Torque creation and force variation along the cutting edges of Acheulean handaxes: implications for tip thinning, resharpening, and *tranchet* flake removals

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Keywords: Biface; Performance Characteristics; Experimental Archaeology; Ergonomics; Cutting Stress

Declarations of interest: None

Abstract

One of the defining characteristics of Acheulean handaxes is the presence of a substantial length of sharp cutting edge, often covering the majority or entirety of their plan-form outline. Recently, factors affecting the efficiency and effectiveness of handaxes for cutting have come under increased scrutiny. Most studies investigate how shape, size, symmetry and other metrics influence cutting performance characteristics. This includes investigations of edge morphology. To date, it is unknown how cutting performance may vary within an individual handaxe dependent on which aspect of its edge is used. Here, we experimentally investigate how loading capabilities (applied forces) vary along the edges of handaxes, from tip to base. Significant differences were identified dependent on the edge-point loaded, with greater forces recorded at the tip of tools relative to more proximally located edges. Notably, at ~20% of a handaxe's length away from the tip, loading levels were reduced by around 24%. Acheulean hominins concerned with maximising cutting stress potential during tool use should, therefore, have preferentially used the tip portion of handaxes when possible. During broader, sweeping cutting motions that use substantial lengths of cutting edge, our data suggest different portions of the edge create variable cutting-stress levels. Such differences likely derive from increases and decreases in torque creation, and the interaction between cutting forces and ergonomic relationships at the hand-tool interface. We discuss how these relationships may have influenced handaxe design during the Acheulean period, including tip focused modifications such as *tranchet* flake removals, thinning, and increased resharpening.

Introduction

Acheulean handaxes display substantial lengths of sharp cutting edge around their perimeter. Indeed, extended flaked edges are a recurrent and defining (Wynn, 1995; White, 1998; Marshall et al., 2002; Gowlett, 2006, 2013; Shea, 2013) technological characteristic of handaxes, seen even in the earliest bifaces (Diez-Martin and Eren, 2012; Beyene et al., 2013; Diez-Martin et al., 2018). Their predetermined forms, intentionally created through structured reduction strategies (Isaac, 1986; Wynn, 1995; Vaughan, 2001; Pope et al., 2006; Lycett and Gowlett, 2008, 2011; Stout et al., 2014; García-Medrano et al. 2019) indicate that the production of these extended sharp edges were not accidental.

Some portions of sharp edge were almost certainly created through tool shaping and the pursuit of, as Gowlett (2006; Wynn and Gowlett, 2018) describes, a set of morphological imperatives linked to ergonomic requirements (tool mass, size, etc.). That is, to create an effective large cutting tool (LCT) capable of comfortably being held and wielded by the hand, there is a necessity to remove portions of stone through bifacial flaking processes, in turn, automatically creating lengths of sharp edge suitable for cutting (Figure 1).

The substantive lengths of cutting edge seen on handaxes are, however, also strongly linked to their use as cutting tools (Gowlett, 2015; Key and Lycett 2017a). An array of evidence suggests handaxes were likely employed to separate and fracture animal tissues (meat, bone, shells) during butchery behaviours, soft and fibrous plant matter when processing food resources, wood during tool production, and soil when used to dig (Jones, 1980; Dominguez-Rodrigo et al., 2001; Bello et al., 2009; Toth and Schick, 2009; Yravedra et al., 2010; Brumm and Rainey, 2011; Hayden, 2015; Nowell et al., 2016; Key and Lycett, 2017a; Hardy et al., 2018; Finkel and Barkai, 2018). For all cutting activities, irrespective of the material worked, a length of sharp edge would have been essential (Atkins, 2009).

Experimental studies have repeatedly demonstrated that substantial lengths of edge are, at times, recruited during handaxe use (Jones, 1980, 1994; Mitchell, 1996; Machin et al., 2005; Machin et al., 2007; Bello et al., 2009; Key and Lycett, 2017b), usually during cutting activities that allow extended, arching motions of the arm (Mitchell, 1996). As Jones (1980: 158) stated when slicing through the skin of large herbivores, "progress… was limited only by the size of the tool – the longer the edge, the more of the connecting tissue could be cut at each stroke". Thus, long cutting edges have functional advantages in some situations, helping to explain their recurrent presence on Acheulean LCTs, including most tools defined as 'handaxes'.

Equally, however, extended lengths of sharp edge are not always required when using handaxes. It has been demonstrated that some butchery and woodworking activities, among others, can be performed effectively using not only one side of a handaxe's edge, but a limited portion of it (Jones, 1980, 1994; Keeley, 1980; Mitchell, 1996; Machin et al. 2005; Machin et al., 2007). Preference is usually, but not always (Mitchell, 1996), demonstrated for edge portions towards the (distal) tip of tools (Jones, 1980; Machin et al., 2007; Bello et al., 2009), although as Machin et al. (2005: 35) stress, it is the nature and form of the edge that is most importance, "even if this should involve using the butt".

Acheulean artefacts provide evidence of hominins using handaxes in ways similar to the inferences derived from these experimental studies. For example, some researchers have observed microscopic wear traces along the whole working edges of tools (Keeley, 1980; Ollé et al., 2014; Murray, 2017; Hardy et al., 2018), while others describe only their tips exhibiting heavy wear (Keeley, 1980; Soressi and Hays, 2003; Viallet, 2016; Zupancich et al., 2018). Although rarer, similar observations have been made with residue distributions (Dominguez-Rodrigo et al., 2001; Nowell et al., 2016; Hardy et al., 2018). Morphological attributes on artefacts likewise suggest the preferential use of specific edge portions. For example, handaxes from the 500,000-year-old Boxgrove (UK) site, among others (Moncel et al., 2015), regularly display *tranchet* flake removals at their tips (Roberts et al., 1997; Pope et al., 2009). A series of authors (Roberts et al., 1997; Mitchell, 1996; Bello et al., 2009; García-Medrano et al. 2019) have linked this behaviour with the preferential creation and use of highly acute and sharp cutting edges in the distal portion of these tools. Key et al. (2016) similarly link the more acute distal edges observed on handaxes more generally to their increased cutting ability (relative to proximal edges), while Viallet (2019) used relative acuteness to define 'active' cutting edges in the distal aspects of bifaces. Many others have also associated the modification and shaping of the distal edges of Acheulean handaxes with a utilitarian application (e.g., Ashton and McNabb 1993, McNabb et al., 2004; Sharon, 2010; Beyene et al. 2013, Moncel et al. 2013; also see: Herzlinger and Goren-Inbar 2019). In a similar regard, the presence of unflaked edges on the 'butt' of some handaxes made on cobbles (e.g. STIC Casablanca [Marshall et al., 2002]) emphasises the more distal aspects of these tools to be the portion dedicated to cutting. In most instances, 'distal' and 'proximal' refer to tool portions closer to the tip or butt (respectively) of artefacts than their midpoint.

