Looking at handaxes from another angle: assessing the ergonomic and functional importance of edge form in Acheulean bifaces

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Abstract

Edge angle is widely considered to be a morphological attribute that influences the functional performance of lithic technologies. However, the comparative performance capabilities of handaxes that vary in terms of edge angles has never been investigated under experimental conditions. Similarly, detailed accounts of Acheulean handaxe angle variation from archaeological examples have not been reported in the literature. Consequently, it has not previously been possible to assess the extent to which Palaeolithic individuals adhered to specific edge angle ranges during handaxe production or whether resultant artifactual properties may have been in response to varying rates of utility. Here, using a substantial experimental program (n = 500 handaxes), we investigate the impact that edge angle variation has on the cutting efficiency of handaxes at a "whole tool" and "edge-point localized" level. We then examine edge angles in a temporally and geographically wide range of handaxes (n = 643) and assess the extent to which hominins were likely altering tool production choices in response to functional pressures. Our experimental results demonstrate that, up to a certain value, higher edge angles in handaxes can actually increase functional performance. Furthermore, results indicate that edges in the proximal portion of handaxes have the greatest influence over efficiency rates. Combined with examination of archaeological specimens, these results suggest that hominins actively pursued the production of more obtuse edges in the proximal (butt) portion of handaxes in order to increase ergonomic features that facilitated greater efficiency during use. Edge angle values in the proximal portion of the archaeological handaxes were, however, consistently found to be below an efficiency threshold identified at ~70 degrees, above which, an edge's ability to effectively be applied to cutting tasks decreases markedly. This further suggests that the proximal edges of handaxes, at least occasionally, were required as a functional working edge.

1. Introduction

Large bifacially flaked stone tools, generally referred to as "handaxes," were a prominent component of the archaeological record across the Old World for over one million years (Lycett and Gowlett, 2008). Originating in sub-Saharan Africa at least ~1.75 MYA (Beyene et al., 2013; Lepre et al., 2011; Diez-Martín et al., 2015), they were subsequently produced at sites ranging geographically from South Africa to the Levant, and from western Europe to as far east as Korea (e.g., Leakey, 1971; Isaac and Curtis, 1974; Gowlett and Crompton, 1994; Goren-Inbar and Saragusti, 1996; Norton et al., 2006; Santonja and Villa, 2006; Petraglia and Shipton, 2008; Chauhan, 2009; Hosfield, 2011; Pappu et al., 2011; de la Torre, 2011; Bae et al., 2012; Wang et al., 2014). Fundamentally, handaxes represent a means by which individuals were able to modify aspects of the physical environment around them, principally by cutting, splitting, or otherwise deforming organic materials. Indeed, a number of lines of evidence indicate their widespread use during butchery activities and plant modification behaviors (e.g., Keeley and Toth, 1981; Shipman et al., 1981; Domínguez-Rodrigo et al., 2001; Shea, 2007; Rabinovich et al., 2008; Solodenko et al., 2015). This is not to automatically rule out additional roles for handaxes within hominin behavioral strategies (e.g., Pope et al., 2006), but rather, that across their broad temporal and geographic expanse, handaxes were principally produced as functional objects that were modified to undertake task-orientated activities—i.e., they were "tools" (sensu Shumaker et al., 2011).

Given their practical role, it has been hypothesized that a majority of handaxes made during the Palaeolithic would have been made within functionally viable ranges of variation (Crompton and Gowlett, 1993; Vaughan, 2001; Simão, 2002; Gowlett, 2009; Lycett et al., 2016), a statement that has recently found support through experiments designed to assess the functional effectiveness of handaxes that varied widely in terms of their size and shape (Key and Lycett, 2016b). Notably, however, handaxe edge angles were not examined in that experimental study (Key and Lycett, 2016b). Indeed, while handaxe edge form has often been theoretically linked with varying functional performance capabilities (e.g., Posnansky, 1959; Kleindienst, 1962; Kleindienst and Keller, 1976; Jones, 1980; Mitchell, 1995; Phillipson, 1997; Gowlett, 2006; Machin et al., 2007; Toth and Schick, 2009; Galán and Domínguez-Rodrigo, 2014; Key and Lycett, 2016a), edge angle data are not typically reported for Acheulean handaxes recovered archaeologically. Moreover, the issue of variation in the angles of Acheulean handaxes has never been directly compared with functional experimental data. While previous research has discussed the necessary role of a handaxe's edge morphology in determining its functional performance capabilities, even suggesting that certain forms may have been preferentially sought (e.g., Posnansky, 1959; Kleindienst and Keller, 1976; Gowlett, 2006), detailed mechanical models and explicit experimental procedures designed to test any hypothesized relationships between varying handaxe edge forms and functional performance characteristics are lacking. Indeed, current suggestions are limited to subjective comments or those made within the context of research pertaining to other matters (e.g., Posnansky, 1959; Kleindienst, 1962; Jones, 1980, 1994; Mitchell, 1995; McCall, 2005; Machin et al., 2007; Toth and Schick, 2009; Merritt, 2012; Iovita, 2014; Key and Lycett, 2016a).

This situation is potentially critical given the fundamental role that the form of a stone tool's working edge is known to have on its functional performance capabilities. Indeed, it has long been understood that the angle, relative straightness, length, and uniformity of a flake tool's cutting edge is of potential consequence to its efficiency when undertaking cutting tasks (Wilmsen, 1968; Crabtree, 1977; Walker, 1978; Jones, 1980; Jobson, 1986). This has recently been further emphasized in experimental and morphological investigations examining the varying functional potential of flake cutting tools in respect to their edge morphology (Collins, 2008; Borel et al., 2013; Key and Lycett, 2011, 2015; Romagnoli et al., 2015; Eren and Lycett, 2016; Key, 2016). In specific respect to the issue of edge angles, Key and Lycett (2015) recently demonstrated that for flakes, an automatic relationship between more acute cutting edges and increased functional efficiency (in terms of time) cannot be automatically assumed, and that while relatively small flakes tend to display such a relationship, larger tools facilitate increased working loads that are able to counteract the increased resistance caused by more obtuse working edges.

Ultimately, any influence that the edge angle of a handaxe has on its functional performance is caused by either an alteration to the cutting mechanics experienced between the working edge of the tool and material being cut, or the ergonomic relationship between the tool user and edge points in contact with the hand (Key, 2016). Indeed, the angle on the working edge of a cutting tool is known to directly influence the cutting stress enacted on a worked material, with more obtuse edges decreasing the stress created (Ackerly, 1978; Atkins, 2009; McCarthy et al., 2010; Key, 2016). Hence, if angles on a tool's cutting edge increase, then individuals must increase variables that contribute to the "slice-push ratio," which describes cutting stress, if cutting effectiveness is to be maintained. That is, they must either increase the working load (force) applied and/or the speed with which the cut is performed in order to maintain similar material deformation rates (Atkins et al., 2004; Atkins, 2006). A further noted feature of handaxes is that they incorporate a "handle" that provides both support and forward extension to the working edge as it is held in the hand (Gowlett, 2006). Outside of archaeology, research has been undertaken into the design theory of tool–handle ergonomic "optimization" in relation to modern tools (e.g., Hall, 1997; Edgren et al., 2004; Seo and Armstrong, 2008). Understandably, however, there has been little research into how sharp-edged "handles" interact with the palm of the hand or fingers in the existing ergonomics literature, which might be more relevant in the case of at least some prehistoric handaxes. Indeed, the production of a sharp edge at the point of contact between a hand and a handaxe appears ergonomically flawed given that the hand is at an obvious risk of lacerations/cuts. As has been made clear through previous experimental research, however, despite the presence of sharp edges in the proximal (butt) portion of some handaxes, they can still be effectively used as cutting tools (Jones, 1980, 1994; Pitts and Roberts 1997: 223-231; Machin et al., 2007; Galán and Domínguez-Rodrigo, 2014). Nevertheless, further work that examines the relationship between edge angle and efficiency in handaxes appears desirable given the direct interaction of this variable with the hand during use.

