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

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ABSTRACT

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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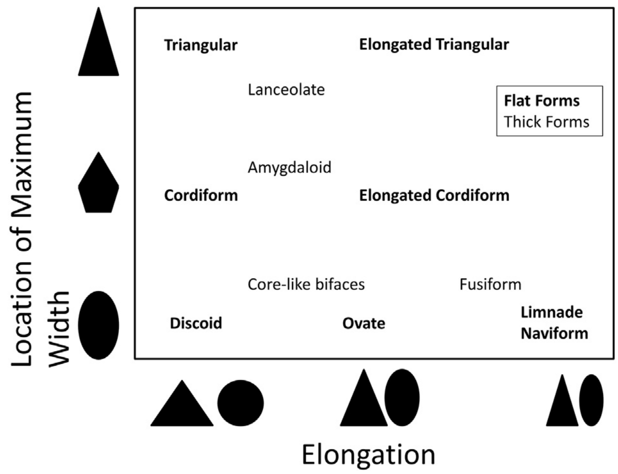

Fig. 1. Bordes' typological classification of handaxe morphologies. (Modified after Debénath and Dibble, 1994).

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 affecting the decisions made by the knapper, as well as the quality of their execution, his or hers skill level is undoubtedly a central one. The concept of skill is complex as it can be defined in numerous ways, but it is generally agreed that it is related to the ability to practically apply one's knowledge in a goal-oriented context (for a detailed discussion see Bamforth and Finlay, 2008 and references therein). From this somewhat obscure definition it is clear that skill in general builds on both theoretical knowledge and applied practice, two distinct concepts that are not necessarily congruent. This duality is not limited to stone knapping but is applicable to skill in all types of crafts.

In stone knapping, skill involves both theoretical knowledge (*connaissance*) and practical know-how (*savoir-faire*) (Pelegrin, 1990). The theoretical knowledge can be thought of as the ability to hold a conceptual image of the desired end product, as well as to plan in advance the required reduction sequence in order to achieve the desired goal. It also involves the ability to understand what specific reduction procedure is required in relation to the given conditions at each stage of production. This understanding allows the knapper to consider required modifications to the geometry of the raw material in order to overcome unexpected circumstances which may result from raw material flaws or unsuccessful previous blows. The practical know-how is the physical ability to fulfill the intended goal at the level of the individual removal event (the removal of a single flake). As such, it consists of the knapper's motor skill and the practical understanding of the fracture mechanics of the raw materials. An individual's skill level is therefore the product of the complex interplay between these two forms of knowledge. While the former is concerned with the planning and sequencing of the actions, the latter is concerned with their actual execution.

These two components of skill have an incremental nature, and therefore it is generally agreed that skill is an acquired trait (Bamforth and Finlay, 2008). The acquisition of stone knapping skills, especially in traditional societies, occurs in social contexts (Stout, 2005; Bamforth and Finlay, 2008). The process of acquisition always consists of practical training and often involves verbal and non-verbal instruction by one or more skilled individuals, i.e., the common master-apprentice model. In addition, skill can be acquired by individual trial and error or within groups of novices practicing together (Boyd and Richerson, 1993; Grimm, 2000; Finlay, 2008). Thus, social and cultural factors will have an effect on the theoretical and practical components of skill. However, the level of skill assigned to an individual will usually be determined by the amount of time devoted to training and practicing as well as idiosyncratic aspects such as individual preferences or natural talent (Howe et al., 1998; Olausson, 2008). It is worth noting that skill level is assigned to an individual relative to other members of the social group. Furthermore, the assessment of ones skill may be based on a number of social factors and not necessarily on his actual performance (Stout et al., 2002).

Much of prehistoric research in general, including that of the Acheulian technocomplex, is concerned with variability within and between lithic assemblages (Lycett and Gowlett, 2008). This variability, which is observed in the size, location and composition of the assemblages, can be expressed in terms of technology, typology and morphology. In many cases it is interpreted as stemming from various economic, demographic, cognitive or social factors. However, interpretations of lithic variability only rarely consider the idea that at least part of that variability must derive from differing skill levels (for exceptions see McNabb et al., 2004; Machin, 2009; Assaf et al., 2016). As skill is a trait which is acquired by practice, a significant part of the discarded lithic components which make up the archaeological record must be the products made by novices in their training process. Previous studies avoided this interpretation due to the lack of practical and well established methods to differentiate skill levels in many Acheulian lithic assemblages (Bamforth and Finlay, 2008). Given the complex and dynamic nature of stone knapping, which is heavily dependent on the individual knapper and his decisions and actions, we hypothesize that the knapper's skill level would affect the shape of the produced handaxe. While shape differences between tools produced by knappers of differing skill levels may not be substantial in terms of overall shape, we assume that some, possibly minute shape properties would reflect the differing levels of skill (Nonaka et al., 2010). Hence, assuming that those shape properties would be detectable, it should be possible to use them in order to classify the handaxes according to the skill level of their producers.

Our newly developed 3D landmark positioning tool, which allows a significantly higher analytical resolution than currently available methods, may therefore be used to record these shape differences. Subsequent application of multivariate statistical analyses and procedures may help identify these differences and classify the handaxes according to their knapper's skill level. Hence, our methodology is applied to a number of experimental handaxe assemblages produced by knappers of varying skill levels as a case study. The results demonstrate how the skill level of knappers can in fact be quantitatively assessed based on the shapes of their products.

