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Handaxe shape variation in a relative context

Variation de forme des bifaces acheuléens dans un contexte relatif

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ABSTRACT

The nature, extent and causes of shape variation within and between Acheulean handaxe assemblages represent one of the most heavily theorised aspects of Lower Palaeolithic archaeology. To date, however, handaxe shape variation has only ever been studied within an artefact-based comparative context. Here, the 2D and 3D shape of 698 Acheulean handaxes, selected from ten assemblages, is contextualised within a theoretically possible range of forms defined by two intentionally highly diverse modern replica biface sets. Results demonstrate that handaxe artefacts are highly diverse in their 2D plan-view shape, displaying near complete overlap with the shape space of the intentionally diverse replica tools, along with similar levels of variation. The 3D shape of handaxe artefacts, however, displays much stronger form limitations, occupying under 50% of the shape space created by the replica bifaces. Principally, flat and more 'tabular' handaxe forms that display low thickness to width ratios were revealed as absent from the archaeological record. It is argued that while there is considerable diversity and variability in the shape of Acheulean handaxe artefacts, their form is nonetheless restricted by strong material volume and 'refinement' limits.

RÉSUMÉ

La nature, l'étendue et les causes de la variation de forme dans et entre les assemblages de bifaces acheuléens constituent l'un des domaines où existent le plus de théories en archéologie du Paléolithique inférieur. À ce jour, cependant, la variation de forme des bifaces n'a été étudiée que dans un contexte comparatif, fondé sur des artefacts. Ici, la forme en 2D et 3D de 698 bifaces acheuléens, sélectionnés parmi dix assemblages, est contextualisée au sein d'une gamme de formes théoriquement possible, définie par deux ensembles de répliques modernes de bifaces, intentionnellement très divers. Les résultats démontrent que les artefacts de bifaces sont très divers dans leur forme en 2D, révélant un chevauchement presque complet avec l'espace de forme des répliques d'outils intentionnellement diverses, avec des niveaux de variation similaires. La forme en 3D des artefacts de bifaces montre toutefois des limitations de forme beaucoup plus importantes, occupant moins de 50 % de l'espace créé par les répliques de bifaces. Principalement, on a trouvé que les formes plates et plus « tabulaires » des bifaces aux faibles rapports épaisseur/largeur étaient

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absentes des données archéologiques. Il est soutenu que si les artefacts de bifaces acheuléens présentent une diversité et une variabilité considérables dans leur forme en 2D, leur forme en 3D est néanmoins restreinte par un important volume matériel et des limites de « raffinement ».

1. Shape variation in Acheulean handaxes

Our understanding of Pleistocene hominin behaviour is predominantly informed by lithic artefacts. As has long been recognised, a complex set of variables interacted to produce the stone tools that we recover from archaeological contexts (Isaac, 1977; Kuhn, 1994; Schiffer and Skibo, 1997; Torrence, 1989). Once the influence of an individual variable on a lithic artefact's formal properties is identified, however, it becomes possible to comment on a diverse range of behavioural factors, including cognitive and manipulative capabilities (Key and Dunmore, 2018; Morgan et al., 2015; Stout et al., 2014), landscape use (McHenry and de la Torre, 2018; Pope et al., 2006), raw material selection (Braun et al., 2009; Eren et al., 2014), and technological strategies (Diez-Martín et al., 2011; Reti, 2016), among many others.

Underpinning a substantial portion of this research is our understanding of morphological variation within and between stone tool assemblages. Indeed, comment is frequently made to 'limitations', 'preferences', and 'selectivity' in artefact morphologies, or alternatively, displays of form 'variability', 'free-play', and 'diversity'. These perceptions of form help unravel how hominins behaved; in part, by allowing hypothesis construction and testing based on why specific tool-form preferences may or may not have been enacted (intentionally or otherwise) (Eren et al., 2016; Lin et al., 2017).

For over 150 years handaxe shape variation has received considerable attention from archaeologists (Ashton and McNabb, 1994; Evans, 1872; Key and Lycett, 2017a; Prestwich, 1860). Such is the interest, it constitutes one of the most heavily investigated and theorised aspects of Lower Palaeolithic literature. Traditionally, handaxes were typologically categorised dependent on gross differences in their plan-view (2D) shape, famously epitomised by Roe's (1968, 1981) description of 'pointed', 'ovate', 'cleaver' biface groups, among others. Quantitative studies of handaxe shape variation have since come to replace subjective typological categorisations (Crompton and Gowlett, 1993; Costa, 2010; Grosman et al., 2008; Herzlinger et al., 2017; Iovita and McPherron, 2011; Isaac, 1977; Lycett et al., 2006; Okumura and Araujo, 2019; Saragusti et al., 2005; Vaughan, 2001; Wynn and Tierson, 1990).

Irrespective of the techniques used to discriminate between tool forms, there is argued to be both diversity and uniformity in the shape of handaxes. Indeed, inherent form consistencies in the '*Bauplan*' of handaxes (Lycett and Gowlett, 2008), coupled with diversity observed within and between individual assemblages, led Glynn Isaac (1977) to famously describe the tools as displaying a "variable sameness", a phrase repeated and re-emphasised in subsequent work (Gowlett, 2011a, 2015; Gowlett and Crompton, 1994; Lycett and Gowlett, 2008; Lycett et al., 2016). Previous explanations about why the shape of these tools may have been amplified or restricted at particular sites have included functional factors, cultural evolutionary mechanisms, technological convergence, allometry, reduction intensity or stage, and raw material factors (Archer and Braun, 2010; Ashton and McNabb, 1994; Crompton and Gowlett, 1993; Gowlett, 2009; Iovita et al., 2017; Isaac, 1969; Li et al., 2014; Lycett and von Cramon-Taubadel, 2015; Machin, 2009; McNabb et al., 2004; McPherron, 1999, 2006; Shipton and Clarkson, 2015; Vaughan, 2001).

Fundamental to most of these studies is the concept of relative form. That is, the interpretation of one assemblage's morphology within the relative context of another comparative sample. Similarities and/or differences inform our understanding of what high or low levels of variation look like, or the morphological predilections of one hominin population over another. Moreover, absence or presence of particular tool forms in one assemblage relative to another further drives behavioural inferences. Despite the relativism of handaxe shape variation being fundamental to how we interpret hominin behaviour, Acheulean comparisons have near universally been performed within the context of other artefacts (e.g., Gowlett, 2015; Gowlett and Crompton, 1994; Iovita et al., 2017; Lycett and Gowlett, 2008; McNabb et al., 2004; Moncel et al., 2015; Petraglia and Shipton, 2008; Roe, 1969, 1981; Shipton, 2018; Vaughan, 2001; Wang et al., 2012; White, 1998; Wynn and Tierson, 1990). Although valuable, all handaxe artefacts likely had some kind of form restrictions imposed on them (Gowlett, 2006, 2009; Lycett, 2008; Lycett et al., 2016, Machin, 2009). Thus, morphological limitations and variation levels are only understood from a perspective informed by tools already restricted in their form.