It is clear that the angles present along the edge of a handaxe might influence the efficiency with which it can be used as a handheld cutting tool, be this via its relationship with the tool-user's hand or the material being worked. To date, however, the extent and nature of any such influence is unknown and has not been tested via experimental procedures. Furthermore, the degree of edge angle variation within and between various Acheulean handaxe assemblages has not been recorded. Hence, it is not currently possible to assess whether hominins controlled for and/or imposed specific edge angle ranges on handaxes during the Lower Palaeolithic in respect to these factors. Accordingly, the present study had two aims. Our primary aim was to experimentally assess the impact that variable edge angles have on a handaxe's functional performance during cutting. Our secondary aim was to examine edge angle variation in a sample of Acheulean (archaeological) examples in the light of our experimental data, in order to determine the implications of our experiments for hominin behavioral patterns with respect to handaxe manufacture and use.

2. Materials and Methods

2.1 Experimental determination of the functional consequences of edge angle variation

Experiments are an important tool for archaeologists interested in addressing a range of questions relating to Palaeolithic technologies (Eren et al. 2016). This includes questions regarding their use, and experiments facilitate a means to examine the extent to which functional factors might have influenced stone tool variation in the archaeological record (e.g., Jones, 1980; Jobson, 1986; McCall, 2005; Machin et al., 2007; Collins, 2008; Sisk and Shea, 2009; Key and Lycett, 2014, 2015, 2016a). Indeed, understanding the comparative functional performance characteristics of variable stone tool morphologies is vital to interpreting what influences practical matters may have imposed on prehistoric tool production behaviors.

2.2 Experimental Assemblage

Given the main research goals of this study, it was necessary to generate a large, replica-handaxe assemblage displaying variable edge angle ranges. These artifacts were then used in a series of experimental cutting tasks to understand what influence, if any, varying edge angles have on a handaxe's effectiveness when used as a cutting tool. Accordingly, 500 handaxes were knapped through a combination of hard and soft-hammer percussion. All handaxes were produced on English flint obtained in Suffolk and Kent. Handaxes were produced to be highly variable in terms of their final morphology, with both "morphologically extreme" and "archaeologically representative" handaxe forms being produced (Table 1; Supplemental Figure 1). Consequently, a range of edge angle values were present along the knapped edges of these replica tools, with a number displaying particularly acute or obtuse edge angles.

2.3 Recording edge angle variability in the handaxes

Edge angle data were collected for all handaxes via the "caliper method," a technique first described by Dibble and Bernard (1980), who found this method to be highly accurate compared with alternative methods. The method operates from a measurement of thickness taken a short distance from, and perpendicular to, the edge of a cutting tool. The angle formed between the edge's apex and thickness measurement can then be calculated using a straightforward trigonometric function (Dibble and Bernard, 1980). Detailed procedural accounts of this technique and its application to lithic technology have recently been described by Key and Lycett (2015) and

Eren and Lycett (2016). Here, thickness measurements were taken at a distance of 4 mm from the edge of each handaxe.

In total, edge angle data were collected from 20 points around each handaxe's edge (Figure 1). To ensure correspondence of measurements across all handaxes, a standardized orientation procedure was used, comprised of several steps. Firstly, the superior surface of each handaxe was defined by the surface displaying the greatest number of surface scars above $0.5cm^2$ (Lycett et al., 2006). Thereafter, each handaxe was orientated around its line of symmetry according to the procedure described by Schillinger et al. (2014). This procedure allows each handaxe to be bisected by a line of maximum symmetry. This line of maximum symmetry was then used to define the points at which edge angle measurements were taken on each handaxe (Figure 1).

Angles were recorded at both the "tip" and "base" of a handaxe, before being recorded on either side of a handaxe's lateral edges at 10% intervals of its length (Figure 1). Edge point locations were first identified on digital images using the digital analysis software ImageJ, subsequent to which the edge angle measurements were taken from the handaxes according to these pre-identified points. The "tip" and "base" of each handaxe were defined as the distal and proximal ends of the line of maximum symmetry respectively. If one of these predefined edge points fell at a point along an edge that had not been knapped (i.e., was cortical) then a record of "not flaked" ("NF") was noted for that data point (Figure 1). Descriptive data detailing the extent to which edges were not flaked are shown in Table 2. To produce a single, summative measure describing "edge angle" at each of the 10% intervals along a handaxe's length, a mean value was calculated from the left and right lateral measurements of each handaxe. Similarly, to produce a "mean edge angle" value for the entire handaxe, a mean value from the 20 independent data points was computed. In both cases, if there was a record of "not flaked" for any point, this edge point would be excluded from the calculation of the mean angle. If both the left and right lateral measurements at a specific 10% length interval had not been flaked then no angle measurement for that particular point on that handaxe was included within the analyses. These 12 edge angle measures (i.e., the "tip" and "base," the nine 10% intervals, and the mean "whole handaxe" value) were the final data points produced for the replica handaxes. Descriptive data for these 12 measurements for the entire experimental assemblage are shown in Table 3. Examples of the variation exhibited in the experimental dataset are shown in Figure 2.

2.4 Participants

Given the quantity of tools (n = 500) involved in this experiment, it was not practical to recruit one participant for each handaxe. To standardize biometric variation between participants, however, which is a known factor of influence in tasks of this sort (Key and Lycett, 2011), only males displaying relatively high levels of manipulative strength (Mathiowetz et al., 1986; Massy-Westropp et al., 2011) were recruited (age range = 23–35, grip strength = 48–70 Kgs). The five participants were all graduate students recruited via advertisement, none of whom were from fields with a focus on Palaeolithic archaeology. The experimental handaxes were divided randomly between participants (100 each) using a random number generator. Prior to taking part, all participants provided informed consent, having received detailed instructions of exactly what was being asked of them during the experiment and having had the cutting task demonstrated to them. Participants were not, however, aware of the precise analytical focus of the investigation in terms of pertinent variables.

Each participant undertook the experimental cutting task 100 times, once with each of the individual handaxes that had been randomly assigned to them. This was achieved by them undertaking the task over a period of 7–10 days, using 10–15 handaxes per day. In order to control for the onset of fatigue during each session, rest periods of at least five minutes were implemented between the use of each handaxe, allowing muscular strength to adequately recover (Pitcher and Miles 1997). Participants only used their next handaxe when they were comfortable doing so. Linear regressions between the order of tool use and efficiency values were not significant, thus confirming that implementation of this experimental strategy was effective.

2.5 Experimental task

The experimental task involved participants cutting though three distinct materials secured to a wooden structure (Figure 3). The materials used in this task were two sheets of double-ply corrugated cardboard (7.5mm thick, board grade = 125), three pieces of polypropylene rope (6 mm thick), and two (neoprene) strips of synthetic rubber (30 mm wide and 2 mm thick). While the use of synthetic materials does not directly replicate Palaeolithic tool-use conditions, it does allow the cutting-task conditions to be identically presented (i.e., consistently controlled) across all of the various handaxes used by each of the five participants. Hence, this procedure facilitates the accurate comparison of cutting effectiveness in the case of large experimental assemblages.

Moreover, these straightforward cutting tasks do not require specialist knowledge or skills to undertake them successfully, a problem identified in previous research involving the butchery of animal carcasses (Machin et al., 2007).

The cutting task itself was comprised of 13 sections and required a variety of cutting positions/actions. In total, 11 lengths of cardboard had to be cut, divided between two 80 × 60 cm sheets (Figure 3b). The lengths of cardboard to be cut were drawn using premade stencils to ensure consistency across all 1000 sheets. The neoprene strips and pieces of polypropylene rope were also positioned within a central cavity on the wooden structure (Figure 3b). Participants were required to undertake the task according to the numerical order shown in Figure 3. They were also informed that the entire length drawn on the cardboard must be cut. The system of wooden beams forming the structure on which all these materials were placed (Figure 3a) was designed in such a way that while handaxes were not obstructed when cutting, it provided ridged support for the materials during the task. Each sheet of cardboard was secured onto the wooden frame using steel wingnut bolts (12 mm thick). The neoprene strips and rope were pulled taut and secured into positon using 25 mm staple nails.

To ensure their safety during the experiments, participants wore a leather glove on their dominant (cutting) hand. This was ethically necessary given that the handaxes used during the experiment possessed 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 of each glove (up to the proximal interphalangeal joint) were, however, cut from the glove so that it was still possible for the handaxe to interact directly with the participant's fingers. As such, these gloves protected the palm of the hand, yet allowed free movement of the hand, and facilitated direct contact of fingers and thumb with the surface of each handaxe.