2. Methods

Our method provides an enhancement to the currently available geometric morphometric analysis. In general, geometric morphometric shape analysis is based on distance measurements of relative shape change by the use of homologous landmarks placed at specific locations on artifacts. The shapes are expressed as a cloud of points in Cartesian space that takes into consideration a substantially larger degree of shape complexity, which thus enables a much more realistic representation of the artifacts. The geometric morphometric method is composed of two distinct stages. The first includes data acquisition, while the second is concerned with its statistical processing. In this study we present a novel method for 3D data acquisition that substantially improves on currently existing methods. As described in the previous section, several inherent technical difficulties complicate the application of the geometric morphometric method to anthropogenic objects. The newly presented method deals efficiently with these issues and provides appropriate solutions.

The main difficulty that has hindered the adoption of the geometric morphometric method for lithic analysis is the lack of readily identifiable homologous landmarks on anthropogenic objects (Lycett and Chauhan, 2010). The homology of the landmarks refers to an intrinsic identity that is shared by all the analyzed objects in a given sample. It is the principle that underlies the quantitative expression of shape differences between the different objects. There are three types of landmarks: anatomical, mathematical and semi-landmarks. These types reflect differences in the way that homology is defined (Dryden and Mardia, 1998). For the first type of landmark, the homology is anatomically defined, for example the intersection point of specific cranial sutures on a skull. For the second type, the homology is mathematically defined, for example the vertices of a pyramid or points of extreme curvature on an ellipse. The third type of landmark, the semi-landmark, is usually the main type used for the analysis of anthropogenic objects. These can be identified by a consistent positioning protocol of the objects and the landmarks (e.g. in the form of a grid) (Lycett et al., 2006).

Another difficulty is related to the technical process of collecting the coordinate data of the homologous landmarks. The geometric morphometric method conceives the shapes of different items as sets of points in a common Cartesian space, in contrast to traditional quantitative shape analysis methods, which only measure distances between points on the items themselves without referring to a common set of axes. This difference in concept poses complexities in two aspects of data acquisition. The first is related to the common coordinate system, which requires that all landmarks on all objects will refer to a common origin. Thus, if the landmarks are placed on the physical object itself, there must be some restraining mechanism that will ensure its fixation during the entire data collection process and for all objects (Lycett et al., 2006). The second aspect consists of the amount of data that has to be collected. While in the traditional methods a single distance value is measured between two points, in the geometric morphometric approach two or three values must be registered for each point, depending on whether the analysis is 2D or 3D. Thus, for each measurement taken in traditional shape analysis, four or six values need to be taken in the geometric morphometric method. The manual extraction of these values is difficult and inaccurate and affects the reliability of the subsequent results and conclusions.

2.1. Data acquisition

The method presented in this study offers a new way of harnessing computerized tools for the collection of homologous landmarks in 3D coordinate data that provides an efficient and straightforward solution for the difficulties described above. The procedure uses 3D digital data of the object's surface on which the landmarks are placed. In our study the digital models were acquired by structured light technology (scanner produced by Polymeric) for obtaining a closed mesh.

To provide the homology required for the subsequent analysis our tool consists of a protocol designed to objectively and consistently position the 3D digital models as well as to place the landmark in an indexed orthogonal grid system. These two procedures are the principles which underlie the landmarks' homology across all objects in the sample (Dryden and Mardia, 1998; Lycett et al., 2006; Grosman et al., 2008). Prior to the execution of the protocol, the user is requested to enter the number of desired landmarks per object. Given that the landmarks are placed in the form of a grid, the user specifically defines the number of latitudes per object, and the number of landmarks per latitude. The total number of landmarks will determine the resolution of the analysis, and as the resolution grows, the analysis could account for finer shape differences. It is important to note that as the subsequent statistical procedures requires equal input size for all objects in a sample, the number of latitudes and landmarks per latitude should be consistent for all objects in the sample. Thus, this interface allows the user to adjust the resolution of the subsequent analysis according to the specific requirements and constrains of each individual sample.

The model positioning and landmarks placement protocol consists of the following discrete steps:

1. Item positioning:
   a. 3D rotation of the model according to the distribution of the normal vectors on its surface (Grosman et al., 2008). The normal vectors are uniform sized vectors which are perpendicular to the surface of each polygon in the mesh. This procedure positions the model so that the plain of intersection between its two largest opposed surfaces would be parallel to the XY plain and perpendicular to the Z axis. For handaxes, as well as other artifacts with two similarly sized and opposed faces such as points or arrowheads, it would position the items in a planform view (Fig. 2a).
   b. 2D rotation of the model along the XY plain according to the maximal measured distance (i.e., maximal length). The object is the positioned so that its maximal length is parallel to the Y axis (Fig. 2b). Steps *a* and *b* are automatically applied based on geometric criteria, thus providing an objective geometric basis for the semi-landmark homology.
2. Landmark placement:
   a. Building a 3D orthogonal grid on the surface of the object. The maximal length of the item in planform view, now parallel to the Y axis, forms the prime meridian of the grid, and its two extremities are the two mathematical landmarks corresponding to the "poles" of the object. Equidistant latitudes are then drawn at fixed intervals along the maximal length. These are calculated by the distance function to the nearest neighboring available vertices on the mesh and correspond to the number of latitudes requested by the user. The length of each latitude corresponds to the width of the artifact at each of the intersection points along the maximal length (Fig. 3a). For example, if the user requested 5 latitudes, the length of the second from the bottom will be equal to the object's width at 40% of its maximal length in planform view.
   b. Placement of semi-landmarks on the grid and recording their 3D coordinates. An equal number of equidistant 3D landmarks are placed at fixed intervals along each latitude, corresponding to the number requested by the user. Similar to the previous step, the coordinates of the each landmark are calculated by the distance function to the nearest neighboring available vertices. This procedure is repeated for the two opposing faces of the object (Fig. 3b).

