A Volumetric Analysis of Handaxe Symmetry Referencing a Known Symmetrical Ideal

James M. Hicks (james.hicks@arch.ox.ac.uk)
University of Oxford

Research Article

Keywords: Acheulean handaxe, 3D symmetry, Omega (ω) coefficient, volumetric morphometrics, digital archaeology, evolutionary cognitive archaeology

Posted Date: February 9th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2551323/v1

License: ☑️ This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

This article outlines a novel volumetric approach to analyzing 3D symmetry in Acheulean handaxes. This method offers a high-resolution analysis of Acheulean handaxe symmetry in three dimensions. It increases the resolution of the analytical model by orders of magnitude over current 2D planar and 3D geometric morphometric methods. After reviewing the history, conceptualization, application, and debate of symmetry, I focus on the archaeological discussion and evolutionary importance of symmetry in Acheulean handaxes. I review and critique previous analytical methods before introducing a volumetric approach using digitized stone artifacts and an ideal cordiform. I introduce the Omega (ω) Coefficient of Symmetry, a ratio describing the quotient of 1) the numerator — the maximum volume of an Ideal Cordiform (where Ideal is defined as bilaterally and bifacially symmetrical) that can occupy the topology of a digitized handaxe, and 2) the denominator, the volume of the digitized handaxe. I conclude by discussing the limitations and future applications of this method and its possible applications to unresolved debates in the field of evolutionary cognitive archaeology and beyond.

Introduction

Around 1.7—1.5 Mya, African hominids began to modify the opposing faces of large stone flakes and cobbles into bifaces, the term used to differentiate these Lower and Middle Paleolithic Acheulean tools from their immediate antecedents, the Oldowan, and the earliest Lomekwian technologies manufactured by their predecessors (e.g., Gowlett, 2006; Roche, 2005). Like their Oldowan antecedents, the earliest Acheulean tools were shaped by knapping, which modifies the shape of a stone core by striking it with a hammerstone. Along with an assortment of enigmatic stone spheroids, most Acheulean tools took the form of handaxes, picks, knives, cleavers, and flake tools, named for their presumed function (e.g., Kleindienst, 1961, 1962).

To best describe the breadth of Acheulean technologies and to differentiate them from their predecessors, Gowlett (2006) offered a set of ‘rule sets’ corresponding to task-relevant needs he termed ‘imperatives.’ He noted that these imperatives are supported by principal component analyses of the linear measurements describing the morphology of Acheulean artifacts. These imperatives include a glob-butt, forward extension, support for the working edge, lateral extension, and thickness adjustment. Glob-butt refers to an artifact’s center of mass, generally located at the proximal end of the artifact providing a foundation for the working edge(s). Forward extension describes the leverage gained in balancing a distal working edge with the proximal center of mass, thus differentiating Acheulean from Oldowan artifacts. Support for the working edge is the geometric mass that connects the butt to the working edge, whether a blade, bit, or pick. Lateral extension refers to the bilateral breadth of the tool, a feature that resists torsion and supports long working edges. Thickness adjustment defines both the edge angle and the ultimate mass of the artifact, simultaneously affecting usability and portability.

Gowlett emphasized that these imperatives were not specific, but rather a loose association of geometric possibilities that could be adjusted to meet the task at hand. Gowlett also noted that these imperatives
can explain the symmetry inherent in many Acheulean artifacts as it has a direct effect upon balance and usability. Cleavers offered a single bit as the working edge located at the distal end, backed by an oblong butt at the opposing proximal end. Like cleavers, picks were triangular in cross section backed by an oblong butt at the opposing proximal end but featured a tip knapped into a point at the distal end. Knives featured a single lengthwise cutting edge down one side of their long axis. Handaxes, the focus of the present study, featured two opposing working edges, organized bilaterally along the long axis of the tool. They were knapped into a variety of ovate and elongated morphologies. Some cordiform handaxes featured a rounded oblong butt at the proximal end, while others (particularly ovates) were continuously knapped to extend the cutting edge around the full circumference of the tool. Note that Acheulean flake tools appeared in much the same form as their Oldowan predecessors.

Though archaeologists have used a variety of terms to describe aspect views of handaxes, this paper will refer to bilateral and bipolar symmetry in plan view (a) and bifacial symmetry in profile view (b), as shown in Fig. 1.

Figure 1

Plan (a) and Profile (b) Perspectives of Stone Artifacts

Acheulean knappers discovered inherently problematic planes of separation hidden within the core of course-grained stone such as quartzite, basalt, and lava. These inclusions increased the probability of undesirable fractures during the knapping process, making them less amenable to shaping. They also discovered that certain brittle, fine-grained raw materials such andesite, chert, and flint often lacked these troublesome inclusions. When struck with a hammerstone, these fine-grained stones afforded conchoidal ruptures along the stone's surface. The plane of a conchoidal fracture transverses the raw material as a series of concave concentric circles resembling a mussel shell, from the point of contact (i.e., the bulb of percussion; the physical index of a hammerstone strike) propagating across the surface of the core.

Conchoidal fracturing combined with expert knapping enabled the removal of finer, thinner flakes from the core. This technical enhancement could be further augmented by abandoning hammerstones in favor of ‘soft’ hammers made from bone, antler, and wood. The availability of fine-grained, pliable raw materials worked with soft hammers, along with increasing stone knapping expertise resulted in the imposition of extraordinary examples of bilateral and bifacial symmetry throughout the Paleolithic period. As early as 1.69 Mya, expert knappers left evidence of their astonishing skill at several locations around the Old World. For example, stone tools exhibiting ‘near-perfect’ three-dimensional (3D) symmetry have been excavated at FLK West in Tanzania, Gesher Benot Ya’aqov in the Levant, and Kathu Pan in South Africa, among others. Examples are shown in Fig. 2.

Though relatively uncommon before 500 kya, these precocious examples of combined plan and profile view symmetry have long intrigued archaeologists. They have also generated spirited debate regarding the myriad factors explaining their production including the seemingly extraordinary time and resources invested in their manufacture (e.g., Burriss, 2009; Cole, 2015; Corbey et al., 2016; Kohn & Mithen, 1999;

**Symmetry In The Arts And Sciences**

The term *symmetry* or “agreement in dimensions, due proportion, or arrangement,” was first documented in English in the 16th century. It had roots in the Latin word *symmetria*, “having a common measure, even, proportionate,” which in turn was an assimilated form of *symmetros* (συμμέτρος) in Greek. Its antonym is *asymmetry*, which refers to an absence or violation of symmetry. Symmetry can be recognized in a variety of ways. *Mathematical symmetry* is the invariance of an object under transformation. Examples of transformations include reflection, rotation, scale, and translation. *Planar symmetry* refers to the relationships between two-dimensional linear shapes (e.g., squares, circles, triangles, etc.) divided into identical portions by a line or point on a plane. *Geometric symmetry* refers to the relationships between components of solids (e.g., cubes, spheres, pyramids, etc.) divided into identical portions by a plane in three-dimensional space.

The most familiar symmetrical pattern is bilateral, also known as reflectional or *mirror symmetry*. Here, one half of the pattern is duplicated across a centralized line (planar) or plane (geometrical). Mirror symmetry is pervasive in the natural world, forming the primary physical structures of countless molecules, crystals, plants, and animals. *Bilateral symmetry* — the degree to which the shape of the left side of an object is reflected on the right side (or vice versa) — has received the most attention in archaeology, and it remains the primary focus of most analyses of stone tool symmetry. Regarding stone tools, bilateral symmetry describes the shape of opposing sides referenced to the long axis of a stone tool when displayed in plan view. Weyl (2016) offers the following precise, elegant geometric definition of bilateral symmetry:

A body, a spatial configuration, is symmetric with respect to a given plane $E$ if it is carried into itself by reflection in $E$. Take any line $l$ perpendicular to $E$ and any point $p$ on $l$: there exists one and only one point $p'$ on $l$ which has the same distance from $E$ but lies on the other side. The point $p'$ coincides with $p$ only if $p$ is on $E$. Reflection in $E$ is that mapping of space upon itself, $S: p \mapsto p'$, that carries the arbitrary point $p$ into this its mirror image $p'$ with respect to $E$. A mapping is designed whenever a rule is established by which every point $p$ is associated with an image $p'$ (pp. 4–5).

This definition is illustrated in Fig. 3.

