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Influence of handaxe size and shape on cutting efficiency: a large-scale experiment and morphometric analysis

Alastair J. M. Key[1]* and Stephen J. Lycett[2]

*Corresponding Author: a.j.m.key@kent.ac.uk +44(0)1227 827056

[1] School of Anthropology and Conservation, University of Kent, Canterbury, Kent, CT2 7NR, U.K.

[2] Department of Anthropology (Evolutionary Anthropology Laboratory), University at Buffalo, SUNY, 380 MFAC-Ellicott Complex, Amherst, Buffalo, NY 14261, U.S.A.

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Abstract

Handaxes represent one of the most temporally enduring and geographically widespread of Palaeolithic artifacts and thus comprised a key technological strategy of many hominin populations. Archaeologically observable variation in the size (i.e., mass) and shape properties of handaxes has been frequently noted. It is logical to ask whether some of this variability may have had functional implications. Here, we report the results of a large-scale (n = 500 handaxes) experiment designed to examine the influence of variation in handaxe size and shape on cutting efficiency rates during a laboratory task. We used a comprehensive dataset of morphometric (size-adjusted) shape variables and statistical methods (including multivariate methods) to address this issue. Our first set of analyses focused on handaxe mass/size variability. This analysis demonstrated that, at a broad-scale level of variation, handaxe mass may have been free to vary independently of functional (cutting) efficiency. Our analysis also, however, identified that there will be a task-specific threshold in terms of functional effectiveness at the lower end of handaxe mass variation. This implies that hominins may have targeted design forms to meet minimal (task-specific) thresholds, and may also have managed handaxe reduction and discard in respect to such factors. Our second set of analyses focused on handaxe shape variability. This analysis also indicated that considerable variation in handaxe shape may occur independently of any strong effect on cutting efficiency. We discuss how these results have several implications for considerations of handaxe variation in the archaeological record. At a general level, our results demonstrate that variability within and between handaxe assemblages in terms of their size and shape properties will not necessarily have had immediate or strong impact on their effectiveness when used for cutting, and that such variability may have been related to factors other than functional issues.

Introduction

Handaxes represent one of the most temporally enduring and geographically widespread of Palaeolithic artifacts, surpassed in this regard only by simple flake tools and cores (Schick 1998; Gowlett 2011a). From their origin in the Lower Palaeolithic at least ~1.7 million years ago (Lepre et al. 2011; Beyene et al. 2013; Diez-Martín et al. 2015) through to their continued production deep into the Middle Palaeolithic, handaxes represent a key technological component of hominin behavioral strategies throughout the majority of the Old World (Clark 1994; Shea 2007). Handaxes were eventually produced by hominins for over one million years, with a geographic distribution that includes large parts of Africa, through to western Europe, and into the Near East and the Indian subcontinent (Clark 1994; Lycett and Gowlett 2008). Famously, this prodigious geographic and temporal distribution of handaxe artifacts has been described collectively as the "Acheulean" techno-complex. Such artifacts were once considered to be largely absent from East Asia (Movius 1948). However, in recent years, it has become apparent that handaxes were produced, at least sporadically, in parts of eastern Asia (Hou et al. 2000; Norton et al. 2006; Li et al. 2014; Wang et al. 2012), demonstrating that here too hominins occasionally found a need to produce these characteristic artifacts.

Handaxes are traditionally characterized as being "teardrop," "ovate," or "triangular" in their basic outline form. They may essentially be defined by the imposition of a long-axis on artifact form by means of invasive bifacial knapping around the edge of a core, nodule or large flake blank, which results in a tool that has a sharp edge extending around at least the tip (and sometimes the entire outline) of its bilaterally organized form (Roe 1976; Isaac 1977; Gowlett 2006). The archaeological contexts of handaxes along with studies of cut-marks, residue analyses, and design theory indicate these items were used first and foremost (unsurprisingly) as cutting tools in a variety of situations (Roberts and Partfitt 1999; Domínguez-Rodrigo et al. 2001; Simão 2002; Gowlett 2006; Bello et al. 2009; Yravedra et al. 2010; Solodenko et al. 2015). Experimental studies have also demonstrated that handaxes can make highly effective cutting tools, especially during butchery tasks (Jones 1980; Mitchell 1995; Shea 2007; Toth and Schick 2009; Galán and Domínguez-Rodrigo 2014; Key and Lycett 2016). At a basic level of description, there is thus a general pattern seen in Early-Middle Pleistocene handaxes (i.e., essential elements of form) shared by these artifacts over wide periods of time and geographic space (Gowlett 1996, 2006; Mithen 1999). These essential elements of handaxe form or their "bauplan" (sensu Lycett and Gowlett 2008) is, of course, driven by their primary functional role as hand-held cutting tools, or as Gowlett (2011a: 100) aptly put it, "a culturally maintained set of functional solutions to everyday tasks which recur."

Despite an element of stability within the Acheulean techno-complex with respect to basic components of handaxe form, variability within and between assemblages of handaxes has, however, long been a major focus of discussion (e.g., Posnansky 1959; Roe 1968; Isaac 1969; Gilead 1970; Wynn and Tierson 1990; Vaughan 2001; Noll and Petraglia 2003; Pope et al. 2006; Zaidner et al. 2006; Sharon 2007; Chauhan 2010; de la Torre 2011; Beyene et al. 2013; Eren et al. 2014; Stout et al. 2014; Gowlett 2015; Lycett et al. 2016). Indeed, variability within and between assemblages of handaxes in terms of their size and shape properties has been noted as one of their most dominant characteristics (e.g., Isaac 1977; Gowlett 2006: 203). Given their primary role as cutting tools, an obvious question to ask is whether some of this variability may have impacted upon effectiveness and efficiency during cutting tasks. The notion that variation between different artifacts might influence their functional capabilities is described by what Schiffer and Skibo (1997: 31) refer to as the "performance characteristics" of any given artifact. Performance characteristics is a term that refers to activity-specific interactions that will influence how an artifact will perform in a given task in relation to a set of functional properties (Skibo and Schiffer 2001: 143). As Schiffer and Skibo (1997: 31) note, therefore, "performance characteristics are strongly influenced by an artifact's formal properties." Of course, artifact makers (in principle) have the capacity to manipulate these characteristics for their own ends (Bleed 2001; Skibo and Schiffer 2001). In one sense, therefore, study of artifact variability with respect to performance characteristics is a potential route "to begin examination of human adaptation and adaptedness" (O'Brien et al. 1994: 261) in different contexts.

Experimental studies are an obvious way in which performance attributes might be examined (Schiffer and Skibo 1987). Surprisingly, however, there has been little detailed examination of how variation in the form of handaxes might influence their performance during cutting activities. It is only the experimental undertakings of Machin et al. (2007) that have attempted to provide a detailed account of how variable measures in handaxe form influence functional performance capabilities. Specifically, they examined how symmetry variation in an assemblage of 60 replica handaxes influenced the efficiency with which deer carcasses could be butchered. Their intention was to test the hypothesis that varying levels of symmetry associated with handaxes might impact on variable performance rates. Results were, however, largely inconclusive, with only limited evidence for a relationship between higher symmetry levels and increased performance rates.

As we have highlighted, two striking components of variability within and between different handaxe assemblages can be seen in their size (i.e., mass) and shape properties. Here, therefore, we report the results of a large-scale (n = 500 handaxes) experimental study designed to examine the influence of variation in handaxe size and shape on efficiency rates (time taken to complete task) during a controlled cutting task. We utilized a comprehensive dataset of morphometric (size-adjusted) shape variables and statistical methods (including multivariate methods) in our analyses.

Materials and Methods

Experimental Assemblage

To examine how size and shape potentially influences a handaxe's ability to be used as an effective cutting tool, we produced a large and variable experimental assemblage likely to include relatively efficient and inefficient tool forms (i.e., if there is a strong relationship between form and function). Moreover, it was necessary for replica tool forms to go beyond those typically found in the archaeological record, in order to push the ranges of variability. Consequently, although tools at the extremities of variation in the experimental assemblage may not traditionally be considered typical of classic Early-Middle Pleistocene handaxes (although many are), all the artifacts used here were bifacially flaked forms and possessed a sharp edge suitable for cutting (i.e., they are bifaces in the general sense). Despite the morphological variability in the experimental assemblage, all tools are hereafter referred to as handaxes for ease and clarity.

Over the course of 18 months, 500 handaxes were knapped by the authors from English flint sourced in Suffolk and Kent (480 were knapped by AJMK and 20 were knapped by SJL). These 500 handaxes are depicted in Figure 1. Hard and soft (antler) hammer percussion was used and handaxes were produced from both nodules and large flake spalls. Tool forms were purposefully produced to be highly variable, with both morphologically extreme and archaeologically representative handaxe forms being produced. Hence, handaxe length in our experimental assemblage ranged from 38.8 to 296.3 mm, while mass ranged from 8 g in the smallest example to 4485 g in the largest. Our primary consideration, despite this variability, was that (in principle) the resultant handaxe could be used as a hand-held tool by participants during the experimental cutting task. Following production, handaxes were individually numbered (1–500) to facilitate monitoring during the experiment. Table 1 describes a series of summary statistics for a set of basic morphological variables for the experimental assemblage (i.e., length, width, thickness, mass, elongation [width/length], and refinement [width/thickness]) alongside equivalent data (where available) for a series of Pleistocene handaxe assemblages. Although we utilize a more comprehensive set of morphometric (shape) variables for our main analyses (see below) these descriptive statistics provide a general depiction of variability within the experimental assemblage and allow comparison to archaeological examples.