One as-of-yet unexplored route to understand the relativity of handaxe shape variation is through the use of modern replica tool assemblages. Although previous works have recreated handaxes to test specific form-related hypotheses (e.g., Archer and Braun, 2010; Eren et al., 2014; Stout et al., 2014), replica tool-sets are rarely used as a gauge of artefact variation levels (Diez-Martín and Eren, 2012; Eren et al., 2016). Specifically, our understanding of Acheulean handaxe variation would be advanced if artefact assemblages were compared to modern tool-sets displaying little to no restrictions on their form. Doing so would provide novel insight into the strength and direction of selective pressures acting on the morphology of these tools during the Pleistocene. In the past decade two substantial replica handaxe assemblages have been produced that intentionally display few restrictions on their form (Key and Lycett, 2017b; Machin et al., 2007). Here, these tools are compared to multiple Acheulean assemblages to

Table 1
The ten Acheulean assemblages compared against the two replica toolsets. All represent randomly selected subsamples from larger assemblages from their respective repository.
Tableau 1
Les dix assemblages acheuléens comparés aux deux répliques de séries d'outils. Tous représentent des sous-échantillonnages sélectionnés au hasard à partir d'assemblages plus larges de leur dépôt respectif.

Site	Location	Age	*n*
Amanzi Springs	South Africa	Middle Pleistocene	31
Boxgrove	UK	500,000	214
Cunnette	Morocco	600,000–400,000	40
Elandsfontein	South Africa	700,000–400,000	40
El Sotillo	Spain	Middle Pleistocene	34
HK, Olduvai Gorge	Tanzania	800,000	53
Porzuna	Spain	Middle Pleistocene	133
St Acheul	France	Middle Pleistocene	38
S.T.I.C.	Morocco	Middle Pleistocene	40
Tabun	Israel	300,000	75

identify the shape tendencies and levels of variation imposed on handaxes by Pleistocene hominins.

2. Methods

2.1. Replica handaxe assemblages

In 2007 Machin et al. published an experimental investigation into the impact of symmetry on handaxe butchery efficiency. For the study John Lord, a highly skilled and experienced UK-based flintknapper, was commissioned to produce a set of 104 replica handaxes of "varying degrees of frontal and side symmetry," from which a random subsample of 60 were selected (Machin et al., 2007: 884). More recently Key and Lycett (2017b; Key and Lycett, 2019) published a series of experimental studies utilising an assemblage of 500 replica Acheulean handaxes; 480 of which were produced by a single individual. These handaxes were "purposefully produced to be highly variable, with both morphologically extreme and archaeologically representative handaxe forms being produced" (Key and Lycett, 2017b: 517). Both replica assemblages were knapped to intentionally exhibit high levels of variation but had no strict morphological criteria to follow. Further, both knappers had no prior knowledge that the tools would be used in the present study. Of course, these two assemblages ($n = 60$ and 480) will not encompass all possible biface forms, and modern knappers are just as likely as their Palaeolithic counterparts to display socially informed shape biases (*cf.* Lycett et al., 2016). Nonetheless, together these two assemblages represent the best sample available for understanding shape limitations and variation in Acheulean handaxe artefacts, as revealed by possible tool forms produced by modern flint knappers.

2.2. Acheulean handaxe assemblages

In total, 698 artefacts from ten Acheulean sites dating to between ~1–0.3 million years ago were sampled (Table 1). Artefacts were analysed and photographed in person at the British Museum and Museo Provincial of Ciudad Real ($n = 494$), or data and images were extracted from the Biface Database ($n = 204$) (Marshall et al., 2002).

2.3. Recording handaxe shape variation

Multiple quantitative methods exist to describe handaxe shape variation (e.g., Grosman et al., 2008; Lycett et al., 2006; Saragusti et al., 2005). Here, shape is recorded via a Cartesian co-ordinate system that, once a handaxe is correctly orientated, allows a specified point on a tool to be defined by its distance from a predetermined axis (Costa, 2010; Eren et al., 2014; Lycett, 2008; Schillinger et al., 2017). The system's axis is defined by a line of maximum symmetry representing the *y* axis and the line of maximum width representing the *x* axis (Fig. 1). The line of maximum symmetry was defined following Costa (2010). To measure shape variation, specified points representing recorded co-ordinates were defined by a handaxe's edge profile, which in turn can be defined by their distance from the predetermined axis of known orientation. Both 2D and 3D shape analyses are undertaken here to better understand how traditional concepts of handaxe shape variation, which stress 2D plan-view differences (e.g., McPherron, 1999; Roe, 1968), may vary relative to 3D studies which also account for tool volume/mass distributions and thickness (e.g., Archer and Braun, 2010; Iovita et al., 2017; Lycett and von Cramon-Taubadel, 2015).

Using the image analysis software *ImageJ*, 26 'edge co-ordinate' defined bi-lateral measurements were recorded from scaled digital photos of each handaxe, in addition to measures to maximum length, width, and thickness. To do this, superior surface and side profile images of each tool were required (defined following Lycett et al., 2006). 13 measurements were recorded from each image, defined by co-ordinates located at specific percentage points along the tool's line of maximum symmetry (Fig. 1). All 29 measurements were used in the 3D shape analysis. The 2D analyses only used the 13 superior (plan-view) surface measurements, in addition to maximum length and maximum width. To control for the influence of raw isometrically scaled size differences among artefacts all measurements were size adjusted via their (a tool's) geometric mean (individually for the 2D and 3D analyses). As outlined elsewhere (Jungers et al., 1995; Lycett et al., 2006), this effectively corrects for size by dividing each target variable (i.e. width at 5% of length) by the geometric mean of all other variables (i.e. the 29 or 15 measurements used for that individual handaxe). The geometric mean is defined as the n^{th} root of the product of n variables, and is calculated as:

$$GM = \sqrt[n]{\prod_{n}^{i=1} x_i}$$

where x_i = measurements requiring size adjustment, and n = number of measurements requiring size adjustment. Adjustments were undertaken individually for each handaxe. Principal component analysis (PCA) was used to reduce the 29 and 15 measurements for 3D and 2D measures of handaxe shape, respectfully, into individual data points (principal components) that describe each tool's