The output provided by the computerized tool is a data file containing 4 $n_{rows} \times m_{columns}$ matrices in which the number of rows corresponds to the number of latitudes and the number of columns to the number of landmarks per latitude. Each matrix contains the coordinates of all points for a certain dimension. The Z dimension coordinate data is recorded in two different matrices, one for each face of the objects. Such a file is provided for each object. These matrices can then be converted to a list format containing $n_{rows} \times 3_{columns}$ in which the number of rows corresponds to the total number of landmarks and the three columns to its 3D coordinates. Because of the consistent model orientation and landmark placement protocol, each landmark in the list corresponds to an indexed position on the grid. Geometric morphometric analysis can be performed given the selected grid dimension, the consistent positioning and the identical indexing for all objects in the sample. Hence, identically indexed landmarks on different objects in the sample share the homology required for the geometric morphometric analysis.

This procedure is repeated for each object in the analyzed sample. Finally, all the lists produced for each of the objects are combined to form a dataset containing the coordinate data of the entire sample.

2.2. Case study methodology

A datasets of landmarks referring to the volumetric configuration of the experimental handaxes was compiled and analyzed. So that the dataset would be sensitive to shape differences, a high-resolution 48×50 grid configuration of the landmarks was placed, providing 4802 homologous landmarks per item. The landmarks cover the entire surface of the object in a dense grid pattern. Thus, differences in the positions of landmarks on the grid would correspond to differences in 3D shape between objects in the sample. Finally, the coordinate data of all items were pooled to form a complete dataset representing the entire assemblage.

Following the stage of data acquisition, the data was subjected to a series of multivariate statistical procedures and analyses (Dryden and Mardia, 1998). These were performed by the Addinsoft XLStat add-in for Microsoft Excel. The dataset was first subjected to a generalized Procrustes analysis for superimposition and scaling to centroid size of all the models. This procedure removed all non-shape-related variability that stems from differences in location, rotation and scale. As a result, differences among the coordinates of homologous landmarks in the dataset reflected only differences in the shapes of the items.

Next, the dataset was subjected to a principal component analysis intended to reduce dimensionality and identify the major axes of shape variability in the dataset. The principal component analysis provided a number of components (i.e., variables or axes) equal to the number of items in the sample, sorted in descending order according to the proportion of variability that they explain. Each principal component reflects a specific shape trend, that is, a mutual change in the values of a number of homologous landmarks. Each analyzed item receives a value for each principal component, which is based on the values of its relevant coordinates in relation to the shape trend described by that

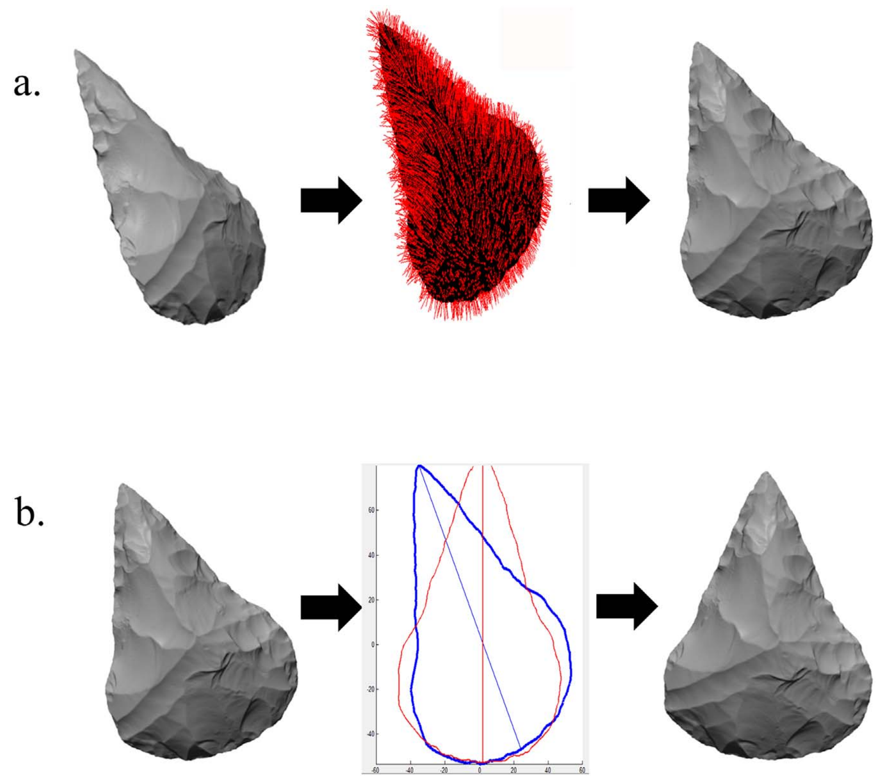

Fig. 2. Graphical representation of the automated model positioning. a: 3D rotation to planform view according to the distribution of normal vectors (in red); b: 2D rotation on XY plane according to maximal length in planform view. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

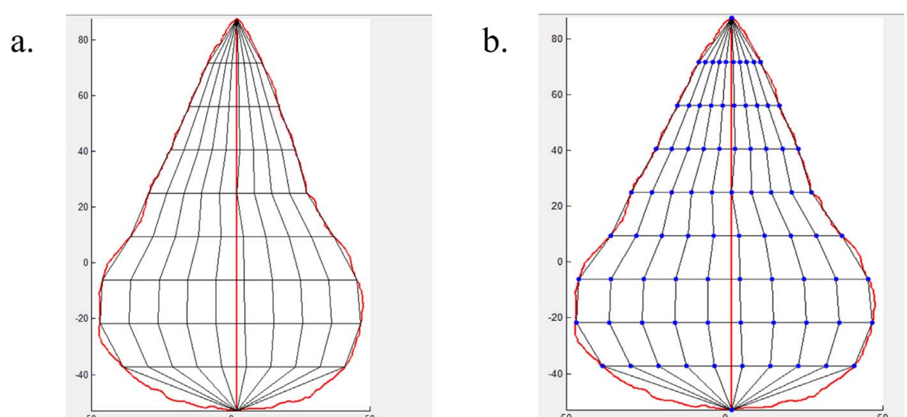

Fig. 3. Graphical representation of the automated landmark positioning. a: Building of 3D grid around the items surface (visualized in 2D); b: Positioning of homologous semi-landmarks on the grid and recording their coordinates (visualized in 2D).

particular principal component. Hence, each item is defined by a series of principal component scores that describe its relative position in relation to the other items in the sample for each specific trend.