Measuring size (mass) and shape variability in the experimental handaxes

Size (Mass)

Size and shape are two distinct properties of any three-dimensional object (Jungers et al. 1995) including lithic artifacts (Lycett 2009). Shape, in quantitative terms, is inherently a multivariate property of an object and its measurement is, therefore, reliant on the relative relationships between multiple aspects of morphometric variation in a given object. The size of an object, however, is a univariate property and can thus be adequately described in quantitative terms by a single measure of scale such as volume. Where differences in density between the objects being measured is not a major factor (e.g., when raw material is the same across objects), then mass will adequately describe differences in size between objects. In the case of stone tools, mass/size differences between different artifacts is particularly relevant in a functional context since it has been shown that such scaling differences may relate to loading factors (i.e., force applied during cutting) and, in turn, efficiency patterns in cutting tasks (Key and Lycett 2014, 2015). Given that all the experimental handaxes under consideration here were comprised of the same raw material (i.e., flint) mass was, therefore, used as a convenient measure of size variability across the 500 handaxes. Mass was recorded to the nearest tenth of a gram (g) using digital scales. It should also be noted that mass was highly correlated with dimensional variables, such as length ($p = <0.0001$, $R^2 = 0.68$), so discussion of mass variation inevitably also relates to raw dimensional variability.

Shape

We used a morphometric dataset of 29 size-adjusted (scale-free) variables to capture shape variability in the 500 experimental handaxes. A digital–photographic system, similar to that used elsewhere (e.g., Schillinger et al. 2014; Eren et al. 2014) was employed to obtain the morphometric data. For consistency, it was necessary to first orientate each handaxe into a standardized position. The superior surface of each handaxe was identified as the surface exhibiting the greatest number of flake scars above $0.5cm^2$ (Lycett et al. 2006). Thereafter, each handaxe was positioned on a photographic copy-stand next to a 10 cm scale bar with the camera lens placed at a fixed distance (30cm). The scale bar was positioned level with the handaxe's cutting edge in each instance. As in previous studies (e.g., Costa 2010; Schillinger et al. 2014), the orientation procedure proceeded on a step-by-step basis:

1) The digital image was loaded into the open source image-analysis program Image J.
2) Using the scale bar, the scale of the image was set so that each pixel represented a known distance in mm.
3) The tip and base ends of each handaxe were identified. Ideally, the tip was defined as the longitudinal end of the handaxe that forms the most acute angle at the intersect of the left and right cutting edges. When this was not immediately obvious (e.g., ovate or more discoidal handaxes) the base was identified as the portion containing the proportionately higher proportion of mass.
4) A line of maximum length was then recorded on the digital image using Image J. The line of maximum length in each case was defined as the longest continuous straight line observable across the superior surface of the handaxe (Figure 2).
5) The distal (tip) end of the line of maximum length subsequently defined a locked landmark used for subsequent orientation (Figure 2).
6) A longitudinal straight line was then drawn from the locked landmark so that the maximum distances to the left and right edges of the handaxes were equal to this line.

This procedure thus orientates each handaxe around its axis of maximum symmetry. This line was saved onto each image using the overlay feature within Image J (Figure 2).

7) Finally, the handaxe image is then orientated so that the line of maximum symmetry is vertical. This is then the final orientated position for each handaxe (Figure 2).

Following orientation, a series of 29 metric variables were recorded in mm using Image J (Figure 3). These 29 metric variables included maximum length (by orientation), maximum width (by orientation), maximum thickness (by orientation), and 26 additional variables in both plan- and profile-views (Figure 3). These latter 26 variables included 13 plan-view (width) measurements recorded at specified percentage points along the length of each handaxe, and an equivalent set of 13 measurements capturing variation in thickness (profile-view) measurements down the length of each handaxe (Figure 3).

To ensure dimensional data reflected shape properties (rather than merely size or scaling differences) between handaxes, all raw measurements were size-adjusted via use of the geometric mean method (Lycett et al. 2006). This method of size-adjustment has been shown to effectively remove isometric size (scaling) differences between specimens, while retaining their relevant shape information (Falsetti et al. 1993; Jungers et al. 1995). The geometric mean for a series of n variables (e.g., a_1 to a_n) may be computed as: $\sqrt[n]{a_1 \times a_2 \times a_3 \times \ldots \times a_n}$. In straightforward terms, the geometric mean is the nth root of the product of all n variables (Sokal and Rohlf 1995: 43). The method proceeds on a specimen-by-specimen basis, and involves simply dividing each variable for a particular specimen, in turn, by the geometric mean of all the variables for that specimen.

Participants and division of the experimental handaxe assemblage

Five participants were recruited via advertisement from the graduate student population at the University of Kent. None of the participants were from disciplines focusing on Palaeolithic archaeology. Each was paid a nominal remuneration of GBP£50 (~US$75) for their participation. Only five participants were used to deliberately limit (i.e., control) the extent of inter-participant variability during the experiment, and thus place greatest emphasis on variability in the 500 handaxes. Consequently, each participant used 100 handaxes (i.e., repeating the experimental task 100 times, once with each handaxe they were assigned). To further minimize biometric inter-participant variation (cf. Key and Lycett 2011; Key 2013), only males displaying relatively high manipulative strength capabilities were recruited for the experiment (Mathiowetz et al. 1986; Massy-Westropp et al. 2011). Their grip and pad-to-side pinch strength ranged from 48–70 kg and 8.1–13.7 kg respectively, which was measured using a Jamar dynamometer and pinch-strength gauge. We also cross-checked that statistical patterns were consistent both when data across all five participants were examined, as well as at the individual level.

It has been suggested that specific derived features of the hominin hand and wrist originated at least by the time handaxes appear in the archaeological record (Tocheri et al. 2008), perhaps also suggesting that hominin anatomy had to be close to that of modern humans to be able to make and use such technology effectively. Indeed, recent fossil discoveries support the contention that modern human-like hands and post-cranial anatomy emerged prior to, or coincident with, the first appearance of handaxes (Ward et al. 2014; Domínguez-Rodrigo et al. 2015; Lorenzo et al. 2015). This makes experiments using modern humans useful referents for Pleistocene handaxe users.

The 500 handaxes were randomly divided into five groups of 100 handaxes for use by each of the participants. This evenly distributed the morphological (size and shape) variation observed within the experimental assemblage between participants. To determine that participants did indeed receive, on average, similar distributions of handaxes of equal mass, a one-way analysis of variance (ANOVA) was undertaken to test for any statistical differences between the sets of handaxes assigned to each participant. This analysis indicated that the masses of the 100 handaxes assigned to each participant were, on average, statistically equivalent (F [4, 495] = 1.253, p = 0.288). Likewise, to test that handaxe shape variability was statistically even between participants, a multivariate analysis of variance (MANOVA) was undertaken on all size-adjusted shape variables of the handaxes assigned to each participant. Again, this analysis revealed no statistical differences between the handaxe sets assigned to each participant, using two different test statistics (Wilks' lambda = 0.7661, F [116, 1858] = 1.111, p = 0.204; Pillai's trace = 0.2573, F [116, 1880] = 1.114, p = 0.197). Hence, it can be confidently stated that each participant was assigned a set of handaxes displaying statistically similar size and shape properties.

Experimental task

A specific aim of our experiment was to provide identical, replicable cutting-task conditions in order that performance characteristics of the 500 handaxes could be compared under consistent cutting demands. Hence, we designed a task that used industrially produced and synthetic products that invoked a variety of cutting/deformation requirements (i.e., piercing, cutting, slicing). While this experimental protocol does not directly replicate Lower Palaeolithic behaviors, it provides identical (i.e., consistently controlled) cutting demands across all 500 handaxes. Moreover, all tasks are intrinsically straightforward and thus control for the effects of varying skill level that become pertinent in tasks that require more specialized knowledge, a problem identified in previous experiments involving butchery of real animal products (see e.g., Machin et al. 2007).

Due to the varied material contexts in which handaxes were likely to have been used, we utilized different types of material during the task. These were sheets of double-walled corrugated cardboard (7.5mm thick, board grade = 125), two solid neoprene (synthetic rubber) strips (30 mm wide × 2 mm thick), and three sections of polypropylene rope (6 mm thick). All three types of material are industrially produced, easily sourced, consistent in terms of their material properties across multiple samples, and importantly, are amenable for employment in cutting tasks using handaxes (i.e., handaxes are able to cut each material type within a practical period of time). Importantly, however, they also have divergent material properties and present distinct task conditions during their separation (i.e., when being cut). At a general level, these materials can be divided into those requiring forceful and relatively inaccurate cutting motions, where substantial lengths of material are required to be cut (i.e., the cardboard), and those requiring more accurate, precise cutting motions being applied repeatedly (localized cutting) on materials of limited volume (i.e., rope/neoprene strips). We also designed the experiment so that different cutting angles were required during the tasks. When cutting the cardboard, for instance, several different cutting angles needed to be applied, while the rope and neoprene only required cutting motions along a single axis (Figure 4). The importance of this is that Paleolithic handaxe use is unlikely to have been solely characterized by repetitive linear actions along horizontal/vertical plains, but rather, would have been variable and required readjustment and realignment of hand and tool during cutting. Our tasks replicated this demand.

The three materials and cutting tasks were positioned on a wooden structure that was presented to participants (Figure 4). There were 11 lengths of cardboard that had to be cut, with these being spread across two sheets fixed onto either side of the structure using steel wing-nut bolts. The variable designs of these 11 lengths are shown in Figure 4. These designs were individually drawn on each of the 1000 (2 × 500) sheets of cardboard using premade stencils and, hence, the design and length of cardboard was identical in each instance. Participants undertook the task in the numerical order outlined in Figure 4, and were instructed that the entire length drawn upon the cardboard must be cut.

