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Quantifying Edge Sharpness on Stone Flakes: Comparing Mechanical and Micro-Geometric Definitions Across Multiple Raw Materials from Olduvai Gorge (Tanzania)

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Abstract

In line with engineering research focusing on metal tools, techniques to record the attribute of 'edge sharpness' on stone tools can include both mechanical and micro-geometric approaches. Mechanically-defined sharpness techniques used in lithic studies are now well established and align with engineering research. The single micro-geometrically-defined technique—tip curvature—is novel relative to approaches used elsewhere, and has not explicitly been tested for its ability to describe the attribute of sharpness. Here, using experimental flakes produced on basalt, chert, and quartzite sourced at Olduvai Gorge (Tanzania), we investigate the relationship between tip curvature and the force and work required to initiate a cut. We do this using controlled cutting tests and analysis of high-resolution microCT scans. Results indicate cutting force and work to display significant dependent relationships with tip curvature, suggesting the latter to be an appropriate metric to record the sharpness of lithic tools. Differences in relationship strength were observed dependent on the measurement scales and edge distances used. Tip curvature is also demonstrated to distinguish between the sharpness of different raw materials. Our data also indicate the predictive relationship between tip curvature and cutting force/work to be one of the strongest yet identified between a stone tool morphological attribute and its cutting performance. Together, this study demonstrates tip curvature to be an appropriate attribute for describing the sharpness of a stone tool's working edge in diverse raw material scenarios, and that it can be highly predictive of a stone tool's functional performance.

Keywords Edge Geometry · Cutting Performance · Focus Variation Microscopy · Edge Profile Curvature Analysis · MicroCT · Basalt, Chert, Quartzite

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Introduction

Edge sharpness is one of the most important attributes influencing the functional performance of cutting technologies. It is key to determining the force and energy (work) required for a cut (fracture) to be formed in a worked material, and the level of material deformation created while doing so. This relationship is known to apply equally to metal and stone cutting edges in modern and archaeological contexts, and has been demonstrated in diverse worked material contexts (Atkins, 2009; Key, 2016; Reilly *et al.*, 2004). Understanding of a relationship between edge sharpness and stone tool cutting performance is commonplace in lithic archaeology (*e.g.*, Jones, 1980; Tryon *et al.*, 2005; Dewbury & Russell, 2007; Machin *et al.*, 2007; Braun *et al.*, 2008; Bebber *et al.*, 2019; Stemp *et al.*, 2019; Lin & Marreiros, 2021), with references from as early as the nineteenth century (Lartet & Christy, 1875; Prestwich, 1860). Indeed, the intuitive, often common-sense, connections between the formal properties of an object and the individual interacting with it mean that functional considerations—such as the relationship between sharpness and cutting performance—are widely considered within Palaeolithic research, an example of which is the influential typological list developed by F. Bordes (1961). These perceptions are typically formed through a process of analogical reasoning or the experimental use of replica stone tools.

Analogical reasoning has a long history of informing form-function relationships in stone tool technologies (Key & Lycett, 2017a; Pettitt & White, 2013), including when it comes to edge sharpness. We are as dependent today on hand-held cutting tools as we were during the Palaeolithic, and fundamental principles, such as the impact that edge dulling (reducing sharpness) has on modern metal cutting tool performance, can be readily transferred to stone technology. With the growth of experimental archaeology and the use of replica stone tools to provide referential frameworks for understanding artefacts (Eren *et al.*, 2016; Lin *et al.*, 2018; Outram, 2008), our senses further reinforce these analogical links. Indeed, perceptions of 'effort' and cutting 'ease' as we use stone tools inform us about which aspects of their morphology may be influencing their cutting performance. In the present context, this means that as replica stone tools are used for extended durations and cutting edges start to dull, there are changes to the relative performance characteristics (*c.f.*, Schiffer & Skibo, 1997) that become perceptible to tool users (*e.g.*, increased working forces).

Together, this has contributed to the widely held understanding that edge sharpness would have been important to stone tool users in Palaeolithic, ethnographic, and historical contexts. Such is its prominence, the requirement to maintain a sharp working edge is the functional selective pressure underpinning important theoretical frameworks emphasising edge 'resharpening' and/or 'rejuvenation' (*e.g.*, Kuhn, 1990; McPherron, 1999; Iovita, 2010; Eren *et al.*, 2013; Morales & Verges, 2014; Buchanan *et al.*, 2015; Schimelmitz *et al.*, 2017; Maloney, 2019), or explaining the heat treatment of stone tool raw materials (Domanski & Webb, 2007; Key *et al.*, 2021; Rick & Chappell, 1983). Ethnographic and experimental accounts have even detailed how much 'use' is required prior to edges becoming blunt enough to require resharpening. Weedman's (2006) account of Gamo hide workers in Ethiopia, for example, details hafted stone scrapers used during hide preparation to require resharpening after an average of 281 'scrapes'. Notably, the impact of sharpness on tool performance can also include ergonomic interactions that require edges to be dulled to improve safety and 'ease' of handling. Usually this takes the form of 'backing' or intentional blunting at the point of interaction between the hand and the gripped portion of the tool (Delpiano *et al.*, 2019; Parush *et al.*, 2015; Tringham *et al.*, 1974). There are even indications that the earliest stone toolmaker hominins would have been aware of the benefits of using sharper and more durable stone edges (Braun *et al.*, 2008; Key *et al.*, 2020). Even Kanzi, the bonobo (*Pan paniscus*) trained to flake and use stone tools, was observed testing the relative sharpness of flake edges using his tongue (Schick *et al.*, 1999; Toth *et al.*, 1993).

Despite the likely importance of edge sharpness to past populations, direct investigation of this attribute on lithic tools is surprisingly sparse. Multiple experiments have examined stone tool performance over time (*e.g.*, Jones, 1980; Machin *et al.*, 2007; Collins, 2008; Toth & Schick, 2009; Clarkson *et al.*, 2015; Gummesson *et al.*, 2017; Merritt & Peters, 2019), from which indirect measures of sharpness, such as volumes of cut/scraped material, have been recorded to change in line with tool-use duration. However, these measures are only proxies. As defined in mechanical engineering research, which has directly investigated the attribute of 'edge sharpness' for decades, sharpness is most often conceptualised through either mechanical or geometric definitions (Atkins, 2009; Reilly *et al.*, 2004). Geometric definitions focus on the curvature and radius of an edge's apex (Crofts *et al.*, 2019; Gao *et al.*, 2009; Rahman *et al.*, 2018; Schuldt *et al.*, 2013). This does not include the angle observed between the two intersecting faces of the edge, with wedge angle ('edge angle' in lithic studies) being demonstrably independent of other sharpness metrics (Schuldt *et al.*, 2016). Mechanical definitions consider the 'ease' with which cuts are made (Atkins, 2009), and most often rely on recording the cutting forces required to initiate a fracture (cut) in a worked material (Chu *et al.*, 2019; Marsot *et al.*, 2007; McCarthy *et al.*, 2007, 2010; Savescu *et al.*, 2018; Schuldt *et al.*, 2016). So, while there is not a definitive single definition for edge sharpness, geometric (2D and 3D optical) and mechanical (experimental) procedures are routinely applied to record this attribute on metal cutting tools.