Hypotheses relating to reduction and resharpening have also tended to emphasise that more frequent resharpening events, and by association higher blunting rates, occur in the distal portions of a handaxe's cutting edge (McPherron, 1999; 2006). The narrow and pointed tips of highly elongated handaxes (Figure 1) have also been linked to cutting processes involving "an unusual degree of 'winkling' out a small part from the larger whole" (Gowlett, 2013: 7). This includes the separation of joints during butchery, where the additional leverage provided by these elongated tools may be advantageous. Other analyses suggest that the proximal base portion of these tools was best suited to be gripped, with the tip being used to cut (Marzke and Shackley, 1986; Grosman et al., 2011; Key et al., 2018).

Alternatively, Key et al. (2016: 53) identify a ~70° cutting efficiency threshold that the proximal (base) edges of handaxes repeatedly adhere to, indicating that at times "the proximal portion may be required to perform cutting tasks". More recently, Brumm et al. (2019) examined Acheulean handaxe discard and re-use behaviours, where individuals (re)flaked previously discarded bifaces. At times hominins focused on distal edge portions, but artefacts also indicated mid and base portions being re-sharpened for use (Brumm et al., 2019). Bifaces from other Acheulean sites similarly show a propensity towards proximal thinning and bulb of percussion removal that may be linked to cutting edge production and maintenance (e.g. White, 1998; Hosfield, 2011; de la Torre et al., 2014; Viallet, 2019). Some handaxes, including examples from Kalambo Falls (Clark et al., 2001), also display evidence of slight secondary 'point' or edge production on the butt.

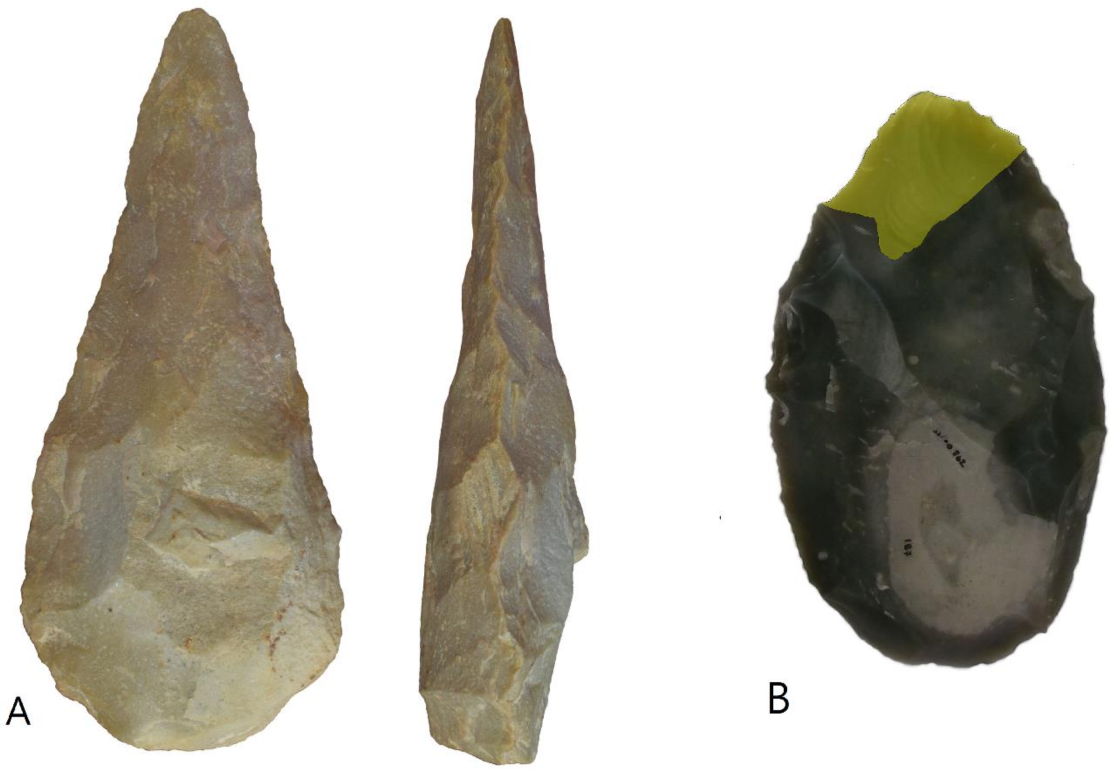

Figure 1: Handaxes from the late Acheulean sites of Porzuna in Spain (A) and Boxgrove in the UK (B). Both display morphologies suggestive of their distal portions having been the focus for use. The distal half of the Porzuna tool has been finely flaked relative to its proximal ('butt') portion, with smaller removals producing a straighter, more homogenous edge. The Boxgrove biface displays a typically characteristic *tranchet* flake removal originating from the top right of the tool (in yellow).

In sum, combined, experimental and artefactual evidence indicates that the cutting edges of handaxes are amenable to multiple types of cutting behaviours and tasks, with this affecting the portion of edge used. Questions remain, however, about precisely how the cutting edges of handaxes interact with worked materials and how such relationships may have influenced tool design strategies (*c.f.* Bleed, 1986; Bleed and Bleed, 1987). Why is it beneficial to use distal edge portions over more proximal aspects, for example, and how (if at all) is this linked to localised edge modification processes? Moreover, when long lengths of cutting edge are required, do all sections perform equally?

These questions can be investigated from two distinct, but related, perspectives. First, the mechanics of how variable edge morphologies interact with worked materials remains to be clearly understood (i.e. the tool-material interface) at both a micro- and macro-scale (Atkins, 2009; Key, 2016). Second, ergonomic (ease-of-use) considerations at the hand-tool interface remain only broadly described (e.g. Gowlett, 2006; Grosman et al., 2011; Wynn and Gowlett, 2018), and are rarely studied from an empirically defined basis focused on understanding how muscular force is transferred into cutting force. Here, we combine both approaches to investigate how cutting performance varies along the edges of handaxes, from their tip to base. Specifically, we set out to understand how loading potential (and, in turn, cutting stress) varies along the edges of handaxes and how this affects the creation of torque and, ultimately, the resistance of these forces by the hand.