2.6 Measuring cutting efficiency of handaxes

Cutting efficiency was calculated as the time taken to complete the whole cutting task (i.e., cut all 13 sections). While efficiency rates during cutting are more appropriately defined by the energy (i.e., work) required to undertake the task (Bleed and Bleed, 1987; Key, 2016), "time-taken" is a valid substitute since physical activity time and energy expenditure are inevitably related. Time values were recorded in seconds from videos of each participant as they undertook the experiment. Hence, in total, 500 individual time records were produced. Any pauses in cutting (readjustments to the grip used, moving between sections, etc.) were not included in the final efficiency value. The cutting time in each case was recorded from when each handaxe first made contact with the material to when it broke contact on the final cutting stroke of the task, minus any pauses. Participants were asked to undertake the task as quickly as possible while maintaining control over the tool and the cutting actions employed.

2.7 Statistical analyses of handaxe efficiency data

We undertook two sets of analyses to investigate the influence of edge angle variation on cutting efficiency in handaxes. The first set of analyses investigated the potential influence of edge angle variation at the "whole handaxe" (i.e., mean angle) level. This was achieved through linear regression ($\alpha = 0.05$) of the mean edge angle measurements for all handaxes and their respective "time taken" efficiency values. As, however, is increasingly being observed in experimental Palaeolithic research, relationships between tool-form aspects and performance measures may not always be linear across broad ranges of morphological variability (Key and Lycett, 2014, 2015, 2016b). Certainly, the relationship between a flake tool's working edge angle and cutting efficiency has been shown to be variable, with tools displaying size-related "thresholds" beyond which angle efficiency relationships markedly alter (Key and Lycett, 2015). Consequently, in addition to the linear regression, a LOESS line of best fit model was also created between mean edge angles and time values. LOESS modeling uses individual data values to produce a regression line that is fitted using a weighted least-squares algorithm, whereby a relatively greater contribution (i.e., higher weighting) to the determination of the line is given by data points nearer the point at which the line is being defined at that time (Cleveland, 1979; Cleveland and Delvin, 1988). This allowed the investigation of any potential changing relationships between edge angle values and efficiency rates across the full range of variability exhibited in our experimental data. Thus, it becomes possible to track localized changes in the relationship between edge angle variation and efficiency rates. To undertake the analysis, the smoothing parameter of the line was defined to fit 20% of data points. Having used LOESS modeling to identify any potential patterns in the data, we were then able to undertake additional linear regressions on subsets of the total data in order to investigate the statistical significance of patterns in these subsets of the data.

The second set of analyses investigated whether specific points along the edges of handaxes disproportionately contributed toward their relative efficiency. To achieve this, the 11 data points that describe edge angle variation along the length of a handaxe were entered into a backwards stepwise regression and compared against cutting times. Backwards stepwise regression begins by placing all predictors (points at which edge angle was measured) into the regression analyses, and then calculates the contribution of each datum to the model's prediction of tool efficiency. If a variable is not making a statistically significant contribution to the model, it is removed and the model is re-estimated for the remaining predictors. This process is continued on a stepwise basis until only variables that make a significant contribution to the model's prediction remain. This method allows production of an "order of contribution" that shows the relative strength of relationship between each measurement of edge angle and the functional efficiency of the handaxes. Stepping method criteria used an entry and removal value of 0.05 and 0.10, respectively.

2.8 Examination of edge angles in archaeological handaxes

In order to contextualize our experimental data and results within a firmer archaeological framework, we examined edge angles in a series of archaeological handaxe assemblages. Given the current dearth of reported edge angle data for Acheulean handaxes, statements made on the basis of these samples must be considered somewhat preliminary. Nevertheless, this is an important initial step toward understanding the potential implications of handaxe edge angle variation in the archaeological record. Moreover, at least one of our chosen assemblages (Boxgrove, UK) is comprised of a relatively large (n = 254) excavated sample thus providing a firm comparative foundation in this case, and certain other samples in our comparative data (e.g., Tabun E, Israel) are also from excavated contexts. In total, edge angle data were collected from nine Acheulean and two Lower-to-Middle Palaeolithic transition handaxe assemblages (n = 643 artifacts in total) using the same procedures described for the experimental handaxes. Assemblages were chosen primarily to cover a broad temporal and geographical range, with sites dating to between ~1–0.2 Myr and comprising samples from East and West Africa, the UK, France, the Levant, and southern India (Table 1). Descriptive morphological data (length, width, thickness, mass, elongation [width/length], and refinement [thickness/width]) for these assemblages alongside the experimental handaxes can be seen in Table 1.

For nine of the assemblages, data were only collected from artifacts that did not exhibit rolling or edge abrasion. Conversely, the handaxes examined from Stoke Newington (UK) and Forum River (Nigeria) did exhibit noticeable edge abrasion due to their fluvial contexts. The latter two assemblages were included specifically to examine the impact of post-depositional damage on the reliable recording of edge angle data. To accomplish this, we statistically compared edge angles in each of the two rolled assemblages to all remaining assemblages using an ANOVA with Tukey post-hoc comparisons ($\alpha = 0.05$).

3. Results

3.1 Influence of edge angles on cutting performance in the experimental handaxes

Somewhat counterintuitively, the linear regression between mean edge angle (across the whole tool) and the time taken during the cutting task indicated that relatively more obtuse edges significantly increase the efficiency with which handaxes can be used ($p = 0.0003$, $r = -0.159$). That is, the more obtuse the edges are on a handaxe, the more efficient a handaxe can be used, with this being to a statistically significant extent (Figure 4a). The LOESS model similarly confirms a relationship between increasing edge angles and a decrease in time taken to perform the cutting task (Figure 4b). This is, however, only when mean angles are below around 70 degrees (Figure 4b). Indeed, once a handaxe's mean edge angle increase over ~70 degrees there is a very clear increase in the time it took participants to complete the cutting task (i.e., there is a substantial decrease in cutting efficiency) and this relationship is statistically significant (Figure 4c). In fact, with the removal of just a single outlier, increasing mean edge angles explain as much as 22% of the variability in the overall efficiency of the most obtuse-edged handaxes (Figure 4d). A regression of the 450 most acute-angled handaxes (Figure 4e) confirms the significant negative relationship between increasing mean edge angles and cutting efficiency levels. In sum, what this first set of analyses indicates is that there is a relatively weak but statistically significant relationship between higher mean edge angles and increased cutting efficiency, accounting for around 4% of the variability in efficiency of the most acute angled handaxes (see Figure 4e). Conversely, once a threshold of around 70 degrees is reached, higher mean edge angles lead rapidly to a decrease in cutting efficiency, accounting for as much as 22% of the variability in the overall efficiency of the most obtuse-edged handaxes (Figure 4d). We also undertook an additional analysis regressing the CV (coefficient of variation) for the edge angles of each handaxe in our analysis against efficiency. This analysis did not reveal a significant relationship between angle variability and efficiency ($p = 0.959$), which also emphasizes that mean edge angle is more important in determining the efficiency of a handaxe than variability of edge angle.

In our second set of analyses, the backwards stepwise regression analysis identified edge points located at 70%, 80%, and 90% of a handaxe's length (from tip to base) to be three of the four most important variables in the prediction of handaxe efficiency (1st, 3rd, and 4th in their order of contribution respectively: Table 4). Somewhat conversely, the second most influential edge point is located at 10% of a handaxe's length (Table 4). In sum, this second set of analyses identifies edge angles in the base (butt) of handaxes (i.e., at 70–90% of overall length) to have been of particular influence to their overall cutting efficiency in the experiment.