Engineering-focused studies have recently motivated the examination of lithic edge sharpness through records of force and energy (work) during machine-controlled cutting tasks (Key, 2016; Torchy, 2015). This includes Key *et al.* (2018), who demonstrated sharpness reduces quickly during the earliest stages of a stone tool's use, helping to explain expedient tool use behaviours and requirements for resharpening-related edge modification. Bebber *et al.* (2019) took the technique further, comparing copper and stone cutting edges in terms of their durability and sharpness. Their results demonstrated copper to be more durable than chert, but that the stone was initially sharper; helping to explain why North American hunter-gatherer populations abandoned copper tools in favour of stone after 3,000 BP (Bebber *et al.*, 2019). Other studies have since applied the techniques of Key *et al.* (2018) to mechanically record edge sharpness in other archaeological contexts.

At a similar time, the first studies of tip curvature at a micro-scale were being performed on lithic materials. Stemp *et al.* (2019) applied imaging confocal microscopy, laser scanning confocal microscopy, and focus variation microscopy when mathematically documenting edge cross-section profiles and curvature using the hybrid Heron's formula on stone flakes made from basalt, chert, obsidian, and quartz. Their results demonstrated focus variation to reliably document the edges of these stone types. Macdonald *et al.* (2020) later used focus variation microscopy on replica chert microliths used to harvest wheat, measuring edge curvature over multiple scales and identifying that maximum edge curvature increases as the duration of a tool's use increases. More recently, microCT scans of quartzite flakes from Olduvai Gorge (Tanzania) were used to record the complex edge geometry of this notoriously irregular crystalline raw material (Macdonald *et al.*, 2022). This included the first formal analysis of lithic 're-entrant' features, where the complex surface structure of quartzite often leads to overhang features invisible to optical 3D scanning techniques. Moreover, Macdonald *et al.* (2022) applied a revised edge curvature algorithm, where equally spaced points along a scanned edge profile are used to fit a triangle from which curvature is calculated.

These studies are the first to integrate a mechanical understanding of edge sharpness into archaeological literature. One aspect that remains unknown with regard to lithic edges, however, is the strength of the relationship between geometric and mechanical definitions of sharpness. Indeed, although the substantial explanatory power of techniques developed within engineering research is well-known in lithic archaeology (Cotterell & Kamminga, 1990; Key, 2016; Marreiros *et al.*, 2020; Stemp *et al.*, 2016), there are still substantial gaps between the two fields. Studies investigating industrially produced metal blades have, for example, demonstrated strong predictive relationships between measurements of tip radius and cutting forces (McCarthy *et al.*, 2010; Schuldt *et al.*, 2016). While this relationship has similarly been hypothesised for stone tools (Key, 2016; Torchy, 2015), it remains to be demonstrated that tip curvature and radius do impact the forces and energy required for lithic technologies to cut. Going further, Schuldt *et al.* (2013) compared geometric and mechanical measurements of sharpness and demonstrated force measurements to be more sensitive to edge deterioration (*i.e.*, blunting) relative to tip radius records. Again, this finding has not been investigated in lithic research, and we have little understanding of how the two sharpness measurement techniques compare. Here, we address this current deficiency in archaeological literature and investigate the relationship between mechanical and micro-geometric measurements of edge sharpness for three stone types commonly used to make tools; basalt, quartzite, and chert.

Methods

Raw Materials

Diverse stone materials were selected for this study to produce results relevant to varied archaeological contexts. Olduvai Gorge in Tanzania provides an excellent case study in this regard, as three distinct raw materials were routinely used by hominins to produce stone tools over ~ 1.8 million years. This includes basalt, which is widely available at the Olduvai basin and displays a fine-grained and homogenous structure. Basalt and other lava cobbles were collected by hominins from river streams flowing from the Ngorongoro Highlands into the Olduvai paleolake basin. Quartzite is also widely available at Olduvai and is characterised by displaying coarse-grained quartz crystal sizes. Blocks and fragments of quartzite were often collected from the Naibor Soit inselberg north and east of the Main Gorge. During the lower Pleistocene, chert was only available as a raw material at Olduvai for brief periods in Bed II, when it was formed in lake deposits (Hay, 1976). Although nodules are irregular in shape, the Olduvai chert is fine-grained and produces homogenous edges. Chert nodules were collected from local outcrops, particularly during Lower-Middle Bed II times (de la Torre & Mora, 2018; Stiles *et al*., 1974).

For this study, two nodules of each raw material (basalt, quartzite, and chert) were collected from Olduvai Gorge and flaked through hard hammer percussion. The intention of the knapper was to produce flakes with an edge suitable for cutting. From the ~ 60 flakes produced from each raw material, 30 of each material were selected on the basis of displaying straight, relatively acute, and homogenous edges that were suitable for cutting. A 10 mm segment of this edge, chosen for being straight, homogenous, and relatively acute, was marked and assigned as the portion subjected to the sharpness tests.

Mechanical Records of Sharpness

Following previous studies (Bebber *et al*., 2019; Key *et al*., 2018), mechanical records of sharpness were investigated via the force and energy (work) required for each of the marked edge portions to cut through a standardised material using a tensile testing machine (in this case a Instron 3345; Fig. 1). This follows mechanical definitions of sharpness insofar as it records the ability of an edge to initiate a cut at low force and material deformation, and with minimal energy expenditure (*i.e*., with greater ‘ease’) (Atkins, 2009; Schuldt *et al*., 2016). The following procedure was identical for all flakes across all raw materials. The Instron machine is capable of recording the force (N) and material deformation (mm) required for a stone edge to cut through a material in a vertical plane. It works by lowering a hydraulic arm at a predefined rate towards an object secured beneath it, before recording the forces exerted by the arm when resistance is met. Using these data, it is then possible to calculate the energy (work) required for a cut to be formed. ‘Energy’ and ‘work’ can be used interchangeably, and here are measured in joules (J), which equates to the work of one newton (N [*i.e*., force]) over one meter.

The sharpness data used here come directly from the study undertaken by Key *et al*. (2020), and thus the methods are identical to those previously published in all but one regard. The only difference is an alteration to the calculation of work (see below). Each stone flake was secured into a wooden block using polyurethane adhesive, with each block being secured into the upper grip of the Instron device during testing ($n = 30$ for each raw material). The wooden blocks were orientated such that