Lastly, discriminant analysis was conducted on the principal component scores. The discriminant analysis is a multivariate analytical procedure that tests to which degree a set of continuous variables can be used to classify an object into one of several predefined discrete qualitative categories. In this study, the discriminant analysis is used following a stepwise forward selection model. In other words, the analysis is performed after a multiple-step model that in each step selects the next principal component that provides the best categorical prediction until the change in prediction is no longer significant. Thus, only those shape trends that when pooled together provide the best discrimination between categories based on their between-group variance are included in the analysis. Subsequently, discriminant functions are computed based on the selected components in order to classify items into skill groups. Thus, it highlights which shape trends are the most significant for the classification. It should be noted that, while this analysis is mathematically similar to the principal component analysis, it is used here to test which of the principal can be used to separate between the groups and to what degree (Zhao et al., 1998). It is required since those principal components that provide the best separation are not necessarily those which account for most shape variability in the sample. For example, the third principal component, which accounts for a relatively substantial portion of the shape variability, does not provide a good enough separation between groups and hence does not improve the overall classification. On the other hand, a principal component explaining a very minute portion of the sample's shape variability, corresponding to fine differences in the position of scars and ridges, may show substantial separation. For this reason the discriminant analysis, which detects the shape trends that provide the best discrimination, even if they account only for a small

Table 1
Characteristics and number of items produced by the experimental knappers.

Knapper	Years of experience	Familiarity with archaeological record	Skill level	No. of items
I	20 +	High	High	10
II	20 +	High	High	7
III	5 +	Medium	Medium	10
IV	4	High	Low	10
V	10	Low	Medium	5
VI	4	Low	Low	10

degree of variability is used as a complementary procedure to the principal component analysis, which highlights the shape trends that account for most of the variability in the sample.

3. Materials

The assemblages include 52 artifacts produced by six different knappers (Table 1). These knappers produced the handaxes for several independent experiments conducted in the past decade, and this study took advantage of the available handaxe replica assemblages. Given this, it was essential to apply several criteria for the selection of artifacts in an attempt to isolate the knapper skill level as the only significant independent variable to the highest possible degree. First, the selection included only artifacts made under the general instruction to produce Acheulian-like handaxes, without additional instruction regarding more specific properties of their shapes. This was done to prevent bias that may stem from differing experimental protocols. Naturally, these criteria may introduce some variability stemming from the knapper's individual preference. However, it should be remembered that the preference itself is strongly related to the knapper's skill level, as it is affected by the notion of what shape an Acheulian handaxe should have. Secondly, only artifacts made on locally available, fine grained, high quality flint were included in the assemblage. These criteria restricted the selection to only one type of raw material, excluding others which are significantly different in their properties. Furthermore, as the material was available in large blocks, all the handaxes were modified on flake blanks rather than cobbles. Thirdly, all artifacts were produced using the traditional techniques, that is, direct hand-held percussion using hammers of hard or soft stone or organic materials. Due to the above, while the selection criteria somewhat limited the potential sample size, it minimized the effects of other variables allowing us to monitor the skill level of the knappers.

The six knappers were classified into three different skill levels (high, medium and low). Because the concept of skill is abstract, complex and builds on cultural and social perceptions, the objective evaluation of an individual's skill level entails some difficulties (Finlay, 2008). Hence, the classification was based on two variables corresponding to the defined components composing skill (see above). These include knapping experience (in years), and familiarity with the relevant archaeological record and current knowledge regarding lithic reduction sequences (Table 1).

The first variable, years of knapping experience, corresponds to the practical component of skill. It is generally accepted that the amount of time invested in training is correlated with the skill level of an individual (Howe et al., 1998). Furthermore, various experiments in stone knapping, as well as other crafts, have clearly shown that the amount of experience possessed by individuals (measured in time units, usually years) can be used to determine their skill levels and is positively correlated with their performance (Finlay, 2008; Geribàs et al., 2010; Nonaka et al., 2010; Gandon et al., 2013).

The second variable, familiarity with the relevant archaeological record and current knowledge regarding past lithic reduction sequences, corresponds to the theoretical component of skill. This variable was very important, as it reflects both the individual's familiarity with the reduction sequence used for handaxe production and the understanding of what is a handaxe and what shape it should have. The reduction sequence used for handaxe production is composed of three distinct and ordered stages (roughing-out, thinning and shaping, and finishing), each consisting of multiple reduction events (Newcomer, 1971). Familiarity with this reduction sequence is important, as it may affect the action planning and decision making of the knapper. An erroneous reordering of the sequence will necessarily impact the shape of the final product.

Familiarity with the archaeological record is also very important, as it dictates the mental template of the individual knapper. The mental template consists of the conceptual image that the knapper intends to realize in the physical raw material (Chase, 2008). It can be thought of as a set of formal criteria with which the object must comply in order to be considered as such. Handaxes are not part of the systematic context, as they are exclusively archaeological objects. In other words, they do not have a mundane function for their modern knapper, but rather their essence is dictated by their archaeological definition. Thus the range of acceptable shapes a handaxe should possess in order to be considered as such is directly derived from the familiarity of the knapper with archaeological examples. Therefore, in addition to the years of experience accounting for the practical aspect of skill, the degree of familiarity with the archaeological record was also used to determine the knappers' skill level.