3.2 Edge angle variation in the archaeological handaxes

There are a number of clear trends within the artifact edge angle data. Perhaps the clearest is that along the length of a handaxe, from its tip to its base, there is a consistent trend towards edges displaying more obtuse angle ranges (Figure 5, Table 3). Essentially, edge angles become more obtuse the further away from the tip of a handaxe that measurements are taken. This is a trend that is consistent across all eleven handaxe assemblages; in no assemblage are edge angles at the base directly equal to those seen at the tip-end of handaxes (i.e., above and below 50% of length). In the nine assemblages that excluded handaxes exhibiting edge damage, mean angle ranges increase from 38–61 degrees at 10% of length to around 57–70 degrees at 90% of overall length (Table 3, Figure 5). Regarding the percentages of handaxes displaying unknapped (cortical) edge-point locations, it is notable that in all cases, individual edge points are knapped for at least some proportion of handaxes within an assemblage (Table 2) although the proximal (butt) end of a handaxes routinely exhibit lower frequencies of flaking (Table 2). Inevitably, of course, some of these patterns emerge as a result of the typological designation of "handaxe" artifacts and the orientation protocol used here. Nevertheless, it remains to be asked why hominins persistently made these characteristically tapered objects when, in principle, tips and bases could have been more balanced in form. The results of the stepwise regression discussed above provide some insight on this, in that they demonstrate that there is a clear functional benefit to producing handaxes with relatively more obtuse edge angles at 70–90% of a handaxe's length.

Finally, it is clear that the two assemblages containing handaxes exhibiting edge damage (Stoke Newington and Forum River) display substantially greater edge angle values than those only including relatively "fresh" edges (Figure 5, Table 3). The ANOVA and Tukey's post-hoc tests confirmed that in all cases except for Attirampakkam, differences between the edge angles of rolled and unrolled assemblages were statistically significant (Table 5). Hence, there is strong evidence that post-depositional effects can have a marked effect on handaxe edge angles. It is unclear at present why the Attirampakkam specimens are less different from the Stoke Newington and Forum River specimens, although Figure 5 indicates they are not markedly different from the majority of assemblages in terms of overall angles.

4. Discussion

In recent years there has been increasing use of statistically robust experiments and detailed examinations of stone artifacts to provide information about the nature and extent to which functional issues may have influenced the forms of cutting edges observed in Palaeolithic technologies (e.g., Machin et al., 2007; Collins, 2008; Key and Lycett, 2011, 2015; Terradillos-Bernal and Rodríguez, 2012; Eren, 2013; Borel et al., 2013; Seeman et al., 2013; Eren and Lycett, 2016). To date, however, no study has specifically investigated the influence of edge angles in respect to handaxe cutting effectiveness. Accordingly, this study undertook a substantial experimental program to examine how the angles present on a handaxe's working edge influence the efficiency with which it can be used as a cutting tool. In addition, we examined handaxes from a temporally and geographically wide range of artifact assemblages to identify whether any patterns of edge angle variation may have been influenced by functional requirements.

In accordance with expectations, our results identify there to be a statistically significant relationship between edge angle variation and functional efficiency in handaxes. Somewhat surprisingly, however, results indicated that handaxe efficiency rates increased as mean edge angles increased. Essentially, our experimental results indicated that as angles increase on a handaxe's edge, then the functional performance of the tool increases accordingly, with this being to a statistically significant extent. However, when combined with the LOESS model it was clear that this relationship is only evident until mean edge angle reached values of around 70 degrees. At this point, there was a clear change in the observed relationship and when edge angles were over ~70 degrees there was a negative effect on handaxe efficiency rates.

A relationship between increasing edge angles and increased cutting efficiency seems counterintuitive at first, particularly within the context of cutting mechanics. Indeed, it is known that more obtuse angles generally increase resistance as the cutting edge comes into contact with material and, consequently, lead to decreased cutting efficiency (Ackerly, 1978; Atkins, 2009; Key, 2016). Hence, a lineal relationship between more acute edges and increased efficiency rates would more likely typically be expected. However, the direct application of this logic to handaxes does not account for the fact that during use, one edge of a handaxe is in direct contact with the tool user's hand. Hence, it is our inference that relatively more obtuse angles on a handaxe's edge alter the ergonomic nature (i.e., comfort/functional design) of the interaction between the hand and handaxe, with more obtuse edges increasing the ease with which high loads may be applied during tool-use, with this in turn increasing the cutting stress enacted by the handaxe's working edge on the material being deformed (Key, 2016). Consequently, this increases the efficiency with which handaxes can be used as cutting tools. In other words, the negative influence that more obtuse edges may have in increasing material resistance/diffusing cutting stress are outweighed by the mechanical benefits of being able to increase working loads. It is notable that this effect was observed during our experiments even though (due to ethical reasons) the participants were required to wear gloves. Hence, it is likely that the relationship between the ergonomic and functional components of handaxe use may plausibly have been even stronger in the case of prehistoric hominin populations.

As demonstrated during our experiments, however, a relationship between increasing handaxe edge angles and increasing cutting efficiency is not continuous. Rather, there is a threshold beyond which any beneficial increases to working load are outweighed by the lower cutting stresses created at the handaxe's working edge. Here, this threshold appears to be when handaxe edges reached a mean value of ~70 degrees. Importantly, however, this threshold has been determined during a relatively resistant cutting task that was undertaken by individuals displaying moderate-high manipulative strength capabilities. It is likely that alternative worked materials and/or weaker and stronger tool users would alter the precise value of this threshold. In fact, it is increasingly becoming clear that relationships between aspects of a stone tool's morphology and functional performance characteristics are dependent upon the task being undertaken (Key and Lycett, 2016a; Key, 2016). Nevertheless, the results returned by the stepwise regression reflect the importance of the interaction between the tool user's hand and the handaxe's edge to efficiency rates, whereupon edge angles located between 70–90% of a handaxe length were the most important in predicting efficiency rates. This is congruent with the notion that support for a handaxe is predominantly provided through its proximal portion and the tool user's palm (Aldien et al., 2005; Gowlett, 2006), consequently meaning that these edge points have the greatest levels of interaction with the hand and influence efficiency rates to the greatest extent. Hence, on the basis of these experiments, functional selective pressures favoring the production of relatively obtuse edges will likely have been strongest in the proximal portion of handaxes (i.e., towards the base/butt).

The examination of edge angles in the study of archaeological handaxe examples undertaken here identified several patterns. Firstly, it was identified that edge angles increase along the length of a handaxe's edge (from tip to base) and that this trend was universally observed in all handaxes assemblages investigated, irrespective of their temporal or geographic origin. As noted earlier, some of these patterns emerge as a result of the typological designation of "handaxe" artifacts and the orientation protocol used here. Nevertheless, it remains to be asked why hominins persistently made these characteristically tapered objects when, in principle, tips and bases could have been more balanced in form, especially if maximizing the overall length of cutting edges was of primary concern. In light of our results, however, the repeated production of these forms across such wide expanses of time and space can be seen as consistent with the hypothesis that hominins were actively producing more obtuse edges on the proximal (butt) portion of handaxes in order to facilitate the application of greater working loads during use as hand-held tools. Indeed, our experimental results show a clear functional benefit to the production of more obtuse edges at 70–90% of a handaxe's length. Hominins concerned with energetic efficiency and the maximization of a tool's functional (cutting) performance could, therefore, have profitably altered tool forms in response to this relationship. While this result may seem intuitive, it is the first time that definite experimental support has been provided for the persistent production of characteristic "handaxe" forms, across such wide geographic and temporal expanses.

The production of relatively obtuse edges in the proximal portions of handaxes can, however, also be linked to previously suggested requirements for a greater material mass to be located in this portion of the tool (Gowlett, 2006). Indeed, locating a handaxe's highest point of mass centrally within the hand's grip has previously been noted as being of consequence to tool-use capabilities (Simão, 2002; Gowlett, 2006, 2009; Toth and Schick, 2009). Teasing apart the relative contribution of each of these related, but notably distinct, morphological aspects will require further experimental work. It is notable, however, that recent experimental work has shown that handaxe shape has relatively little influence on functional efficiency during cutting (Key and Lycett 2016b). This suggests that edge angles, rather than shape per se, may have been a more functionally relevant trait of concern for handaxe-producing hominins and that, in principle, handaxe shape will have been free to vary independently from functional concerns regarding edge angles, especially in plan-form.