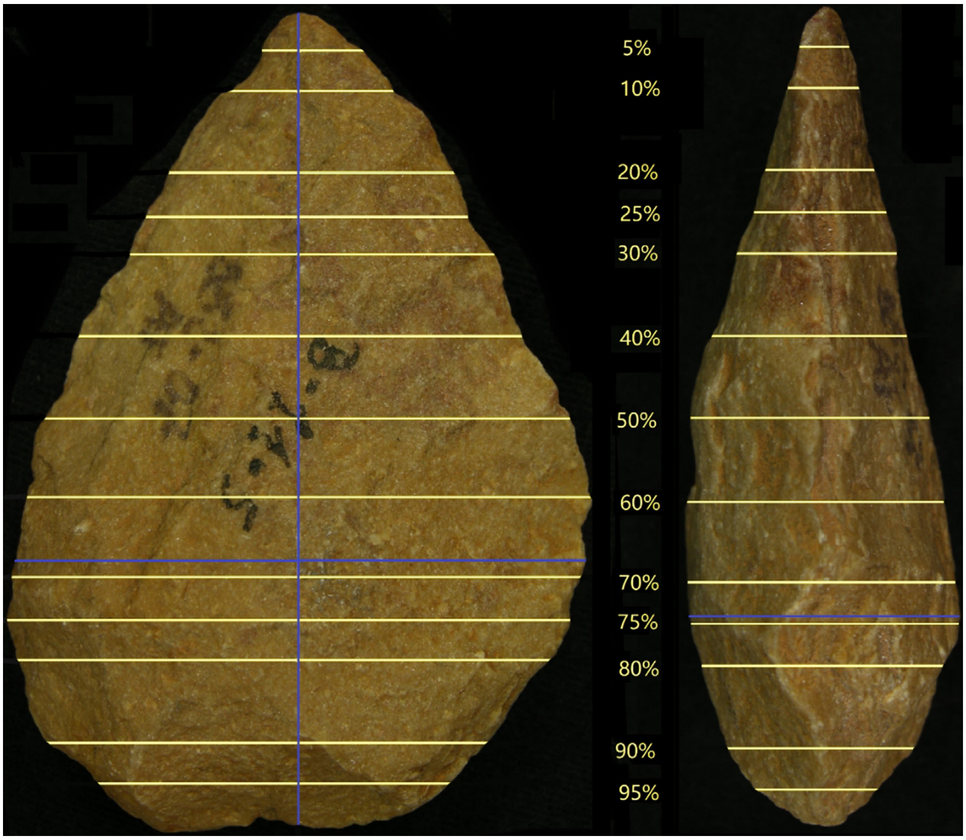

Fig. 1. The 29 bilateral co-ordinate measurements that define each handaxe's shape. The blue lines indicate the measures of maximum length (symmetry), width and thickness. Only the 15 plan-view measurements (left) were included in the 2D analyses.

Fig. 1. Les 29 mesures bilatérales de même rang, qui définissent la forme de chaque biface. Les lignes bleues indiquent les mesures de longueur (symétrie), largeur et épaisseur maximales. Seules les 15 mesures en vue planaire (à gauche) ont été incluses dans les analyses 2D.

shape. PCA analyses were individually performed for all tools used in the 2D and 3D studies.

2.4. Data analysis

2.4.1. 2D Shape comparisons

Plan-view (2D) shape data were collected from all replica (n = 540) and artefact (n = 698) handaxes. Descriptive PCA data for each assemblage is presented in Table 2. PC1 describes 52% of the shape variation observed across all tools and is most heavily loaded by the size-adjusted measurements of handaxe length. PC2 describes 26% of the shape variation and is principally loaded by (the size-adjusted) width measurements in the base of tools (70–95% of tool length). To investigate whether there were significant shape differences between the replica tools and artefacts, PC1 and PC2 values were grouped dependent on whether they came from modern tools or artefacts (i.e. n = 540 and 698 tools, respectively). Shapiro-Wilk tests identified that data sets were not normally distributed ($p < .05$). Thus, a Kruskal Wallis test was used to test whether samples displayed significantly different median values. Standard deviation values allow comparisons of variation levels. All analyses were repeated using equal samples, where a randomly chosen sub-sample of 540 artefacts was selected from the original 698. Following this, all comparisons were repeated using Mann–Whitney U tests.

2.4.2. 3D Shape comparisons

It was only possible to collect 3D shape data from the larger sample of replica handaxes (n = 480) as side-view photos from the Machin et al. (2007) assemblage have not been retained. Similarly, the Boxgrove, Saint-Acheul, and Tabun artefacts did not have side-view photos available and thus were not included in the 3D shape analysis (i.e. n = 371). In all other instances, however, the 3D shape comparisons mirrored those performed for the 2D analyses (including the repeat tests). It was similarly the case that all data sets were not normally distributed ($p < .050$). Descriptive data for PC1 and PC2 can be viewed in Table 2. Here, PC1 describes 59.8% of the 3D shape variation and is most heavily loaded by the size adjusted maximum length of tools and superior surface width at 60-80% of their length. PC2, which is heavily loaded by the size adjusted maximum length and superior surface width at 10–30% of a tool's length, describes 16.8% of the shape variation.

Table 2
Descriptive data for PC1 and PC2 values used in the 2D and 3D shape analyses.
Tableau 2
Données descriptives pour les valeurs de PC1 et PC2 utilisées dans les analyses de forme en 2D et 3D.

Assemblage		2D				3D			
	n	PC1		PC2		PC1		PC2	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Key and Lycett (2017b)	480	−0.035	0.420	0.068	0.308	0.531	1.097	−0.096	0.640
Machin et al. (2007)	60	−0.186	0.211	0.171	0.239	–	–	–	–
Replica Tools Combined	**540**	**−0.052**	**0.405**	**0.079**	**0.303**	**0.531**	**1.097**	**−0.096**	**0.640**
Amanzi Springs	31	0.150	0.283	−0.106	0.184	−0.604	0.565	0.169	0.407
Boxgrove	214	−0.185	0.191	−0.063	0.204	–	–	–	–
Cunnette	40	−0.053	0.329	0.137	0.210	0.143	0.614	−0.166	0.488
Elandsfontein	40	0.148	0.327	−0.009	0.296	−0.239	0.598	0.162	0.442
El Sotillo	34	0.064	0.245	−0.124	0.194	−0.941	0.430	0.035	0.308
HK, Olduvai Gorge	53	0.043	0.269	−0.125	0.223	−0.378	0.496	−0.019	0.368
Porzuna	133	0.125	0.464	−0.102	0.293	−1.189	0.539	0.092	0.532
St-Acheul	38	0.172	0.305	−0.259	0.304	–	–	–	–
S.T.I.C.	40	0.577	0.322	−0.096	0.240	−0.559	0.560	0.712	0.421
Tabun	75	0.116	0.555	0.091	0.264	–	–	–	–
Artefacts combined	**698**	**0.040**	**0.395**	**−0.061**	**0.259**	**−0.688**	**0.710**	**0.124**	**0.507**

3. Results

Significant shape differences were identified between the replica and artefact assemblages in all instances. The Kruskal Wallis 2D shape comparisons returned *p* values of .0002 and <.0001 between the replica tools and artefacts, for PC1 and PC2 respectively. Similarly, the 3D data revealed PC1 and PC2 to vary significantly between samples, returning *p* values of <.0001 in each instance. All significant differences were mirrored by the repeat tests run with equal samples sizes and using Mann-Whitney *U* tests (Supplementary Information, Table 1).