**Figure 3**
Bilateral Symmetry or Reflection in E. (Redrawn from Weyl, 2016)

Ironically, bifacial symmetry, the degree to which the front surface of a stone tool is reflected in the rear surface, has received relatively little attention, even though ‘refinement’ — or the combined bifacial symmetry and relative thinness of a handaxe — has been historically considered an exemplar of increased technical sophistication (e.g., Clark & Bishop, 1966; Deacon, 1970; Gilead, 1970; van Riet Lowe, 1951; Roe, 1968, 1970, 1975; Ronen et al., 1974; Toth, 1990; Wymer, 1988; Wynn, 1989). Bifacial symmetry applies the same rule-based geometric mapping across a plane \( E \) as described above, but at a perpendicular angle to \( E \). It describes the shape of opposing faces referenced to the long axis of a stone tool when displayed in profile view. Other common natural forms include radial, rotational, and translational symmetry. Whereas reflectional symmetry reiterates a pattern around a line or plane, radial symmetry repeats a pattern around a point in two dimensions (e.g., forming a circle) while rotational symmetry does the same in three dimensions without inverting or reversing the pattern (e.g., forming a sphere). In the case of translational symmetry, the pattern is repeated in a sequence without reversal or rotation.

Debate regarding the conceptualization, nature, and utility of symmetry has garnered significant debate in both the arts and sciences (e.g., Hargittai, 1986, 1989; Shepard, 1948; Stewart & Golubitsky, 2010; Washburn & Crowe, 1988; Weyl, 2016). Hon and Goldstein (2008) have argued that the conceptualizations of symmetry evolved along two trajectories. One was mathematical, encapsulated in the philosophies of Plato, Euclid, Archimedes, and Barrow. The second trajectory was aesthetic, whose major proponents included Vitruvius, Alberti, Perrault, and Montesquieu. Both trajectories conceptualized symmetry as the harmonious proportionality of parts with respect to a whole, highlighting the absence of a precise mathematical definition until Legendre (1794) argued that symmetry means “similarity and equality without superimposition.” Not until the mid-18th century did the concept of symmetry find its way into the incipient sciences, most notably natural history and physics (e.g., Hon & Goldstein, 2008; Katzir, 2004). Symmetry has since become the focus of an increasing number of cross-disciplinary research projects and an important component of human origins and cognitive evolution studies.

As artifacts associated with the Acheulean technocomplex represent the initial imposition of symmetrical form in the archaeological record, both Paleolithic and evolutionary cognitive archaeology have embraced the theoretical and analytical exploration of this unique aspect of human behavior. As Wynn (2002) suggested, there are at least three good reasons to highlight artifact symmetry as a primary marker of cognitive evolution. First, symmetry is a pattern and concept that is universally recognized; second, it has been integrated into myriad developmental, perceptual, and cognitive theories thereby providing direct articulation between archaeological artifacts and the literature of cognitive science; and third, it is easy to represent visually. Symmetry is ubiquitous throughout material culture, from tools to music and literature to architecture. Nonetheless, archaeologists have debated the factors underlying the emergence of symmetry in the Acheulean technocomplex.
Theory Regarding The Emergence Of Technological Symmetry

Archaeologists have introduced several theories to explain the emergence of Acheulean stone tool symmetries. Some focused on the influence of raw material size and shape, blank form, flaking strategy, and degree of reduction at discard (Ashton & McNabb, 1994; Ashton et al., 2008; Davidson & Noble, 1989, 1993; Emery, 2010; Iovita & McPherron, 2011; Jones, 1979, 1994; McPherron, 1999, 2000, 2013; Noble & Davidson, 1993; Sharon & Goren-Inbar, 1999; White, 1998, 2006), others on functional adaptations to the increasing importance of cutting and chopping during the Acheulean period (Chase & Dibble, 1987; Crompton & Gowlett, 1993; Galán & Domínguez-Rodrigo, 2014; Gowlett, 2006; Gowlett & Crompton, 1994; Jones, 1980; Machin et al. 2007; Mitchell, 1995; Sharon, 2007; Simão, 2002). Others emphasize social, affective, or cognitive models including communication and learning (Mithen, 1994), aesthetics (Edwards, 2001; Hodgson, 2010, 2011; Pelegrin, 1993; Pope et al., 2006; Reber, 2002), visuo-spatial acuity or social intelligence (Cole, 2012; Goren-Inbar & Sharon, 2006; Hodgson, 2015; Shipton et al., 2013, 2018; Wynn, 1995; 2000, 2002).

This debate has highlighted and emphasized the importance of symmetry to the Acheulean knapper, as evident in both single artifacts and across multiple assemblages and archeological sites. Therefore, it is imperative to understand the historical quantification of shape in archaeology, as well as the history of measuring, qualifying, and quantifying Acheulean morphological variation in respect to symmetry, discussed in the following section.

Quantification In Archaeology

Archaeologists were slow to adopt both computational methods to the morphological quantification of artifacts, as well as statistical approaches to hypothesis testing. Early examples include Myers (1950), who employed correlation coefficients, regression analysis, and analyses of variance and covariance to test hypotheses regarding the chronological and cultural relationships between flint artifacts and pottery sherds at a series of Egyptian sites. Borrowing statistical methods from biology, Alimen and Vignal (1952) coined the term archaeometry to describe their approach which included frequency distributions, Pearson product-moment correlations, and linear regressions to investigate handaxe types from a quarry at Commont’s Workshop in St. Acheul, France.

Influenced by the culture-history approach in anthropology prior to the 1950s, archaeologists adhered to an ad hoc typological methodology when describing the variety of bifacial stone tools first discovered at St. Acheul. This type-fossil (or fossils directeurs) approach endeavored to identify signature morphological variables based upon a few choice exemplars deemed the most sophisticated within a particular assemblage. These exemplars were used to argue for a chrono-stratigraphic evolutionary sequence exhibiting a putative linear increase in technological refinement throughout prehistory. Thus, in the case of Lower and Middle Paleolithic large cutting tools (LCTs), the many were defined by the few, leaving most artifacts ignored and unexamined. The result was a nebulous array of various lithic forms based on a subjective characterization of their apparent level of sophistication.
During the mid-twentieth century, the subjectivity of this traditional culture-history approach was replaced by a growing number of studies based upon morphological quantifications of stone tools using calipers or micrometers to perform linear physical measurements (i.e., length, breadth, thickness, etc.). These linear metrics provided the continuous variables necessary for the covariation matrices employed in multivariate statistical analyses. These multivariate analyses enabled archaeologists to explore the breadth of technological, typological, and morphological variability in European (e.g., Alimen & Vignal, 1952; Bordes, 1961; Bordes & Bourgon, 1951; Sackett, 1982), African (Isaac, 1979), and American (Judge, 1970) lithic assemblages. For example, Chenhall (1968) notes that Judge applied a computer-aided factor analysis to the trait variables of 201 Paleo-Indian end-scrapers to determine alterations in technological trajectory, as opposed to typological descriptions. According to Cattell (1965), factor analysis can explain relations among continuous and discrete variables in terms of simpler relations inherent in the underlying covariance between traits.

From this relatively impartial perspective focusing on intra- and inter-assemblage variability, Roe (1964, 1968) measured a small set of planar metrics and analyzed a large body of Acheulean bifaces gathered from 38 sites in Southern Britain to document the variability in size, shape, and refinement of whole assemblages or groups of assemblages. Roe states his investigation was designed with an eye toward quantifying the preferences of Acheulean knappers as a prequel to establishing an empirical typology, and perhaps a phylogenetic sequence. Therefore, he employed five ratios based on seven linear (planar) measurements (in millimeters) and the weight (in ounces) of an artifact shown in Fig. 4.

**Figure 4**

**Roe’s Planar Metrics and Ratios for Quantifying LCT Size, Shape, and Refinement**

Using these planar metrics and related ratios, Roe was able to make inferences regarding typology, as his analyses sorted cleavers, pointed handaxes, and ovate handaxes into distinct categories. He displayed these as scattergrams also known as ‘tripartite diagrams.’ Roe’s ratios (sometimes referred to as indexes, e.g., Wynn & Tiersten, 1990) enabled a plethora of novel statistical approaches to Acheulean morphometrics that continues into the 21st century (e.g., McNabb, 2021).

**Roe’s Ratios And Statistical Analyses Of Acheulean Artifacts**

The introduction of computing applications for performing multivariate statistics reduced the time necessary to analyze the relationships between these variables. Linear metrics and ratios have remained the most historically prevalent approach for both analog and digital multivariate statistical investigations of variability in Acheulean lithic morphology. These ratios have been featured in many morphological analyses using a wide variety of univariate and multivariate statistics including canonical variate (Graham & Roe, 1970), k-means cluster (Gaillard et al., 1986; Hodson, 1971), k-furthest neighbor cluster (Tyldesley et al., 1985), canonical correlation (Clarke & Kurashina, 1979; Kurashina, 1978), discriminant
function (Brink et al., 2012; Caruana & Herries, 2020; Clarke & Kurashina, 1979; Crompton & Gowlett, 1993; Gowlett & Crompton, 1994; Kurashina, 1978; Lycett & Gowlett, 2008), factor (Clarke & Kurashina, 1979, 1980; Gaillard et al., 1986), and most commonly principal components analyses (Caruana & Herries, 2020; Clarke & Kurashina, 1979, 1980; Crompton & Gowlett, 1993; Gowlett & Crompton, 1994) as well as emerging geometric morphometric analyses (GMA; García-Medrano et al., 2020; Herzlinger & Goren-Inbar, 2020; Key, 2019; Key & Lycett, 2017; Muller et al., 2022). Most PCA approaches have been based on extrapolations of a limited set of predefined two-dimensional curve coordinates measured in plan view and profile view (e.g., Caruana, 2020, 2021; Caruana & Herries, 2021; García-Medrano et al., 2019; Li et al., 2016, 2018;) per Bordes (1961), Roe (1964, 1968), and Isaac (1979), referred to collectively as ‘planar’ or ‘linear’ metrics and ratios throughout this essay. Emerging GM analyses calculate the values of superimposed homologous semi-landmarks placed at equidistant points on both faces of the artifact (e.g., Brande & Saragusti, 1996; Brand, Saragusti, & Cline, 1999; García-Medrano et al., 2020; Herzlinger & Goren-Inbar, 2020; Key, 2019; Key & Lycett, 2017; Muller et al., 2022).