Knapper I is an experienced and professional knapper who mastered his flint knapping skills in various European schools. He is an experimental archaeologist who has participated in numerous scientific archaeological projects that used his great skill and proficiency in flint knapping. Hence, he possesses a wide academic familiarity with the artifacts represented in the European and Levantine archaeological records.

Knapper II is a highly skilled and experienced professional knapper. He is an autodidact who mastered his craft over many years. He is a professional archaeologist who has participated in numerous archaeological projects in Israel. He too has a wide knowledge of the artifacts of the Levantine archaeological record.

Knapper III is an industrial and artistic designer who has only a few years of knapping experience. He has little familiarity with the archaeological record. His knapping skill was acquired from various flint knapping demonstrations and by trial and error. After several years of training he reached a level where he could produce replicas of Acheulian handaxes.

Knapper IV is a PhD candidate (author GH) in archaeology who practices flint knapping in various demonstrations and archaeological experiments. His flint knapping skill was acquired via various online flint knapping instruction as well as participation in a few knapping workshops and personal training. He has a high degree of familiarity with the archaeological record and theoretical knowledge of various production methods and techniques. His items were produced on different occasions as part of his knapping practice before the beginning of this study and were randomly selected for analysis.

Knapper V is a professional, fairly experienced and skilled flint knapper. He utilized his knapping skills at various survival and craftsmanship workshops. Since he is not a professional archaeologist, his familiarity with the archaeological record is rather limited in comparison to Knappers I, II and IV.

Knapper VI is an amateur but a fairly experienced flint knapper. He is an individual interested in archaeology and ancient weapon and tool technologies. He does not practice knapping in a professional manner but as a hobby, in an attempt to replicate various ancient stone tools. He is an autodidact and never learned the skill in an “official” manner, basing his learning on various online instructions and personal practice. He has no formal archaeological training, but is sufficiently familiar with the Acheulian culture and the Lower Paleolithic to produce handaxes.

Table 2
Variability removed in each stage of the generalized Procrustes analysis.

	Sum of square distances	%
Initial value	40,755,246	100.00
Removed by repositioning	5,617,045	13.78
Removed by reorientationing	401,382	0.98
Removed by scaling	30,000,490	73.61
Total residual	4,736,327	11.62

4. Results

4.1. Variability in shape opposed to size

The generalized Procrustes analysis removed from the sample any variability that was non-shape-related. The variability was removed at each stage, leaving only the total variability that stems from shape differences (Table 2). The vast majority of variability was removed by the scaling to centroid size process, while much smaller amounts were removed by the positioning and rotation processes. This is to be expected, given the relatively large size differences of artifacts produced by different knappers and the automated positioning protocol applied prior to the placement of the semi-landmarks.

4.2. Quantification of shape variability – major shape trends

The superimposed coordinate data was subjected to principal component analysis. More than 80% of the variability is explained by the first ten principal components (Fig. 4). The scores represent the relative expression of each shape trend in each object in the assemblage. Accordingly, the first two principal components, which are accountable for approximately half of the shape variability, were plotted alongside the hypothetical shapes on their extremities (Fig. 5). The first principal component represents a shape trend that changes from a rounded thick globular shape to a pointed elongated thin shape. The second principal component represents a shape trend that changes from a triangular shape with slightly concave edges and a thick lenticular cross-section to a triangle with more convex edges and a thin and flat cross-section. Clearly, there is a substantial overlap in the general shape of the products of knapper at different skill levels (Fig. 5) in terms of these specific shape trends, accountable for almost half of the shape variability in the sample. Nevertheless, it is interesting to note that the circumference of the ellipse of less skilled knappers is greater, while the expert knappers are represented by a narrower ellipse (Fig. 5). Thus, the sample made by the two expert knappers is the most homogeneous, while that made by the two novice knappers presents substantially higher shape variability. These results suggest differences between skill levels with regard to the shape variability in their respective assemblages. This observation is corroborated by a *t*-test conducted on the Euclidean distances of the items in each group from the group centroid, which serves here as a univariate index to the shape variability of that group. The distances were calculated using the multidimensional coordinates of each item in the shape space (i.e., its principal component scores). The results support the observation apparent on the scatterplot of the first two principal components, namely, that the high skill knappers produced a significantly more homogenous sample than the low skill level knappers at a 0.05 confidence level. The medium level knappers also present a significantly more homogeneous sample than the low level knappers, however there was no significant difference between them and the high skill level knappers.

4.3. Identification of skill level

Notwithstanding the fact that there are differences in the shape variability of the items in the different skill groups, these still do not allow the classification of individual artifacts into skill groups. To achieve this, the principal component scores were subjected to a discriminant analysis in order to determine whether they can be used to differentiate between the products of the different skill groups. Seven principal components out of 51 were selected for the analysis by using the stepwise forward-selection model. This model is used to highlight those principal components achieving maximal separation between predefined groups. Thus, the analysis incorporated the minimal number of principal components providing the maximal degree of separation. The criterion used to select the principal components was that their