Plots of PC1 against PC2 similarly reveal shape differences between the replica and artefact assemblages (Figs. 2 and 3). In both sets of analysis, the replica tools take up a greater amount of shape space than the artefacts, and thus exhibit greater form diversity. Comparison of the 2D and 3D plots, however, identify the former to have substantially greater shape space overlap between the artefacts and replica tools. Both the convex hulls (Figs. 2b and 3b) and 95% ellipses (Figs. 2c and 3c) highlight this greater overlapping of plan-view shape. Indeed, despite the 2D PC1 and PC2 median values being significantly different, the plots identify few tools (artefact or replica) laying outside of the shared shape space. In other words, the "highly variable" (Key and Lycett, 2017b: 517) replica handaxe forms are mirrored by the diversity of plan-view shapes produced by Acheulean hominins. Standard deviation values for PC1 and PC2 in the 2D analyses also indicate similar levels of shape variation between the tool-sets, with the replica tools displaying only marginally greater values. Thus, when viewed from a broad multi-assemblage level, there appear to be weak restrictions on the 2D plan-view shape of handaxes during the Acheulean techno-complex.

There is considerable overlap between the two tool-group's 3D shape spaces, with nearly all artefacts being subsumed within the convex hull of the 480 replica bifaces. In contrast to the 2D analyses, there are clear limits to an Acheulean handaxe's 3D form. Indeed, Figs. 3b and 3c identify numerous replica biface forms that have no equivalent in the artefact record (see also: Figs. 4–6). Acheulean handaxes therefore display strong shape thresholds. Importantly, it is only through 3D analyses that this is revealed, suggesting that tool thickness and material volume drive these form limitations. Indeed, those bifaces not observed in the artefact record typically display high PC1 values, indicating low thickness to width ratios (i.e. high 'refinement' levels). Figs. 4 and 5 demonstrate that most bifaces found outside of the artefact's 3D shape space are relatively thin. Acheulean handaxes do, therefore, demonstrate strong shape thresholds defined by lower limits to their relative thinness.

There is some indication that tools with particularly low PC2 values, which point towards low elongation ratios (i.e. near circular tools), are also not reported in the archaeological record (Figs. 4–6). Principal component standard deviation values indicate the 3D shape variation of Acheulean handaxes to be restricted relative to the replica tools in all instances (Table 2). In many instances artefact assemblages display only half the variation observed in the replica tools.

Mean PC1 and PC2 values, along with the shape space plots in Figs. 2a and 3a, reveal subtle and not so subtle variation in the 2D and 3D shape of all 10 artefact assemblages. Although the present study is focused on Acheulean handaxes at a very broad technological level, it is clear there is also inter and intra-site variability in the shape of these tools. This variability is similarly reflected in each artefact assemblage's standard deviation values, with clear differences observed between some shape variation levels.

4. Discussion

Replica stone tool assemblages are rarely used to understand morphological limits and variation levels in Palaeolithic artefacts. Here, this technique has been used to better understand the shape of Acheulean handaxes. It has been demonstrated that handaxe artefacts vary highly in their plan-view (2D) shape, with few limitations observed relative to two substantial and intentionally diverse replica tool-sets. Stricter morphological thresholds were, however, observed in the thickness and material volume of the Pleistocene tools. Indeed, the same handaxe artefacts occupied under 50% of the 3D shape space created by the replica bifaces. Thus, while the plan-view shape of handaxes appears to have been free to vary during the Lower Palaeolithic, stronger thresholds were observed regarding their 3D form. This does not mean that Acheulean handaxes are not variable in their 3D shape. Rather, the replica assemblage reveals a range of handaxe forms that could theoretically have been produced by Lower Palaeolithic hominins, but were not.

The replica handaxes not reciprocated in the archaeological record are, predominantly, relatively thin, flat and 'tabular' in form (Fig. 5). The use of principal component analysis makes it difficult to empirically define a threshold for any one morphological trait, but the tendency for artefacts to avoid high PC1 values in the 3D analysis, not going beyond 1.26, supports this conclusion. Avoidance of these handaxe forms was observed across the 371 artefacts in the 3D sample, despite their diverse origins. Their absence suggests that strong pressures limiting the production of highly thin or 'refined' tools were acting on Acheulean hominins. Consistent with traditional Palaeolithic terminology, 'refinement' refers only to a tool's thickness relative to its width.

The thickness of a handaxe relative to its width is a widely recorded shape trait. Unsurprisingly then, reports detailing the absence of highly 'refined' Acheulean bifaces is not novel in and of itself (e.g., Gowlett, 2011a, 2015; Li et al., 2014; Moncel et al., 2015; Norton et al., 2006; Petraglia and Shipton, 2008). Despite considerable 'refinement' diversity being reported (Emery, 2010; Isaac, 1969; McNabb and Cole, 2015; Shipton and Petraglia, 2010), rarely do artefacts display thickness to width ratios below 0.3, while mean values frequently range between 0.4 and 0.5.

Presented here, however, is evidence pertaining to the limits placed on Acheulean handaxe thickness within the context of what could *theoretically* have been produced by hominins. It has been demonstrated that while there is variation in the shape of handaxe artefacts, including their relative thinness and globular/tabular nature, when compared to the *potential* variability that could have