The edge form of handaxes is likely to reflect trade-offs between concerns to produce viable cutting edges balanced against the ergonomic issues highlighted in our results. This was further highlighted by the fact that edge angle at 10% of length, an edge point at the distal end of the tool and therefore likely to be important in initiating cutting actions, was also found to be among the most important individual variables in contributing to efficiency levels alongside those observed at the base of the handaxe. Accordingly, selective pressures acting on edge angle ranges in the distal portion of handaxes may, in part, represent a trade-off between ergonomic requirements that necessitate more obtuse angles in order to increase working loads, and mechanical requirements that would demand more acute edges in order to increase cutting stress during use. Given recent research into the angles observed on the edges of flakes experimentally produced during Levallois-style reduction schemes (Eren and Lycett, 2016), it is also reasonable to hypothesize that the angles observed on the distal edges of handaxes may, in part, represent an optimization between cutting efficiency and resistance to breaking/fracturing during use. Consequently, edge angle values are not as obtuse as those observed in the proximal (butt) portion of handaxes, but neither are they highly acute, with mean angles at 10% of length in the archaeological handaxes never dropping below 38 degrees and frequently exceeding 40 degrees. These values are broadly similar to the range (i.e., ~35–58 degrees) reported in several ethnographic studies examining mean edge angles in flake tools (Gould et al., 1971; White and Thomas, 1972; White et al., 1977; Gould, 1980) that plausibly represent competing trade-offs in optimality factors between cutting capabilities on the one hand, and durability of edge on the other (Eren and Lycett, 2016). Further research might, therefore, profitably be directed toward identifying how edge angle in handaxe-like tools relates to issues such as edge strength and edge durability.

Given our findings regarding the ergonomic advantages of relatively more obtuse angles in the basal portions of handaxes, it is intriguing that our study of knapped edges in the archaeological handaxes identified the frequent flaking of the basal ends of handaxes. After all, an obvious way of increasing ergonomic "handle" properties of handaxes would simply been to have left the proximal portion of the piece unflaked. In all of the samples we examined here, however, basal portions of handaxes were frequently flaked, albeit less so than points closer toward their tips. Hence, there are clearly pressures beyond the ergonomic and mechanical requirements discussed thus far influencing the removal of cortex in the base portion of handaxes. At least in part, the most likely reason for this is that at some point during the reduction sequences of handaxes, consideration was given to the notion that the proximal portion may be required to perform cutting tasks. Indeed, it is noteworthy that in the nine assemblages that do not contain edge damaged artifacts, mean proximal edge angle values do not increase above the 70 degrees threshold noted in the experimental results (excluding the single base measurement within the Attirampakkam assemblage). Hence, although more obtuse than tip-located edge points, the proximal edges of many of the handaxes examined here are within functionally viable ranges of variation and could have been employed effectively during cutting. An ability to do this would not only increase the tool's longevity between resharpening events and maximize the length of cutting edge able to be utilized during cutting strokes, but it would also increase the total amount of cutting edge able to be produced relative to the tool's material mass. Previous research supports such a conclusion, identifying that in some contexts the proximal (base/butt) portion of handaxes can make an effective working edge (e.g., Mitchell, 1995; Toth and Schick, 2009).

5. Conclusions

Identifying relationships between aspects of stone tool morphology and functional performance characteristics is essential to determining the nature of tool production behaviors in Palaeolithic populations (Schiffer and Skibo, 1997; Eren et al. 2016). Indeed, in the majority of cases, prehistoric stone tools were first and foremost going to have been functional objects tasked with the deformation/cutting of aspects of the physical environment. Understanding how tool form influences a tool-user's ability to efficiently and effectively undertake such behaviors is, then, vital to understanding why hominins may have created the tool forms observed in the archaeological record. Here, for the first time, a substantial experimental program has been undertaken to examine the influence that edge angle variation has on the functional efficiency of handaxes during standardized cutting tasks and how this varies dependent upon the location of angle measurement on a handaxe's edge. Simultaneously, the angles observed along the edges of a temporally and geographically broad range of handaxes have been recorded in order to understand the extent to which Acheulean hominins may have controlled edge angle ranges during handaxe production.

Experimental results identified that the production of relatively more obtuse edges on handaxes would have significantly increased their efficiency during cutting behaviors. This would, however, have only been until mean angle ranges reached a context-dependent threshold (identified here as being ~70 degrees), at which point efficiency rates would have decreased in accordance with increased edge angles. Results further indicated that the angles observed on a handaxe's edge between 70–90% of its length were the most influential in terms of predicting efficiency rates. When combined with the edge-angle data collected from the artifact assemblages there are a number of clear implications for the tool production behaviors of Acheulean hominins. Principally, it appears that hominins may have preferentially produced relatively more obtuse edges in the proximal (butt) portion of handaxes for ergonomic reasons, which in turn increased functional performance. Finally, given the widespread flaking of the proximal portions of handaxes edges across broad temporal and geographic ranges, and the identification that edge angle ranges at these points remain within functionally viable boundaries (below ~70 degrees), it is concluded that the flaking of proximal edge points is likely to be in response to their use (at least occasionally) as a functional working edge.

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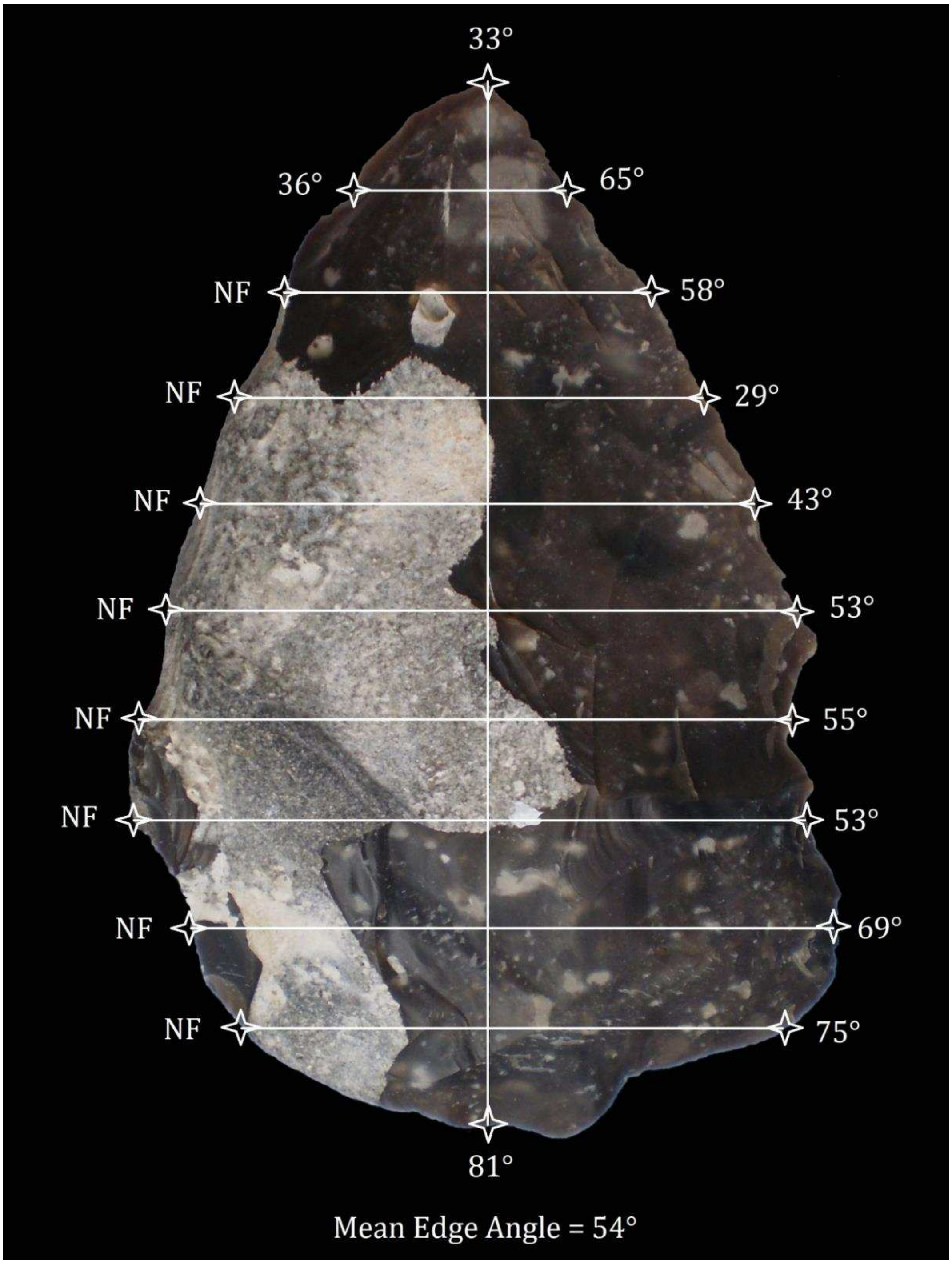

Figure 1: The points at which edge angle was measured on handaxes. The line bisecting the left and right lateral portions of the handaxe is the "line of maximum symmetry" described by Schillinger et al. (2014). If one of the predefined points of measurement fell upon an area that had not been flaked then a record of "NF" (i.e., "not flaked") was recorded.