The rope and neoprene strips were attached (10 cm wide) between the two sheets of cardboard on the wooden frame (Figure 4). Both were pulled taut and secured into place using 25mm staple nails. Participants were required to cut the two neoprene strips before the three rope strips. The wooden structure was designed so that beams did not obstruct handaxe use during the tasks, but provided support to the cardboard so that it did not unduly bend or distort under pressure (Figure 4). As shown in Figure 5, the wooden structure was placed on the floor during the task rather than on a table, thus requiring a body position that is more likely similar to that used in Palaeolithic contexts. More importantly, this also allowed the structure to be stabilized against a wall and substantial force to be applied during cutting, if required.

Each participant took part in 7–10 days of experimental sessions, using between 10–15 handaxes each day. A random number generator was used to determine the order of handaxe use. Due to the use of several handaxes per day, there was the risk of fatigue and, consequently, the potential for this to influence results. In order to control for this, each participant took at least five minutes rest between cutting sessions, allowing muscular strength to adequately recover (Pitcher and Miles 1997). Participants only undertook the task using the next handaxe when they felt comfortable doing so. Linear regression confirmed that there were no statistically significant relationships between the order of tool use within experimental sessions and efficiency values, thus verifying the success of this experimental strategy.

All participants were provided with personal protective equipment: knee pads, a face mask, and a thin, durable glove for the working hand (Figure 5). The latter was essential for health and safety purposes since handaxes can exhibit highly variable sharp edges and the likelihood to cuts to the hand was high (particularly given the number and variety of tools required to be used by each participant). The distal tips of the fingers (up to the proximal interphalangeal joint) were, however, removed from the glove so that it was still possible for the handaxe to interact directly with the participant's hand. Essentially, the finger-less glove protected the palm of the hand while allowing free movement and direct contact of fingers with the surface of each tool.

Participants were instructed that they must complete the task in as quick a time as possible and that all cutting actions should be undertaken in a controlled manner. Prior to the experiment, participants were shown a video of one of the authors (AJMK) completing the task to facilitate comprehension of what was required.

Measuring cutting efficiency rates

Energy and time expenditure are the two principal methods by which efficiency rates have been considered in relation to lithic tool use patterns (e.g., Bleed and Bleed 1987; Torrence 1989). Of course, in the case of manual labor, time expenditure and energy expenditure will inevitably be related. Here, cutting efficiency was measured by the time taken to complete the task, recorded in seconds. Time is widely used in experimental analyses investigating stone tool efficiency and is known to be highly correlated with other efficiency measures, such as the number of cutting strokes used (Jobson 1986; Machin et al. 2007; Key and Lycett 2014).

Time data were recorded from when each handaxe first made contact with the material to when it broke contact on the final cutting stroke of the task. On occasions when participants stopped, readjusted the handaxe, or otherwise ceased from cutting, the timing was paused and only continued when cutting commenced again. Hence, our recorded cutting efficiency times only reflect the actual time that a handaxe was actively engaged in cutting, not total task time.

Statistical analyses and predictions

Handaxe size and efficiency

Handaxe mass/size differences may be relevant in a functional context, especially since tool size has been shown to influence loading factors (i.e., force applied during cutting) and, in turn, efficiency patterns in cutting tasks (Key and Lycett 2014, 2015). Here, we tested the hypothesis that handaxe size was related to functional efficiency by determining if there was a statistically significant (α = 0.05) relationship between cutting times and handaxe mass using linear (least squares) regression. The regression was undertaken using PAST v.3.08 (Hammer et al. 2001).

One potential problem with the above approach, is that efficiency rates may not directly increase with greater handaxe size/mass, but rather, only relatively small/light handaxes may be markedly inefficient. That is, rather than there necessarily being a strong relationship between increasing handaxe mass and efficiency when all 500 handaxes are considered, there is a (task-specific) size/mass threshold below which tools tend to become markedly inefficient compared to larger, heavier examples. Certainly, such a pattern has been found previously in respect to stone flake tools (Key and Lycett 2014). Accordingly, we also ran a second analysis to determine if this might be the case for handaxes. This involved repeating the linear regression as before, but examining just the lightest 10% (i.e., n = 50) of handaxes from the total sample of 500. If only particularly lighter/smaller handaxes are markedly inefficient, we should expect to see a stronger relationship between handaxe mass and cutting efficiency rates here than when all 500 handaxes are considered collectively, whereupon the efficiency of heavier examples might dilute any statistical signal of relative ineffectiveness in the smallest examples. Running this second analysis allows us to circumvent this problem and determine if there is a threshold effect with respect to small/light handaxes and cutting efficiency. We also undertook the same procedure examining the 50 handaxes with the greatest mass to look for a potential relationship at the upper end of our range.

Handaxe shape and efficiency

To assess the potential influence of handaxe shape on cutting efficiency, we used the 29 size-adjusted shape variables recorded on the 500 handaxes. Firstly, to examine shape variability among all 500 handaxes, we undertook a Principal Components Analysis (PCA). PCA allows major patterns of shape variation between individual objects (in this case handaxes) to be examined in a hierarchical fashion, whereby the first PC describes the major axis of shape variation (size having already been controlled for here), the second PC describes the second major axis of shape variation, and so on (Quinn and Keough 2002; for similar applications using lithic data see e.g., Lycett et al. 2010; Eren et al. 2014). We undertook the PCA using PAST v.3.08 (Hammer et al. 2001). Thereafter, we regressed the scores from the first PC (i.e., the major axis of shape variation in the data) against cutting times for all 500 handaxes. If handaxe shape is having a major impact on cutting efficiency, there should be a marked and statistically significant ($\alpha = 0.05$) relationship between these two variables. Given that the first PC only accounts for a portion of the total shape variation in the data (albeit the major component), we undertook a second statistical analysis whereupon we regressed scores from multiple PCs that accounted (cumulatively) for at least 95% of total shape variation in the data. This was achieved by implementing a multiple linear regression of the relevant PC scores against cutting times.

Results

Handaxe size and efficiency

Regression of the mass of all 500 handaxes against cutting times (Figure 6) indicated no significant relationship between these two variables ($R^2 = 0.003$; $p = 0.252$). Hence, when data for all 500 handaxes are considered collectively, size/mass appears to have had little impact on the functional efficiency of handaxes during the experimental cutting task.

Regression of the lightest 10 % (i.e., $n = 50$) of handaxes, however, indicated a statistically significant result (Figure 7; $R^2 = 0.27$, $p = 0.0001$). The results of this latter analysis thus indicate that although cutting efficiency does not strictly increase linearly with increasing handaxe size/mass when all 500 handaxes are considered, there is a (task specific) threshold effect with respect to handaxe size/mass, below which, particularly light/small handaxes become markedly inefficient with respect to handaxes above that threshold. We also identified a statistical (but weaker) relationship in the heaviest 10 % of handaxes ($p = 0.041$, $R^2 = 0.084$). This in line with the fact that (inevitably) there will be a change in efficiency for handaxes of high mass at some point, even though an absolute cut-off for use was not identified here.

Regressions of mass against efficiency for individual participants and their 100 handaxes found no statistically significant relationships between these two variables (see online supplementary Table 1). Hence, patterns seen across all 500 handaxes were consistent when data for individual participants were considered, thus controlling for any inter-participant variation.

Handaxe shape and efficiency

Figure 8 shows the major patterns of shape variation as revealed by the Principal Components Analysis. Regression of the scores from the first PC (57.2 % of total shape variation) against cutting times did not indicate a statistically significant relationship between shape variation across the 500 handaxes and their functional efficiency during the experimental cutting task (Figure 9; $R^2 = 0.007$, $p = 0.069$). (It should be noted that even if this result is considered to approach significance [i.e., $p < 0.1$], less than one percent of variation in efficiency is explained by shape variation). No statistically significant relationships were observed at the extremes (upper and lowest 10 % values for PC1) of the shape data (supplementary information). Multiple regression of the scores from PCs 1–6 (i.e., cumulatively accounting for 95.4% of total shape variation) also indicated no significant relationship between handaxe shape variation and cutting time ($F = 1.7632$, $p = 0.105$). In sum, these analyses indicate that shape variation between handaxes had no significant impact on their cutting efficiency during the experimental task.

A multiple regression of the component scores for the first six PCs derived from separate analysis of the 100 handaxes assigned to each of the five individual participants, supported the conclusion that shape had no major impact on cutting efficiency. Analysis of the relevant data for four out of the five participants indicated no significant relationship between PC scores and cutting times (see online supplementary Table 2). Although a significant relationship between shape data and cutting time was indicated for one of the participants, only around 20% of variation in cutting rates exhibited a relationship with handaxe shape in this single instance (online supplementary information). No such relationship could be detected in the data for the remaining four participants. Hence, patterns seen across all 500 handaxes were consistent when data for participants were considered individually, and supported the conclusion that handaxe shape variability had no marked impact on cutting efficiency, even when inter-participant variation was controlled for.

Discussion

The production of handaxes is a feature of Pleistocene hominin societies that stretched over three different continents and for in excess of one million years—a behavioral pattern traditionally linked under the term “Acheulean.” Unsurprisingly, given these swathes of time and space, variability within and between different assemblages of handaxes is a notable feature of the

Acheulean techno-complex (e.g., Roe 1968; Isaac 1977; Wynn and Tierson 1990; Crompton and Gowlett 1993; Lycett and Gowlett 2008; Petraglia and Shipton 2008; Beyene et al. 2013). As others have noted, it is logical to ask whether some of this variability in both size and shape properties may have had functional implications (Posnansky 1959; Isaac 1977; Jones 1980; Crompton and Gowlett 1993; Phillipson 1997; Vaughan 2001; Shipton et al. 2013). Here, we assessed this question via a large-scale experiment involving 500 handaxes, examining links between handaxe form and functional efficiency in a laboratory cutting task. We deliberately focused on how variation in shape and size—two empirically distinct but recognizable features in handaxe assemblages—might impact upon cutting efficiency. We used morphometric data and statistical procedures to formally evaluate any such relationships.