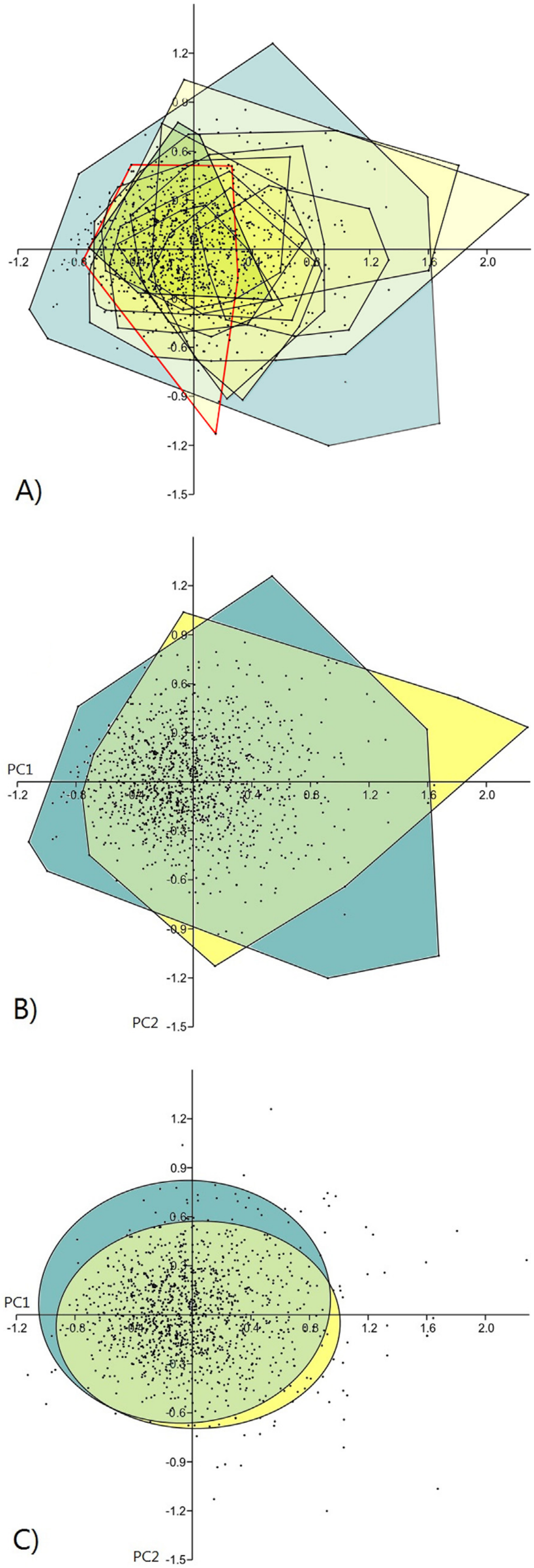

Fig. 2. PC1 plotted against PC2 in the 2D shape analysis. The replica handaxes are depicted in teal, while the artefacts are represented in yellow. Plot A depicts the individual shape space of all assemblages in the analysis, as highlighted by their convex hulls. Boxgrove's convex hull is depicted in red. Plot B illustrates the convex hulls of each grouped sample (replica tools and artefacts). Plot C depicts the 95% confidence ellipse of each grouped sample. The considerable overlap in shape space between each sample is evident in each plot.

Fig. 2. Diagramme figurant PC1 en fonction de PC2 dans le cas de l'analyse de forme 2D. Les répliques de bifaces sont figurées en bleu canard, et les artéfacts en jaune. La partie A représente l'espace de forme propre à tous les assemblages analysés, soulignés par leur enveloppe convexe. L'enveloppe convexe de Boxgrove est dessinée en rouge. La partie B illustre les enveloppes convexes de chaque groupe échantillonné (répliques d'outils et d'artéfacts). La partie C figure l'ellipse de confiance à 95 % de chaque groupe échantillonné. Un important recouvrement de l'espace de forme entre chaque groupe est évident dans chaque partie.

been produced there are strong shape-space restrictions and central tendencies. Moreover, these predilections are pervasive across the cultural variability observed in the Acheulean techno-complex (Lycett and Gowlett, 2008), and exist in spite of any allometric size-shape shifts (Crompton and Gowlett, 1993). Thus, in spite of any observed 3D shape variation, this newly defined relative context reveals a strong central tendency in Acheulean handaxe 3D morphologies. Further evincing the 'variable sameness' observed by Glynn Isaac and others (Gowlett, 2011b, 2015; Isaac, 1977; Lycett and Gowlett, 2008).

This tool-form propensity is likely due to several interacting factors. While handaxe shape, broadly speaking, has been shown to be weakly related to cutting performance (Key and Lycett, 2017b; Machin et al., 2007), the production of highly 'refined' tools (particularly in their proximal [base] portion) may limit the amount of force able to be exerted during cutting activities (Jones, 1980; Key and Lycett, 2019; Key et al., 2016). Working edges also require support from sufficient volumes of material to resist loading, prevent breakage during use, and reduce torque (Gowlett, 2006; Key, 2016). Relatedly, limited use-lives (Shipton and Clarkson, 2015) could have reduced reduction and flaking levels, preventing proximal shifts of a tool's centre of mass and maintaining thickness more generally across the tool (Archer and Braun, 2010; McPherron, 2006).

Thickness and 'refinement' measures are also strongly linked to a tool's material volume, and in turn, weight. This is important because substantive weight decreases (beyond context-dependent thresholds) have potential to negatively influence a stone tool's ability to be applied during functional tasks (Gowlett, 2009; Key and Lycett, 2017b). Moreover, specific functional tasks may have preferentially necessitated the production of thicker, heavier handaxes (Wynn and Gowlett, 2018). Additionally, handaxe shape (including 'refinement') is known to influence grip choice in tool users (Key et al., 2018), and the globular nature of Acheulean handaxe bases (i.e. a relatively thick base) has been argued to aid tool ergonomics and position its centre of gravity in the hand (Grosman et al., 2011; Jones, 1980, 1981; Wynn and Gowlett, 2018). Combined, these factors would promote the production of relatively thicker mean