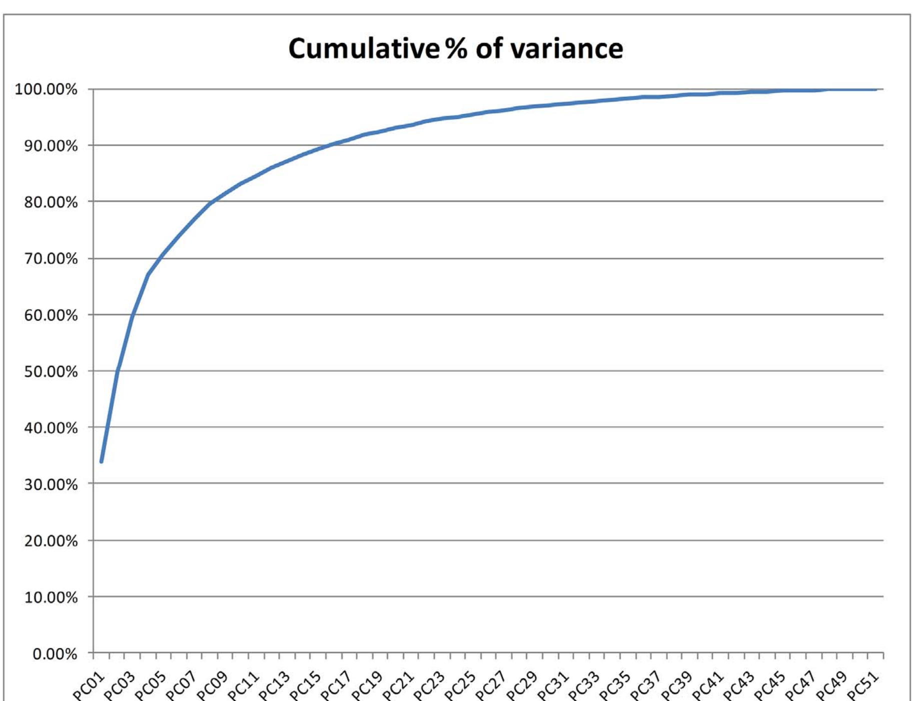

Fig. 4. Cumulative percentage of variance explained by principal components.

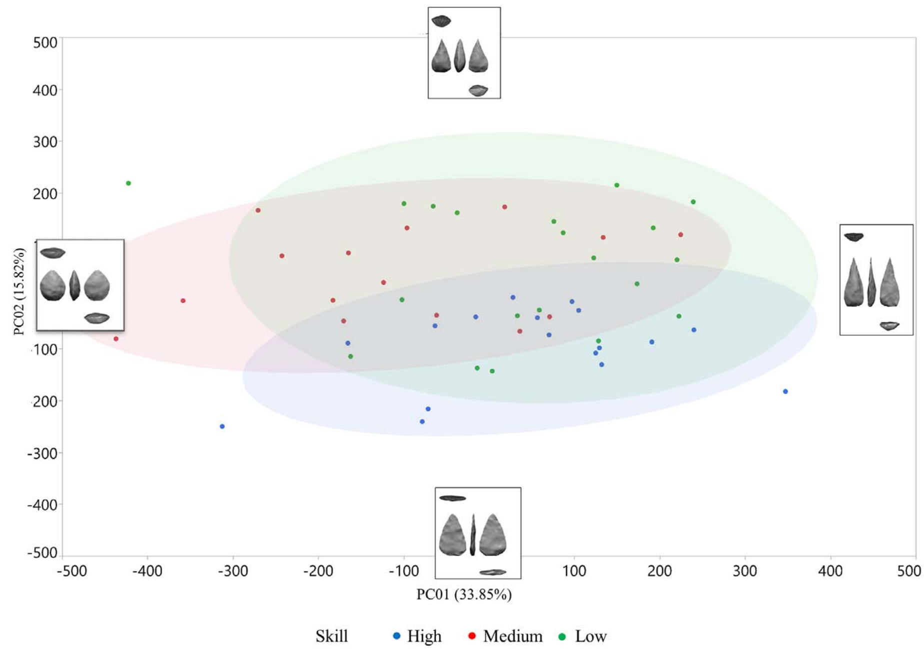

Fig. 5. Scatter plot of principal components 1 and 2. Ellipses represent 90% coverage. The figures represent hypothetical artifacts on the PC's extremities.

Table 3
Principal components selected to be used in the discriminant analysis by the stepwise forward selection model.

Principal component	Eigenvalue	explained variability (%)	F ratio	Prob > F
PC01	31,435	33.85	5.40	0.01
PC02	14,687	15.82	16.40	0.01
PC12	1246	1.34	2.78	0.07
PC13	1123	1.21	2.83	0.07
PC17	790	0.85	3.51	0.04
PC20	561	0.60	3.10	0.06
PC23	448	0.48	3.23	0.05

Table 4
Confusion matrix of discriminant analysis.

Actual skill level	Predicted skill level		
	High	Medium	Low
High	17	0	0
Medium	0	14	1
Low	1	1	18

different groups' mean scores would be significantly different from one another at the 0.1 level (Table 3). Hence, the selected principal components are not necessarily those which explain the most shape variability, rather those that when pooled together provide the best separation. The results of the selection model indicated that these seven specific components provide the highest degree of separation between the groups. The entire assemblage was taken as a training set, used to compute the discriminant functions, and was then subjected to a cross-validation test applying the computed discriminant functions. Three items out of 52 were misclassified, giving a misclassification rate of 5.7% (Table 4).

The results for items on the two canonical functions are shown in Fig. 6. Clear separation was achieved on canonical function 1 between the knappers at a high level of skill at its negative end and the knappers at medium and low levels of skill at its positive one. Canonical function 2 is used to separate the low skill group at its negative end from the medium skill group at the opposite one. Canonical function 1 is influenced mainly by the scores on PC02, PC17 and PC20, and canonical function 2 is based mostly on those of PC01, PC23 and PC12 (Table 5). It can be clearly seen that neither the shape variability explained by the principal components nor their individual separation of group means (F-ratio) have a direct correlation to the degree they affect the canonical functions. Rather, the standardized scoring coefficients, indicating the importance of each principal component to the functions, are calculated from the pooled within-group covariance matrix. Nevertheless, even with this satisfactory separation, there is still some overlap, as is evident from the three misclassified items. One item was misclassified due to overlap on canonical function 1, while two others were misclassified on canonical function 2.