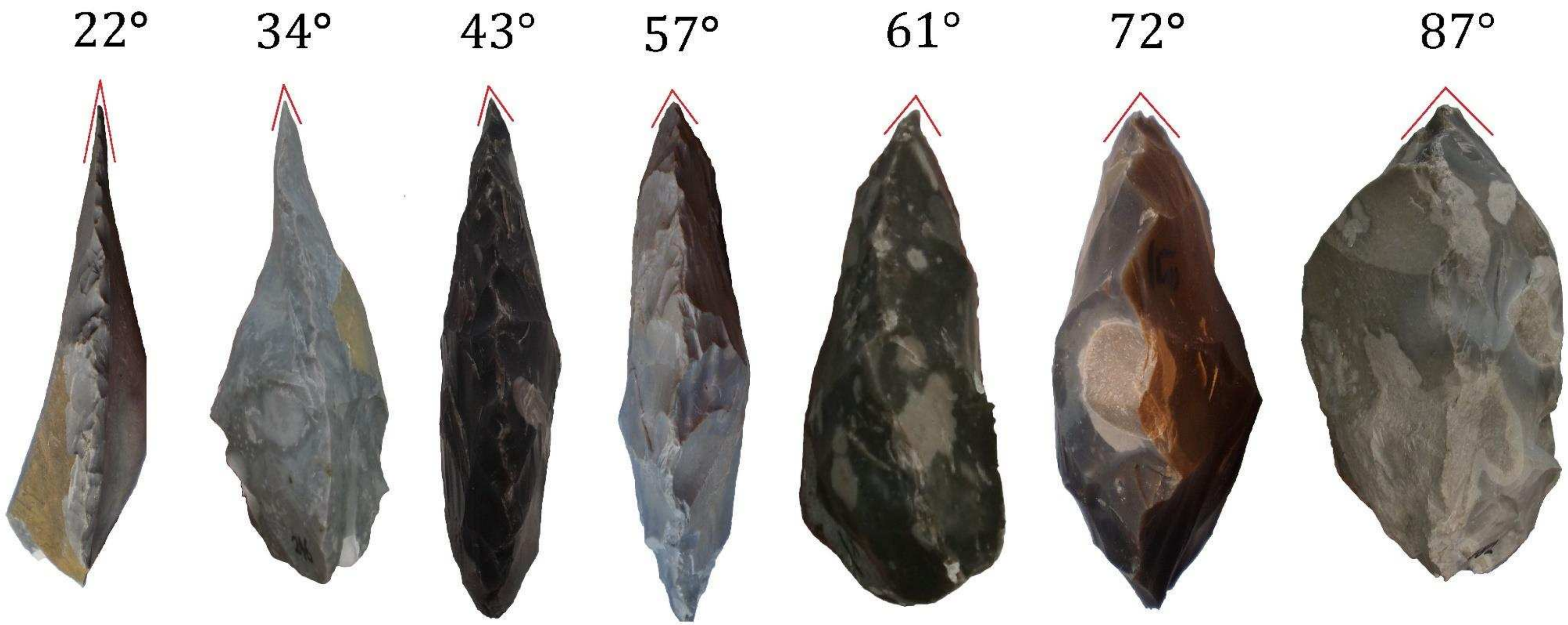

Figure 2: Examples of variation in edge angles in the experimental handaxes. The angles noted here are for the tip of each handaxe.

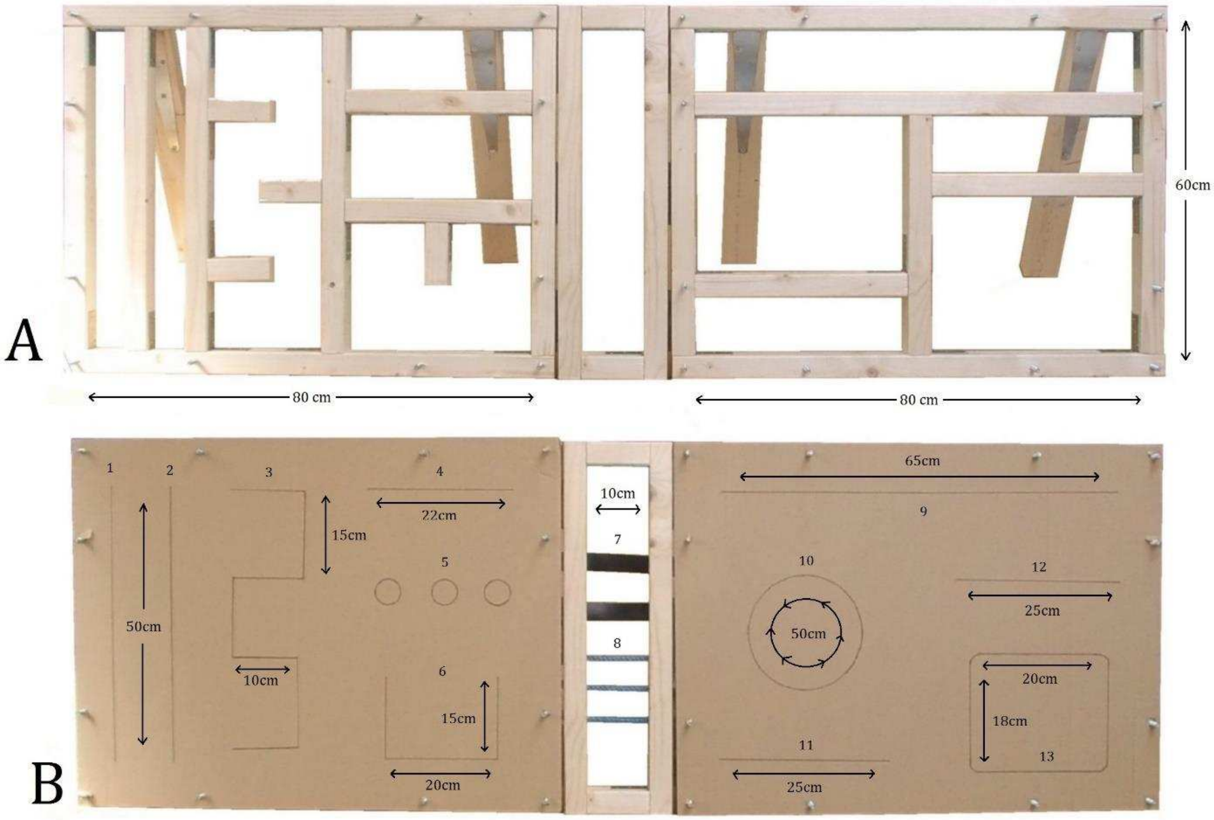

Figure 3: The experimental task undertaken by participants. Part A shows the wooden structure on which the cardboard, rope and neoprene strips were secured during the experiment. Note that support is provided for the cardboard in such a way that handaxes would not be obstructed during cutting. Part B shows the 11 lengths of cardboard, two strips of neoprene, and three lengths of rope in their final secured position ready for cutting.