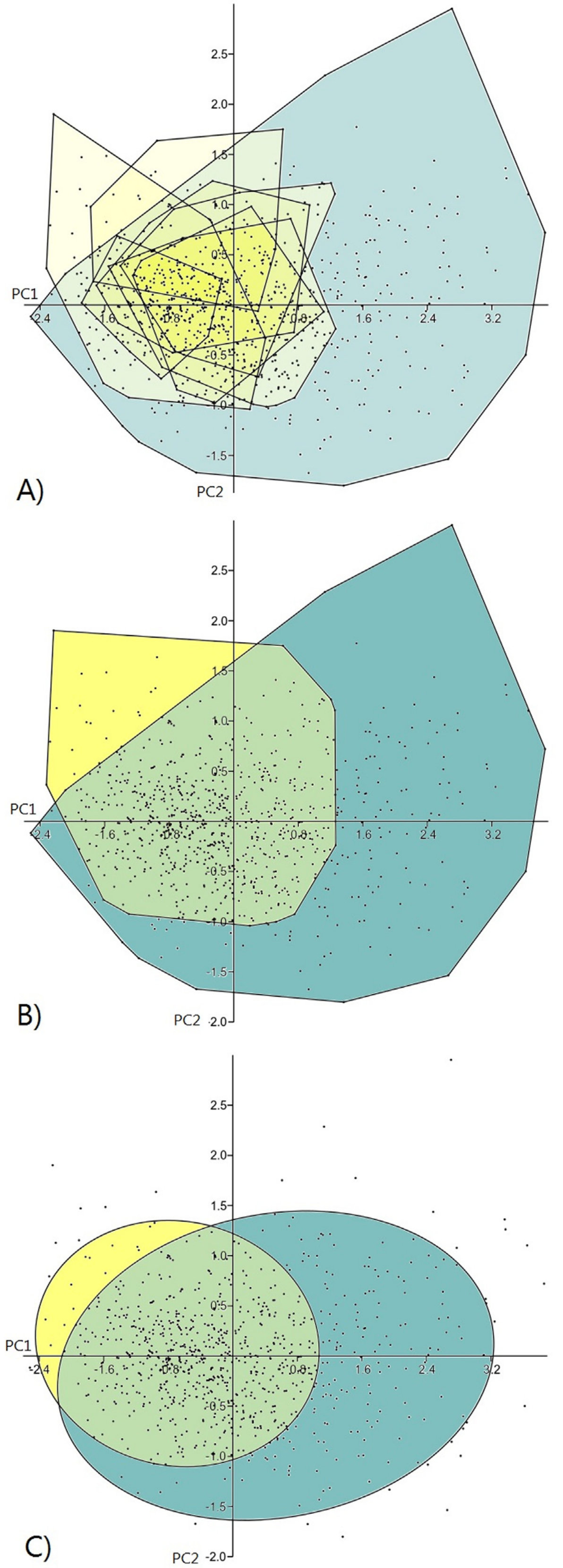

Fig. 3. PC1 plotted against PC2 in the 3D shape analysis. The replica handaxes are depicted in teal, while the artefacts are represented in yellow. Plot A depicts the shape space of all individual assemblages in the analysis, as highlighted by their independent convex hulls. Plot B illustrates the convex hulls of each grouped sample (replica tools and artefacts). Plot C depicts the 95% confidence ellipse of each grouped sample. The shape space divergence between each sample is observed in each plot, with the replica tools evidently displaying greater tool-form limits.

Fig. 3. Diagramme figurant PC1 en fonction de PC2 dans le cas de l'analyse de forme 3D. Les répliques de bifaces sont figurées en bleu canard et les artéfacts en jaune. La partie A représente l'espace de forme propre à tous les assemblages analysés, soulignés par leurs enveloppes convexes indépendantes. La partie B illustre les enveloppes convexes de chaque groupe échantillonnés (répliques d'outils et d'artéfacts). La partie C figure l'ellipse de confiance à 95 % de chaque groupe échantillonné. La divergence de l'espace de forme entre chaque groupe est observée dans chaque partie, avec les répliques d'outils montrant à l'évidence de plus grandes limites forme-outil.

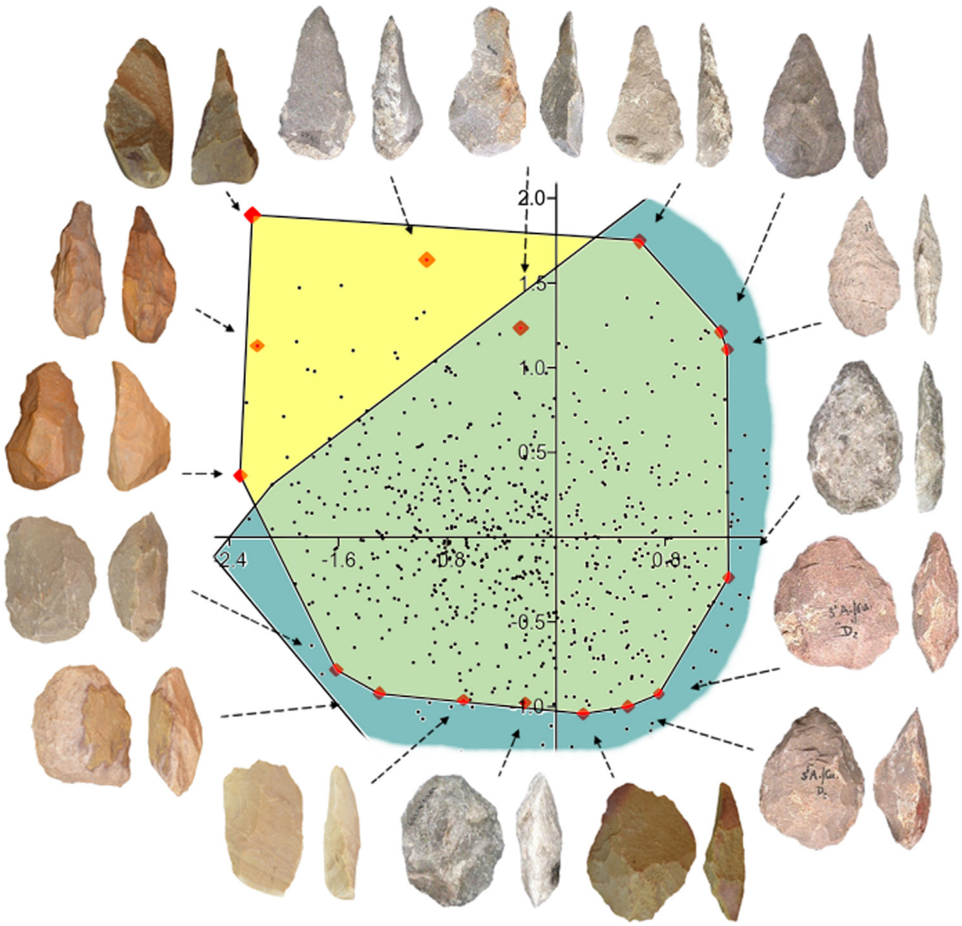

Fig. 4. The 3D shape threshold identified from the seven Acheulean handaxe assemblages. These tools define the convex hull of the 371 artefacts included in the 3D analysis, and thus, represent the outer limits of shape diversity from the tools sampled here. While additional tool forms will occur in artefact assemblages, the overwhelming majority of Acheulean handaxes will likely have been produced within the threshold outlined here.

Fig. 4. Limite inférieure (seuil de forme en 3D déterminé(e) à partir de sept assemblages de bifaces acheuléens. Ces outils définissent l'enveloppe convexe des 371 artéfacts inclus dans l'analyse 3D et, en conséquence, représentent les limites extérieures de diversité de forme d'après les outils échantillonnés ici. Si des formes additionnelles d'outils peuvent être présentes dans des assemblages d'artéfacts, la très grande majorité de bifaces acheuléens ont vraisemblablement été produits dans la limite figurée ici.

forms. Thus, the tool-form limits identified here may represent 'primary performance characteristic thresholds', as proposed by Schiffer and Skibo (1997).