In light of the successful classification rates, and the fact that the morphometric analysis is inherently sample specific, it is highly important to understand the shape properties on which it was based. The shape trends expressed by each of the selected principal components can be described using their coefficients (i.e., factor loadings). Due to the very large amount of data, stemming from the high resolution in which the analysis was conducted, this description is provided through two distinct elements underlying shape difference. The first consists of the distribution of the standardized principal component coefficients across all the landmarks for each of the principal components (Fig. 7). This distribution reflects which of the 4802 homologous landmarks change the most along the shape trend described by the specific principal component. The second is the distribution of the total standardized principal component coefficients across the three dimensions (Table 6). This distribution reflects the nature of change along the described trend, or in other words, on which axis the relevant landmarks show the highest variability.

These results express those shape properties which are significant to the differentiation between products in the three skill level groups. The landmarks' and dimensions' contribution to the first two shape trends correspond to their description in the scatter plot. The first describes a change in the planform view, mainly by configuration of the distal parts of the lateral edges in the width and length dimensions (X and Y respectively). The second describes a change in thickness (Z dimension) of the central part of the handaxe, alongside a less pronounced change in the left edge of the tool which probably corresponds to the width dimension. It is important to note that these two shape trends are accountable for substantial shape variability, corresponding to a larger

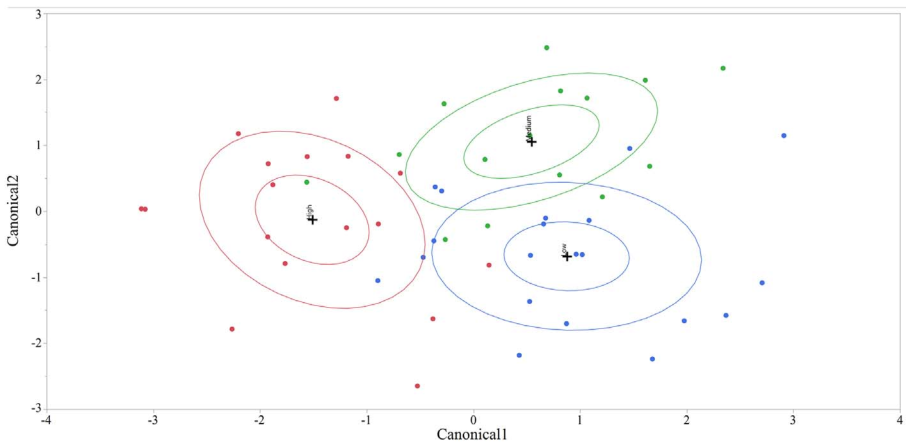

Fig. 6. Scatter plot of canonical axes 1 and 2.

Table 5
Standardized canonical scoring coefficients.

	PC01	PC02	PC12	PC13	PC17	PC20	PC23
CF1	− 0.27	0.96	0.21	− 0.37	0.49	0.48	− 0.09
CF2	− 0.70	0.04	− 0.52	0.36	0.25	− 0.17	0.61

change in the overall shape of the tool. In other words, the trends of PC01 and PC02 correspond to differences in the large scale geometry of the handaxes. Alongside these two, the additional five trends demonstrate a general similarity to that of PC02 with respect to the dimensions' distribution, but are distinctly different with regards to that of the landmarks'. The landmarks' contribution is more evenly distributed. Additionally, some of these trends present 'hotspots', or areas showing higher contribution to the trend, which are fairly small and restricted, corresponding to specific areas of the peripheral edge of the tool. These landmarks mainly change along the Z axis, and explain a small degree of overall shape variability. Thus, these trends can be interpreted as reflecting differences in the regularity of the edges and various aspect of the scar pattern. These may be related to the depth and concavity of specific scars, their concentration at specific areas and regularity with respect to their ridges. Such shape properties are substantially less pronounced than the overall thickness or planform shape, having a much smaller effect on the general large scale geometry of the tool.

The mean shapes produced by each skill level group are presented in Fig. 8 (a–c, Supplementary data). They demonstrate the large scale geometric differences between knappers. It should be noted though, that the relatively stark differences seen in the mean shape reflect the averaging of the shape trends explaining relatively high shape variability in the assemblage. Therefore, these differences would not suffice to provide secure classification of artifacts, and the finer shape trends are masked in these models.

5. Discussion and conclusion

One of the main tools harnessed by archaeologist for comparison between assemblages of various material remains is shape analysis. This study presents a novel and convenient method for describing and analyzing artifact shapes using 3D geometric morphometric analysis and multivariate statistical methods. The data acquisition tool allows automatic positioning and extraction of semi-landmarks. Accordingly, it resolves some of the most fundamental inherent technical difficulties of geometric morphometric analysis of objects. This method can be applied to numerous tool types with two opposed faces with relatively similar size which can be consistently positioned along their maximal length in planform view. Furthermore, it provides objective and consistent classification of artifacts into various categories according to their shape. Thus, it can be used to verify existing relative chronological, regional and cultural classifications, as well as using experimental materials to provide criteria for other types of classification, such as typological ones.

Our test case consisted of experimental handaxes knapped by six different knappers. We were able to confirm the classification of the skill level of knappers based on the shape of their products. In the future, we hope that larger assemblages produced by additional knappers under differing conditions will verify our conclusions.

