades. One of the earliest endeavors attempted to quantitatively describe and analyze morphological differences in the bifacial assemblages of two different layers at the site of Gesher Benot-Ya'aqov (Brande and Saragusti, 1996). However, due to technical limitations related to 3D documentation and computing power available at that time the analysis was conducted in 2D and in very low resolution. Despite of its limitations, the 2D approach is still being used where the tools outline shape are in question (e.g. Lycett and von Cramon-Taubadel, 2008; Costa, 2010).

Recently a 3D cross-caliper and an explicit landmark positioning protocol for Acheulian handaxes was developed (Lycett et al., 2006). This allowed the application of real 3D geometric morphometric shape analysis to handaxes, as well as other lithic tool types. Thus, it provided the standard methodology in studies addressing questions related to the morphological variability in various types of stone tools (e.g. Archer and Braun, 2010; Lycett et al., 2010; Eren and Lycett, 2012; Wang et al., 2012; for a detailed review see Grosman, 2016). These studies have provided quantitative and objective 3D observations on which further interpretations were based. However, the manual nature of data acquisition using the 3D cross-caliper has substantially limited both the sample sizes and the resolutions in which the analyses were conducted.

This paper presents a newly developed method for recording 3D homologous landmarks for geometric morphometric shape analysis of tools. The method consist of a computer procedure that was designed to automatically position and record the 3D Cartesian coordinates of homologous landmarks placed on the surface of high-resolution, 3D digital models of objects. After the fully automated positioning procedure of the model (Grosman et al., 2008; Grosman et al., 2014), landmarks are placed and their coordinates are recorded. Furthermore, the method allows the user to select the desired resolution (i.e. the number and density of landmarks). This procedure provides a quick and accurate manipulation of the collection of 3D homologous landmark coordinate data.

The method was originally designed for Acheulian handaxes, but can be applied to other assemblages of tools, such as arrowheads and points, that have two opposed faces of relatively similar size intersected by a circumferential edge, and can be consistently positioned along their maximal length in planform view. Our new methodology will be applied to a case study which tries to differentiate between skill levels of flint knappers.

1.1. The case study

Handaxe are among the longest-studied stone tools in the history of prehistoric research and are considered the "guide fossil" of the Acheulian technocomplex (Lycett and Gowlett, 2008). This tool type presents an unparalleled chronological and geographical distribution alongside substantial shape variability. Therefore, this phenomenon became one of the most intensively studied and discussed issues in the research of various behavioral aspects of Lower Paleolithic hominins. Shape variability in handaxes has been viewed as stemming from factors such as cultural traditions (Wynn and Tierson, 1990), raw material availability and selection (White, 1998; Sharon, 2008), the life histories of tools (McPherron, 1999) and cognitive capabilities (Hodgson, 2015), to mention but a few.

The manufacture of stone tools involves the reduction of material by flaking to produce the end product, in this particular case a handaxe. This reduction process is composed of a long series of removals, each reflecting a decision made by the knapper. The long and dynamic sequence eventually dictates the shape of the end product. Consequently, no two handaxes are identical in shape, and similarity among them is only to a degree. While there are multiple factors