Experimental Methods

Replica Tool-Set

Following well-established experimental precedents (Eren et al., 2016; Lin et al., 2018), we employ a substantial assemblage of modern replica handaxes in place of ancient artefacts. We used 457 replica flint handaxes previously employed by Key and Lycett (2019) (Figure 2). We had originally intended to use a slightly larger sample of 460 handaxes, however, due to unforeseen circumstances, one individual was only able to use seven handaxes prior to ending their participation (for reasons unrelated to the study). Hence, the final used assemblage consisted of 457 handaxes. All tools were designed to display substantial variation in their shape and size (Figure 3), encompassing the majority of biface forms recovered from the Acheulean artefact record (Key, 2019). The majority displayed completely flaked edges (i.e. 100% of their circumference exhibited a scalloped, bifacially flaked edge), although a large number retained some cortex towards their base (Figure 3). A small number retained cortex on edge portions located towards the midline or tip of tools (i.e. at or above 50% of their length). Tool sizes ranged between 39–296 millimetres in length and between 8–4485 grams in terms of mass. The use of such a large, highly variable assemblage allowed results to be applied at a broad technological level with application to tools across the Acheulean, and not just to artefacts fulfilling limited morphological criteria.

Broadly defined as the force acting on an object in a manner to accelerate rotation around a pivot, *torque* (moment of force) has potential to affect the use of elongated hand-tools, such as handaxes (Kong and Lowe, 2005). Torque also has potential to create torsion (twisting) in the tool itself (Gowlett, 2006). To investigate torque's relationship with handaxe elongation we calculated a widely used Elongation Index for each tool, where smaller values indicate relatively longer tool forms (length relative to width); calculated by dividing the width of each tool by its length. Elongation Indexes ranged from 0.308 to 1.100 (three tools were wider than they were long).

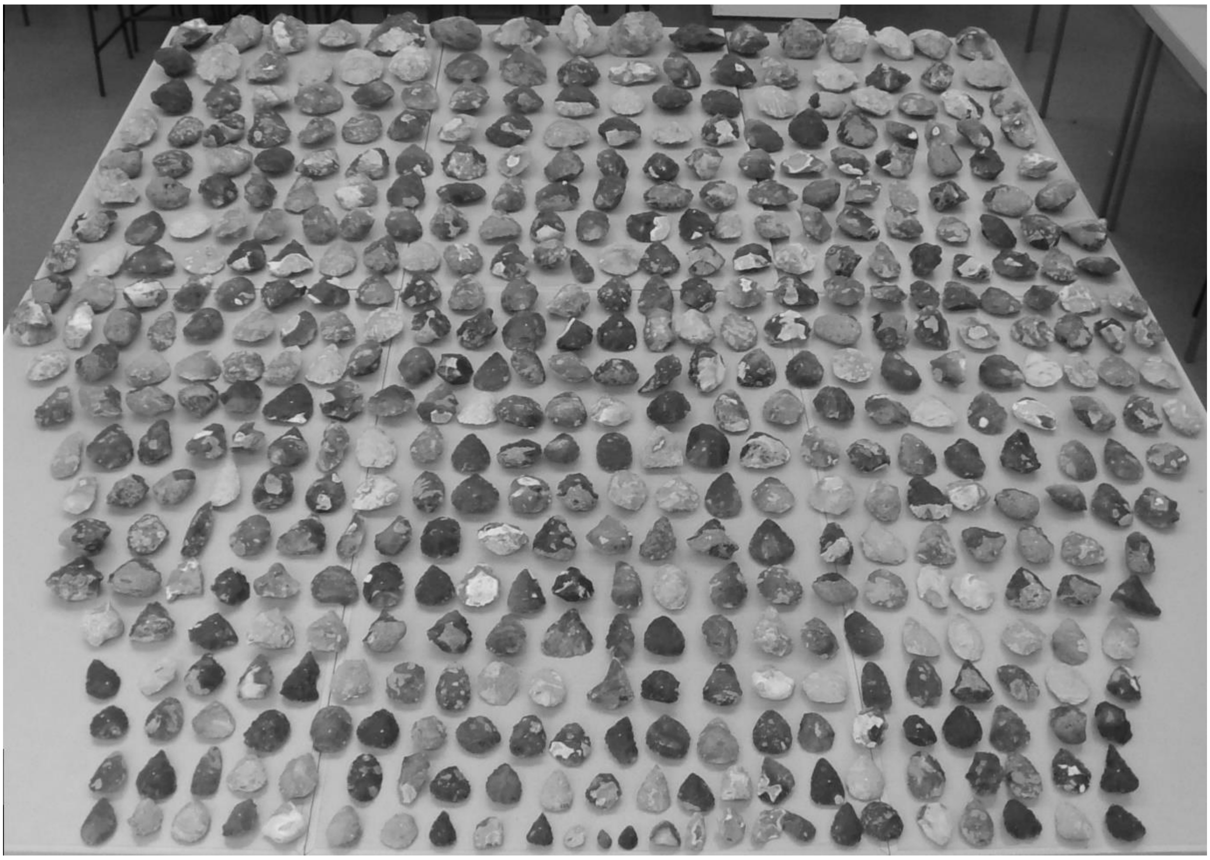

Figure 2: The 457 replica handaxes used in the experiment. Note the biased image perspective such that the smaller tools at the front appear relatively larger compared to the more substantial tools at the back.

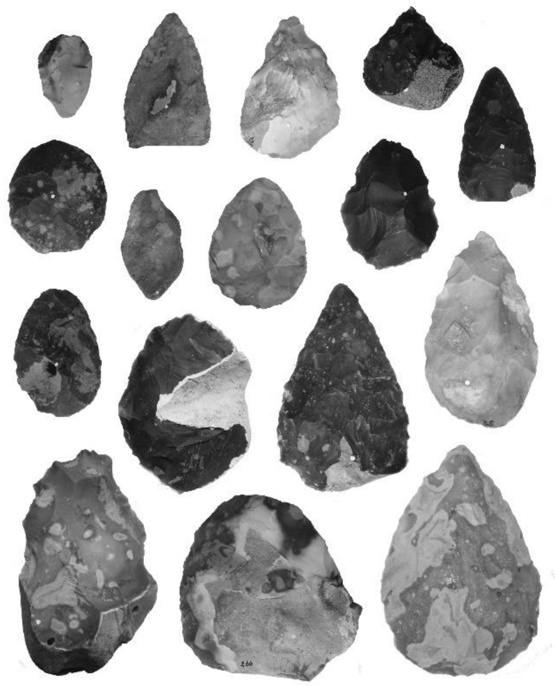

Figure 3: A selection of replica bifaces from the experimental assemblage. Those displayed here were chosen to emphasise the variation present in tool size, shape, and cortex distribution.