During this time, archaeologists have focused on analyzing plan view (bilateral) symmetry, with occasional investigations of profile view (bifacial) symmetry, by examining their individual and combined contributions to tool morphology. With few exceptions (e.g., Marathe, 1980; Wynn & Tierson, 1990), previous analyses of handaxe symmetry have eschewed Roe's metrics by focusing on its bilateral aspect using two-dimensional approaches. Regardless, Roe's planar metrics and indexes have enabled an astonishing number of discoveries, driving increasingly detailed quantification of lithic morphologies from around the globe spanning the entire Paleolithic material record. Though Roe's metrics have become the standard method employed in measuring inter- and intra-assemblage variance in shape via PCA, they are insufficient for a precise analysis of symmetry, as is also the case for GMA using homologous semi-landmarks.

In response to this methodological lacuna, I turn to several creative alternative methods offered as a means of qualifying and quantifying symmetry in Acheulean handaxes.

Methods For The Analysis Of Symmetry In Acheulean Lcts

The following sections highlight several approaches to the analysis of bilateral symmetry: a radial qualification approach (Marathe, 1980), a radial quantification approach (Wynn & Tierson, 1990), the Continuous Symmetry Measure (Saragusti et al., 1998), a mental folding method (McNabb et al., 2004), the Index of Symmetry measure (Lycett et al., 2008) and the Index of Deviation of Symmetry by Feizi et al. (2018, 2020). The most popular approach to 2D analyses of bilateral symmetry has been the Flip Test and its Asymmetry Index (Couzens, 2013; Hardaker & Dunn, 2005; Keen et al. 2006; Lee, 2016; Putt et al., 2014; Shipton, 2018; Underhill, 2007; White & Fouls, 2018). To simultaneously quantify both bilateral and bifacial handaxe symmetry, Li et al. (2016, 2018) introduced a novel correlative approach based on analyzing the volumes of opposing halves of bifurcated 3D models of handaxes. My review of these individual approaches to handaxe symmetry begins with an unconventional radial qualification approach.
Radial Qualification of Handaxe Bilateral Symmetry

Marathe (1980) published this method as a novel techno-typological qualification of handaxe morphology focused on discriminating 260 handaxes from two Indian locales — an Early-to-Middle Acheulean site at Chirki-on-Pravara and a Late Acheulean site at Paleru. Marathe measured the standard planar attributes of length, width, and thickness (independent variables), along with handaxe weight (dependent variable), then performed product-moment correlations, multiple correlations, and regression analyses on pairs of attributes. He claimed that the highest correlations represented an advanced technological ‘character.’ Marathe hypothesized: as knapping reduces the weight of a handaxe, high correlations between the independent variables (length, width, and thickness) and the dependent variable (weight) should be observed. He also calculated a coefficient of symmetry measured along both the plan and profile aspects. This equation as well as the range of values denoting symmetrical and asymmetrical handaxes was referenced to an earlier work (Joshi & Marathe, 1976) which I have unfortunately been unable acquire for detailed review. This coefficient of symmetry was used to categorize each handaxe as symmetrical or asymmetrical. The frequencies of symmetrical handaxes were converted into a fraction of the total assemblage. The product-moment correlation coefficients, the multiple correlation coefficient, and the percentage of symmetrical handaxes were then displayed on a radial graph. As both percentages and correlation coefficients are represented by a value between 0 and 1, Marathe chose a radial graph to display his results. The center of Marathe’s graph represented a percentage or correlation coefficient of 1 with expanding concentric rings marking decreasing correlation coefficient values and percentages. He inferred that higher group correlation coefficients and percentages (closer to the center of the circle) implied an advanced technological stage, while lower coefficients (closer to the edge of the diagram) represented a primitive technological stage. The analyzed values from the Early-to-Middle Acheulean site at Chirki were represented by X, while the values from the Late Acheulean site at Paleru were denoted by 0, and the five variables ($r_{WL}$, $r_{WB}$, $r_{WT}$, $R$, and Percent of Symmetrical Handaxes) were displayed by a radial graph.

This method appears to support the author’s hypothesis that, excepting the regression coefficient $R$, the remaining four variables depict the values for Paleru closer to the center of the graph than those of Chirki-on-Pravara, supporting their typological categorizations as Late Acheulean and Early-to-Middle Acheulean, respectively. Next, we turn to another novel radial quantification of bilateral handaxe symmetry, published a decade later.

Radial Quantification of Handaxe Bilateral Symmetry

Wynn & Tierson (1990) developed a radial approach to measuring bilateral symmetry using the plan view outlines of 1178 handaxes excavated in Europe, the Near East, East Africa, and India. After reproducing the outlines by tracing the artifacts on an overlay, they imposed a series of 22 radial measurements referenced to a point bisecting the plan view length (tip-to-butt) and the edge-to-edge width measurement at the midpoint of the long axis, always placing the side with the greater area to the left of the reference point.
Wynn and Tierson argued their radial approach was superior to metrics like Roe's ratios because it was quicker and more accurate at measuring bilateral asymmetries, though they granted it did not evaluate refinement (i.e., the bifacial symmetry in profile view and thinness of the artifact) and may not have precisely detected the point of maximum breadth. Their initial statistical tests included PCAs of the four combined groups, finding two eigenvalues greater than 1, with the former component accounting for 83.1% of the variance, and the latter 6.5%. As both components had a loading factor greater than 0.3, they determined that both were related to differences in size. To reveal the variance attributable to shape differences alone, they controlled for size by dividing the value of each radian measurement by sum of the 0° and 180° radian values (i.e., the length of the long axis of the artifact), making all radial measurements proportioned to the length of each artifact.

A subsequent PCA identified four principal components with eigenvalues greater than 1, accounting for 84.3% of the variance. They labelled these — along with the percentage of variance accounted for — as shape differences along the left side (PC1, 54.7%), at the tip (PC2, 15.6%), lower right-side (PC3, 9.0%), and the butt (PC4, 5.0%). Since their null hypothesis stated there were no differences between the four geographical areas (i.e., a nominal dependent variable) they performed a step-wise discriminant analysis using the left-side, right-side, and tip variables of the entire sample (both completely trimmed and partially trimmed artifacts) to determine differences between groups. The resulting between-group F ratios were significant at $p < 0.001$, supporting their alternative hypothesis that shape differences existed between groups.

Unfortunately, their classification matrix correctly identified only 42.4% of the artifacts, signaling that there were larger differences between some groups when compared to others. They removed the untrimmed artifacts from the sample and performed a second discriminant analysis on the remaining 611 which slightly increased the percentage of those correctly identified to 46.3%. In summary, they proposed that their results suggested that the Acheulean was not as homogenous as others have argued. Their radial approach was criticized by McPherron (2000) on the basis that by controlling for size by dividing the 22 radial measurements by the handaxe's length, “they scaled their handaxes to a standard length. As a result, 2 of the 22 measurements (V0 and V180) were lost because they were coincident with handaxe length.” McPherron continued, “In doing this, however, the width measurements (V90 and V180) are, in essence, transformed into elongation ratios since elongation is equal to width divided by length” (p. 657). He suggests the authors should have focused on the remaining components of their initial PCA, per Whallon (1982).

Having reviewed past radial approaches to the analyses of handaxe symmetry, we turn to other planar approaches to this enduring question.