Equally, there may have been no, or only very weak, pressure selecting for highly 'refined' handaxes forms. Certainly, factors promoting highly thin forms in other bifacial technologies, such as hafting or their use as a projectile, are not frequently applied to Acheulean handaxes. Thus, irrespective of any pressures promoting thicker tools, there may have been little cause to thin bifaces beyond what was necessary to shape the tool and maintaining a sharp, relatively acute, cutting edge. Alternatively, hominins may also have been limited in their ability to produce relatively thinner and more 'refined' handaxes. Indeed, due to manipulative, cognitive or technological limitations (Key and Dunmore, 2018, Muller et al., 2017; Stout et al., 2014; Wynn, 2002), it may not have been possible for early handaxe-producing hominins to produce highly 'refined' handaxes. Although restrictions would have reduced once populations displayed increasingly modern human-like anatomy. Relative thickness has also been linked to raw material availability (Ashton and McNabb, 1994; White, 1998). For example, the production of handaxes from large stone flakes or bone, as opposed to stone nodules, has been suggested to aid the production of relatively thinner tools (Li et al., 2014; Moncel et al., 2015; Sharon, 2009; Zutovski and Barkai, 2016). Although Shipton (2018) highlights how raw material and relative thickness relationships can vary between individual sites. Irrespective, the diversity of artefact raw materials examined here, along with their production on nodules and large flakes by multiple hominin species, means that raw material and evolutionary factors cannot alone explain the thresholds observed here.

It is, perhaps, more surprising that the 2D shape diversity observed in the replica assemblage was closely matched by the Acheulean artefacts. Indeed, there was

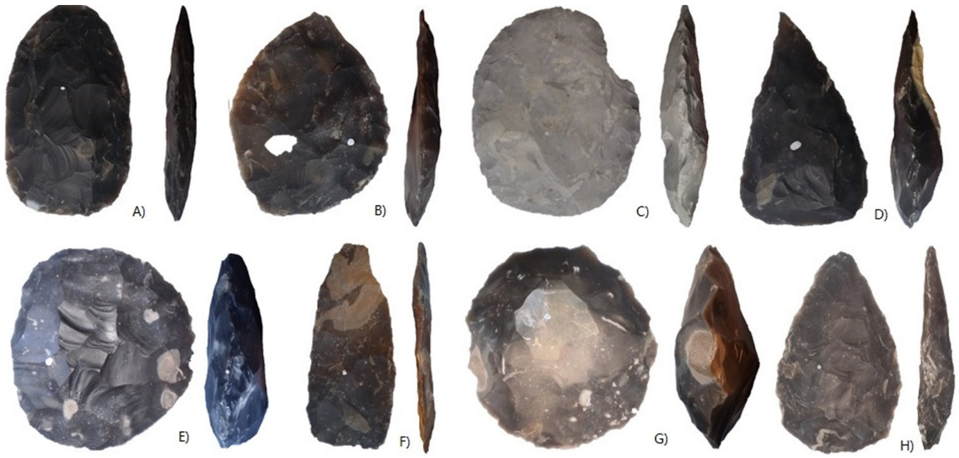

Fig. 5. Eight replica handaxe forms not reciprocated in the archaeological sample (3D analyses). These tools were selected from areas of the shape space not shared with artefacts. Key distinctions in these replica tools, relative to the artefacts, include their low thickness to width ratios and/or lack of elongation.
Fig. 5. Formes de huit répliques de bifaces non réciproques dans l'échantillonnage archéologique (analyses 3D). Ces outils ont été sélectionnés à partir de zones d'espace de forme non partagés avec les artéfacts. Des distinctions clé dans ces répliques d'outils en relation avec les artéfacts correspondent à des rapports épaisseur/largeur bas ou à un manque d'élongation.

near total overlap in their convex hulls and 95% confidence ellipses. Further, both assemblage's principal component standard deviation values are similar, indicating comparable levels of variation. When considered at a broad, technological level (i.e. not at an assemblage level), these results identify substantial variation in the plan-view shape of handaxes produced by Lower Palaeolithic hominins.

It is not surprising that considerable diversity was observed in the artefacts, as previous studies identifying shape variation within and between handaxe assemblages attest to this (Hosfield et al., 2018; Lycett and von Cramon-Taubadel, 2015; McPherron, 1999; Roe, 1981; Vaughan, 2001; Wynn and Tierson, 1990). Nor is it surprising that plan-view shape variation is controlled independently from a handaxe's third axis (Archer and Braun, 2010; Gowlett, 2006). Certainly, Acheulean populations appear to place stronger emphasis on controlling the distribution of mass and relative thickness than 2D plan-view shape. What is revealing, however, is that artefact shape diversity matches two replica assemblages that were *purposefully* produced to be highly variable. This suggests that any universally observed pressures working to limit handaxe plan-view shape in the Acheulean were likely very weak. Given that handaxes were, ultimately, functional objects applied to cutting tasks, these results emphasise the limited impact that plan-view shape variation likely has on their utilitarian capabilities (at least within a generalised functional environment) (Key and Lycett, 2017b; Machin et al., 2007; Schiffer and Skibo, 1997). Further, these data highlight the 'area of free play' available for handaxe's, within which shape can vary without impacting utility (Crompton and Gowlett, 1993; Gowlett, 2009; Lycett et al., 2016). The artefact shape space outlined in the PC plots provides a framework for understanding this area of free play.

4.1. Inter-site variation

As revealed by the mean principal component values and shape space plots (both 2D and 3D), shape differences exist between most artefact assemblages. This supports numerous previous studies that identify inter-site shape variation in Acheulean handaxes (Crompton and Gowlett, 1993; Lycett and Gowlett, 2008; Lycett and von Cramon-Taubadel, 2015 McNabb et al., 2004; Roe, 1981; Wang et al., 2012; Wynn and Tierson, 1990), Thus, while there is substantial diversity in the artefact forms examined here, greater restrictions are observed at an individual site level. Boxgrove, for example, displays remarkably low shape diversity, having a relatively small convex hull despite its sample containing at least 80 more tools than any other assemblage (Fig. 2a). Moreover, its principal component standard deviation values (and therefore shape variation levels) are considerably lower than most other artefact assemblages; both supporting suggestions that the Boxgrove handaxes display shared shape tendencies (García-Medrano et al., 2019; McNabb, 2017), and providing new evidence of their limited form variation relative to many other Acheulean sites.