Our first set of analyses focused on how size variability across different handaxes potentially impacted upon function. Size is a feature of stone tool variation that is inevitably linked to the issue of tool mass. Size/mass of stone cutting-tools may be particularly relevant in a functional context in respect to its potential influence on loading factors (i.e., force applied) and, in turn, efficiency patterns during cutting (Key and Lycett 2014, 2015). Across the 500 handaxes used in our experiment, regression of handaxe mass against cutting times indicated no statistically significant relationship between these two variables. This pattern also held when we examined the data for different individuals. This implies that across all 500 handaxes, variation in mass had no immediate or strong impact upon their effectiveness and efficiency rates during the cutting task. In other words, at a broad scale of variation, handaxe mass may, in some situations, have been free to vary independently of functional (cutting) efficiency in archaeological contexts.

In designing our statistical analyses we noted, however, that cutting efficiency may not necessarily increase directly with greater handaxe size/mass. That is, rather than there necessarily being a strict relationship between increasing handaxe mass and efficiency when all 500 handaxes are considered, there could potentially be a (task-specific) size/mass threshold below which only the (relatively) smallest handaxes tend to become markedly inefficient compared to larger, heavier examples. We also, therefore, undertook a second analysis of mass variation and cutting efficiency, examining just the lightest 10 % of handaxes from our total dataset. This second analysis revealed a statistically significant relationship between handaxe mass and cutting times. What this second analysis indicates is that although mass variation seen in many handaxe assemblages (at a broad scale), may not have necessarily had immediate or strong impact upon effectiveness, there is a (task-specific) size/mass threshold below which handaxes tend to become markedly inefficient compared to larger, heavier examples. In other words, while cutting efficiency does not necessarily increase directly with greater handaxe size/mass, there is a threshold at the lower end of handaxe mass that has definite implications in terms of cutting efficiency. It should be stressed that this threshold is task-specific, with the details of individual cutting tasks (resistance of material, etc.) resulting in variation of the precise drop-off point at which the lower range of mass becomes statistically potent. Nevertheless, these results demonstrate that the lower end of variation in handaxe mass may have been functionally relevant to hominins in specific circumstances. Indeed, we find it suggestive that in the lightest 50 (10 % of total) handaxes that we analyzed, only five of those were above 100 mm in length. This is interesting given that it has been frequently noted that a majority of Early-Middle Pleistocene handaxes generally possess a length greater than 100 mm across many regions (e.g., Isaac 1969; Wynn 1995; Sharon 2010; Beyene et al. 2013; Gowlett 2015). Hence, the results of this experiment indicate why hominins may have routinely targeted the production of handaxes with sizes that exceed this range (see e.g., Table 1).

These experimental results, with respect to issues of handaxe size, have several additional archaeological implications. Firstly, in regard to cutting efficiency, we cannot immediately assume that size variation within handaxe assemblages was directly related to concerns about functional effectiveness in cutting tasks. A reasonable implication from our results is, in fact, that handaxes will have been free to vary in terms of their size/mass properties without necessarily incurring any immediate or strong impact upon their effectiveness and efficiency rates when used as cutting tools. Our results also caution against assuming that relatively large examples of prehistoric handaxes (see e.g., Wenban-Smith 2004; Wang et al. 2014) were necessarily functionally inviable. Indeed, a specimen such as that from Furze Platt, England (Wymer 1968: 224), which at 2800 g has sometimes been considered too large for functional application (e.g., Kohn and Mithen 1999: 518) is well within the range of mass variation (i.e., 8–4484 g) used during our experiment. There will, of course, inevitably be some upper size threshold for efficient handaxe use, and this is supported by our results here. However, as previously noted by others (e.g., Crompton and Gowlett 1993: 198), it is possible to effectively utilize handaxes with two hands (dependent upon the task) and this is likely to have increased the point at which handaxes became too large to be used as efficiently cutting tools. In fact, our results imply that intra-population physical variability on the part of handaxe-users may be a more important factor in determining the observable size variation in archaeological assemblages, than a direct relationship between handaxe mass and cutting effectiveness per se, at least with respect to the majority of handaxes in the archaeological record. Participant physical variability in our experiments was strategically constrained; that is, the experimental participants we used here were males of moderate strength, and weaker individuals would perhaps not have used the heaviest examples of handaxes in our experiment with such deftness, while extremely strong individuals within extinct hominin populations may have been able to use even heavier handaxes than used here. As others have noted, we can reasonably expect that population variability in hominin societies, with respect to individual strengths and preferences (see e.g., Niewoehner 2001), may have influenced some of the assemblage-level variability observable in the archaeological record (Jones 1980; Crompton and Gowlett 1993; Kempe et al. 2012). Our results support this contention, while noting that an individual hominin may not necessarily have gained any benefit by maximizing tool size relative to their own strength; that is, using a lighter handaxe may have resulted in equally effective cutting.

At the lightest/smallest extreme of handaxe mass variability, our results have further archaeological implications. As we have noted, concerns to manage this lower threshold property would not only potentially have driven acceptable limits on the minimum viable size of a handaxe, but may also have implications for the management of resharpening and discard behaviors, which have sometimes been argued to have been a feature affecting variation within and between different sets of handaxes (e.g., McPherron 1999). Such considerations may also explain why handaxe size parameters in archaeological assemblages tend to fall within specified ranges over large swathes of time and space during the Paleolithic (Kempe et al. 2012). That is, handaxes too large to be utilized effectively would understandably have been relatively rare, while on the other hand a majority were either deliberately made above ~100 mm in length or discarded above this size (see e.g., Tables 1). However, while resharpening may be a factor affecting size and/or shape in some handaxe assemblages, Shipton and Clarkson (2015) have recently shown that certain handaxe assemblages in Britain at least, contained examples that do not seem to have been resharpened extensively. Indeed, Shipton and Clarkson (2015: 417-418) contend that British handaxes of the Middle Pleistocene were discarded prior to exhaustion, such that this implies short handaxe use-lives and short-term activity planning on the part of hominins. Given that only the smallest/lightest 10% of handaxes (~ ≤ 100 g) displayed reduced effectiveness during the experiment, and the comparative data from at least some British sites (e.g., Table 1), our experimental results appear to support Shipton and Clarkson's (2015) conclusions. Extending this pattern at a broader geographic scale (see e.g., Table 1) our experimental results would imply that a majority of Early-Middle Pleistocene handaxes were discarded at a point of size/mass when they still had much potential as effective tools.

These findings also imply that the occurrence of assemblages of relatively small or so-called "diminutive" handaxes, as noted, for instance, on the Indian subcontinent (James and Petraglia 2005; Chauhan 2009; Shipton et al. 2013), may have been used in tasks demanding somewhat different considerations (i.e., activities other than cutting) than those motivating the production of larger handaxes. Scraping perhaps provides the most obvious functional alternative, although it would go beyond our results to speculate further on this. Intriguingly, however, Gowlett (2011b) has noted in a discussion of potential links between handaxe size and function that in certain modern tools—for example, screwdrivers—there is greater variety in the small ones that appears to be task-specific (e.g., slender electrical screwdrivers versus small stubby versions for larger screws in small workspaces). Experimental studies examining the functional capacities of larger versus smaller handaxes in tasks other than cutting (e.g. scraping) would, therefore, be an interesting extension of our results.

Our second set of analyses focused on the issue of how handaxe shape variability potentially impacted upon functional efficiency during the experimental cutting task. To assess the hypothesis that the observed shape variability within and between different archaeological handaxe assemblages may have impacted upon their cutting efficiency, we undertook a multivariate (Principal Component) analysis of the morphometric shape variables recorded on the 500 handaxes in our experimental dataset. In our first analysis, we regressed the scores from the first PC (i.e., the major axis of shape variation in the data) against cutting times for all 500 handaxes. This analysis found no statistically significant relationship between shape variability and cutting efficiency. In a second analysis, we regressed scores from multiple PCs that accounted (cumulatively) for at least 95 % of total shape variation in the data against cutting time. Consistent with our first analysis, this also found no statistically significant relationships between handaxe shape variability and cutting times. We also analyzed the data for individual participants, regressing multiple PCs (≥ 95 % of total shape variation) derived from analysis of their handaxes against cutting times. In four out of five cases, these analyses found no evidence of a significant relationship between handaxe shape and cutting effectiveness in the task. Collectively, therefore, these results overwhelmingly support the conclusion that handaxe shape had no immediate or strong effect on cutting efficiency rates during the course of the experiment.

This second set of analyses suggest that handaxe shape variation observed archaeologically, within and between various assemblages, will not necessarily have had functional consequences in respect to cutting effectiveness. At the very least, our experimental results suggest that considerable variation in handaxe shape may occur in the absence of any immediate or strong effect on cutting efficiency. Gowlett (2006) has indicated that handaxe production may have been primarily geared toward imposing what he terms a set of functional "imperatives," including: elongate form, forward extension, and support for the working edge. What our analyses indicate, however, is that once these basic and rather general aspects of handaxe form have been imposed, shape has limited functional inference thereafter. Indeed, the notion of a considerable zone of free play in respect to handaxe shape variability has been a steadily recurring theme of discussion within the literature (Isaac 1972; Crompton and Gowlett 1993; Gowlett et al. 2001; Lycett et al. 2016). Given our results, the existence of such evident shape variability in the archaeological record is all the more intriguing if it is not obviously tied to cutting effectiveness. One heavily discussed possibility for driving handaxe shape variability is raw material properties (e.g., Roe 1968; Isaac 1977; Wynn and Tierson 1990; Schick 1994; Clark, 2001; Noll and Petraglia 2003). However, recent studies of archaeological material (e.g., Sharon 2008; Costa 2010; Lycett and von Cramon-Taubadel 2015) as well as experimental studies (Eren et al. 2014) suggest that raw material is not necessarily the paramount driver of handaxe shape variability. An alternative is that differential reduction and/or resharpening is driving the variation (McPherron 1999), although as we have noted, other studies have also questioned the role of this factor at least as a predominant or singular factor (Shipton and Clarkson 2015). Given these issues, and the findings reported here, the role that cultural (i.e., socially learned) factors related to manufacturing and discard behaviors may have in influencing patterns of handaxe variability can be highlighted (e.g., Petraglia et al. 2005; Stout et al. 2014; Lycett and von Cramon-Taubadel 2015; Lycett et al. 2016). Indeed, our experimental results are consistent with suggestions that non-functional aspects of handaxe shape variation may have been subject to cultural drift within hominin systems of social transmission (Lycett 2008; Lycett and von Cramon-Taubadel 2008).