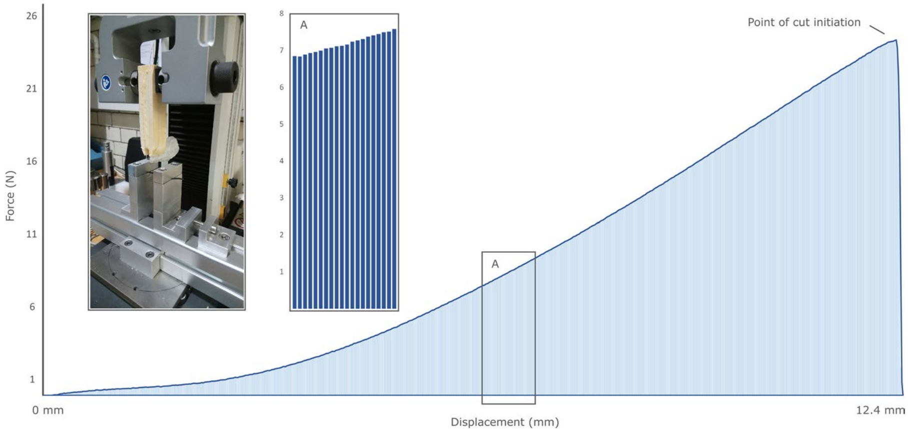


Fig. 1 A force–displacement curve for one of the chert flakes alongside the experimental setup used to record mechanical sharpness data. The area in light blue represents the energy required for a cut to form. Box A highlights the ‘rectangular areas’ used to calculate work. Note that although there are gaps between each rectangle in box A for demonstration purposes, this is not the case during work calculations

the 10 mm segment of edge assigned for testing was horizontal and each face of the flake was symmetrical relative to vertical. The material cut was a 2 mm thick piece of polyvinyl chloride (PVC) tubing, which was suspended directly beneath the flake’s edge using a custom-built steel frame. The tubing was manually fixed such that it was fully extended but not stretched. As such, some minor variation in tension can be expected. This experimental set-up allowed the upper grip of the Instron to be lowered towards the PVC. Before each cutting test started, the flake’s edge was aligned with the surface of the PVC and the Instron device was ‘zeroed’. From that point, when the flake was moved downwards it loaded the PVC tubing using the pre-assigned segment of edge.

Flakes were lowered into the PVC at a rate of 20 mm/min. This continued until enough stress was created in the tubing by the flake’s edge for it to fracture (*i.e.*, cut). Force and material deformation (vertical extension) data were recorded throughout at a rate of 20 Hz. The lower the force (N) and energy (J) required for the PVC tubing to be cut, the sharper the edge is demonstrated to be. Force (N) and material deformation (mm) at the point of cut initiation were recorded for all flakes. Work (J) was calculated as the area under each test’s force–displacement curve; although a slightly modified technique relative to Key *et al.* (2020) was used (note that the original raw data from the original study was used in this revised method). Work was calculated by visualising each curve as a series of rectangles defined by the displacement recorded between each data point on the *x*-axis (usually at a rate of 0.01 to 0.03 mm per second) and force measurements on the *y*-axis (Fig. 1). By identifying the area of these rectangles it becomes possible to combine them and calculate the area under the curve (with a small margin of error).

In the original study, sharpness data were collected from 15 flakes only once (*i.e.*, in their ‘fresh’ condition), while the other 15 were tested a further five times. Each additional test for these 15 flakes was after they had been used to perform a single cut across an oak branch so that by sharpness test 6 flakes had cut across the branch five times. In the original experiment, this was conducted to investigate the relative durability of the three raw materials (Key *et al*., 2020). A random selection of 10 flakes from each raw material was selected from these two groups for the micro-geometric analyses (*i.e.*, $n = 10$ in the micro-geometric analyses, with these ten flakes being selected randomly from the original 30 in the mechanical tests). This meant that some flakes in the micro-geometric analysis had cut through the PVC tube once, while others have been blunted by cutting a wooden branch five times in addition to cutting through the PVC tube six times. This was undertaken to ensure diversity in the edge profiles examined. We only present force (N) and work (J) data from these ten flakes for each raw material in this study. Thus, the mechanical sharpness data presented here reflect both the 'fresh' and 'five times worn' flake groups and any raw material differences cannot be directly compared to those presented in the original study (Key *et al*., 2020).

Micro-Geometric Records of Sharpness

Ten flakes from each raw material (basalt, quartzite, chert) were selected to record tip curvature (*i.e*., geometric sharpness). Sharpness analyses were performed after the flakes were used in the cutting experiments described above, and thus they do not reflect each raw material in a 'fresh' state. Although those used to cut the PVC only once will display minimal to negligible wear. Irrespective, we are able to compare the micro-geometry of each flake's edge directly after it had the last force and work data recorded (after testing in 2019, all flakes were securely stored and have not been used or damaged).

Following Macdonald *et al*. (2022), first we performed microCT scanning of each edge to acquire its 3D geometry (Fig. 2). The main motivation to use X-ray computed tomography here was the fact that other metrological techniques (like optical microscopy) are unable to capture complex surfaces with re-entrant features, steep edges, or high tip curvature (small tip radius). Another issue is that quartzite is extremely hard to measure with optical microscopy, without dying or coating, due to its transparency and crystalline structure. The microCT scanner used in these experiments was a Baker Hughes/General Electric v|tome|x s model. Parameters for the microCT scanner include a voltage of 150 kV, a current of 120 µA, a magnification of × 19.848, a voxel size of 10.077 µm, an exposure time of 400 ms, and a detector sensitivity of 1. The number of projections by the scanner was 2000. The software used for image acquisition and 3D model reconstruction was phoenix datosx. VolumeGraphics VGSTUDIO MAX 3.4 was used on the reconstructed 3D models and GOM Inspect was used for the extraction of the 2D profiles.

For the curvature calculations, 21 profiles were extracted from the demarcated 10 mm segment along the edge at 0.4–0.5 mm intervals. We calculated the curvature of each profile as a function of the location and scale following the technique proposed in Macdonald *et al*. (2022). In brief, our applied method employs Heron's formula to calculate the inverse of the radius as a function of the scale of observation

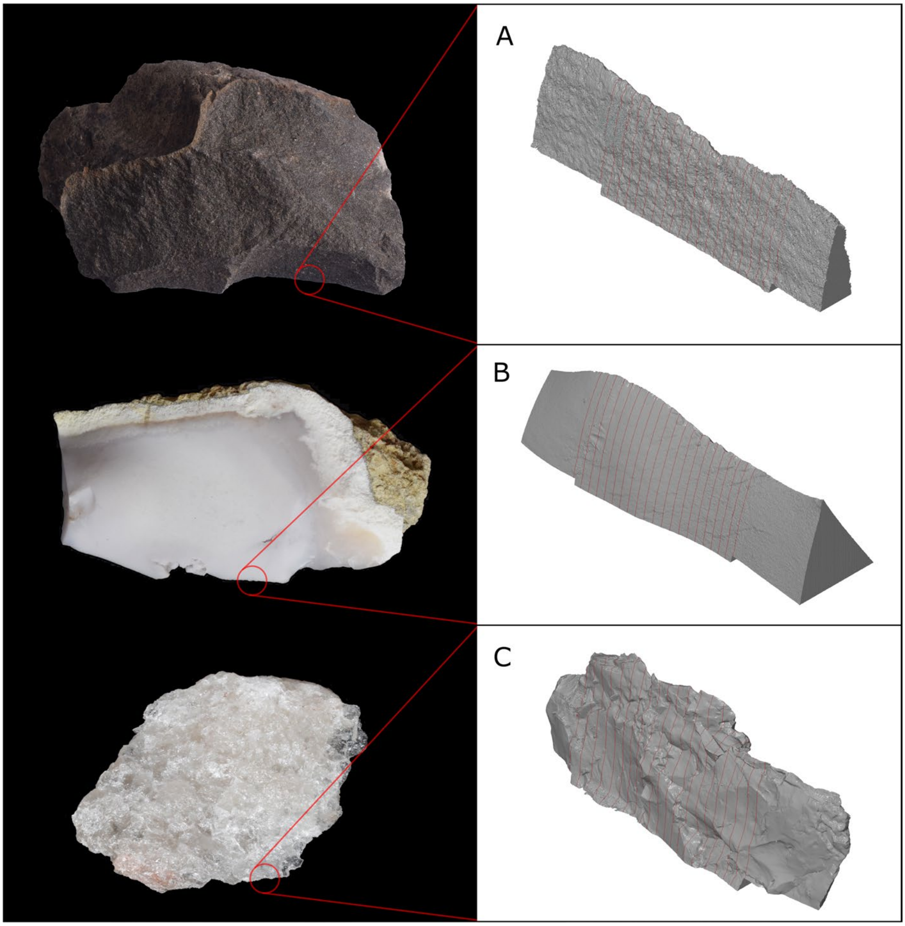


Fig. 2 Basalt (**A**), chert (**B**), and quartzite (**C**) Olduvai experimental flakes (left) and edges (right) as measured with microCT. Red lines on the microCT images indicate investigated profiles