**Continuous Symmetry Measure**

In another imaginative approach to quantifying bilateral symmetry in Acheulean handaxes, Saragusti et al. (1998) employed a Continuous Symmetry Measure (CSM) represented by the variable $S(\sigma)$. The CSM approach uses a ‘folding-unfolding’ algorithm to find the nearest symmetrical shape around a general...
boundary line, first developed by Zabrodsky and Avnir (1995) as a solution for quantifying variations in symmetry between continuous molecular structures. Using the CSM, Saragusti and colleagues investigated the claim that the overall symmetry of handaxes increased over time (granted one must assume that overall symmetry referred to bilateral symmetry exclusively in the context of the study) by sampling artifacts from three Levantine sites. Indeed, this claim was supported as they found the oldest handaxes from Ubeidiya dated to 1.4 Mya \((N=20)\) with a mean \(S(\sigma) = 0.91\), were more asymmetrical than the handaxes from Gesher Benot Ya’aqov dated to 0.78 Mya \((N=16)\) with a mean \(S(\sigma) = 0.77\), with the handaxes from Ma’ayan Barukh dated to 0.13 Mya \((N=8)\) with a mean \(S(\sigma) = 0.27\) being the most symmetrical of the three assemblages, thereby also supporting their claim that inter-assemblage standardization increases over time.

In a subsequent study, Saragusti et al. (2005) took the opposite tact by employing an alternative to CSM, a measure of asymmetry to evaluate the same hypothesis regarding a decrease in asymmetry over time. Here they evaluated handaxe samples from the same Levantine sites as the 1998 study along with the addition of two sites from Tabun Cave: Layer E dated to 0.35 Mya and the undated, but stratigraphically lower thus older site of Bed 90, as well as sample of modern ceramic flowerpots. Their results supported the 1998 claim that bilateral symmetry increases over time while variability decreases. Several other important studies have quantified bilateral symmetry using the CSM to evaluate its effect on butchery utility (Machin et al., 2005, 2007), and variations in bifacial symmetry across several pan-European Acheulean sites (Iovita et al., 2017), among others. Intriguingly, Machin and associates found that bilateral symmetry had little discernable effect on cutting utility during a series of experimental butchery tasks.

As an alternative to quantifying bilateral symmetry, we turn to another ‘folding’ metaphor to qualify bilateral symmetry.

**Mental Folding (By Eye) Qualification**

Further exploiting the ‘hinge’ metaphor, McNabb et al. (2004) qualified handaxe symmetry via a ‘mental folding’ method. The authors hoped to refute the hypothesis that community sanctioned practices commensurate with strong social learning were the primary influence on LCT morphology during the Late-Early and Middle Pleistocene in southern Africa. This approach considered bilateral symmetry from a novel qualitative perspective, as the artifact’s plan view was bisected along its major axis and then subdivided into tip, medial, and base sections. The left tip section was mentally folded across the longitudinal bisector and a subjective judgement of symmetry was recorded in relation to the opposing right tip: YES if symmetrical and NO if asymmetrical. In this way, each LCT could be represented by three YES/NO scores and categorized into one of the eight possible combinations. Regarding both tip shape and bilateral (plan view) symmetry, results indicated that, though near symmetrical artifacts were present across all seven sites, cultural templates were not influential. Rather the shape of individual LCTs was a ‘variable idea in the mind of the knapper’ based upon exemplars which had surrounded them throughout their lives.
McNabb (2013) outlines a similar qualitative approach to edge proximity. Moving from a qualitative to a quantitative approach to support their step-and-stasis model of variable equilibria, McNabb and Cole (2015) employed a method focused on the area of overlap between the left and right side of the plan view outlines divided by the width of the artifact to evaluate bilateral symmetry in a sample of 50 Cuxton handaxes. This method shares some important aspects with an earlier approach, the Flip Test, described below.

**Flip Test**

Hardaker and Dunn (2005) introduced the Flip Test, a bespoke computer application and an alternative to the CSM and other methods of quantifying 2D bilateral symmetry in handaxes. Packaged as a Windows application, the program traces the plan view outlines of both the ventral and dorsal face of an artifact when flipped about its long (tip to butt) axis. It then measures the Asymmetry Index (AI) or the area in pixels defined between the two outlines then dividing this value by the squared sum of the pixel length and pixel width of the artifact as a path toward standardizing the scale of the object. AI values 1.0 to 1.49 describe a virtually perfect level of symmetry, 1.50 to 2.99 very high, 3.0 to 3.99 high, 4.0 to 4.99 moderate, 5.0 to 5.99 low, 6.0 or more very low levels of symmetry. Hardaker (2006) used the Flip Test to compare the relative levels of symmetry of two cleavers and two demi-facons found 44 km apart at different sites along the Upper Thames. Since its introduction, the Flip Test has been the preferred tool for measuring 2D bilateral symmetry. It has been applied to evaluations of the relative bilateral symmetry of Cave of Hearths LCTs (Underhill, 2007), experimental bifaces (Putt et al., 2014), South Korean handaxes (Lee, 2016), British Cromerian-era handaxes (Keen et al. 2006), African handaxes from Rietputs and Cave of Hearths (Couzens, 2013), biface morphology and its influence upon haptics (Silva-Gago et al., 2021), and knapping skill in the Eastern Rift Valley (Shipton, 2018), among other topics.

Regarding handaxe aesthetics, White and Foulds (2018) used the Flip Test to show that 52% of a sample of British handaxes are highly symmetrical or better (with AI values between 1.00 and 3.99) to support their claim that bilateral symmetry emerged because the perception of symmetry is associated with increased dopaminergic neurophysiology, sharing a direct relationship with the activation of the brain's pleasure and reward system. Notably, Hutchence and Debackere (2019) created a Python script which also measured a pixel-based AI ratio based on plan view photos of handaxes. A series of Pearson product moment correlations with the AI and planar metrics found low correlations between symmetry and elongation, suggesting thinning and edge straightness contributed more to utility than symmetry.

**Index of Symmetry**

Lycett et al. (2006) introduced a novel data acquisition apparatus, the crossbeam co-ordinate caliper. They featured its use with an accompanying Index of Symmetry (IoS) equation as an alternative to standard planar metrics and ratios to examine morphological variance between three assemblages: a Mode 1 industry from Soan River Valley, Pakistan, and a pair of Mode 2 industry sites in Attirampakkam, India, and St. Acheul, France. The IoS was based on a ratio of the square root of the squared differences between the left and right lengths of a series of perpendicular lines placed along the length of the biface.
at homologous intervals (i.e., percentages of the handaxe length) divided by the sum of the same two lengths for each vertical distance landmarked from tip to base.

The IoS offered an index where a value of zero represented perfect bilateral symmetry. Geometric mean size adjusted results of a principal components analysis of the 51 semi-landmarks revealed that PC1 distinguished the outline roundness and domed convexity of the Mode 1 assemblage from the pointed outlines and thin profiles of the Mode 2 assemblages, PC2 distinguished thick pointed tools from thin ovate morphologies, and PC3 distinguished bilateral asymmetry on tools with more rounded bases from opposing side asymmetries on tools with a more pointed base. Lycett (2009) used the IoS to infer that handaxe symmetry was subject to selection as the result of functional, social, or adaptive factors. Lycett and von Cramon-Taubadel (2008) used the IoS to analyze a sample of African and Eurasian handaxes to support their hypothesis that Acheulean technologies evolved in Africa and dispersed to northern and western Eurasia with migrating populations.

**Index of Deviation from Symmetry**

In a pair of recent papers, Feizi et al. (2018, 2020) have developed a novel Index of Deviation from Symmetry (IDS) as an approach to quantifying symmetry’s relationship with the cognitive ability of archaic *Homo* by focusing on an assemblage from Mirak, Iran, an open-air Middle Paleolithic site. To evaluate bilateral symmetry, the IDS is calculated by enclosing a 3D model of an artifact within a quadrangle, then bifurcated the quadrangle down the long axis at 50% of the total width. The surface area of each side is calculated before the difference of these two areas is divided by the total plan view area of the 3D point cloud model to produce the IDS value. The former article focused on Middle Paleolithic Levallois points determining that the entire sample (\(N = 153\)) was bilaterally symmetrical but that only 133 artifacts exhibited 3D symmetries. The latter article used the same method to compare the Mirak (\(N = 118\)) artifacts to those from Chah-e Jam (\(N = 49\)), Kuhrang (\(N = 23\)), the Mehran plain (\(N = 31\)), and Bandepey, Iran (\(N = 27\)). They found that artifacts from Mirak, Chah-e Jam, and the Mehran Plain were more symmetrical than those found at Bandepey and Kuhrang and that there was a significant positive correlation between symmetry and preparation removals, suggesting that the knappers in Mirak, Chah-e Jam, and the Mehran Plain paid more conscious attention to artifact symmetry than those at Bandepey and Kuhrang.