We do, however, (re)emphasize that certain caveats must be applied to the implications derived from our experiment. Firstly, our analyses have taken a broad sweep approach to variability in handaxe size and shape; it may, therefore, yet be feasible that very particular aspects of handaxe form could be found to have an impact on handaxe functionality other than indicated by our experiments. This includes further investigation of issues such as symmetry (Machin et al. 2007) as well as variability in the edge form of handaxes (Jones 1980; Key and Lycett, 2016), which was not necessarily captured in detail by the morphometric approach to handaxe shape variation that we adopted here. Likewise, we emphasize that issues of handaxe form (particularly mass variation) and how this might relate to issues of fatigue during extended bouts of cutting, would be profitable lines of enquiry for future experiments to investigate. Moreover, it is possible that when handaxes were used in tasks such as butchery, the presence of blood may have meant that handaxe shape properties were particularly useful to help prevent slippage. However, it is notable that our analyses identify no specific shapes that seem to influence gripping such that it notably influenced cutting effectiveness during the experiment.

Conclusions

Variability in the size and shape of handaxes is a feature that is often commented on by Palaeolithic archaeologists. Here, we have experimentally investigated whether variation in handaxe shape and size—two empirically distinct but archaeologically quantifiable features—imposed a strong and immediate impact on cutting efficiency. Despite the large scale of our experimental handaxe assemblage that, by design, contained considerable variability, we found no evidence that shape and size variation had a strong or immediate impact on variation in cutting efficiency during the experimental (laboratory) cutting tasks. These results indicate that both handaxe mass and shape will have been free to vary (within limits) independently of functional cutting-efficiency in archaeological contexts. We did, however, find evidence that at the lower end of handaxe mass variability, there will be a task-specific threshold in terms of cutting effectiveness, below which, handaxes will have been less efficient than larger, heavier examples. This implies that hominins may have targeted design forms to meet minimum thresholds for effectiveness. In particular, our results demonstrate why hominins may have routinely targeted the production of handaxes greater than 100 mm in length. Our results also indicate that a majority of handaxes appear to have been discarded well before they were exhausted as viable cutting tools. This supports previous suggestions that handaxe use-lives were short and is consistent with suggestions of short-term activity planning on the part of Early-Middle Pleistocene handaxe producers. Our results also indicate that markedly small (diminutive) bifaces found in some regions may have been specifically targeted for activities other than cutting, although further work on the functional capabilities of such examples is needed. We caution that very specific attributes, not considered explicitly in our analyses, might yet still be found to have important performance characteristics in future experiments. However, our results demonstrate that at a general level, variability within and between handaxe assemblages in terms of their size and shape properties will not necessarily have had an immediate or strong impact on their effectiveness and efficiency rates when used for cutting. These results thus reiterate that beyond the imposition of a general handaxe bauplan, there is considerable scope for a zone of free play within which handaxe size and shape can potentially vary, independent of functional considerations.

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Figures

Figure 1. The 500 handaxes forming the experimental assemblage utilized here. Note that although arranged in order of gross size (smaller handaxes at front), the image's perspective is biased towards the handaxes in the foreground appearing relatively larger. For descriptive statistics referring to this assemblage, see Table 1.

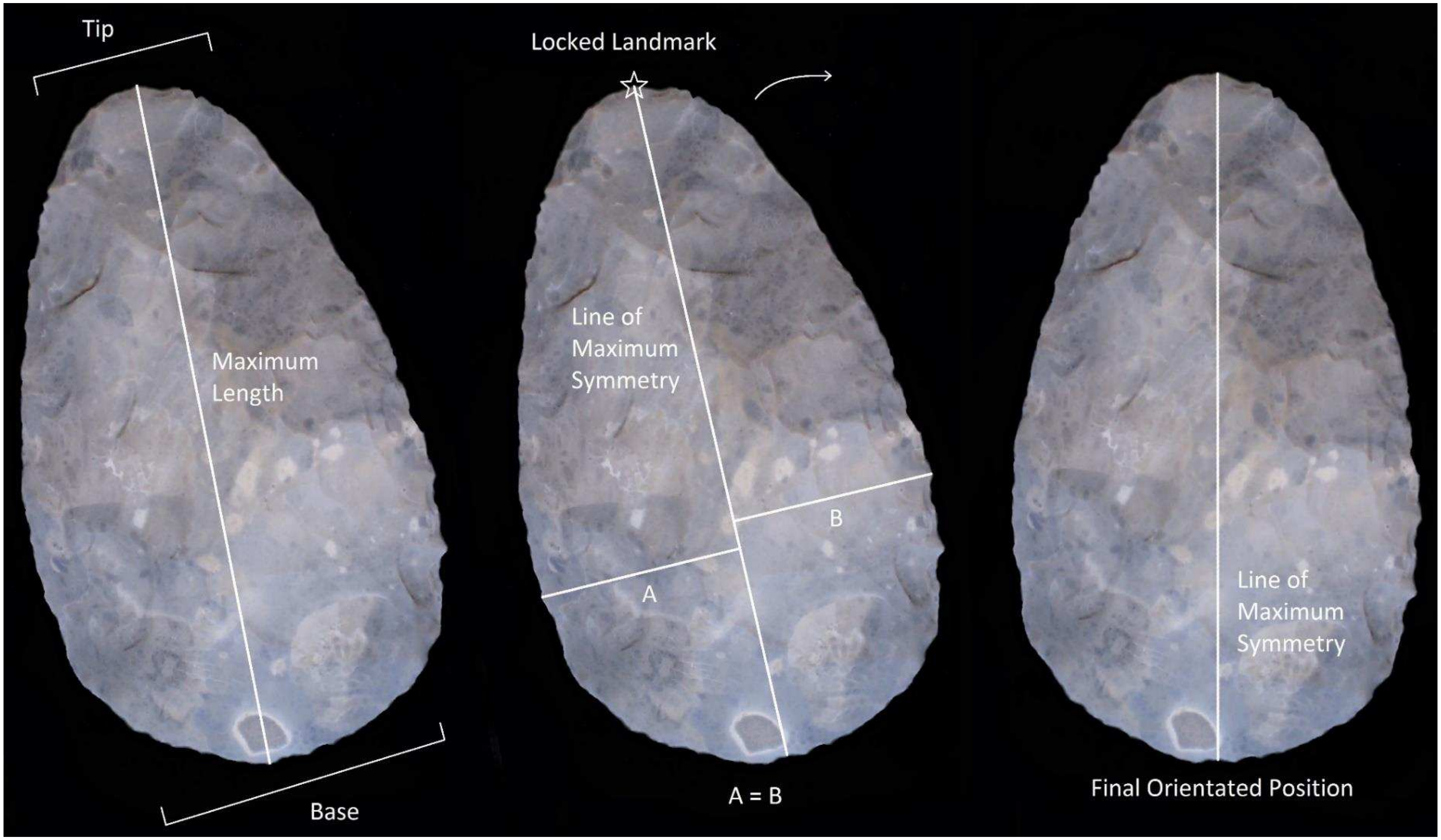

Figure 2. Annotated image detailing the orientation procedure utilized (see text for discussion).