on an edge profile. Three data points are always considered to determine the curvature at each location. Due to the nature of microCT measurement, their spacing is associated with the voxel size or side length of the grid, not with the lateral or vertical resolution as in optical or tactile profilometry. The algorithm steps along the profile and fits the triangle to three adjacent points. At a given scale, the area of the circumscribed virtual triangle is used to calculate the edge curvature of the profile using Heron's formula. At the finest scale, those three points are always three consecutive points observed on the edge profile (Fig. 3a, b). For k-times larger scales, every kth point is considered as a triangle vertex (see Fig. 3c, d).

In this study, scales ranging from 5 μm to 1 mm, with an interval of 5 μm were considered (Fig. 4). Additionally, we calculated all curvature values separately for edge profiles at 0.1 mm, 0.5 mm, 1 mm, and 2 mm away from the edge (tip) apex

$$k_\mathrm{h} = \frac{4A}{a+b+c}, \qquad A = \sqrt{s(s-a)(s-b)(s-c)}, \qquad s = \frac{a+b+c}{2}$$

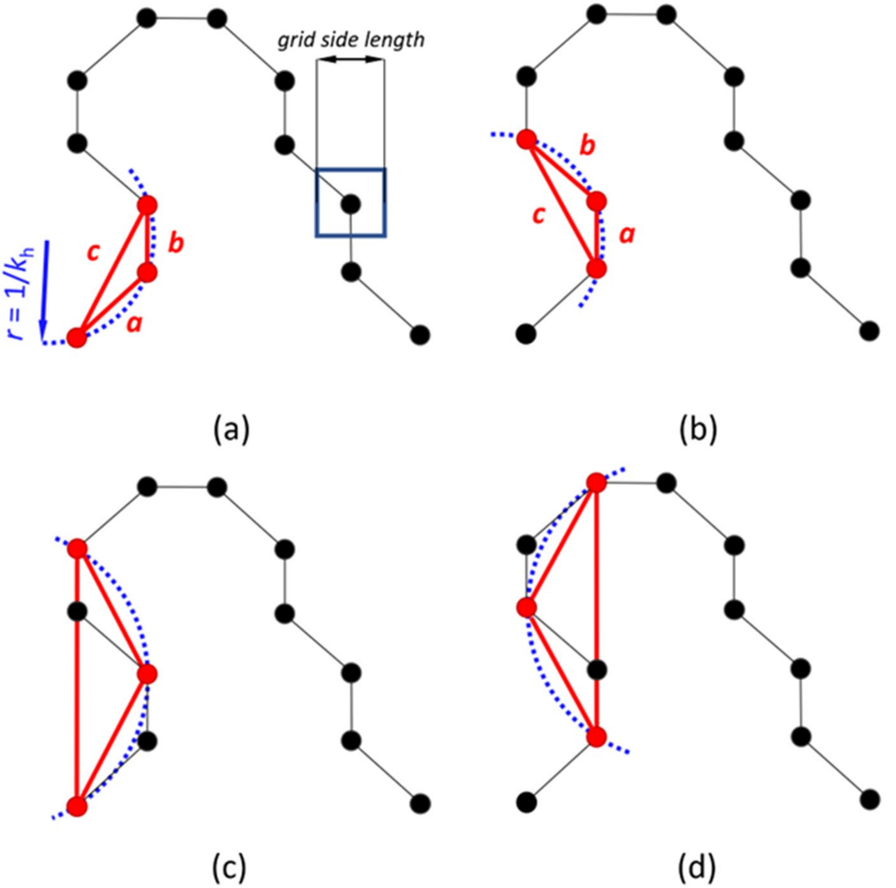


Fig. 3 Calculation of edge curvature: (**a**) first and (**b**) second iteration running at the finest scale equal to grid side length; (**c**) first and (**d**) second iteration running at scale equal to 2 × grid side length. Note that a, b, c are triangle side lengths, s is the semiperimeter, A is the area and r is radius of curvature k_h.

(Fig. 4). Average curvature of all twenty-one profiles was considered as a geometric measure of flake sharpness.

Statistical Methods

Our main objective in this study is to better understand the relationship between mechanical and micro-geometric definitions of sharpness in stone tool technologies. To this end, we examined the relationship between tip curvature (measured using data up to 1 mm from the edge's apex) and both force and work in all 30 flakes using