**Volumetric Correlational Approach to Symmetry**

In the first of what may be the only examples of a volumetric approach to quantifying both bilateral and bifacial symmetry in LCTs, Li et al. (2016) analyzed 3D models from a sample of handaxes from the Danjiangkou Reservoir Region in central China. These handaxes were taken from two distinct archaeological horizons, the Middle Pleistocene Terrace 3 (\(N = 92\)) and the Late Pleistocene Terrace 2 (\(N = 25\)). NextEngine and Range 7 laser scanners were used to digitize the artifacts. Avizo Fire 3D imaging software was employed to bifurcate the 3D models first bilaterally and then bifacially along the long axis of each handaxe before analyzing the volume of each half. Their primary claim was the closer in volume each half was to its matched pair — bifurcated in either plan or profile view — the higher the degree of
bilateral and bifacial symmetry, respectively. To capture the range of symmetry across all samples, the authors converted the degree of deviation from perfect symmetry into an absolute distance, by first subtracting the volume of one half from the volume of the opposing half, dividing this remainder by the square root of 2, then taking the absolute value of this quotient. In this manner, the authors suggested both bilateral and bifacial halves can be interchanged to calculate a value for deviation from perfect symmetry for a particular handaxe. Pearson product-moment correlation analyses of the paired volumes (left and right halves for bilateral symmetry and dorsal and ventral halves for bifacial symmetry) determined the two halves were strongly correlated between bilateral pairs ($r = .909, p < 0.001$ and $r = .871, p < 0.001$ for Terrace 3 and Terrace 2, respectively), but weakly correlated between bifacial pairs ($r = .217, p < 0.05$ and $r = .129, p < 0.539$, respectively). The authors interpreted these results as supporting their claim that bilateral (i.e., plan view) symmetry is significantly higher than bifacial symmetry, and that there is probably no bifacial symmetry (i.e., profile view) across both assemblages.

In their second effort, Li et al. (2018) analyzed 3D models of a sample of handaxes from Rietputs 15 an Early Acheulean site dated to ca 1.3 Mya, and Cave of Hearths a Late Acheulean site dated to ca 0.5 Mya. Avizo Fire 3D imaging software was employed to bifurcate the 3D models first bilaterally and then bifacially down the long axis of each handaxe before analyzing the volume of each half. Pearson product-moment correlation analyses of the paired volumes (left and right halves for bilateral symmetry and dorsal and ventral halves for bifacial symmetry) determined there was a significant overall degree of symmetry between bilateral pairs ($r = .935, p < 0.001$ and $r = .946, p < 0.001$ for Rietputs 15 and Cave of Hearths, respectively) as well as bifacial pairs ($r = .654, p < 0.001$ and $r = .662, p < 0.001$, respectively).

Having reviewed these various approaches to the analysis of LCT symmetry, I now turn to a critique of the same.

**Limitations Of Current Morphometric Methods For Quantifying Handaxe Symmetry**

As this précis of past investigations illustrates, the analysis of Acheulean handaxe symmetry has progressed from the subjective type-fossils characterizations to the objective quantification of inter- and intra-assemblage morphology through a variety of planar and geometric approaches. These analytical innovations have qualified and quantified the morphological variation of myriad artifacts and assemblages, invariably expanding our knowledge of the technical choices and behavior of Paleolithic hominids around the world to their modern human counterparts in the Neolithic era. These metrics have employed the latest analytic technologies to measure and analyze morphology with increasing precision and reliability. Next, I will focus on three significant limitations inherent in traditional approaches to lithic symmetry: 1) the measurement resolution associated with the devices employed during data acquisition as well as the methodological resolutions of the analytical models unique to planar and geometric methods, 2) the emphasis on analyses of bilateral symmetry at the expense of bifacial symmetry, and 3) methods suggesting correlations of opposing volumes as a warrant for 3D symmetry.
Morphometric Precision And Measurement Resolution

Advances in measurement resolution have been an important factor in the analytical precision of Paleolithic morphometry during the 21st century. Therefore, clarifying the Janus nature of ‘measurement resolution’ is critical to understanding its role in lithic morphometry. Measurement resolution affects precision at two distinct phases of the morphometric process: data acquisition and analytical model definition. Whereas acquisitional resolution is a property of the device used to scan the artifact, analytical resolution is a property of the method used to define the morphology of the 3D model subjected subsequent multivariate statistical analyses. Parsing the distinct contributions of measurement resolution at both the acquisitional and analytical stages of modern morphometry is sine qua non to understanding the advantages and limitations of planar, geometric, and volumetric approaches to the quantification of stone tool symmetry. Therefore, I will first discuss the role of measurement resolution during data acquisition.

Acquisitional Resolution

Two critical properties associated with data acquisition are the measurement resolution and accuracy of the data acquisition device — in the case of lithic morphometry typically a laser or structured light scanner. In the data acquisition phase, acquisitional accuracy refers to how close a stated measurement is to its true or tolerable value. Acquisitional resolution refers to the number of points a device can capture in a specified area. In other words what is the minimal distance from one point on the artifact’s surface to the next that the scanner can distinguish? This value ultimately affects the wire frame or mesh resolution, representing the distances between two points in virtual 3D space. In the case of digital scanners, each point exhibiting a change in the artifact’s surface topology is represented as a vertex in the mesh of the resulting 3D model. Thus, in general, scanners with higher measurement resolution can produce 3D models with a higher number of vertices, offering finer topological detail, with greater coherence between the actual morphology of the physical artifact and its digitized 3D model. In terms of measurement resolution, digital scanners offered a manifold increase of several orders of magnitude in acquisition resolution over the caliper measurements typical of 20th century planar metrics.

Planar methods employing calipers as their input device remained state-of-the-art in morphometrics until the late 20th century, when advances in computational technology enabled the digitization, visualization, measurement, and analysis of solid three-dimensional structures in ‘virtual reality,’ (i.e., a space computationally modeled and displayed graphically in three dimensions). In the clinical sciences, technologies such as magnetic resonance imaging (MRI) and computed tomography (CT) enabled the detection, display, and measurement of solid three-dimensional biological structures, while laser and structured light scanning, reflectance transformation imaging, and photogrammetry enabled the 3D digitization of cultural artifacts for the archaeologist and anthropologist. Today, laser and structured light scanners can detect morphological variations as small as 7 micrometers, resulting in 3D models of lithic artifacts that can contain upwards of 500,000 vertices. Digital scanners and the 3D models they produced enabled new methods for generating higher resolution analytical models, which I turn to next.
Analytical Resolution

In contrast to acquisitional resolution, *analytical resolution* refers to the number of vertices defining the analytical model subject to subsequent multivariate statistical analyses. Therefore, analytical resolution is a property of the *methods* used to generate the analytical model, whether planar, geometric, or volumetric. Planar metrics provided a path to quantifying stone tool morphology by trading precision (in this case the resolution of the analytical model) for the continuous two-dimensional linear variables necessary to construct the covariation matrices underlying multivariate statistical analysis. Planar metrics (length, breadth, depth, and the ratios formed by combining these in different equations) are descriptions of a linear distance from one point to another. For example, the point at the tip of a handaxe to the furthest point of the butt — the length of the long axis, or the point on the left edge of the handaxe furthest from the point on the right edge along a line in the horizontal plane perpendicular to the long axis — the maximum breadth of the handaxe. Vertices are formed where these planes meet (hence, the term *planar* metrics). Therefore, these vertices define and constrain the resolution of the analytical model, i.e., the geometry of the shape subjected to subsequent multivariate statistical analysis. Consequently, for most of the 20th century, the complex morphology of an artifact was condensed from the hundreds of thousands of vertices inherent in its physical geometry to a 14-vertex analytical model created by measuring the linear dimensions of an artifact with a set of calipers.

In the following series of images, a digital scanner was employed to generate a high-resolution 3D model of the West Tofts handaxe, famed for featuring a fossil of a Cretaceous bivalve mollusk *Spondylus spinosus* on its surface. The 3D model is shown in Fig. 5a with photorealistic shading on its surface. In Fig. 5b, the surface shading is removed to display the underlying polygon mesh or 'wire frame' of the 3D model. In Fig. 5c, a close-up of the tip of the handaxe model displaying the geometric detail of a small portion of the 250,539 vertices that form the high-resolution 3D model generated by the digital scanner.

In Fig. 6a, another polygon mesh representing the wire frame formed by the 14 vertices offered by caliper-measured planar metrics and ratios (per Roe, 1968). A blue-shaded version of the mesh is shown in context with the 3D model in Fig. 6b. In Fig. 6c, the analytical model — the 14-vertex polygon generated by caliper measurements of linear distances — is shown with its wire frame shaded in blue. Like all artifacts measured using calipers, this low-fidelity 14-vertex polygon representing the West Tofts handaxe is the analytical model, the shape evaluated by subsequent multivariate analysis. This is the case for many traditional morphological studies of handaxe morphology using planar metrics and a PCA approach.

**Figure 6**
**14-Vertex Analytical Model Associated with Traditional PCAs of Linear Caliper Measurements**

After decades constrained to low-fidelity 14-vertex analytical models, archaeologists studying lithic morphometry enjoyed a manifold orders-of-magnitude increase in acquisitional resolution with the use of digital scanners as well as a subsequent increase in analytical model resolution with the introduction of a
new method: geometric morphometric analysis (GMA) of homologous semi-landmarks, a method capable of producing analytical models containing up to 5000 vertices. Having first borrowed statistical methods from evolutionary biology, archaeologists and anthropologists now followed suit with GMA (e.g., Brande & Saragusti, 1998; Brande et al., 1999; Grosman et al., 2008). Dryden and Mardia (2016) suggested GMA provides an objective quantification of morphological variation. But Wärmländer et al. (2019) have recently asserted that inconsistencies in its application have generated both measurement errors and confusing results in the literature.