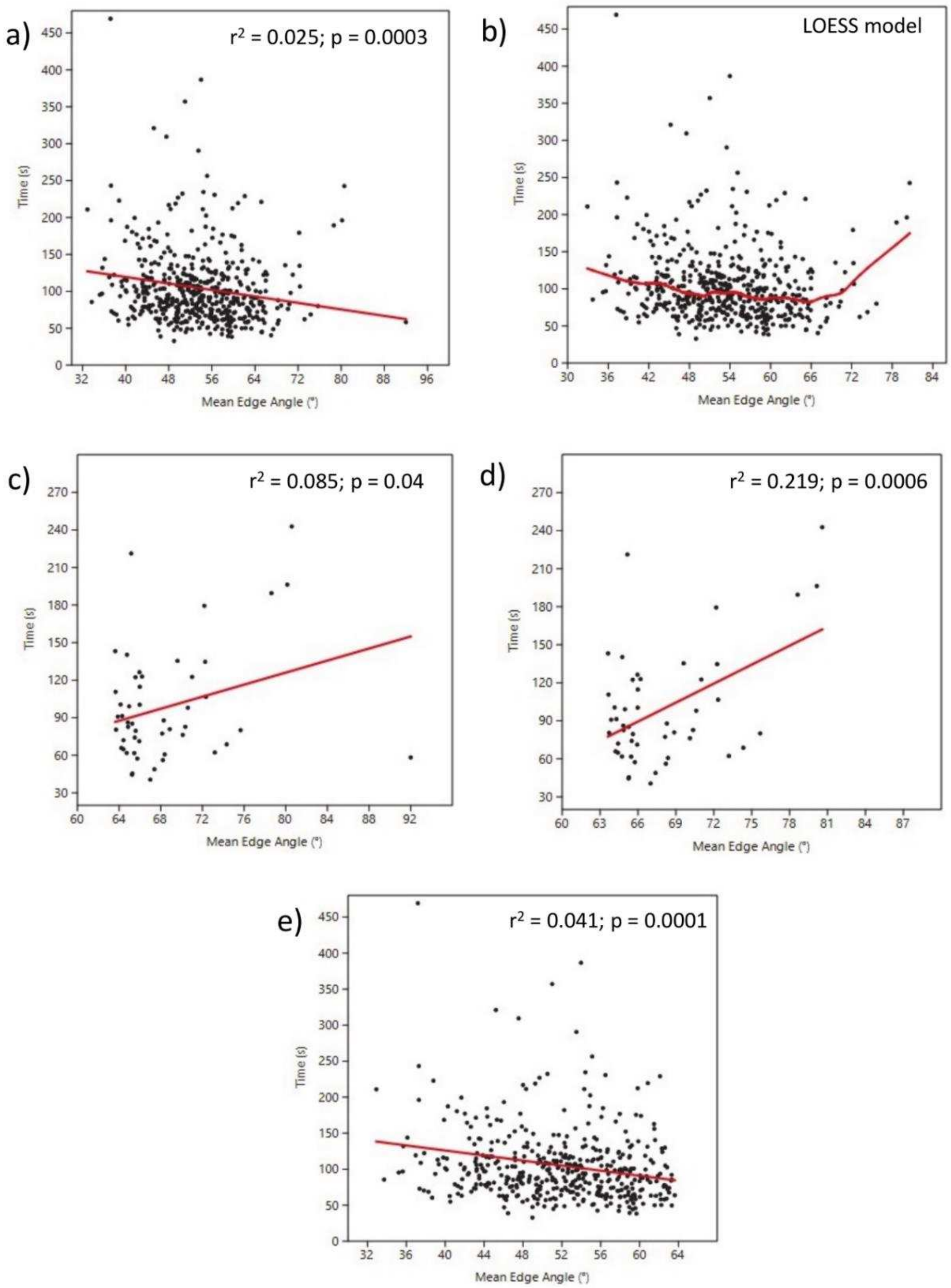

Figure 4: (a) Regression of mean edge angles against time taken; (b) the Loess model of mean edge angles against time taken; (c) regression of mean edge angles against time taken for the 50 handaxes (i.e. 10%) displaying the most obtuse edges in the experimental assemblage; (d) regression of mean edge angles against time taken for most obtuse handaxes with single outlier removed; (e) regression of mean edge angles against time taken for the 450 most acute-angled handaxes. Note that for the Loess model (b) one outlier has been removed. While its inclusion does not alter the presently displayed trend (a trend which is, importantly, significant even with its inclusion [c]), it creates a final dip to the line of fit (after the displayed increase) due to the localized weighting of the model and the relative distance of the data point from the others.

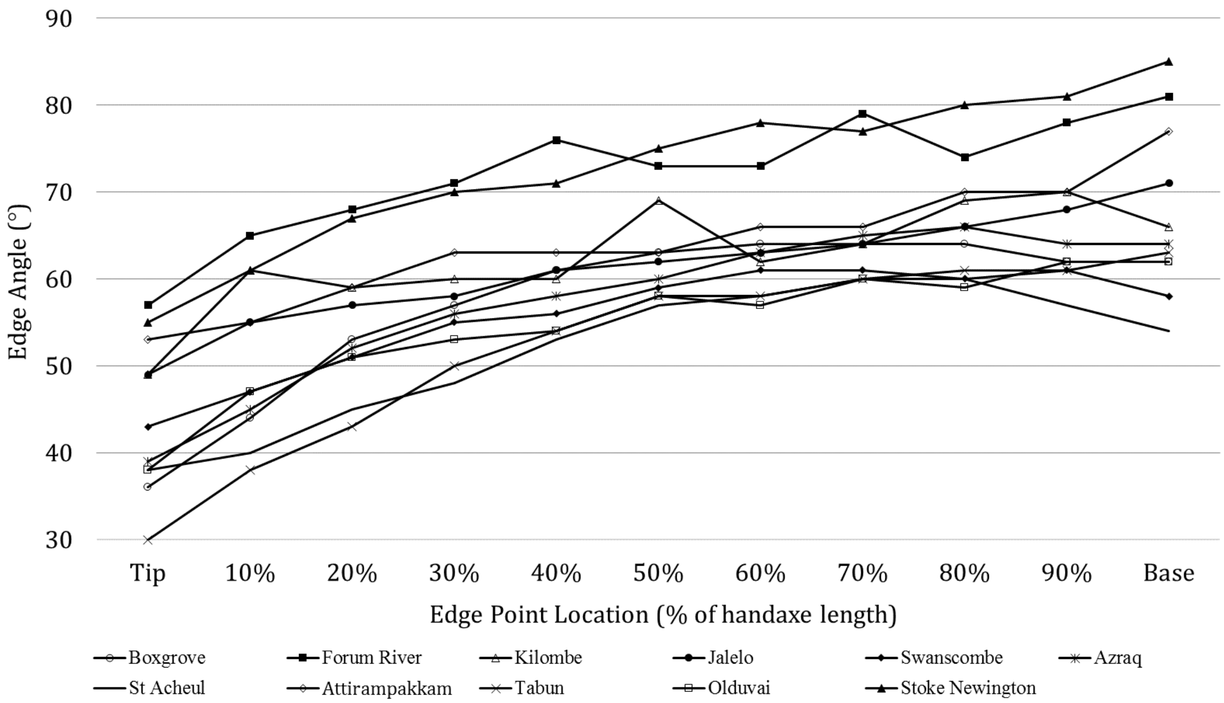

Figure 5: Plot showing the mean edge angle values observed on all 11 archaeological handaxe assemblages. Note the Forum River and Stoke Newington assemblages display a similar trend to the others but higher edge-angle values due to their post-depositional damage.

Tables

Table 1: Descriptive morphological data collected from the experimental and Palaeolithic assemblages examined in this study

Handaxe Assemblage		**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Mass (g)**	**Elongation (width/length)**	**Refinement (thickness/width)**
Experimental Assemblage (n = 500)	**Mean**	135.9	91.9	40.7	577	0.688	0.428
	S.D.	38.4	26.3	17.3	559	0.120	0.131
Boxgrove, UK (n = 254)	Mean	117.8	76.2	28.9	286.2	0.655	0.384
	S.D.	26.8	15.2	6.2	165.6	0.067	0.073
Forum River (Jos Plateau), Nigeria (n = 8)	Mean	175.7	99.2	46.9	892.1	0.569	0.476
	S.D.	29.7	13.9	8.8	313.8	0.032	0.081
Kilombe, Kenya (n = 8)	Mean	152.6	87.3	34.1	476.1	0.581	0.389
	S.D.	27.7	10.5	7.2	181.1	0.067	0.068
Jalelo, Somaliland (n = 42)	Mean	113	65.4	35.6	340.5	0.582	0.536
	S.D.	32.6	20.3	17.5	637.8	0.083	0.136
Swanscombe, UK (n = 63)	Mean	101.4	64.7	32	214.5	0.653	0.502
	S.D.	29.4	16.5	10.6	169.2	0.124	0.139
Azraq, Jordan (n=83)	Mean	102.6	71.3	30.8	223.9	0.705	0.435
	S.D.	19.4	12.3	7.2	114.3	0.088	0.103
Saint Acheul, France (n = 37)	Mean	136	73.3	36.3	393.1	0.550	0.49
	S.D.	36.7	16.1	12.1	302.8	0.081	0.109
Attirampakkam, India (n = 26)	Mean	112.7	74.3	36.5	333.1	0.679	0.503
	S.D.	30.2	13	9	188.8	0.116	0.132
Stoke Newington, UK (n = 31)	Mean	85.2	54.9	28.1	127.3	0.651	0.515
	S.D.	14.1	8.5	6.2	53.6	0.084	0.093
Tabun E (Acheulo-Yabrudian), Israel (n = 75)	Mean	98.2	65.1	31.8	189.7	0.676	0.495
	S.D.	23.8	12.8	7.7	105.9	0.097	0.102
Olduvai Bed IV, Tanzania (n = 15)	Mean	168.9	92.3	42.9	789	0.554	0.474
	S.D.	49	24.1	13.8	745.7	0.091	0.125