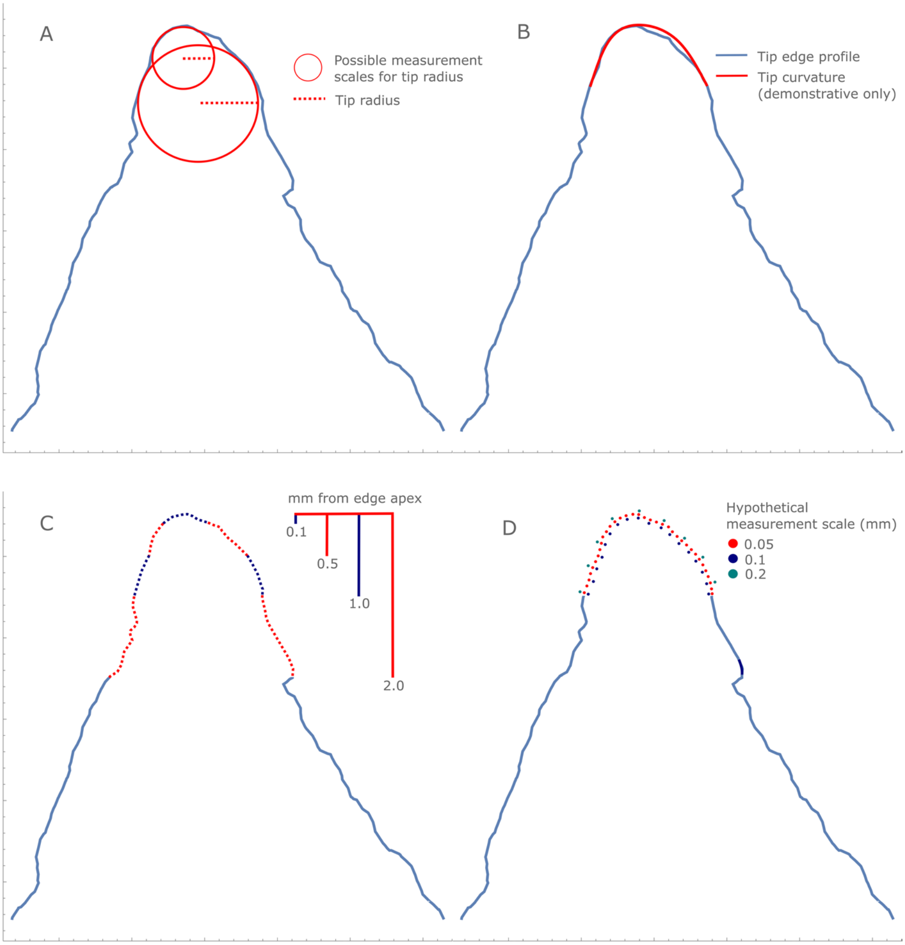


Fig. 4 The profile of a basalt edge used in the present analyses. **A** Depicts tip radius measurements at two different scales. Tip radius is the typical micro-geometric approach used to measure edge sharpness on metal tools. **B** Provides a demonstration of tip curvature relative to the true profile of the tool's edge (note, it is not an accurate depiction of how tip curvature was calculated [See Fig. 3]). **C** Illustrates the different distances away from the tip apex used to calculate tip curvature. **D** Demonstrates different measurement scales, and in turn frequencies of 'steps' used by the algorithm to calculate tip curvature (not to scale) (see also: Fig. 7 in Macdonald *et al*. [2022])

linear regression. We repeated these tests for the first 20 measurement scales used here (*i.e.,* 0.005 mm through to 0.1 mm). These tests allowed us to identify whether force and work records are significantly related to cutting-edge morphology at a micro-scale. Significant relationships were identified if $\alpha \leq 0.0025$ (following a Bonferonni correction). If significant relationships are returned, it confirms tip curvature to be an appropriate variable for quantifying sharpness in stone tools. That is, if tip curvature displays a strong positive and predictive relationship with cutting force and work, then lower curvature values will indicate 'the ability of a blade to initiate a cut at low force and deformation', with this being a widely observed definition of sharpness (Schuldt *et al.*, 2016: 13).

Following similar logic, we subsequently separated the flakes by their respective raw material groupings (*i.e.*, $n = 10$) and separately correlated edge curvature with force and work. This allowed us to investigate the strength of correlation between these variables in a scenario that is independent of differences between raw materials (for example, variable surface roughness between materials could alter friction between the worked substrate and cutting edge). Spearman's rank-order correlations were performed (as not all datasets were normally distributed) using curvature data at the three scales demonstrated to display the strongest relationship with force and work in the regression analyses ($\alpha = 0.05$).

As already explained, edge curvature calculations vary depending on how much of an edge, as measured from the edge apex, is included. That is, how much of the edge's surface area is included in the curvature calculation (Macdonald *et al.*, 2022). To understand which distance returns the strongest relationship with force and work, we re-ran the above regressions but used tip curvature records calculated using distances of 2 mm, 0.5 mm, and 0.1 mm from the edge's apex (Fig. 4). We performed these regressions using data recorded at the three scales of measurement that returned the strongest relationships in the first set of regressions (*i.e.*, those run using 1 mm data). Following the logic that sharpness records the ability of an edge to initiate a cut at low force and material deformation, and with minimal energy expenditure, these regressions will reveal which tip curvature distance is best able to characterise micro-geometric measures of 'sharpness' in lithic technologies.

Our second objective is to understand how micro-geometric measures of sharpness vary between the three investigated raw materials. In previous research, Key *et al.* (2020) demonstrated clear differences in mechanical sharpness between basalt, chert, and quartzite at Olduvai Gorge. In this study, we wanted to understand if these differences were similarly observed in the tip curvature data. As our sample contained both fresh and more heavily used edges, we investigated each use condition separately, meaning that we compared four fresh and three worn edges between all three raw materials. We did this at all edge distances used here (*i.e.*, at 2 mm, 1 mm, 0.5 mm, and 0.1 mm) and for the 0.010 mm, 0.020 mm, and 0.030 mm scales of measurement (Fig. 4). We then performed a Kruskal–Wallis test between all data returned for each raw material (*i.e.*, data from all edge distances and scales of measurement combined, with each raw material represented by 36 [worn] or 48 [fresh] data points), with separate tests run for the flakes in the 'fresh' and 'used' conditions. To identify where any significant differences between raw materials lay (if there were any), we ran post hoc Tukey's pairwise tests. All statistical tests were performed using PAST version 4.09.

Results

Descriptive data for the force and work records of each flake are presented in Table 1. These data reveal the same performance differences reported by Key *et al.* (2020). Basalt requires considerably greater force and energy to perform a cut, while

Table 1 Force (N) and work (J) measurements for each flake investigated here. Note that each raw material has a different number of 'fresh' and 'used' flakes

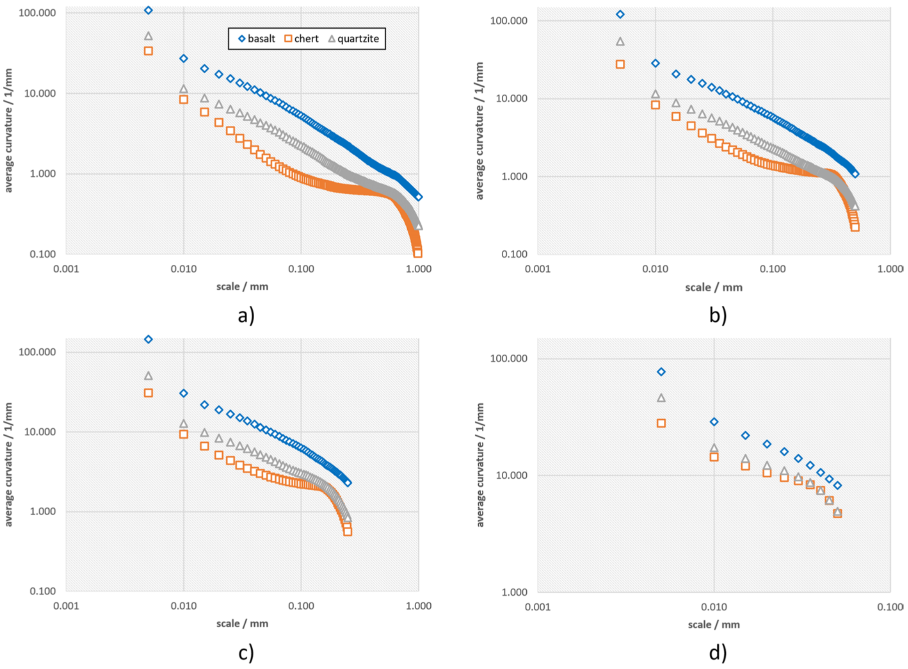
Basalt			Chert			Quartzite		
Flake	Force (N)	Work (J)	Flake	Force (N)	Work (J)	Flake	Force (N)	Work (J)
2	76.7	1.166	1	34.3	0.205	1	38.9	0.252
4	107.9	2.318	5	48.8	0.367	2	41.3	0.339
5	107.2	2.263	6	19.1	0.069	2b*	78.6	1.275
7	120.9	3.321	8	24.4	0.113	3	31.1	0.162
10	98.4	1.727	14	27.8	0.129	8	72.8	1.109
15	100.9	2.685	15	83.3	1.098	16	65.5	0.791
17	113.5	2.454	17	54.7	0.507	17	67.7	0.896
19	111.3	3.215	19	59.2	0.583	24	18.8	0.079
25	102.6	2.491	21	58.1	0.537	22	27.7	0.139
27	80.6	1.173	25	88.5	1.259	26	58.5	0.671
Mean	102.0	2.281	Mean	49.8	0.487	Mean	50.1	0.571