As originally conceived by Bookstein (1978) for the biological sciences, GMA uses a variety of landmarks depending upon the nature of the shape under analysis and the specific research questions at hand. Bookstein (1990, 1997) defined three types of landmarks. Type 1 landmarks describe anatomical relationships, specifically the discrete juxtaposition of tissues, such as the sutures evident in human crania under the bridge of the nose. Type 2 landmarks describe the maxima of curvature or other local morphogenic processes, such as the tips of extrusions (e.g., claws and teeth) and the valleys of invaginations. Type 3 are constructed landmarks unrelated to anatomy. They can describe several relationships: 1) extremal points or information at diverse, finitely separated locations such as the endpoints of diameters, centroids, intersections of inter-landmark sections or the points farthest from them, or 2) points associated with the convenience of extracting data from 2D representations of solid form, such as a solid object depicted in a photograph or drawing. Therefore, Type 3 landmarks are termed ‘semi-landmarks’ as they define points in space without reference to anatomical structures.

In the context of the GMA of stone tools, semi-landmarks satisfy the definition for ‘information at diverse, finitely separated locations.’ Homologous refers to the equivalency of points arranged upon a plane in a lattice configuration which is subsequently superimposed on a series of objects to quantify and compare their geometric variation. For example, a specific semi-landmark might be the point on the surface of a stone tool at 60% the length from its tip and 15% the length from its left edge.

Thus, the homologous semi-landmark GMA method has emerged as a favored approach to quantifying and evaluating the shape of stone artifacts in the 21st century, as it offered a significant increase in analytical model resolution for subsequent multivariate analyses. After scanning a stone tool, the 3D model of the artifact is imported into the analysis space. It is then precisely located and rotated in reference to the common origin, the point in virtual space with a ‘0’ value along each axis. Once imported and oriented, this method entails consistently imposing a homologous grid of semi-landmarks (i.e., repeatedly locating and arranging them at the same predetermined points) along the dorsal and ventral surfaces of a series of artifacts. The analysis begins at the first semi-landmark where a tripartite variable representing the height (X-value), width (Y-value), and depth (Z-value) of the model's closest proximal vertex to a specific semi-landmark is identified and recorded. This process is repeated for each of the up to 2500 semi-landmarks on the dorsal and ventral surfaces of the model.

As most of the morphological variance in any assemblage can be explained by differences in size, a Generalized Procrustes Analysis (GPA) is performed on the raw data prior to morphometric analyses to
normalize any variance associated with differences in size, rotation, and location with respect to the origin point from one artifact to the next. Once the raw data has been normalized, a variety of multivariate analyses can be performed depending on the nature of the research questions. These typically include PCA, factor analysis (FA), cluster (k-means, nearest-neighbor, etc.) analyses, and discriminant function analyses (DF), among others.

This method has been packaged into computer applications developed specifically for the GMA of material artifacts. This added convenience has encouraged its adoption by archaeologists, expanding its presence in the literature. Examples include Artifact3D (Grosman et al., 2022), Artifact GeoMorph Toolbox 3-D (Herzlinger & Grosman, 2018), EVAN Toolbox (O’Higgins, et al., 2012), GLiMR (Davis et al., 2015), GeoMorph (Adams & Otárola-Castillo, 2013), PAST (Hammer et al., 2001), PyLithics (Gellis et al., 2022), MorphoJ (Klingenberg, 2011), Morphologika (O’Higgins & Jones, 1999), and QuARI (Contreras et al., 2021), among others.

Once limited to 14 vertices by caliper-generated planar metrics and indexes, GMA has increased analytical model resolution up to 5000 vertices. The example shown below in Fig. 7 employs 4802 semi-landmarks, 2400 per face as well as a single semi-landmark at both the tip and butt of the handaxe. A blue-shaded version of the mesh is shown in context with the 3D model in Fig. 7b. In Fig. 7c, the analytical model — the 4802-vertex polygon generated by homologous semi-landmarks — is shown with its wire frame shaded in blue. Importantly, while an increase in analytical model resolution from 14 to 5000 vertices is as noteworthy as it is pragmatic, it still falls significantly short of the 500,000 vertices typical of the detailed 3D models generated by modern digital scanners. As such, current GMA based on homologous semi-landmarks are sampling a subset of the available data contained within the digitized 3D model, effectively down-sampling the acquired data, reducing the analytical model resolution by up to two orders of magnitude prior to statistical analyses. This down-sampling can be clearly visualized by comparing the topological detail in Fig. 5c above with the ‘pixelated’ representation shown Fig. 7c.

Figure 7
Analytical Model Resolution using GMA of 4802 Homologous Semi-Landmarks

While semi-landmark based GMA offers a vast improvement in analytical model resolution over the former planar methods, current geometric morphometric approaches leave a significant majority of the morphological data unanalyzed as the result of its inherent down-sampling. GMA using homologous semi-landmarks fails to characterize 4% of the topology of any artifact. In the case of the handaxe shown above, this includes the topology of the butt (2%) and tip (2%) of the tool. In these areas, the existing topological detail is reduced to a series of contiguous triangular planes. It can also be argued this is the case for most of the remaining 96% of the surface topology, as the rectangular planes defined by any four locally associated semi-landmarks misrepresent the underlying topology between them as a flat surface during the statistical analyses, in essence ignoring the majority of the available topological data. Semi-landmark methods may also impose an unquantified measurement error during their imposition. As
noted by Herzlinger et al. (2017), they are calculated to the nearest neighboring vertex of a 3D model's complex mesh, as opposed to the face of the polygon directly below the precise homologous point defined by every semi-landmark. But low-resolution analytical models are not the only limitation to the investigation of the role of symmetry in Acheulean technologies.

I now turn to another traditional constraint of previous morphometric studies of Paleolithic LCTs: the bias toward the analysis of bilateral symmetry at the expense of bifacial symmetry, one of the key components of stone tool refinement.

**Favoring Bilateral Symmetry Over Bifacial Symmetry And ‘refinement’**

Historically, analyses of handaxe symmetry have employed 2D planar methods and focused on bilateral symmetry in reference to the plane of the artifacts' major axis in plan view (e.g., Cole, 2015; Hodgson, 2015; McNabb & Roe, 1964, 1968; Mzalendo-Kibunjia, 1986; Wymer, 1998). Recently, the analysis of bifacial symmetry and thinness in profile view — collectively referred to as ‘refinement’ — has been explored in several studies. Caruana (2020) employed a PCA of planar metrics and indexes to compare 2D cross-sectional planes of handaxes from Rietputs 15 and Cave of Hearths, suggesting an increase in refinement between the Early and Late Acheulean in South Africa. Caruana and Herries (2021) employed planar metrics and indexes with GMA to explore allometric patterns between handaxes from Amanzi Springs, South Africa, Cave of Hearths, and Rietputs, suggesting a continuity in allometric trends across Africa with some differences between eastern and southern assemblages. Caruana (2021) employed a GMA of homologous semi-landmarks to compare 2D cross-sectional planes of Early and Late Acheulean handaxes. The results suggested that the analysis could discriminate between Early and Late Acheulean bifaces and that variance in refinement is associated with reduction strategies.

Given the sheer number of studies devoted to the analysis of bilateral symmetry in Acheulean handaxes, these examples coupled with those previously mentioned represent a significant minority when compared to the scores of articles focused on 2D analyses of bilateral symmetry in Acheulean technologies. This is even more problematic, as the subject of ‘refinement’ has been a long-standing issue predating even the earliest morphological analyses in the mid-20th century (e.g., Clark & Bishop, 1966; Deacon, 1970; Gilead, 1970; van Riet Lowe, 1951; Roe, 1968, 1970, 1975; Ronen et al., 1974; Toth, 1990; Wymer, 1988; Wynn, 1989). Even though these latest examples have only recently appeared in the literature they are still based on the analyses of 2D planar metrics suffering from the same low-fidelity analytical models discussed in the previous section.

This is as encouraging as it is frustrating, as it exposes the relative paucity of GMA or other 3D contributions to this important issue in the study of Paleolithic archaeology and cognitive evolution (but see García-Medrano et al., 2022a, 2022b and Li et al., 2016, 2018 for recent 3D GMA approaches to bifacial symmetry). I would argue that the time has come to afford the analysis of bifacial symmetry the merit it deserves; to move quickly to address its contribution to the wider morphometric debate regarding
Acheulean handaxe symmetry and refinement. This brings the discussion to two of the first 3D volumetric analyses of both bilateral and bifacial handaxe symmetry.