Participants and Tool Assignment

Participants were recruited from the student population at the University of Kent (n = 46), with each being randomly assigned 10 handaxes from the replica assemblage (using www.randomizer.org). Participants gave informed consent prior to taking part in the experiment but were not aware of the specific hypotheses under investigation.

Experimental Task

Previous experiments investigating stone-tool loading levels have used equipment consisting of a hinged platform suspended above a force sensor, onto which a small section of worked material (e.g. rope, wood) is attached (Key and Lycett, 2014; Stemp et al., 2015). Here we use similar apparatus, but due to imprecision when aligning loading values to specific edge locations during 'slicing' cutting actions (*c.f.* Atkins et al., 2004), the experiment involved forcefully applying five predetermined edge points onto the hinged upper platform (Figure 4). A threaded metal bolt (10mm in diameter) was fixed into the upper board to act as the point of contact between the handaxe and the loading platform. On the reverse side of the upper platform (i.e. facing downwards), directly opposing the bolt, a hard rubber stud rested directly on top of a Tekscan ELF Force System™ sensor (Figure 3). Thus, as tool users applied force through the handaxe and onto the metal bolt, it was transferred through the stud and onto the force sensor (Figure 4a). Participants were asked to apply as much force as they comfortably could through the tool during each loading event on each predefined edge point.

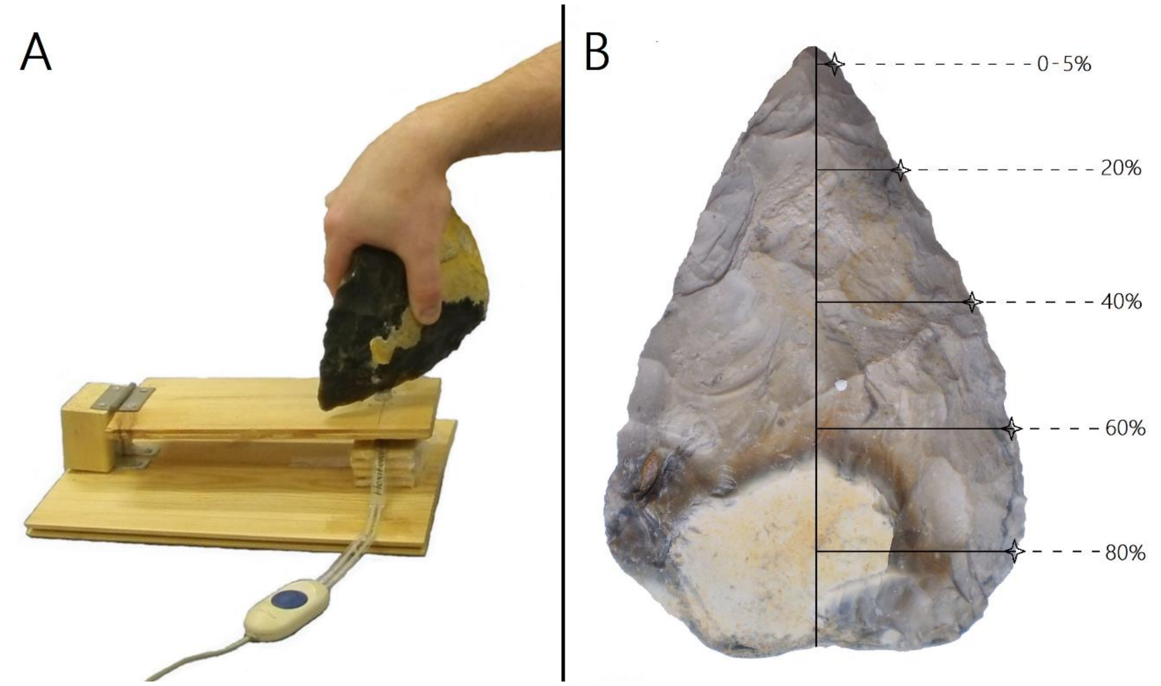

Figure 4: The loading apparatus used in the experiment (A). The lower board measured 30 cm in length while the upper board was 24.5 cm long. A five-jaw buttressed pad-to-pad grip, typical of those used in the experiment, can be seen in the image. Image B illustrates the five points along each handaxe's edge where loading was recorded.

Loading levels were recorded from five locations on each handaxe's edge, with each being defined by the maximum length of the tool (Figure 4b). This allowed points of force application to be standardised between tools irrespective of their shape or size (at a broad level), and for force records to be aligned with specific edge point locations. Loading levels were recorded at the tip of each tool (0-5% of tool length), along with edge points at 20%, 40%, 60% and 80% of a tool's length. This allowed assessment of how loading levels alter along the course of a handaxe's cutting edge, from its tip to its base. Each handaxe had the five edge points marked on them prior to participants arriving to undertake the experiment. These discreet edge locations could then be easily identified and applied to the edge of the bolt, irrespective of the tool's size, meaning that the relationship between edge point location and force could be examined with confidence. Force measurements were recorded from these five edge-point locations in a randomly determined order (again, using www.randomizer.org).

Loading was recorded in kilogram-force (kgf) at a rate of 20 Hz (one kgf equals approximately 9.8 newtons). Loads were applied for 3-5 seconds, recording a total of ~ 60-100 data points. The greatest force recorded for each edge point was used as the representative loading value. Hence, the final data set consisted of 2285 loading records (457 tools × 5 edge locations).

Body position can significantly influence loading levels during the use of hand tools (McGorry et al., 2004). To standardise body position between tools and edge points, all participants were seated during the task and the loading platform was placed on a table in front of them. The height of each participant's chair was adjusted so that their navel was level with the table. Additionally, grips were limited to those where the thumb and fingers secured opposing sides of the handaxe (Figure 4) and the palm only made contact with basal portions of the tool (i.e. the point of contact with the palm could not go beyond the midway point of the tool) (following Marzke and Shackley, 1986; Marzke, 1997; Key et al., 2018). Participants could balance their index finger on the superior edge of the tool if this felt more comfortable. The smallest tools required pad-to-side grips (two and three-jaw, buttressed and unbuttressed) where the whole tool was secured between the thumb and fingers, with additional support from the thenar region.

This task does not replicate Lower Palaeolithic handaxe use in an actualistic manner (i.e., tools are not being used in cutting tasks that directly replicate Palaeolithic hominin behaviours). However, this protocol was essential as the modern ergonomic literature provides clear links between hand-tool working forces and gripping strategies (Hall, 1997; Aldeien et al., 2005; Rossi et al., 2012). In other words, this protocol increases internal validity through the principle of greater experimental control (i.e., removal of 'noise' or specific confounding factors) and clarifies the signal from the target variables of interest, which is desirable in these kinds of experiments (Lycett and Eren 2013).