*Due to a mistake when numbering the flakes there were two '2' flakes in the original assemblage, with the second being labelled 2b.

more minor differences are present between chert and quartzite. There is also notable variation within each raw material, which is expected given we included both 'fresh' and 'used' conditions. Our comparison of tip curvature between each raw material returned results in line with the performance differences (Fig. 5; Supplementary Fig. 1). Indeed, significant differences were identified between raw materials in both Kruskal–Wallis tests (Table 2), with Tukey's pairwise tests revealing basalt to display significantly greater tip curvature values than both chert and quartzite in both the 'fresh' and 'used' flakes (Table 3). No significant difference in tip curvature was recorded between chert and quartzite in the 'fresh' condition, while a significant difference between these two raw materials was recorded in the 'used' flakes (Table 3).

To understand the relationship between mechanical and micro-geometric definitions of sharpness linear regressions were run between tip curvature (measured using edge surfaces up to 1 mm from the apex) and both force and work data for all 30 flakes. Results are consistent in all instances and significant relationships were identified in all regressions, with P-values ≤ 0.0004 (Fig. 6; Supplementary Table 1). Tip curvature explained roughly 6% more variation in the work data compared to the force data, with R^2 values ranging between 0.363 and 0.602 for the former and 0.374 and 0.528 for the latter (Supplementary Table 1). Excluding the 0.005 mm scale of measurement (when R^2 values equally 0.374 and 0.363), it is clear that finer measurement scales are better able to explain the cutting performance of stone tools (Fig. 6). Indeed, the 0.015 mm scale was able to explain 55% of the variation in force data, while the 0.010 scale explained 60% of the variation in work data (Fig. 7; Supplementary Fig. 2).

Relationships between tip curvature and force/work were also examined at an individual raw material level. This required tip curvature data (again, recorded



a) b) c) d)

Fig. 5 Evolution of average curvature of all three material groups as a function of scale, calculated for **a** 2 mm, **b** 1 mm, **c** 0.5 mm, and **d** 0.1 mm distances from the edge's apex. At all measurement scales basalt is demonstrated to be the least sharp raw material

Table 2 Kruskal–Wallis tests comparing tip curvature data between the three raw materials, with separate tests performed for four 'fresh' edged and three 'used' edges. For each flake, tip curvature was included for all edge distances used here (*i.e.*, at 2 mm, 1 mm, 0.5 mm, and 0.1 mm), with each providing data recorded at the 0.010 mm, 0.020 mm, and 0.030 mm scales of measurement. This meant that each flake was represented by 12 data points. Bold values indicate significant differences were identified between the raw materials

'Fresh' flakes		'Used' flakes	
H	*P*	*H*	*P*
63.6	**<.0001**	68.56	**<.0001**

Table 3 Post hoc Tukey's pairwise tests performed between tip curvature data for the three raw materials in the 'fresh' ($n=48$) and 'used' ($n=36$) edge conditions. Bold values indicate significant differences were identified between the raw materials

	'Fresh' flakes		'Used' flakes	
	Chert	Quartzite	Chert	Quartzite
Basalt	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Chert		.8725		**<.0001**

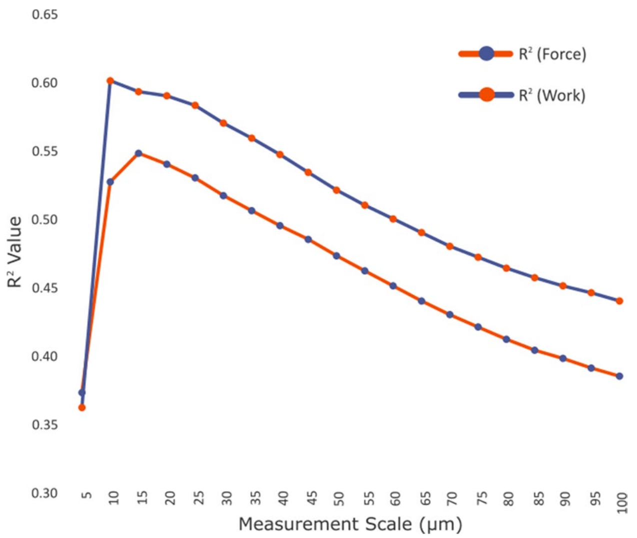


Fig. 6 R^2 values from all linear regression analyses between tip curvature measurements (recorded at 1 mm from the edge's apex) and both force and work data. It is clear that the smallest tip curvature measurement scales demonstrate the strongest predictive relationships with cutting performance

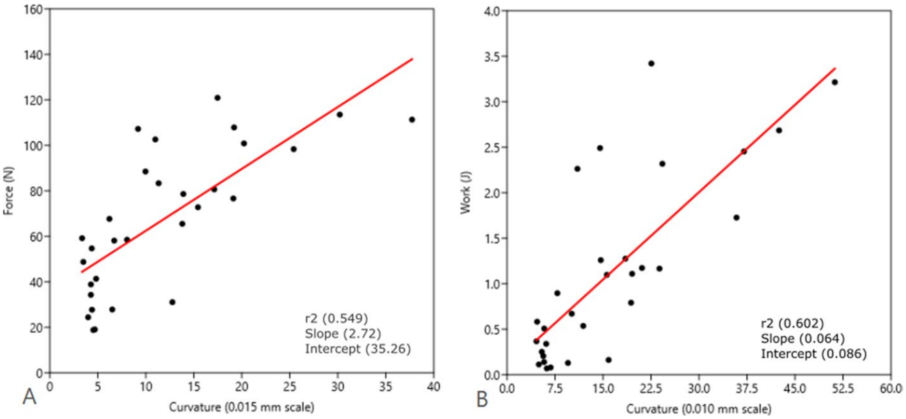


Fig. 7 Linear regression between edge curvature at the 0.015 mm scale and force (**A**) and edge curvature at the 0.010 mm scale and work (**B**). Both are recorded up to 1 mm from the edge apex. These represent the strongest relationships between edge curvature and cutting performance characteristics identified in these analyses. See Supplementary Fig. 2 for the respective residuals

up to 1 mm from the tip apex) being correlated against force and work data using Spearman's rank-order correlations ($n = 10$). Table 4 reveals these correlations to be positive in all instances (Supplementary Fig. 3). There are, however, differences between the strength of correlation recorded with each raw material. Significant correlations were only identified in the quartzite flakes ($P \leq 0.0376$;

Table 4 Spearman's rank-order correlations between tip curvature measurements and the force (N) and work (J) data for each flake. In this analysis, all raw material types are investigated separately such that $n = 10$ in each instance. Bold values indicate significant relationships with tip curvature

Scale (mm)	Force		Scale (mm)	Work	
	P	r_s		P	r_s
Basalt					
0.015	.5109	0.236	0.010	.3466	0.333
0.020	.5639	0.208	0.015	.4888	0.248
0.025	.8548	0.067	0.020	.7770	0.103
Quartzite					
0.015	**.0133**	0.745	0.010	**.0376**	0.661
0.020	**.0376**	0.661	0.015	**.0133**	0.745
0.025	**.0376**	0.661	0.020	**.0376**	0.661
Chert					
0.015	.2931	0.370	0.010	.2443	0.406
0.020	.2931	0.370	0.015	.2931	0.370
0.025	.2443	0.406	0.020	.2931	0.370

$r_s \geq 0.661$). Correlations for the chert and basalt flakes were not significant and were notably weaker (Table 4).