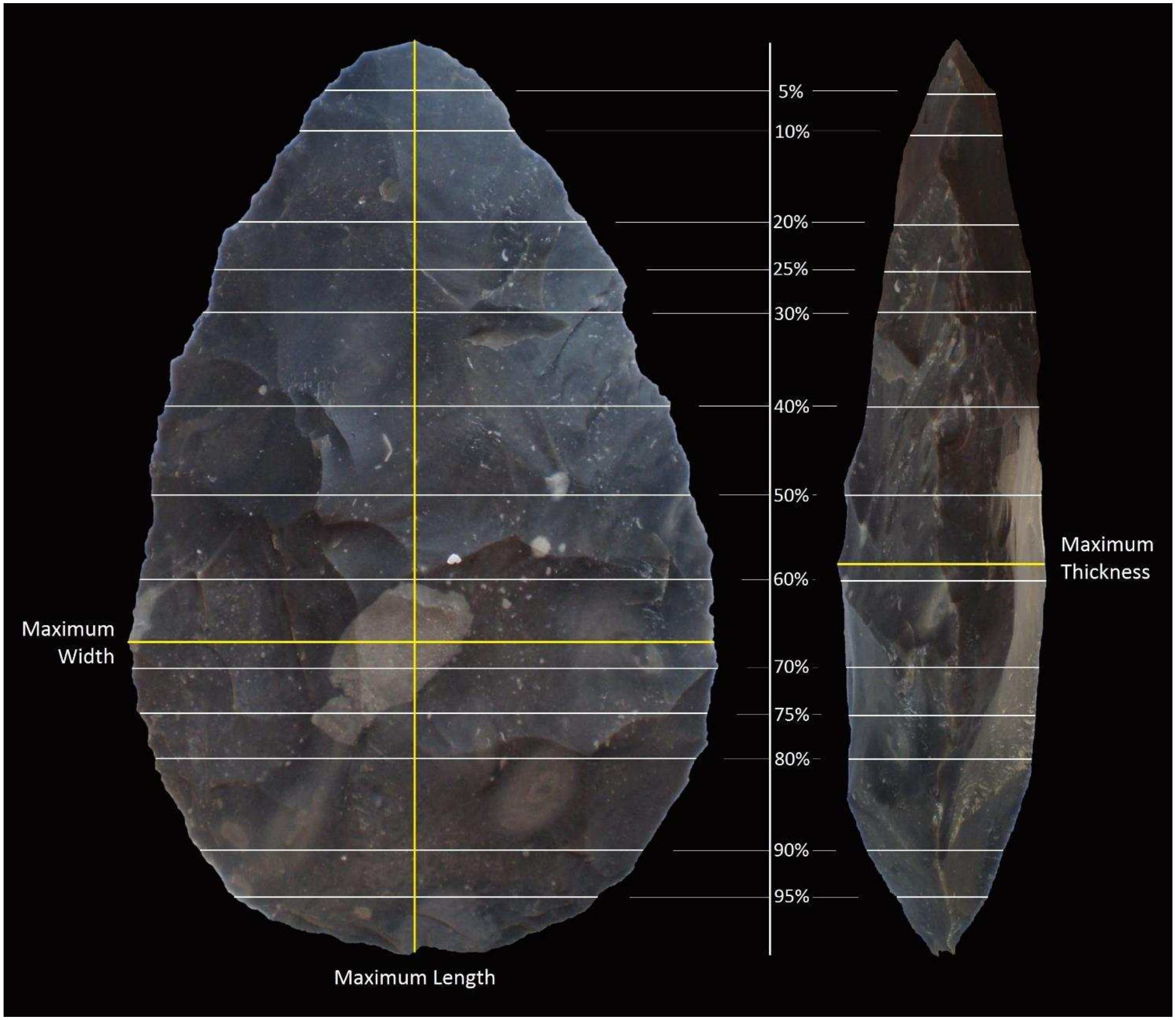

Figure 3. Measurement system of 29 variables obtained on orientated handaxes in plan (left) and profile (right) views

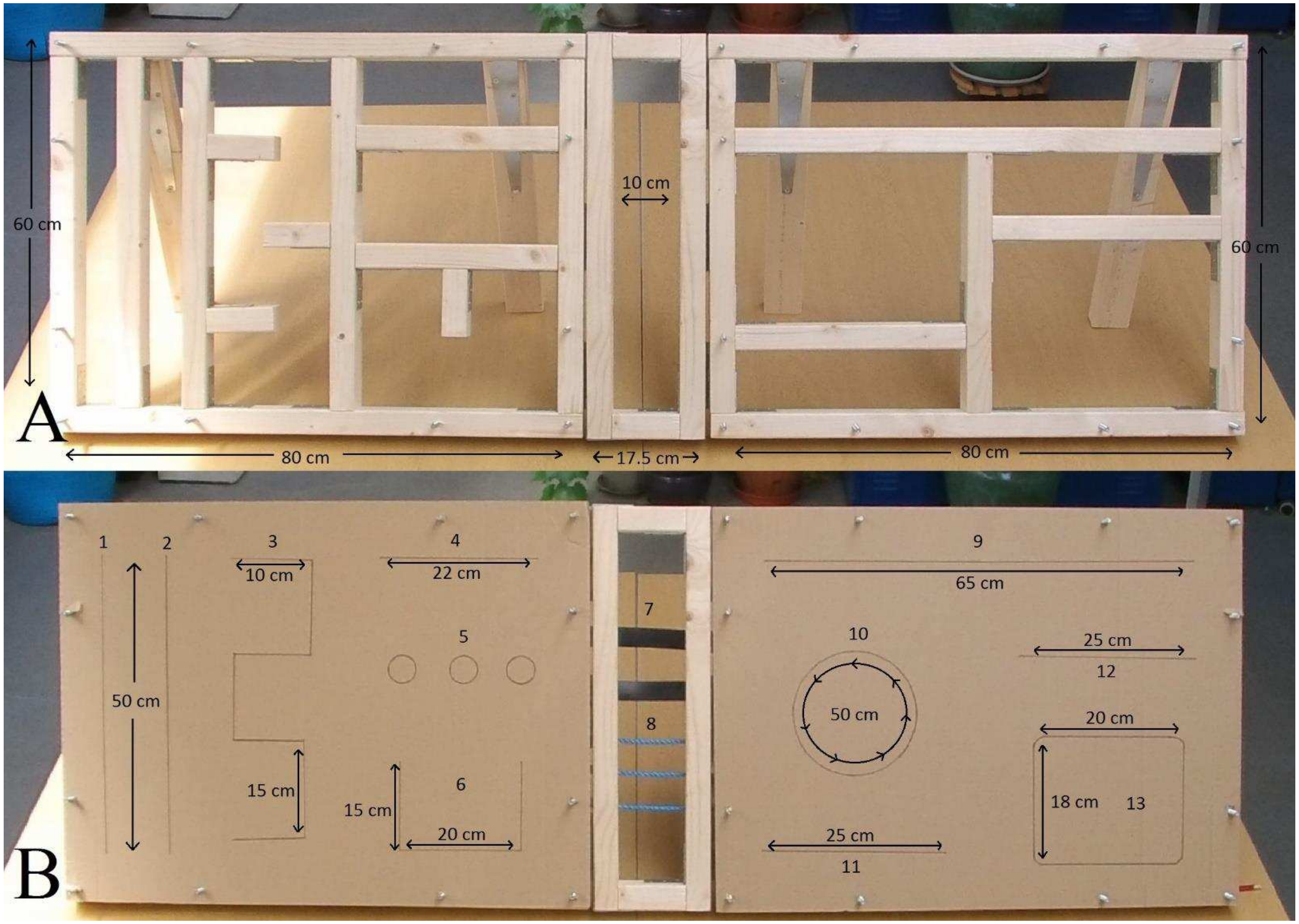

Figure 4. The wooden frame upon which the materials forming the materials requiring cutting during the experimental task were positioned (A) and the cardboard, rope, and neoprene strips in their final task-ready positions (B). Note the lengths of cardboard that were required to be cut in each of the 11 cardboard sections. The thirteen total task sections requiring cutting by each handaxe are numbered. Sections 1–6 and 9–13 denote cardboard cutting, 7 indicates the two neoprene strips, and 8 highlights the three polypropylene rope-segments.

Figure 5: Video frame taken from an initial trial run of the experimental set-up undertaken by one of the authors. Note the three pieces of personal protective equipment and the position of the wooden structure on the floor.

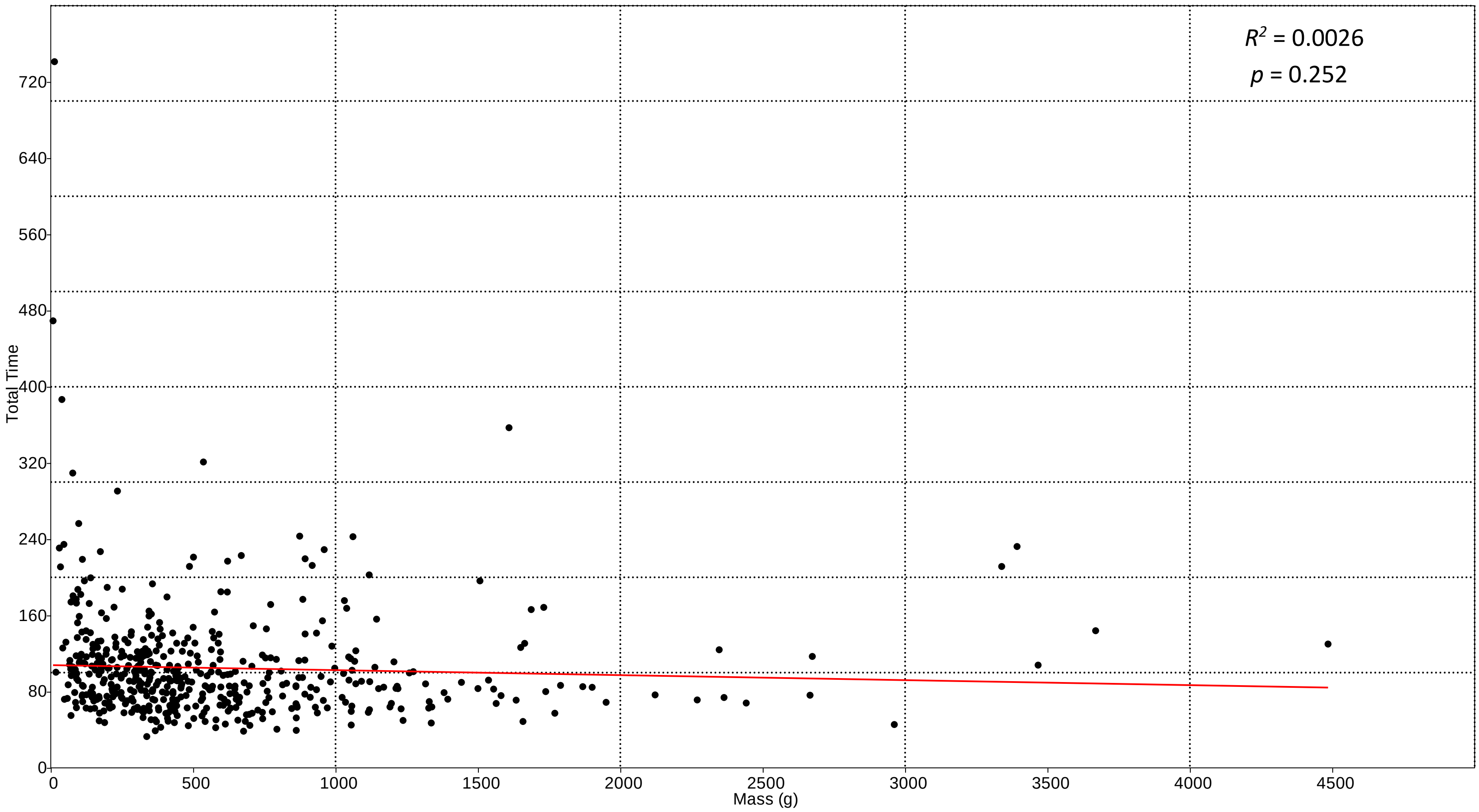

Figure 6. Regression of the mass of the handaxes (n = 500 handaxes) against cutting times.