Table 2: The percentage of edge points within each assemblage that have not been knapped and how this varies dependent upon the edge-point investigated

Edge Point Location (% of handaxe length)	% of edge points that have not been flaked											
	Experimental Assemblage (n = 500)	**Boxgrove (n = 254)**	**Forum River (n = 9)**	**Kilombe (n = 8)**	**Jalelo (n = 42)**	**Swanscombe (n=63)**	**Azraq (n = 83)**	**St. Acheul (n = 37)**	**Attirampakkam (n = 26)**	**Stoke Newington (n = 31)**	**Tabun E (n = 75)**	**Olduvai IV (n = 15)**
Tip	0.6	0	0	0	0	0	1.2	0	0	0	0	0
10%	0.8	0	0	0	0	0.8	0.6	0	0	1.6	0.6	0
20%	1.6	0.4	0	0	1.2	0.8	0.6	0	0	3.2	1.3	0
30%	3	0.4	0	0	1.2	2.4	2.4	4.1	0	4.8	1.3	0
40%	4.4	1	0	6.3	1.2	2.4	5.4	8.1	0	8.1	5.3	0
50%	6.4	1.8	5.6	6.3	1.2	4	9.6	10.8	1.9	17.7	10	3.3
60%	9.4	3	5.6	6.3	0	5.6	12.7	14.9	1.9	25.8	15.3	3.3
70%	12.9	3.1	11.1	6.3	0	11.1	18.7	27	5.8	27.4	22.7	3.3
80%	16.6	4.1	11.1	6.3	0	23.8	25.3	28.4	7.7	35.5	32	6.7
90%	20.9	2.4	11.1	0	0	27.8	28.9	21.6	19.2	37.1	38	10
Base	24.8	0.4	0	0	0	12.7	20.5	16.2	11.5	29	37.3	13.3
Mean	8.9	1.8	4.5	3.1	0.5	5.8	11.5	12.3	4.2	17.6	14.5	3.3

Table 3: Edge angle data from the experimental assemblage and a range of Palaeolithic sites from across the Old World. Degrees are rounded to the nearest whole value. * Indicates sites display some degree of "rolling" and edge abrasion, due to having been found within a fluvial context

		Edge Point Specific Edge Angles										
Assemblage		**Tip**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**Base**
Experimental Assemblage (n = 500)	Mean (°)	41	50	52	53	54	54	55	56	57	56	59
	S.D. (°)	12	11	14	15	16	16	17	18	18	18	19
	C.V. (%)	29	22	27	28	30	30	30	32	32	32	34
Boxgrove (n = 254)	Mean (°)	36	44	53	57	61	63	64	64	64	62	62
	S.D. (°)	17	15	16	15	15	16	16	17	15	15	18
	C.V. (%)	47	34	30	26	26	26	25	26	23	25	28
Forum River * (n = 8)	Mean (°)	57	65	68	71	76	73	73	79	74	78	81
	S.D. (°)	12	10	14	12	14	12	16	13	13	12	10
	C.V. (%)	22	15	21	17	18	17	22	17	17	15	12
Kilombe (n = 8)	Mean (°)	49	61	59	60	60	69	62	64	69	70	66
	S.D. (°)	10	26	13	14	15	14	17	13	16	21	16
	C.V. (%)	20	43	22	23	25	20	27	20	23	30	24
Jalelo (n = 42)	Mean (°)	49	55	57	58	61	62	63	64	66	68	71
	S.D. (°)	10	14	13	12	14	15	17	16	17	17	21
	C.V. (%)	20	25	23	21	23	24	27	25	26	25	30
Swanscombe (n=63)	Mean (°)	43	47	51	55	56	59	61	61	60	61	58
	S.D. (°)	12	11	10	13	12	13	13	11	11	12	10
	C.V. (%)	28	23	20	24	21	22	21	18	18	20	17
Azraq (n = 83)	Mean (°)	39	45	52	56	58	60	63	65	66	64	64
	S.D. (°)	11	12	14	14	14	13	17	14	18	14	14
	C.V. (%)	28	27	27	25	24	22	27	22	27	22	22
St Acheul (n = 37)	Mean (°)	38	40	45	48	53	57	58	60	60	57	54
	S.D. (°)	25	11	13	14	14	15	15	15	13	16	12
	C.V. (%)	66	28	29	29	26	26	26	25	22	28	22
Attirampakkam (n = 26)	Mean (°)	53	55	59	63	63	63	66	66	70	70	77
	S.D. (°)	11	11	13	14	12	12	12	20	13	12	19
	C.V. (%)	21	21	22	22	19	19	18	30	19	17	25
Stoke Newington (n = 31)*	Mean (°)	55	61	67	70	71	75	78	77	80	81	85
	S.D. (°)	13	14	15	15	14	13	13	13	15	15	12
	C.V. (%)	24	23	22	21	20	17	17	17	19	19	14
Tabun E (n = 75)	Mean (°)	30	38	43	50	54	58	58	60	61	61	63
	S.D. (°)	11	12	12	12	14	17	15	17	21	18	18
	C.V. (%)	37	32	28	24	26	29	26	28	34	30	29
Olduvai, Bed IV (n = 15)	Mean (°)	38	47	51	53	54	58	57	60	59	62	62
	S.D. (°)	14	14	13	14	14	15	16	15	16	20	19
	C.V. (%)	37	30	25	26	26	26	28	25	27	32	31

Table 4: Backwards stepwise regressions to determine which areas along a handaxe's edge make the greatest contribution towards the determination of cutting efficiency. Significance values and model R^2 values are displayed on a step-by-step model basis and are inclusive of all predictors within that model. Excluding the final model (#11), stated predictors represent the edge point removed within the model at that point

Order of Contribution	Model	Predictor (Edge Point)	p	R^2
1	11	70%	0.004	0.023
2	10	10%	0.009	0.027
3	9	80%	0.015	0.030
4	8	90%	0.025	0.032
5	7	40%	0.038	0.033
6	6	Base	0.056	0.035
7	5	30%	0.077	0.036
8	4	20%	0.108	0.037
9	3	Tip	0.155	0.038
10	2	50%	0.211	0.038
11	1	60%	0.279	0.038

Table 5: Results of ANOVA tests comparing rolled to unrolled handaxe assemblages. To identify whether mean edge angle values recorded from the two rolled assemblages (Stoke Newington and Forum River) were significantly different from fresh handaxes, they were compared using one-way ANOVA tests. Tukey's post-hoc tests were then used to identify differences between the two rolled assemblages and fresh assemblages.

		Tabun	**Swanscombe**	**St Acheul**	**Attirampakkam**	**Azraq**	**Olduvai**	**Jalelo**	**Kilombe**	**Boxgrove**
Stoke Newington	ANOVA	**0.0001**								
	Tukey's Pairwise	**0.0001**	**0.0001**	**0.0001**	0.1346	**0.0001**	**0.0001**	**0.0038**	**0.0151**	**0.0001**
Forum River	ANOVA	**0.0001**								
	Tukey's Pairwise	**0.0001**	**0.0001**	**0.0001**	0.1889	**0.0001**	**0.0001**	**0.0104**	**0.0318**	**0.0001**

Supplemental Figure 1: The 500 replica handaxes used during the experimental task. Note that the handaxes at the forefront of the image appear relatively larger in proportion to those at the rear due to the images perspective.