To investigate how tip curvature's relationship with cutting force and work varies depending on the distance from the tip's apex used to record curvature, regressions were rerun using data recorded at distances of 0.1 mm, 0.5 mm, and 2 mm from an edge's apex. Consistent with the first regressions, all analyses identified strong significant relationships (Table 5). Tip curvature records created using data from the first 0.5 mm of an edge display the strongest relationships with force and work (Table 5). Indeed, up to 59% of force variation and 63% of work variation could be explained. Tip curvature measurements incorporating 0.1 mm or 2 mm of the edge return notably weaker relationships relative to those incorporating either 0.5 mm or 1 mm (Table 5).

Discussion

The sharpness of an edge can be defined in both mechanical and micro-geometric terms (Atkins, 2009; Key, 2016; Reilly *et al.*, 2004). Previous research has demonstrated how stone tool edge sharpness can be quantified using both approaches (Bebber *et al.*, 2019; Key *et al.*, 2018, 2020; Macdonald *et al.*, 2020, 2022; Stemp *et al.*, 2019). Here, we sought to understand how these two sharpness definitions relate, and whether tip curvature can be confirmed as an appropriate metric to record edge sharpness in stone tool technologies. Specifically, we investigated whether the force (N) and work (J) required for a stone edge to cut ('mechanical sharpness') display a significant and dependent relationship with the curvature observed on the apex of the edge's tip ('micro-geometric sharpness').

Linear regression analyses between force/work and tip curvature returned significant relationships in all instances (Fig. 6; Table 5; Supplementary Table 1).

Table 5 Results of linear regression analyses run between tip curvature measurements and both the force (N) and work (J) data for each flake. Here, tip curvature data recorded at multiple distances from the edge's apex were used. In this analysis, all raw material types have been combined such that $n = 30$. Bold values indicate significant relationships with tip curvature

Scale (mm)	Force		Scale (mm)	Work	
	P	R^2		P	R^2
0.1 mm					
0.015	**.0023**	0.287	0.010	**.0001**	0.409
0.020	**.0068**	0.233	0.015	**.0007**	0.341
0.025	**.0154**	0.192	0.020	**.0025**	0.282
0.5 mm					
0.015	**< .0001**	0.590	0.010	**<.0001**	0.620
0.020	**<.0001**	0.556	0.015	**<.0001**	0.632
0.025	**<.0001**	0.538	0.020	**<.0001**	0.602
1 mm					
0.015	**<.0001**	0.549	0.010	**<.0001**	0.602
0.020	**<.0001**	0.541	0.015	**<.0001**	0.594
0.025	**<.0001**	0.531	0.020	**<.0001**	0.591
2 mm					
0.015	**<.0001**	0.511	0.010	**<.0001**	0.551
0.020	**<.0001**	0.503	0.015	**<.0001**	0.554
0.025	**<.0001**	0.489	0.020	**<.0001**	0.557

For many scales of measurement, and measurement distances, these relationships were strong. Our results do, therefore, suggest that these variables display dependent relationships whereby the micro-geometric attribute of tip curvature significantly impacts the force and work required for a stone tool to perform a cut. In turn, we suggest that both mechanical and micro-geometric definitions of sharpness are appropriate to describe the sharpness of a stone tool's edge. The logic being that tip curvature data can be used to predict the forces and energy needed to perform a cut (*c.f.* Atkins, 2009; Schuldt *et al.*, 2016). The strength of the relationships supports such a conclusion; up to 63% of the observed variation in work data, and 59% of the variation in force data, can be explained by the tip curvature recorded on each flake's edge (Fig. 7). This is consistent with previous investigations into the impact of tip radius on cutting forces (Kim *et al.*, 1999; McCarthy *et al.*, 2010; Reilly *et al.*, 2004; Schuldt *et al.*, 2016). Whether mechanical sharpness records are more sensitive to the detection of lithic edge attrition (*i.e.*, blunting) relative to micro-geometric records, as has been demonstrated with metal tools (Schuldt *et al.*, 2013, 2016), remains to be seen.

These R^2 values are exceptional within Palaeolithic literature. For example, tool length has been demonstrated to only explain 23% of performance variation in flake tools (Key & Lycett, 2014; also see Merritt & Peters, 2019), weight explains 25% of cutting efficiency variation in 'small' handaxes (Key & Lycett, 2017b), and frontal symmetry explains up to 12% of performance variation in late-Acheulean handaxes (Machin *et al.*, 2007). Multiple regression examining the impact of flake length, width, and thickness can demonstrate improved explanatory power, on one occasion explaining 49% of cutting stroke variation used during the butchery of rabbits

(Jobson, 1986). Although the greater external validity of all these experiments, relative to Key *et al.* (2020), may reduce the strength of their observed relationships (Eren *et al.*, 2016; Lin *et al.*, 2018; Lycett & Eren, 2013). To our knowledge, only one other cause and effect relationship between a single morphological attribute and stone tool performance has been observed with this level of explanatory power. Mika *et al.* (2020) demonstrated that the cross-sectional area of stone projectiles can explain up to 69% of their penetration depth (see also: Sitton *et al.* [2020]).

Significant correlations between stone tool form attributes and performance have been recorded elsewhere (*e.g.*, Walker, 1978; Sisk & Shea, 2009; Eren *et al.*, 2020; Khaksar *et al.*, 2022). Other studies have investigated lithic form-function relationships through statistical means that do not provide information about linearity or strength of association (for example, by using ANOVA or Mann–Whitney *U* tests) (*e.g.*, Prasciunas, 2007; Collins, 2008; Merritt, 2012; Clarkson *et al.*, 2015; Bilbao *et al.*, 2019; Biermann Gürbüz & Lycett, 2021; Mika *et al.*, 2021). It is difficult to directly compare these form-function relationships with our present data. The angle observed on a stone tool's working edge comes close to displaying R^2 values similar to those returned here. A controlled cutting experiment similar to the one used by Key *et al.* (2020) indicated 'edge angle' to explain 45%, 38%, and 38% of the material deformation, force, and work variation (respectively) experienced by flake stone tools (Key *et al.*, 2018). Our results, therefore, demonstrate that—as far as we currently know—the most important morphological attribute in the determination of a hand-held stone tool's cutting performance is tip curvature.