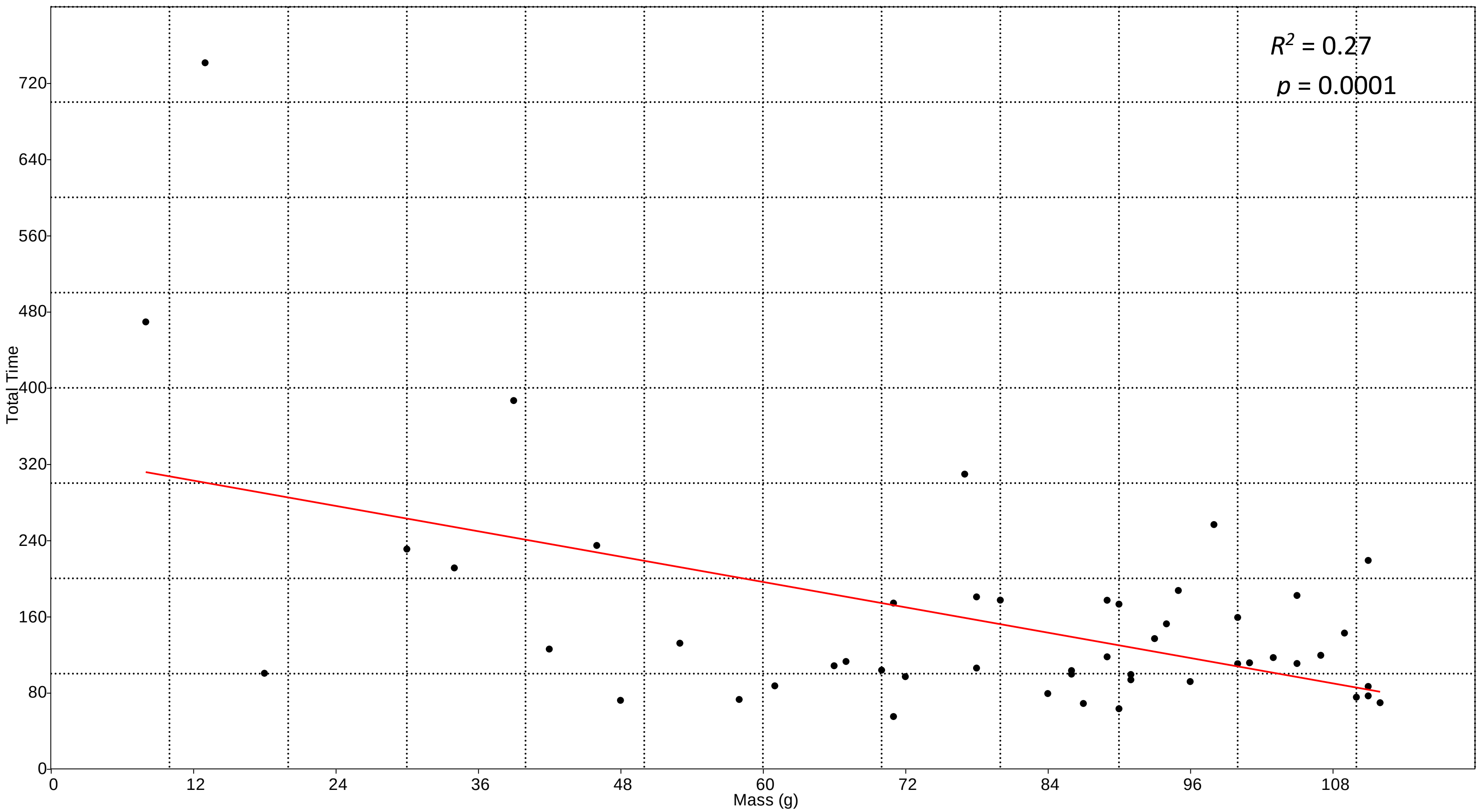

Figure 7. 27% of variation in cutting time can be predicted by mass/size of handaxe if just the smallest 10% of handaxes (n = 50) are considered.

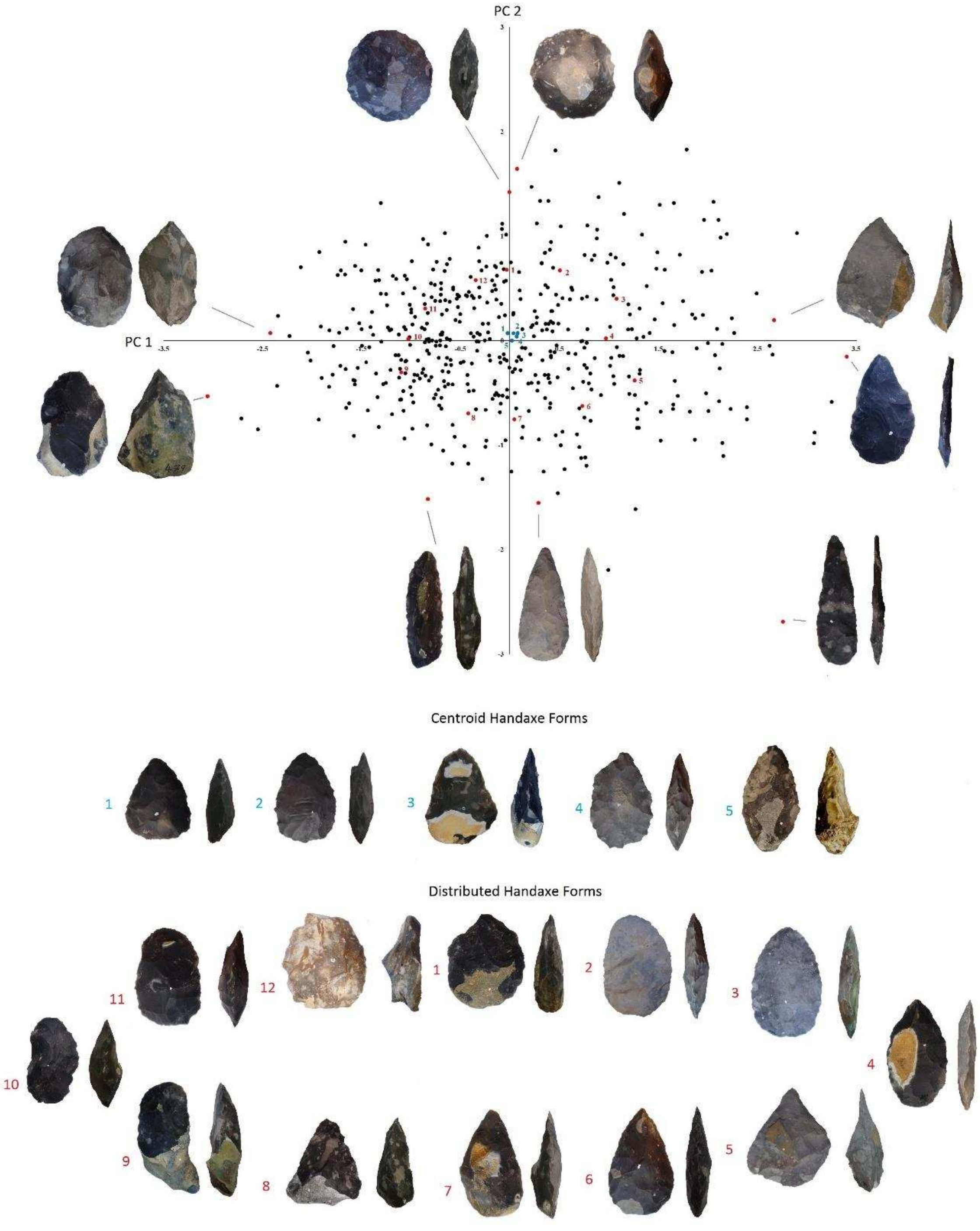

Figure 8. Handaxe shape variation (size-adjusted variables) in the experimental dataset (n = 500 handaxes) as indicated by Principal Components Analysis. PC1 = 57.2 % of total shape variation and PC2 = 17.35 % of total shape variation). Handaxe images (plan view = left image, profile view = right image) indicating shape variation in the dataset.