Here, this task appropriately focuses data collection on the loading levels achievable from specific points along the working edges of handaxes. Moreover, it negates potential confounding factors such as variation in body position and cutting motions, which may easily arise in actualistic conditions.

Statistical Analyses

Force data from all edge point locations were not normally distributed (Shapiro-Wilk tests; p <0.0001 in each instance). In turn, to statistically compare loading levels between the two samples we used Wilcoxon signed ranks tests, which compare the sums of rankings assign to the data in each group. First, using the complete data set (n = 457), we compared force data from the five edge point locations to investigate how loading varies along the length of a handaxe's edge. Second, to investigate the impact of elongation on a handaxe's loading capabilities, and how this varies along their working edges, we repeated these tests but compared force records between equivalent edge points on the 100 most elongated tools (Elongation Index < 0.586) and the 100 least elongated (Elongation Index > 0.778). Given that multiple pairwise comparisons were undertaken, a Bonferroni correction (whereupon, $p = 0.05/N_{\text{pairwise tests}}$) was applied in each instance such that statistical significance was only assumed if p <0.005. All analyses were performed using *PAST* (version 3.25).

Results

Force records were greatest at the tips of handaxes (defined here as edge points between 0–5% of their length), averaging 4.3 kgf. Indeed, mean loads were ~ 0.4–0.8 kgf greater here relative to edge points between 20–80% of a handaxe's length (Table 1). These differences were significant in all instances (Table 2). Edge points at 20 % of a handaxe's length recorded mean loads of 3.5 kgf, which were significantly lower than the other four investigated edge locations (Tables 1 and 2). Mean loading levels in the three most proximal edge locations (40-80% of tool length) ranged between 3.7–3.9 kgf and displayed no significant differences between them (Tables 1 and 2).

Minimum force records are broadly equal across all edge point locations, as are the maximum forces achieved at four edge points. Maximum forces at the tip of these tools was however 27.5 kgf, roughly 2 kgf greater than those achieved elsewhere. Variation levels are consistent across edge point locations, with standard deviation (SD) and coefficient of variation (CV) levels broadly being even in all data sets (Table 1). Although SD could be considered slightly higher in the tip data.

Table 1: Descriptive data for the loading levels (kgf) achievable through each of the five examined edge point locations (n = 457).

	Edge Point Location (relative to tool length)				
	0 – 5%	20 %	40 %	60 %	80 %
Mean (kgf)	4.298	3.478	3.715	3.917	3.832
Min (kgf)	0.191	0.191	0.287	0.191	0.191
Max (kgf)	27.541	25.010	24.413	24.892	25.748
SD (kgf)	4.667	4.111	4.109	4.476	4.301
CV (%)	108.6	118.2	110.6	114.3	112.2

Table 2: Wilcoxon signed ranks tests between the force levels recorded at the five edge point locations (n = 457) (Bonferroni-corrected α = .005).

	20 %	40 %	60 %	80 %
0 – 5%	**<.0001**	**<.0001**	**<.0001**	**<.0001**
20 %		**<.0001**	**<.0001**	**<.0001**
40 %			.0542	.1669
60 %				.2691

Table 3: Descriptive data for the force values (kgf) recorded at each edge point location in the 100 least elongated (i.e. their elongation index was > 0.778) and 100 most elongated (their elongation index was < 0.586) handaxes.

	Elongation Index			
	< 0.586		> 0.778	
	Mean (kgf)	SD (kgf)	Mean (kgf)	SD (kgf)
0-5 %	4.340	4.539	4.926	5.328
20 %	3.289	3.664	4.237	5.064
40 %	3.698	3.815	4.206	4.633
60 %	4.441	4.891	4.366	4.908
80 %	4.049	4.475	4.190	4.572

Table 4: Wilcoxon signed ranks tests between equivalent edge point locations in the 100 most elongated and the 100 least elongated handaxes ($\alpha = .005$). These non-significant result are repeated if the most elongated half of tools (n = 229) are compared to the least elongated (n = 228).

	0-5 %	**20 %**	**40 %**	**60 %**	**80 %**
p	.5402	.3200	.4684	.7803	.5236

The two tool sets exhibiting disparate elongation levels displayed near identical force records along their proximal edges (60% and 80% of a handaxe's length) (Table 3). Any minor differences were not significant (Table 4). Loading levels recorded in the distal half of these tools (0–40% of tool length) however varied. Indeed, handaxes displaying higher elongation indexes (and were therefore shorter relative to their width) displayed greater mean forces (between ~ 0.6–1 kgf greater; Table 3). These differences were not, however, significant (Table 4). When combined with substantially higher SD values in the less elongated tool, it appears that differences in mean force may be driven by a greater number of high-value outliers in the less elongated tools. This is supported by median values being more equal between tool sets, although force values are still lower in the more elongated handaxes.