**Correlations Of Volume As A Proxy For Symmetry**

Li et al. (2016) and Li et al. (2018) are important contributions as they are some of the first volumetric approaches to the quantification of both bilateral and bifacial symmetry in Acheulean handaxes. Compared to traditional analyses of planar metrics and homologous semi-landmarks, these volumetric approaches offer significant increases analytical model resolution as they appear to evaluate every facet of the morphological detail available in modern digitized 3D models. Nevertheless, the claims made by both articles are questionable on several accounts. First, Pearson product-moment correlations should be reported as strengths of association (as opposed to levels of significance), for example small \(r = 0 \text{ to } .3\) or \(0 \text{ to } –.3\), medium \(r = .3 \text{ to } .5 \text{ or } –.3 \text{ to } –.5\), or large \(r > .5 \text{ or } –.5\) along with their linear relationship, either positive (direct) or negative (indirect). Second, levels of significance (in this case \(p < .001\)) describe the probability of making a Type I error (rejecting the null hypothesis when it is true), not the strength of a relationship between bivariate values (i.e., a “significant and large degree of symmetry in plan view” as stated in the 2018 paper, p. 38). Third, and most problematic, both bifacial and bilateral symmetry are examples of reflection or mirror symmetry, where one half of the pattern is duplicated across a bifurcating plane. Critically, matched halves of a bifurcated solid can occupy equal volumes of space while also distributed within asymmetrical geometries. For example, consider the distorted cordiform solid shown below in Fig. 8. Regarding bilateral volumes, the smaller side \(A\) has a volume of \(32.8254 \text{ cm}^3\) as shown in Fig. 8a. In Fig. 8b, the larger side \(B\) has a volume of \(32.8603 \text{ cm}^3\) clearly illustrating that nearly identical volumes can exhibit significant degrees of asymmetry in reference to their shared long axis.

*Figure 8*  

**Very Large Volumetric Correlation \((r = .99)\) with Substantial Bilateral Asymmetry**

Consider the second distorted cordiform solid also bifurcated through the long axis shown in Fig. 9. Regarding bifacial volumes, the smaller face \(C\) has a volume of \(46.5378 \text{ cm}^3\) as shown in Fig. 9a, while the larger face \(D\) on the right has a volume of \(46.7632 \text{ cm}^3\) as shown in Fig. 9b. According to the method proposed by Li et al. (2016, 2018) handaxes bifurcated through the long axis exhibiting Person product-moment correlations greater than \(r = .99\) between each half implies that both sides/faces exhibit *near perfect* bilateral and bifacial symmetry. Again, Fig. 9 clearly illustrates that ventral and dorsal faces of a cordiform solid bifurcated on the same long axis can exhibit significant levels of asymmetry while occupying nearly identical volumes.

*Figure 9*
Very Large Volumetric Correlation (r = .99) with Substantial Bifacial Asymmetry

Referring to Weyl (2016) and his definition of reflectional symmetry illustrated in Fig. 3, in the absence of defined geometric points (p and p’) along the line l sharing the same distance from a common plane E, the shape of one half of a solid bifurcated by its long axis cannot be represented by a comparison of their volumes alone, as claimed by Li et al. (2016, 2018). In the absence of a known symmetrical reference, volume does not share a direct relationship with symmetry, as objects with asymmetrical shapes can exhibit (nearly) identical volumes, as shown in Fig. 8 and Fig. 9.

As such, the preceding evidence should promote the consideration of alternatives to 2D and 3D morphometrics based on planar measurements, homologous semi-landmarks, or correlations of bilateral/bifacial volumes. In the following section, I outline one such path toward a simultaneous analysis of both bilateral and bifacial symmetry which improves analytical model resolution by orders of magnitude over traditional PCA and GMA methods by offering the Omega (ω) Coefficient of Symmetry, a simple ratio based on the quotient of the volume of a high-resolution ideal cordiform divided by the volume of a high-resolution 3D model of a handaxe.

Towards A High-fidelity Volumetric Analysis Of Lithic Symmetry

The preceding review raises several questions. Given the acquisitional resolutions of modern digital scanners, can we consider a volumetric approach to stone tool symmetry based not on correlations of volumes without a symmetrical reference, but on the ratios of volume between the high-resolution mesh of a symmetrical ideal and a high-resolution 3D model of a stone tool — a method which analyzes every vertex in the complex geometry of 3D models without decreasing the analytical model resolution as an inherent step in the process? Can we employ this approach to simultaneously analyze the contributions of both bilateral and bifacial symmetry and represent this value as a simple ratio of lithic symmetry robust to variations in size, orientation, and morphology? Might this volumetric morphometric approach not only provide high-resolution analyses of 3D bilateral symmetry, but insights into questions regarding the underserved analyses of 3D bifacial symmetry? Could this coefficient of symmetry be employed to eventually answer previously unexplored questions regarding the emergence of overdetermination in the archaeological record?

By exploiting the analytical affordances of digitized Paleolithic stone artifacts, this volumetric method proposes an alternative to the analytical constraints and theoretical limitations of past 2D and 3D approaches to handaxe symmetry. This volumetric morphometric analysis offers a method that simultaneously analyzes symmetry in three planes and presents the results as the Omega (ω) Coefficient of Symmetry, a simple ratio of 3D lithic symmetry with a value between 0 and 1. By employing Blender®, an open-source 3D modeling and animation application, this method increases the analytical model resolution by considering the precise volume of the high-fidelity 3D model and comparing that to the volume of a known symmetrical ideal.
**Blender® And The Sciences**

Recently, Kent (2015) and Filippov (2018) have reviewed and discussed the scientific utility of Blender®, a software application which offers cross-platform modeling, rigging, animation, simulation, rendering, compositing, motion tracking, and graphical display of 3D models on Linux, Windows, and Mac operating systems. Blender® enables precision manipulation and analysis of a robust assortment of 3D modeling file formats, including glTF 2.0 (.glb/.gltf), Wavefront (.obj), Stanford (.ply), Collada (.dae), Alembic (.abc), STL, and FBX, and others. Its API for Python enables the creation and implementation customized applications and specialized analysis tools which can be packaged as ‘add-ons’ for the application. Blender® add-ons can be downloaded, installed, and enabled directly in the application to facilitate personalized workflows and analyses.

Since its formal publication as an OpenSource software project, its utility, expandability, and reliability has supported a growing number of researchers in the sciences. Originally envisioned as a design, modeling, and animation platform, it has become an invaluable analysis and visual display tool in the workflow of a wide variety of scientists: chemists (e.g., Rajendiran & Durrant, 2018), geographers (Florinsky & Filippov, 2019), biologists (e.g., Berry et al., 2018; Cassidy et al., 2020), virologists (e.g., Calvelo et al., 2020), roboticists (e.g., Liu et al., 2021), particle physicists (Figueiras et al., 2019), astrophysicists (e.g., Kent, 2017; Kraus et al., 2020; Vogt et al., 2016), and oceanographers (Florinsky & Filippov, 2020) among others. In the following section, I summarize a method utilizing Blender® and its proven 3D modeling environment, add-ons, and Python API to enable a novel volumetric morphometric approach to handaxe symmetry utilizing a known symmetrical reference.

**A Method For Determining The Omega (ω) Coefficient Of Handaxe Symmetry**

In the case of handaxes, this can be accomplished through a short series of steps using a digital scanner and Blender®. To begin, the handaxe is scanned and a 3D model is created. The scanner's software is used to verify the integrity of the wireframe mesh and save the 3D model as a glTF 2.0 file with a unique name. Next, Blender is opened, and its 3D-Print add-on is enabled to measure and record the volume of the artifact's 3D model ($V_{artifact}$). A default cube is inserted into the analysis space, then modified into an ideal sphere. The ideal sphere is then molded into an ideal (symmetrical in plan and profile view) cordiform. This ideal cordiform is manipulated until its volume is maximized without exceeding the boundaries of the artifact while maintaining its bilateral and bifacial symmetry. Blender’s® Print-3D add-on is used to measure and record the volume of the ideal cordiform ($V_{ideal}$). Finally, the *Omega (ω) Coefficient of Symmetry* is calculated by dividing $V_{ideal}$ by $V_{artifact}$ to obtain a high-resolution volumetric analysis of 3D symmetry. Detailed step-by-step instructions outlining the process are available in Appendix A in the online Supplementary Information.