Two main elements enabled the clear classification of skill level. The first was the high resolution of data acquisition that provided a high-density grid of semi-landmarks placed on 3D models of the objects. In contrast to traditional analysis, which deals with the general morphology, this study enabled an analysis that takes into account subtle differences in morphology such as edges regularity and various aspects of the scar pattern. These are shown to be significant to the differences in shape that are produced as a result of differing levels of skill. Second, the application of discriminant analysis as a complementary multivariate method to the results of principal component analysis was very important to the success of this classification. Individual principal component scores demonstrate substantial overlap among the different groups. Nevertheless, combining several principal components, some explaining minute shape differences, into discriminant functions allows a much clearer and reliable separation between the skill groups.

Future studies will integrate this novel method and apply it to archaeological material in order to address various issues related to the morphological aspect of tools. Further experimental work will apply 3D geometric morphometric shape analysis to elucidate the way in which morphological variability is affected by various other factors such as raw material and production technology. Studies using this analytical approach are currently being conducted to quantitatively measure and describe the morphological variability in bifacial tool assemblages from a number of Levantine Acheulian sites. The insights gained from this study, combined with those obtained by further experimental work, will shed light on the cultural, social and cognitive implications of the morphological variability of Acheulian stone tool assemblages.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2017.05.013.

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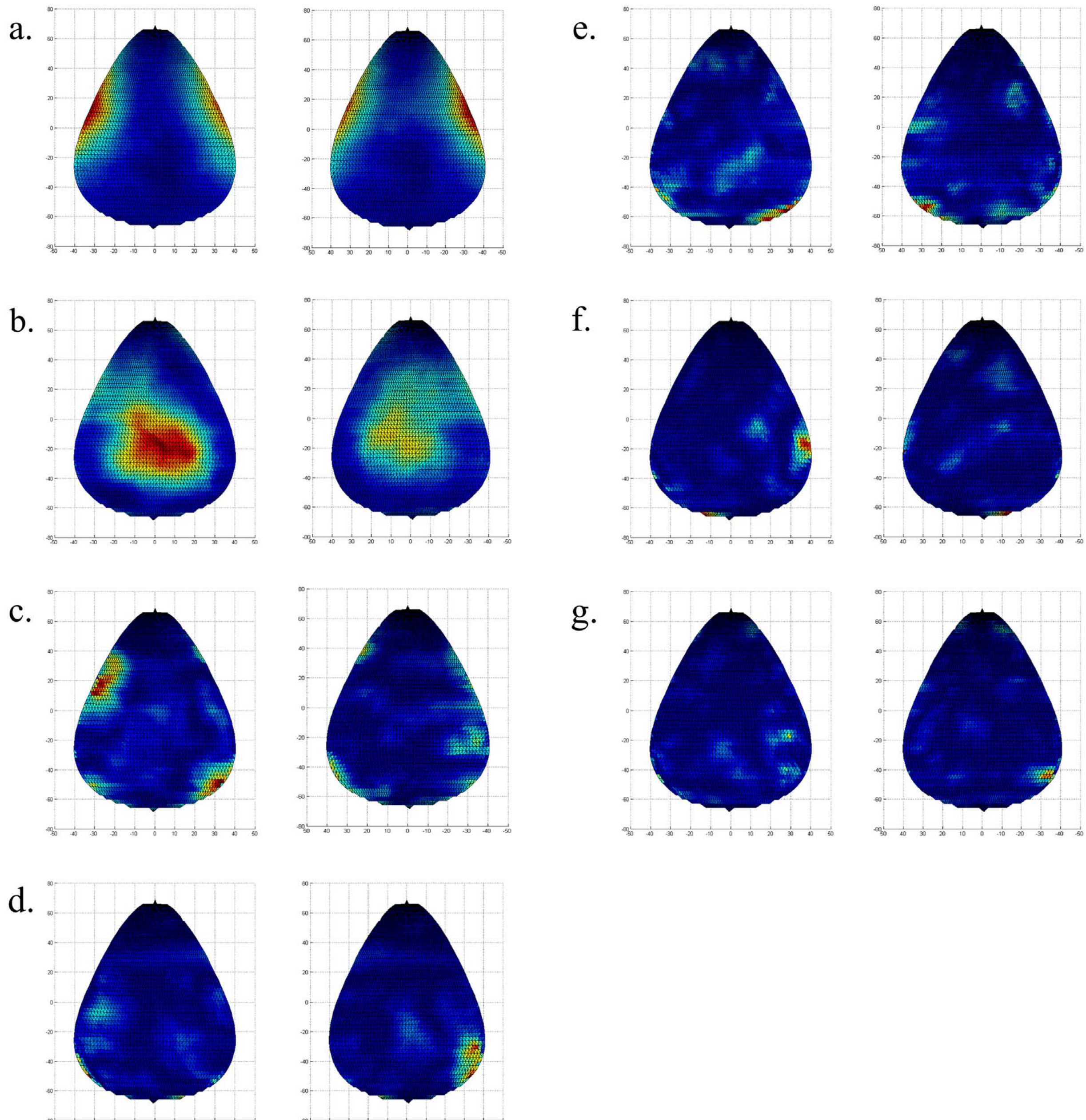

Fig. 7. Distribution of standardized principal component coefficients across landmarks on each of the faces for the selected principal components (blue - low, red - high). a: PC1; b: PC2; c: PC12; d: PC13; e: PC17; f: PC20; g: PC23. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Distribution of total standardized principal component coefficient across dimensions for selected principal components.

	X (%)	Y (%)	Z (%)	Explained variability (%)
PC01	59.26	21.42	19.32	33.85
PC02	26.97	0.24	72.79	15.82
PC12	37.01	0.39	62.60	1.34
PC13	31.94	3.90	64.16	1.21
PC17	30.78	2.03	67.19	0.85
PC20	24.97	0.44	74.60	0.60
PC23	25.23	2.70	72.07	0.48

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