The noted diversity in shape variation levels between artefact assemblages indicates the differential strength of tool-form selective pressures at different sites. Further, although larger assemblages may result in greater shape diversity on occasion (McPherron, 2006), this is clearly not always the case. Potential causes for inter-site variation differences and specific shape preferences have been discussed on multiple previous occasions, and are briefly noted above. Lycett et al. (2016) and Wynn and Gowlett (2018) provide recent reviews of this topic. The present results therefore demonstrate that while the shape of Acheulean handaxes had the potential to vary substantially (and indeed did at times), other factors often worked

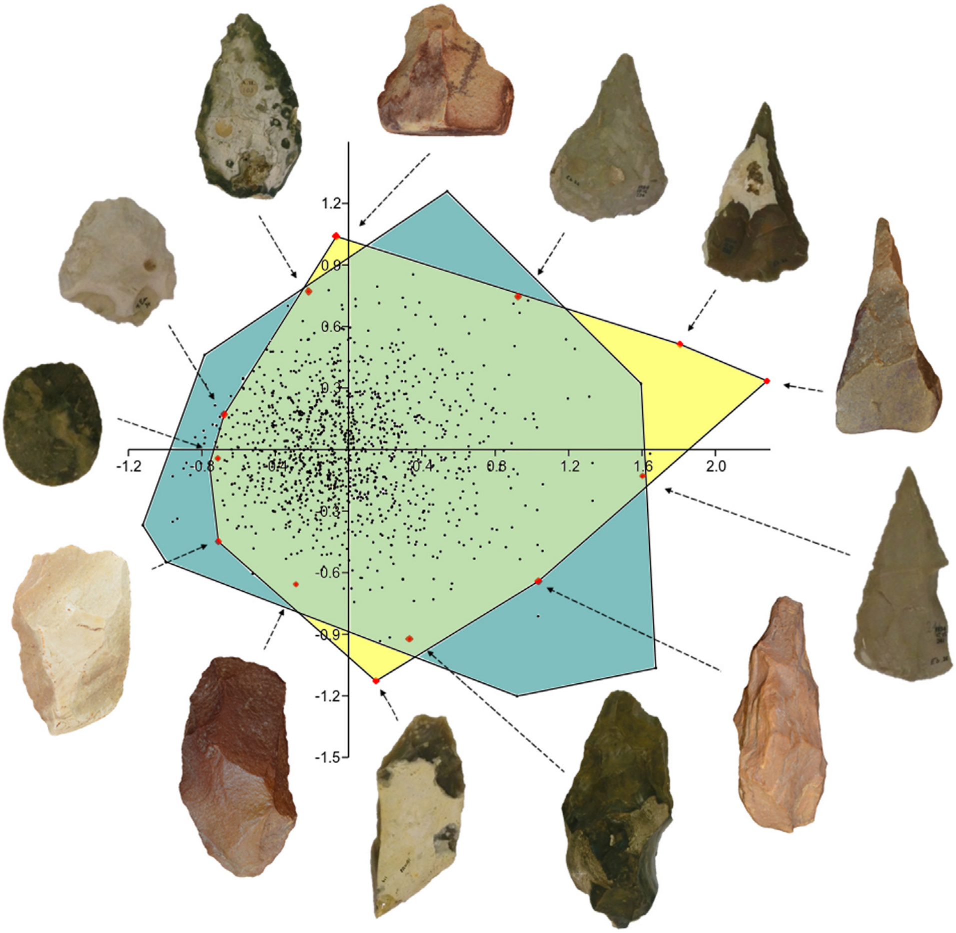

Fig. 6. The 2D shape threshold for the 10 Acheulean handaxe assemblages examined here. These tools define the convex hull of the 698 artefacts included in the 2D analysis, and thus, represent the outer limits of plan-view shape diversity. While additional tool forms may occur in artefact assemblages, the overwhelming majority of Acheulean handaxes will have been produced within the threshold outlined here.

Fig. 6. Limite inférieure (seuil) de forme en analyse 2D pour 10 assemblages de bifaces acheuléens examinés ici. Ces outils définissent l'enveloppe convexe des 698 artéfacts inclus dans l'analyse 2D et, en conséquence représentent les limites extérieures de diversité de forme en vue planaire. Si des formes additionnelles d'outils peuvent être présentes dans des assemblages d'artéfacts, une très grande majorité de bifaces acheuléens ont vraisemblablement été produits dans la limite figurée ici.

to limit handaxe forms. Nonetheless, there is considerable shape-space overlap between assemblages and all conform to a central morphological tendency. A tendency likely structured around Gowlett's (2006, 2015) morphological 'imperatives'.

4.2. Sampling considerations

Inevitably, studies of stone tool shape variation are limited by the artefacts sampled. Although a substantial number of handaxes from a diverse range of assemblages have been included here, it is unavoidable that additional tool forms do exist in the archaeological record and could increase the shape space diversity observed in both the 2D and 3D analyses (e.g., Wenban-Smith, 2004). However, such tool forms will be rare in the Acheulean and will be unlikely to reflect morphological trends observed at a population level. Thus, the shape thresholds identified here provide a robust framework for understanding handaxe variation in the Lower Palaeolithic. Middle Palaeolithic handaxes may display greater overlap with the replica tool 3D shapes due to their, at-times, distinctive forms, lower thickness/width ratios, and suggested high variability (Emery, 2010; Ashton and Scott, 2016; Iovita and McPherron, 2011; Ruebens, 2013); however, further work is required to test this hypothesis.

It is also true that relative to the 2D analysis, the reduced number of artefacts included in the 3D analyses could have contributed to more limited shared shape space with the replica stone tool assemblage; although the latter similarly had a reduced number of tools analysed. To check that the 2D and 3D shape space differences were not merely a function of sample size or site choice, the 2D plots were reproduced using the same tools used in the 3D plots. As detailed in Supplementary Information Fig. 1, these additional 2D plots correspond with those produced using the complete artefact sample. It is not possible to reproduce the 3D plots using all of the artefacts included in the 2D sample, resulting in an inevitable decrease in how representative the sample of 3D analysed artefacts are. The addition of later Acheulean sites that display mean 'refinement' indices close to 0.3, such as Boxgrove (García-Medrano et al., 2019), could certainly have expanded the artefact 3D shape space observed here. Future research expanding on this point would be welcome, but the substantial shape-space differences observed here suggest that there would still be considerable divergence between the replica and artefact assemblages.

5. Conclusion

Acheulean handaxe shape variation is contextualised here within a theoretically possible range of tool-forms, as defined by highly diverse modern replica tool sets. It has been demonstrated that handaxe artefacts exhibit substantial diversity in their 2D plan-view shape, displaying near complete overlap with two intentionally diverse replica tool sets, and similar levels of variation. Much stronger restrictions and central tendencies on a handaxe artefact's 3D form were identified; principally driven by an absence of flat and 'tabular' tools displaying low thickness to width ratios in the artefact record. It is argued that while there is considerable diversity and variability in the shape of Acheulean handaxes, their form is nonetheless restricted by strong material volume and relative thickness limits (driven, in part, by functional factors). Shape diversity is more restricted at an individual assemblage level, while mean shape differences indicate differential central tendencies and shape preferences between sites. Supporting past works emphasising the impact that cultural evolutionary mechanisms, and other localised environmental factors, can have on handaxe shape.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.crpv.2019.04.008.

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