This method offers several advantages over traditional measures of handaxe symmetry discussed above. It differs significantly from the bilateral and bifacial correlations of volume suggested by Li et al.
(2016, 2018) as, rather than an analysis of volumetric correlations lacking a known symmetrical reference, this approach analyses the differences in volumes between the largest possible ideal cordiform and the 3D model of the handaxe. By employing a detailed, high-resolution (typically 100k vertices) ideal cordiform as a known symmetrical reference, 3D symmetry can be measured using the full resolution of the handaxe's 3D model, increasing the analytical model resolution by orders of magnitude over analyses based on planar metrics or homologous semi-landmarks. Any differences in volume between the artifact and the maximized ideal cordiform are a result of the artifact's asymmetries. By representing these volumes as a ratio, the Omega ($\omega$) Coefficient of Symmetry provides a simple ratio that is robust to variations in orientation, size, and morphology. This approach is designed as a standalone assessment of individual artifacts, not as a method for the simultaneous evaluation of morphometric variance at the inter- or intra-assemblage level, though individual artifacts’ Omega ($\omega$) Coefficient of Symmetry can be analyzed at the inter- or intra-assemblage level of analysis through a variety of descriptive statistics. Therefore, issues regarding measurement errors associated with size, rotation, and location differences with respect to the origin point, common to traditional homologous semi-landmark and planar approaches, are not a concern, alleviating the necessity of GPA to normalize measurement variance at the inter- or intra-assemblage level of analysis.

**Limitations**

While this volumetric method presents many advantages over traditional 2D and 3D approaches to handaxe symmetry, it suffers from several limitations. An extensive Python script is being developed to package the processes necessary to perform this analysis as a free Blender® add-on. Until this add-on is available for use, developing the necessary technical fluidity with the Blender® application could be an impediment to researchers lacking experience with the application. This learning period could result in configuration and analysis errors primarily related to maintaining the symmetry of the Ideal Cordiform while manipulating its morphology, orientation, and scale to achieve the maximum possible volume within the constraints of the surface topology of the handaxe. Other limitations include the prerequisites for the 3D handaxe models themselves. To use this method, the model must be imported as a glTF 2.0 file. Models comprised of multiple individual objects must be consolidated into a single ‘watertight’ (i.e., free of any overlapping vertices) wireframe, free of non-contiguous vertices (i.e., holes in the handaxe mesh), and scaled to the actual dimensions of the physical artifact prior to being imported into Blender. Measurement error may also be imposed by varying the analytical model resolution represented by the number of vertices comprising the ideal reference, as analytical model resolution shares a direct relationship with volume (i.e., ideals with a higher number of vertices could potentially occupy more volume than those with less vertices), though this potential source of error could be specified by reporting the analytical model resolution of the ideal along with the Omega coefficient.

**Future Directions**
Looking forward, this volumetric morphometric approach along with the \textit{Omega (\(\omega\)) Coefficient of Symmetry} could be used to infer the emergence of functional overdetermination when applied to an experimental sample of Acheulean handaxe morphologies (i.e., ranging from the large, relatively asymmetrical tools associated with Early Acheulean industries to more refined morphologies associated with the Late Acheulean tools). The resulting replicas could then be scanned and analyzed to quantify each artifact's coefficient of symmetry before performing a controlled butchery or cutting task. The results of this study could be used to determine the value of the \textit{Omega (\(\omega\)) Coefficient of Symmetry} at which increased symmetry no longer affords an increase in functional utility thereby quantifying the ratio of symmetry associated with overdetermination.

This method could also be advantageous to analyses of artifacts exhibiting bipolar symmetries such as double-pointed, limande, discoids, and elongate bifaces or the radial symmetries inherent in spheroids, polyhedrals, bolas and stone balls as it enables the simultaneous analysis of 3D symmetry. It could be employed to analyze symmetries in a variety of material artifacts including ceramics, architecture, ornamentation, weaponry, and other aspects of prehistoric material culture. Though it was designed to assist in the investigation of issues important to evolutionary cognitive archaeology, subsequent extrapolations and extensions of this volumetric morphometric method have the potential to increase analytical precision and reliability in any discipline investigating the relationship between symmetrical forms and human behavior, including paleoneurology, materials sciences, tradecraft, manufacturing, as well as evolutionary biology and clinical research investigating pathogenesis of abnormal tissues.

\textbf{Conclusion}

This essay reviewed the history of the conceptualization of symmetry, its quantification in archaeology, and the morphometric analyses and methods applied to understanding the role of symmetry in Acheulean handaxes. It outlined and critiqued traditional approaches to the problem, offered an alternative volumetric method, discussed its methodological limitations, as well as prospects for future applications within the field of archaeology and beyond. Volumetric morphometry referencing a known symmetrical ideal overcomes many of the constraints of traditional 2D and 3D approaches to quantifying handaxe symmetry, increasing analytical resolution by orders of magnitude over traditional approaches, simultaneously analyzing the symmetry of morphologically complex structures including modern high-resolution digital reproductions of stone artifacts.

As the \textit{Omega (\(\omega\)) Coefficient of Symmetry} is a simple index with a value between 0 and 1, it is robust to large variations in orientation, size, and morphology across individual artifacts and assemblages of artifacts. By employing a volumetric method, evolutionary cognitive archaeologists and others pursuing investigations of the role of symmetry in human behavior can escape the low-resolution constraints associated with previous planar and geometric methods and embrace every facet of the astonishing detail of modern 3D models offered by state-of-the-art laser and structured light scanners. I hope this minor methodological contribution will be incorporated into future morphometric investigations in a
variety of disciplines and continue to contribute to a deeper understanding of the role of symmetry in human behavior and experience.

**Declarations**

**Competing interests**

The author has no relevant financial or non-financial interests to disclose.

**Author’s Contribution**

J. M. H. is the sole author of this manuscript.

**Funding**

No grants, funds, or other support was received.

**Availability of data and materials**

Not applicable.

**Author Note**

James M. Hicks https://orcid.org/0000-0003-2406-9291

I have no conflicts of interest to disclose. Correspondence concerning this article should be sent to James M. Hicks, School of Archaeology, Department of Social Sciences, University of Oxford, 1 South Parks Road, Oxford, OX1 3TG, UK. E-mail james.hicks@arch.ox.ac.uk.

**References**


132. Roux & B. Bril (Eds.), *Stone knapping: The necessary conditions for a uniquely hominin behaviour* (pp. 35–48). McDonald Institute for Archaeological Research.


**Appendix A**

Appendix A is not available with this version.

**Figures**

![Plan (a) and Profile (b) Perspectives of Stone Artifacts](image1)

*Figure 1*

*Plan (a) and Profile (b) Perspectives of Stone Artifacts*

![Handaxes from (a) FLK West, (b) Gesher Benot Ya’aqov, and (c) Kathu Pan](image2)

*Figure 2*

*Handaxes from (a) FLK West, (b) Gesher Benot Ya’aqov, and (c) Kathu Pan (Image credit: Berlant & Wynn, 2018)*
Figure 3

Bilateral Symmetry or Reflection in E. (Redrawn from Weyl, 2016)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>L</td>
</tr>
<tr>
<td>Breadth</td>
<td>B</td>
</tr>
<tr>
<td>Thickness (maximum in profile view)</td>
<td>Th</td>
</tr>
<tr>
<td>Thickness 20% of Length below tip end</td>
<td>T1</td>
</tr>
<tr>
<td>Breadth 20% of Length below tip end</td>
<td>B1</td>
</tr>
<tr>
<td>Breadth 80% of Length below tip end</td>
<td>B2</td>
</tr>
<tr>
<td>Length from butt end to Maximum Width</td>
<td>L1</td>
</tr>
<tr>
<td>Weight</td>
<td>Wt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement or ratio</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size: by Weight</td>
<td>Wt</td>
</tr>
<tr>
<td>Size: by length</td>
<td>L</td>
</tr>
<tr>
<td>Refinement: Whole Artifact</td>
<td>Th/B</td>
</tr>
<tr>
<td>Refinement: Tips of Pointed Handaxes</td>
<td>T1/L</td>
</tr>
<tr>
<td>Shape: Bilateral (Broad to Narrow)</td>
<td>B/L</td>
</tr>
<tr>
<td>Shape: Tip (Pointed to Blunt)</td>
<td>B1/B2</td>
</tr>
<tr>
<td>Shape: Artifact Plan View</td>
<td>L1/L</td>
</tr>
<tr>
<td>Shape: Assemblage Plan View</td>
<td>B1/B2, L1/L</td>
</tr>
</tbody>
</table>

Figure 4

Roe’s Planar Metrics and Ratios for Quantifying LCT Size, Shape, and Refinement
Figure 5

*High-Resolution 3D Model Typical of Modern Digital Scanners (3D model credit: Museum of Archaeology & Anthropology, University of Cambridge, CC BY NC.)*

Figure 6

*14-Vertex Analytical Model Associated with Traditional PCAs of Linear Caliper Measurements*
Figure 7

*Analytical Model Resolution using GMA of 4802 Homologous Semi-Landmarks*

Figure 8

*Very Large Volumetric Correlation (r = .99) with Substantial Bilateral Asymmetry*
Figure 9

*Very Large Volumetric Correlation (r = .99) with Substantial Bifacial Asymmetry*