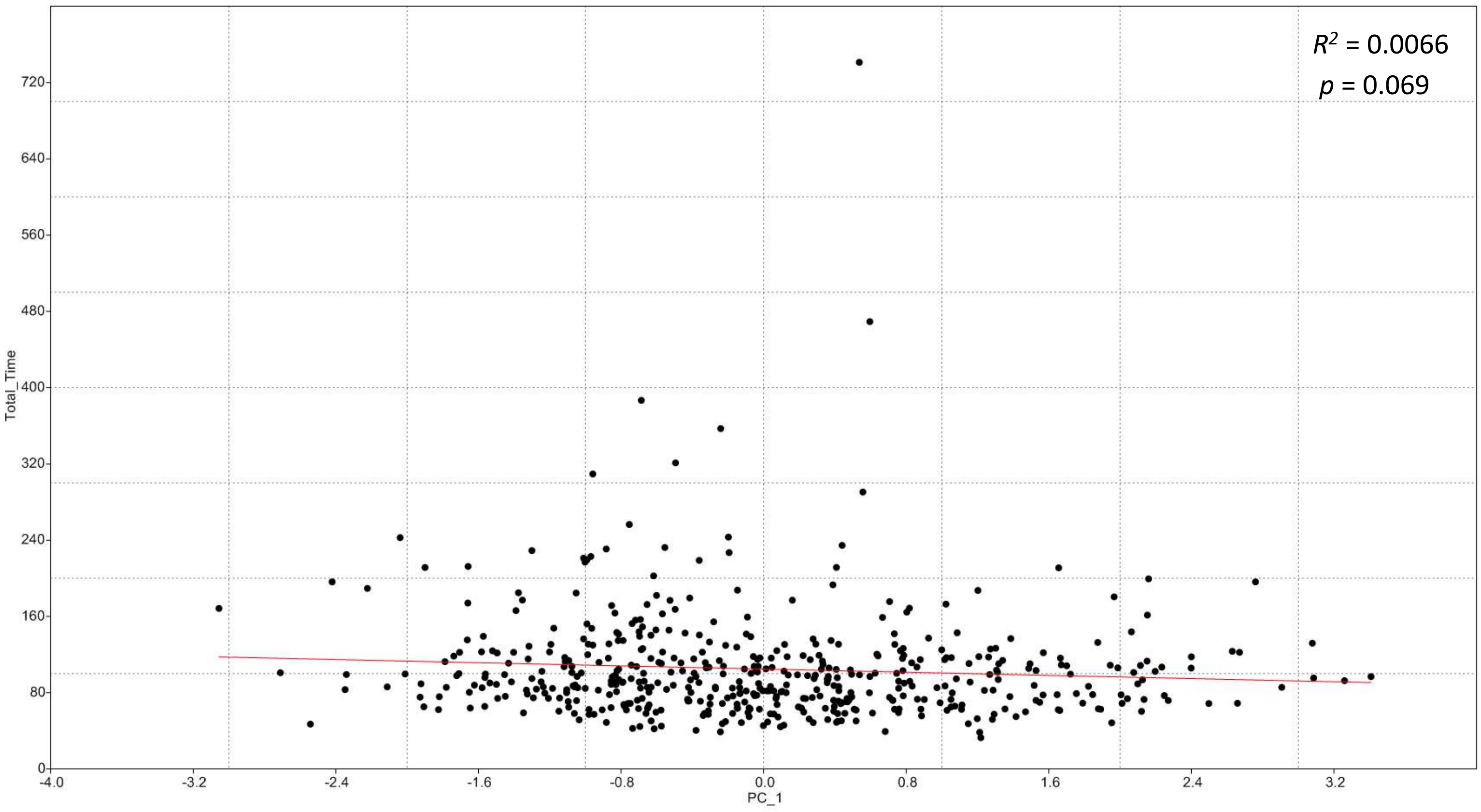

Figure 9. Analysis of handaxe shape and cutting efficiency (n = 500 handaxes). Plot shows regression of first Principal Component **(**57.2 % of shape variation) against handaxe cutting times.

Table 1: Descriptive statistics for morphological variability in the experimental handaxe assemblage compared with Palaeolithic examples

Site (Age)	N		Length (mm)	Width (mm)	Thickness (mm)	Mass (g)	Elongation (Width/Length)	Refinement (Thickness/Width)	Source
Experimental Assemblage (N/A This study)	**500**	**Min – Max**	**38.8 – 296.3**	**24.7 – 200.3**	**7.4 – 106.3**	**8 – 4484**	**0.31 – 1.1**	**0.19 – 1.1**	**Present Experiment**
		Mean	**135.9**	**91.9**	**40.7**	**577**	**0.688**	**0.428**	
		S.D.	**38.4**	**26.3**	**17.3**	**559**	**0.12**	**0.131**	
Konso, Ethiopia (1,750,000 Yrs)	4	Min – Max	-	-	-	-	-	-	Beyene et al. 2013
		Mean	161	-	-	-	0.71	0.41	
		S.D.	37.2	-	-	-	0.08	0.13	
Lepolosi, Olduvai (1,500,000 - 1,400,000 Yrs)	139	Min – Max	102 - 260	70 - 186	31 - 115	293 - 1882	-	-	Diez-Martín et al. 2014
		Mean	163	106	51	817	-	-	
		S.D.	31.8	20.6	12.9	315.9	-	-	
Gadeb 8D, Ethiopia (1,450,000 – 700,000 Yrs)	38	Min – Max	-	-	-	-	-	-	de le Torre 2011
		Mean	151	84	39	537	-	-	
		S.D.	27.8	7.2	9.2	240.6	-	-	
TK, Olduvai (1,400,000 – 1,200,000 Yrs)	18	Min – Max	61 - 262	27 - 106	18 - 74	-	0.40 – 0.98	-	Leakey 1971
		Mean	103	67	38	-	0.69	0.576	
		S.D.	53.6	23.8	16	-	0.182	0.127	
Kilombe, Kenya (1,000,000 – 800,000 Yrs)	394	Min – Max	-	-	-	-	-	-	Gowlett 2011b
		Mean	149	90	42	-	0.61	0.47	
		S.D.	31	16	10	-	0.07	0.11	
Olorgesailie, Kenya (1,000,000 – 750,000 Yrs)	697	Min – Max	-	-	-	-	-	-	Noll and Petraglia 2003
		Mean	162	94	42	-	-	-	
		S.D.	41.9	19.6	10.1	-	-	-	
Isampur, India (~1,000,000 Yrs)	89	Min – Max	-	-	-	-	-	-	Noll and Petraglia 2003

		Mean	175.2	106.5	52.7	-	-	-	
		S.D.	44.13	28.46	14	-	-	-	
Fengshudao, China 800,000 (Yrs)	104	Min – Max	97.4 – 240.5	74.1 – 180.3	34.4 – 99.1	12 - 2440	0.479 – 1.313	0.3 – 0.88	Wang et al. 2014
		Mean	157.7	118.1	67.9	1131	0.762	0.585	
		S.D.	28.1	19.3	14.2	482.1	0.139	0.131	
Gesher Benot Ya’aqov, Israel (800,000 Yrs)	58	Min – Max	-	-	-	-	-	-	Goren-Inbar 1996
		Mean	142	86	39	-	0.61	0.46	
		S.D.	23.5	12.8	5.7	-	0.05	0.06	
Boxgrove, England (500,000 Yrs)	201	Min – Max	-	-	-	-	-	-	Emory 2010
		Mean	123	81	30	-	0.66	0.37	
		S.D.	24.3	13.7	5.7	-	0.05	0.05	
High Lodge, England (500,000 Yrs)	63	Min – Max	-	-	16 - 93	47 - 1056	-	0.23 – 0.90	Petraglia and Shipton 2008
		Mean	-	-	35	259	-	0.44	
		S.D.	-	-	14	208	-	0.13	
Luonan, China (500,000 – 250,000)	236	Min – Max	-	-	27 - 105	159 - 3131	-	0.25 – 0.96	Petraglia and Shipton 2008
		Mean	-	-	58	979	-	0.61	
		S.D.	-	-	13.5	470.6	-	0.14	
Corfe Mullen, England (500,000 – 380, 000 Yrs)	131	Min – Max	-	-	-	-	-	-	Kuman et al. 2014
		Mean	121.6	75.5	37.9	346.6	-	0.51	
		S.D.	27.5	13.8	12.3	191	-	0.16	
Cuxton, England (430,000 – 230, 000 Yrs)	205	Min – Max	-	-	-	-	-	-	Kuman et al. 2014
		Mean	124.1	73.0	44.2	370.3	-	0.61	
		S.D.	34.7	15.9	11.8	252.4	-	0.13	
Imjin/Hantan River Basin, Korea (350,000 – 300,000 Yrs)	58	Min – Max	101 – 239	70.1 - 139	30 - 89	-	0.309 – 1.023	0.31 – 1.02	Norton et al. 2006
		Mean	154	94	60	-	0.626	0.647	
		S.D.	30.5	13.9	12.9	-	0.103	0.14	

Hunsgi V, India (350,000 – 166,000 Yrs)	45	Min – Max	-	-	30 - 70	210 - 1910	-	0.33 – 0.86	Petraglia and Shipton 2008
		Mean	-	-	48	669	-	0.56	
		S.D.	-	-	10	349.6	-	0.11	
Azraq, Jordan (~250,000 Yrs)	42	Min – Max	-	-	7 - 64	62 - 450	-	0.12 – 0.82	Petraglia and Shipton 2008
		Mean	-	-	44	216	-	0.52	
		S.D.	-	-	9.7	86.1	-	0.13	
Broom Pits, England (290,000 – 230,000 Yrs)	241	Min – Max	-	-	-	-	-	-	Kuman et al. 2014
		Mean	125.1	81.1	36.22	359.9	-	0.45	
		S.D.	35.7	17.1	10.2	258.0	-	0.09	

Supplementary Information – Results for individual participants

Online supplementary Table 1. Regression of mass against cutting times for the 100 handaxes of each participant

Participant	Mass	
	R^2	p
1	0.019	0.172
2	0.002	0.699
3	0.007	0.413
4	0.003	0.570
5	0.030	0.087

Online supplementary Table 2. Multiple regression results of PCA analyses for shape variability in the 100 handaxes of each participant against cutting times

Participant	'Shape' (PC1 – 6)		% variance explained by PC1 - 6
	R^2	p	
1	0.206	0.001	95.0
2	0.076	0.276	95.1
3	0.051	0.547	95.0
4	0.045	0.624	96.4
5	0.040	0.695	96.1

Online supplementary Table 3. Results of regression analysis comparing the 50 handaxes with the highest and lowest scores on PC1 respectively

Highest 50 scores PC1	$R^2 = 0.010$	$p = 0.498$
Lowest 50 scores PC1	$R^2 = 0.017$	$p = 0.370$