These data underline how important the attribute of edge sharpness would have been to past populations, reinforcing how energy, time, and risk considerations likely drove raw material selection and edge resharpening behaviours (Bleed & Bleed, 1987; Kuhn, 2020; Schiffer & Skibo, 1987, 1997). It is, however, important to qualify the importance of tip curvature. The tool-use conditions (worked material, anatomy, cognition, tool-design) experienced by past individuals would have been incredibly diverse, and different morphological attributes would have a variable influence on tool performance dependent on the specific tool-use context. For example, despite the high experimental control, 37% and 41% of work and force variation (respectively) remained unexplained in the strongest relationships, potentially being linked to minor differences in the angle of application for each flake, the tautness of the PVC, and each flake's edge angle or surface roughness. In an alternative scenario, the influence of such factors, or others, could be relatively greater.

During the mechanical testing (Key *et al.*, 2020), edge angle data were collected from the edge portions where we recorded tip curvature. Linear regression of these two variables did not identify a significant relationship when using the 0.010 mm, 0.015 mm, and 0.020 mm measurement scales and all edge apex distances ($n = 30$; $P = \geq 0.5676$; $R^2 = \leq 0.012$). Edge sharpness (tip curvature) and edge angle, therefore, appear to be independent attributes that do not covary in stone tools. This further demonstrates that the influence of tip curvature on cutting performance is independent of any impact that edge angle has on performance. This appears distinct to the relationship observed in metal blades, where an increased tip radius does correlate with more obtuse edge (wedge) angles, and the two are co-dependent in determining cutting forces (Schuldt *et al.*, 2016). Potentially, this is due to our study investigating tip curvature, which is distinct to tip radius. Alternatively, it could be linked to the granular structure of lithic edges, and/or differences in this relationship may exist between stone raw materials. More work is required in the future to tease out these distinctions.

We used Spearman's rank-order correlations to investigate the relationship between tip curvature and force/work data in a scenario free from raw material variation. All correlations were positive, aligning with the cause-effect relationship identified by the regression models (Table 4). However, the only raw material to return significant correlations between tip curvature and cutting force/work was quartzite. We interpret the lack of significance in the basalt and chert conditions to potentially be linked to the small ($n = 10$) sample sizes in each. This inference is supported by the presence of positive relationships in all correlations, including those that were not significant (Supplementary Fig. 3). The Spearman's rank-order correlation is also a relatively conservative statistical technique. Equally, the substantially greater mean tip curvature observed in the basalt flakes could be contributing to the lack of significance in this raw material, as these 'blunter' edges would not display the extreme end of the 'sharpness' spectrum (and thus, lowest force and work values). At the other end of the spectrum, quartzite may display other micro-geometric attributes which interact with curvature in a way that is not observed in basalt and chert. Nonetheless, the micro-geometric attribute of edge curvature is expressed and measured in the same way on each raw material—even if some have greater or lesser curvature—and our investigation of how this attribute interacts with a worked material, and in turn, relates to cutting force and work, is appropriate when combined across multiple raw materials. Further work should investigate the impact of raw material variation on the relationship between tip curvature and cutting performance in the future.

Our micro-geometric sharpness (tip curvature) data highlighted differences between the raw materials consistent with the mechanical records of sharpness recorded by Key *et al.* (2020). Basalt was significantly blunter than chert and quartzite, but more limited differences were identified between chert and quartzite (Table 3). Notably, no significant difference in tip curvature was identified between the 'fresh' chert and quartzite edges, but when more heavily used edges from these two raw materials were compared, chert displayed lower curvature values (and was thus sharper). As previously outlined (Key *et al.*, 2020), this is likely linked to the greater durability of chert.

Finally, we investigated how measurement scale and measurement distance (away from the tip's apex) impacted the strength of relationship observed between tip curvature and cutting force/work. Table 5 and Supplementary Table 1 demonstrate that the strongest relationships with force and work were observed when curvature measurement scales of 0.010 mm and 0.015 mm were used. Relationship strength became sequentially weaker as measurement scales increased (Fig. 6). Essentially, the finer the measurement scale used, the stronger the relationship observed between tip curvature and force/work and the more accurate the record of sharpness. This is, however, up to a limit. The lowest scale of measurement used here, 0.005 mm, returned a comparatively weak relationship compared to 0.010 mm (Supplementary Table 1). Research that uses tip curvature data to record edge sharpness should, therefore, preferentially use measurement scales of 0.010 to 0.015 mm, and avoid those that are markedly lower.

The amount of edge incorporated into the measurement of tip curvature (*i.e.*, the distance away from the tip apex) also had a demonstrable impact on the strength of relationship observed between tip curvature and force/work. Indeed, the strongest relationships were observed with force and work when 0.5 mm of edge was investigated (Table 5). 1 mm of edge returned relationships that were only slightly weaker, while use of 0.1 mm and 2 mm of edge returned much weaker results. Thus, microgeometric measurements of edge sharpness should focus on the top 0.5 mm of a cutting edge. This accords with mechanical engineering research, where 'tip radius' is often used to record edge sharpness (McCarthy *et al*., 2010; Reilly *et al*., 2004; Schuldt *et al*., 2016). This is not surprising as the tip curvature method used here effectively records radii curvature across the exposed upper portion of an edge's tip radius (Fig. 4). Further, it suggests that as greater distances are incorporated into the calculation of tip curvature, portions of the flake's surface that do not contribute as strongly to cutting performance are included. Thus, it is the geometry of the first ~ 0.5 mm of a stone tool's cutting edge that has the greatest role in initiating a cut in a worked material, likely due to its role in the creation of stress enough to initiate a fracture (Atkins, 2009; McCarthy *et al*., 2010).

We predict that the relationships presented here are unlikely to change substantially when other materials are cut (*e.g*., animal tissues, plant fibres). Even if an alternative worked material allows for a greater depth of cut, meaning that it comes into contact with greater portions of the edge's surface area, the attribute of edge curvature is only observed at the edge's apex, and in almost all worked-material circumstances the entirety of the tip's apex touches the worked material; no matter how shallow the cut, or thin the cut substance. In turn, other variables, such as edge angle, are more relevant to discussions of how depth of cut and worked material may influence tool performance (Key, 2016). Although if another variable starts to exert greater impact on tool performance, this will understandably affect the strength of relationship observed for edge curvature.

Conclusion

We have demonstrated that the curvature observed on an edge's tip can be used as a method to quantify sharpness in stone tools. Indeed, strong predictive relationships have been observed between tip curvature and the cutting force and work required to create a cut. The lower the tip curvature observed on a cutting edge, the easier it will be to initiate and perform a cut. Through the comparison of tip curvature data from basalt, chert, and quartzite flakes from Olduvai Gorge, we have also demonstrated that tip curvature values can distinguish the comparative sharpness of different raw materials. It is, however, important to consider the scale of measurement and edge distance used when quantifying tip curvature. Our data reveal that (up to a limit) finer measurement scales and edge-apex distances of 0.5 mm were better able to predict a stone tool's cutting force and work requirements. We have also shown that tip curvature is one of the most important attributes in the determination of a stone tool’s functional performance. These findings reinforce the importance of behavioural choices linked to the production or maintenance of sharp edges on stone tools (*e.g.*, raw material selection, edge resharpening, avoiding bone contact during butchery tasks), and indicate tip curvature measurements to appropriately describe edge sharpness on lithic implements.

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Declarations

Competing Interests The authors declare no competing interests.

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