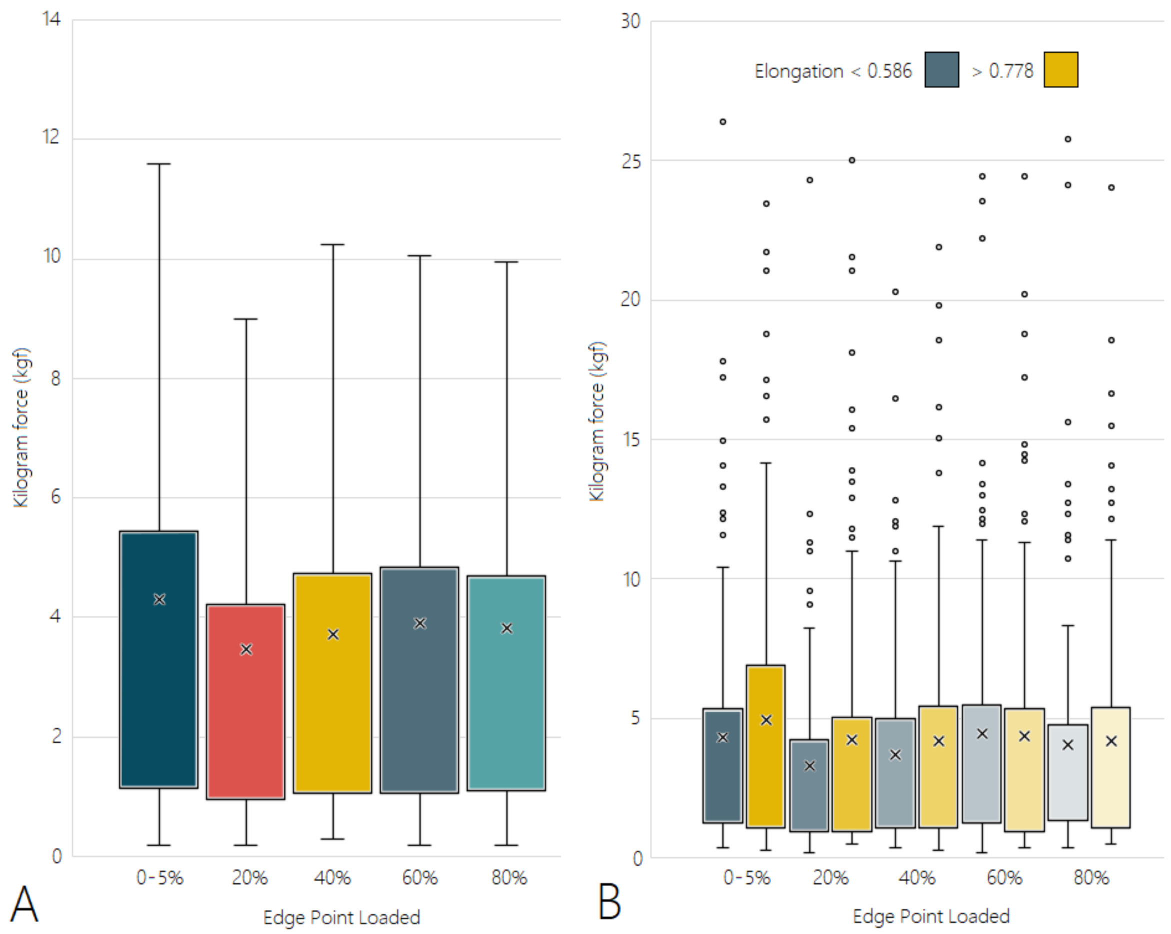

Figure 5: Force values (kgf) from the five edge point location investigated, both from the full assemblage (n = 457) (A) and the samples with high and low levels of elongation (B) (n = 100). Mean values are indicated by 'x'. Outliers are not illustrated in figure A.

Discussion

Direct and indirect evidence indicates that Acheulean handaxes were used to cut a variety of materials (Shea, 2007; Key and Lycett, 2017a). Diverse cutting actions would have been required, with entire lengths of a tool's edge being used at times, while on other occasions only specific portions were applied; most often, distally located 'tip' edges. Artefactual and experimental evidence supports such diversity in the use of their edges (e.g. Jones, 1994; Mitchell, 1996; Dominguez-Rodrigo et al., 2001; Machin et al., 2005; Bello et al., 2009; Nowell, et al., 2016; Hardy et al., 2018).

Here, we demonstrate that the (distal) tips of handaxes facilitate the application of significantly greater loads relative to more proximally located edge aspects. An additional 10-24% more force could applied through this portion of the tool, equating to an increase of 0.4-0.8 kgf relative to other edge point locations. Loading levels at 20% of a handaxe's length were significantly lower than at all other investigated edge point locations. Thus, there is a significant drop-off in loading capabilities immediately after the tip of these tools (Figure 5). More proximally located edge portions (i.e., between 40-80% of a handaxe's length) returned broadly consistent force records that, although greater than those recorded at 20%, were significantly lower than those observed at the tip.

The depth of cut achieved and the efficacy of material fracture are directly proportional to the forces applied through a sharp edge during cutting actions (Atkins, 2009; Key, 2016). Our data, therefore, indicate that—in terms of loading potential—the most effective portion of a handaxe's cutting edge is at their tip. The relative impact of these differences would depend on the material cut. In highly resistant material contexts, greater applied forces may be the difference between a cut being achieved or not. If maximal cutting forces were not required for a task, the relationships observed here would translate into lower muscular effort (i.e. increased 'ease-of-use') and energetic savings. Such energy savings would be multiplied relative to the duration of the specific cutting task performed. A substantial and highly variable assemblage of replica handaxes was used here, indicating this relationship is applicable to the majority of bifacial tool forms defined as 'handaxes' during the Acheulean (although specific shape properties of some tools may influence 'noise' in the relationships observed here). Moreover, these differences were maintained when data from the ten strongest and ten weakest participants were examined independently (with 1.64 kg and 0.35 kg differences between the tip and 20% edge points respectively).

Bleed and Bleed (1987: 196) note that even though some tool designs may demonstrate observable improvements over others, differences "might not actually be great enough to be of importance in the real world. This variation could be so unimportant as to be essentially 'neutral'". In other words, even in a case where selection has guided artefactual forms to vary within specific boundaries, the capacity for drift within and (especially) across assemblages remains (Lycett et al. 2016; Schillinger et al., 2017).

This raises the important question of whether the significant differences identified here would have *actually* influenced the behaviour and tool designs of Acheulean hominins. Instructively, therefore, the tip-focussed edge modification, (re)flaking and use seen in Acheulean handaxes (e.g. Ashton and McNabb, 1993; McPherron, 1999; Gowlett, 2006, 2013; Bello et al., 2009; Sharon, 2010; Moncel et al., 2015; Key et al., 2016; Viallet, 2019) is consistent with the force data observed here. That is, there are indications that the performance differences observed here may have (consciously or otherwise) influenced the behaviour of Acheulean tool makers. Indeed, if the creation of high cutting stress and increased tool performance were of concern to Acheulean individuals, then it is logical that a handaxe's tip would be preferentially employed (Bleed, 1986; Bamforth and Bleed, 1997; Schiffer and Skibo, 1997; Fitzhigh, 2001; Bird and O'Connell, 2006; Atkins, 2009; Key, 2016; Plummer and Bishop, 2016). This would similarly be the case during experimental studies with modern humans, as previously alluded to by Jones (1980) and Machin et al. (2007). A focus on the shaping and flaking of distal aspects of a handaxe's cutting edge during the Acheulean (Figure 1) would similarly have maximised a tool's cutting performance. For example, the *tranchet* flake removals observed at Boxgrove (Roberts et al., 1997; Pope et al., 2009) would have created highly acute edges precisely where the greatest working forces could be created, thus maximising cutting stress potential and depth of cut. This is of particular note given the considerable forces required to butcher large mammals at this site (Bello et al., 2009). Moreover, increased flaking and more acute edges on the distally located portions of handaxes (Key et al., 2016; Wynn and Gowlett, 2018) is consistent with the preferential production of sharp, efficient cutting edges at the point of maximal cutting stress potential. The production of more acute edges at ~20% of a handaxe's length, where loading potential is lowest, would also benefit cutting stress creation at this edge point. Negative allometry of handaxe thickness at this point (Crompton and Gowlett, 1993), provides further independent evidence of hominins responding in this way; i.e., making more acute edges, and thinner tools overall, precisely at the point where force creation is lowest.

Evidence suggests that the entire length of an Acheulean handaxe's edge would have been required for cutting at times (Keeley, 1980; Mitchell, 1996; Machin et al., 2005; Gowlett, 2015; Key et al., 2016; Hardy et al., 2018). Our data are consistent with such occurrences, suggesting that although cutting performance would vary, all edge portions could effectively be used to cut with. Indeed, although force levels can be up to 24% lower in more proximal edge aspects relative to the tip of tools, this is unlikely to preclude their ability to cut.

Relatedly, longer cutting edges facilitate the application of greater forces parallel to a worked material's surface, as observed during 'slicing' cutting actions. That is, the slice-push ratio describing the work (energy) required to initiate a cut depends on forces parallel *and* perpendicular to a material (Atkins et al., 2004; Atkins, 2006), explaining why cutting is subjectively easier when a slicing motion is involved. As Key (2016) notes, "greater edge lengths have the potential to increase the velocity of a cutting stroke, in turn increasing the horizontal force input of the slice-push ratio". Thus, the creation of long cutting edges on handaxes may be linked to the production of greater forces parallel to the surface of a worked materials. This reveals why Mitchell (1996) noted smooth, continuous, curvilinear cutting motions to be particularly effective when using handaxes to butcher deer. Thus, while loading capabilities perpendicular to a material's surface are important (as recorded here), other aspects of a tool's cutting motion could have influenced the production of long edges on Acheulean handaxes. Certainly, we have taken a relatively straightforward approach to investigating how forces vary during the use of hand-held cutting tools; particularly during slicing cutting actions. However, this is an important step in understanding how the transferal of force occurs during handaxe use, from its initiation creation by upper limb muscles through to it creating cutting stress and fractures in worked materials.

Elongation

More elongated handaxes displayed lower mean forces in our experiment, aligning well with Gowlett's (2006: 209) suggestion that lateral extension (relative width) in these tools aids the resistance of torsion during use and supporting Vaughan's (2001) hypothesised links between maximum width and handaxe performance. The differences we identify, however, appear to have been driven (at least in part) by outliers. Hence, we did not find a strong relationship between elongation and handaxe loading capabilities. This does not mean that highly elongated tools are not more effective in specific functional circumstances (e.g. Jones, 1980; Gowlett, 2013), or that lateral extension is not ergonomically linked (Gowlett, 2006). Rather, if producing a handaxe capable of exerting particularly high 'push' cutting forces is of concern, then there is no substantive benefit to making a tool highly elongated.

Our results suggest, therefore, that—at least in terms of elongation—handaxe shape can vary widely with little impact on their ability to generate high cutting forces. While we have not been able to examine other shape traits (e.g., McNabb et al., 2004; Lycett et al., 2006; Lycett, 2008; Archer and Braun, 2010; Costa, 2010; Viallet, 2019), the elongation results are consistent with previous investigations noting the limited impact of handaxe shape on functional trends (Machin et al., 2007; Key and Lycett, 2017c). This stresses the high tolerance of handaxes with respect to their morphology and functional performance, in turn demonstrating why the broadly defined "handaxe" form (or "bauplan" *sensu* Lycett and Gowlett 2008) was found to be an effective and functionally relevant solution to practical problems by hominins widely dispersed in time and space during the Acheulean. As Wynn and Gowlett (2018: 27) recently put it:

> At its most basic the handaxe was an ergonomically guided solution to the problem of producing a sturdy hand-held cutting tool in the context of a knapped-stone technology that lacked hafting. These ergonomic imperatives alone can account for the immense distribution of handaxes in time and space, as well as their appearance in seemingly incongruous times and places.

Moreover, these imperatives provide broad but selectively constraining limits on handaxe form, explaining why, although handaxes vary due to a variety of different factors, they do so within a functionally viable ranges (Crompton and Gowlett, 1993; Kempe et al. 2012; Gowlett, 2015; Lycett et al., 2016; Key and Lycett 2017a).

Torque Variation

The loading variation observed here is likely influenced by a tool user's ability to minimise the creation of torque and effectively resist its influence. Torque, broadly defined as the creation of force acting upon an object in a manner to rotate it around a pivot (Kong and Lowe, 2005), is well recognised in ergonomic studies of modern hand-held tools. Following previous works (Simão, 2002; Gowlett, 2006; Grosman et al., 2008), we would argue that it is also of particular relevance to the use of handaxes (Figure 6).

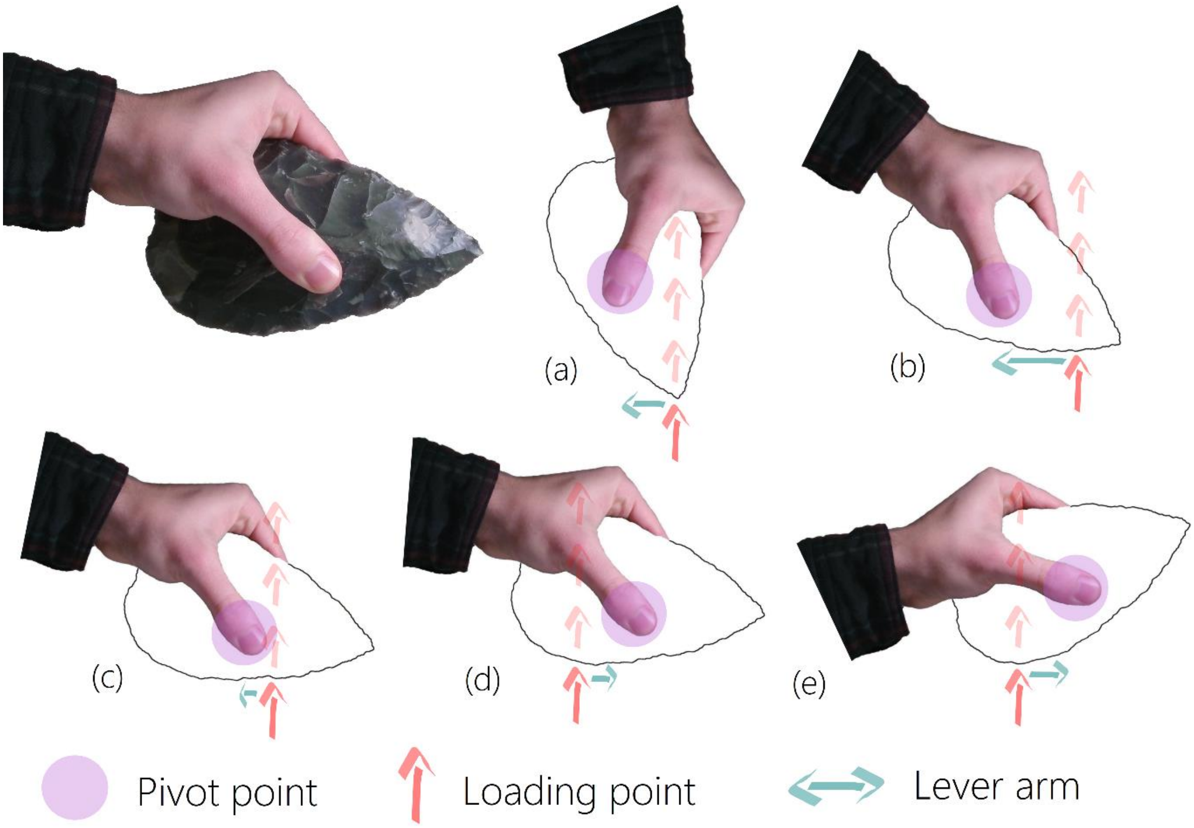

Figure 6: Schematic showing how the lever arm contributing to torque varies depending on exactly where along a handaxe's edge loading is applied. Images (a) through to (e) are representative of edge points from tip through to 80% of the handaxe's length.

When handaxes are gripped, the thumb and fingers oppose each other on either face of the tool, securing it into the hand (Jones, 1980; Mitchell, 1995; Marzke, 1997; Key et al., 2018). This creates a pivot point around which torque can act (Figure 6). The location of this point varies dependent on the size and shape of the tool, the dimensions of the tool user's hand, and the specific positioning of the grip, but for the majority of Acheulean handaxes this 'pivot point' would occur broadly around the tool's midpoint and/or it's point of maximum width (Gowlett, 2006; Grosman et al., 2011; Key et al., 2018; Wynn and Gowlett, 2018). During use, forces applied to the tool's edge will attempt to rotate the tool around this point, creating torque. To maintain a secure grip on the tool and ensure transferal of cutting forces into a worked material, muscles in the hand and forearm must work to counter it.

Torque levels are, however, dependent on the length of the lever arm connecting the point of force application (contact with the worked material) to the pivot point (Figure 6). The longer the lever arm, the greater the torque created. Consequently, the further away from the pivot point that a handaxe's edge is loaded, the greater the torque acting on the tool. Muscular force that could otherwise work to apply greater force onto worked materials instead has to resist greater torque, reducing the loads enacted through the tool's edge.

At first, our finding of greater loading potential at the tip of handaxes appears counterintuitive. However, this does not account for the outline form of handaxes, where distally located edges curve perpendicular to the long axis of the tool, creating 'teardrop' and 'ovate' shapes. This alters the cutting edge's angle of application and requires the hand using the tool to move above the aforementioned pivot point (i.e. above the worked material, with the tool directly beneath). In turn, the lever arm contributing to torque is reduced, while simultaneously moving the palm, which can more easily resist 'push' forces during cutting relative to the fingers (Jones, 1994; Aldien et al., 2005), directly above the point of contact between the worked material and the handaxe's tip (Figure 6). Thus, the hand has to counteract lower torque while simultaneously allowing the palm to contribute directly to force transferal and resistance. This explains why significantly greater loads can be created at the tip of handaxes.

Soon after its tip, handaxe edges are broadly parallel to the tool's long axis, meaning that when force is applied perpendicular to the tool's edge, the lever arm contributing to torque is greater at 20% of a handaxe's length than it is at the tool's tip (despite the edge point being more proximally located). The palm also moves from being directly above the point of contact with the worked material (Figure 6b). This creates greater torque while simultaneously inhibiting the palm's ability to contribute effectively to force transferal. In turn, this results in reduced loading. At 40% of a handaxe's length, edges are still parallel relative to the worked material, but the lever arm contributing to torque is reduced (Figure 6c). It is also possible for the second proximal phalanx and metacarpal head, which often are used to oppose cutting forces during handaxes use (Marzke, 1997; Key et al., 2018), to directly oppose the point of contact with the worked material and contribute to loading. This accords well with the increased force levels observed at this edge point relative to those at 20%. At 60% and 80% of a handaxe's length, lever arms are relatively short and broadly in-line with those at 40% (Figure 6d and 6e). This explains why there is consistency in the loading levels recorded at these three points. Notably, torque will attempt to rotate the tool in the opposing direction relative to more distally located edges. In each case, however, the palm is comfortably located above the point of loading, meaning that it can contribute to and resist relatively high forces

Conclusions

Loading potential varies significantly along the edges of handaxes, with the tip of tools facilitating the creation of greater forces levels relative to those more located more proximally. Acheulean hominins concerned with maximising cutting stress potential during tool use should, therefore, have preferentially used the tip portion of handaxes.

Consistent with our results, tranchet flake removals, more acute edges, and increased flaking intensity on the distal edges of Acheulean handaxes plausibly reflect behaviours exploiting this specific performance characteristic. Torque is presented as a key consideration in explaining why loading varies along a handaxe's working edge. This does not mean that more proximally located edges cannot cut effectively. Moreover, long lengths of cutting edge have the potential to create greater 'pull' forces seen in slicing cutting actions. Instead, it appears that Acheulean individuals chose to produce versatile cutting edges and combine the benefits of both.

Hominins created long and sharp cutting edges, while simultaneously modifying tip portions, maximised their ability to create high cutting stress in handaxe tools.

A range of microevolutionary factors conspire to influence the appearance of fresh variation into the learning networks of Acheulean hominins, upon which both drift and selection over time and space can go to work (Lycett et al. 2016). The results of this experiment further help to demonstrate that the genius of handaxe design is that the essential 'bauplan' (*sensu* Lycett and Gowlett 2008) consistently delivers specific functional features and is tolerant to a substantial range of drift and diversity in overall form (Key, 2019). As stressed earlier, the limits on handaxe form are there, but they are broad and functionally tolerant to much of the variation we see across the Acheulean despite its distribution in time and space. In other words, these results add to a body of evidence that help explain why the Acheulean is chiefly composed of handaxes that paradoxically share what Gowlett (1998) referred to as both a "unity and diversity" of form across broad swathes of time and space.

Acknowledgements

We are grateful to the participants for taking part in this study. The Boxgrove handaxe image used in Figure 1 comes from a study undertaken in 2015, for which we are grateful to Nick Ashton and Mark Roberts.

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