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Early stage blunting causes rapid reductions in stone tool performance

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Abstract

Palaeolithic stone technologies have never been investigated in terms of how sharpness influences their ability to cut. In turn, there is little understanding of how quickly stone cutting edges blunt, how past populations responded to any consequent changes in performance, or how these factors influenced the Palaeolithic archaeological record. Presented here is experimental data quantitatively detailing how variation in edge sharpness influences stone tool cutting performance. Significant increases in force (N) and material displacement (mm) requirements occur rapidly within early stages of blunting, with a single abrasive cutting stroke causing, on average, a 38% increase in the force needed to initiate a cut. In energetic terms, this equates to a 70% increase in work (J). Subsequent to early stages of blunting we identify a substantial drop in the impact of additional edge abrasion. We also demonstrate how edge (included) angle significantly influences cutting force and energy requirements and how it co-varies with sharpness. Amongst other conclusions, we suggest that rapid reductions in performance due to blunting may account for the abundance of lithic artefacts at some archaeological sites, the speed that resharpening behaviours altered tool forms, and the lack of microscopic wear traces on many lithic implements.

Keywords: cutting, fracture mechanics, Palaeolithic, sharpness, lithic artefact, edge angle

1. Introduction

The geometry of a stone tool's edge affects its performance during cutting tasks. Numerous experiments attest to this by demonstrating that variable edge angles, edge lengths, the extent and presence of scalloping/serration, and edge curvature all influence the efficiency of cutting tasks (Walker, 1978; Jones, 1994; Collins, 2008; Clarkson et al., 2015; Key and Lycett, 2015; Key et al. 2016). While the relative influence of each trait is dependent upon the tool's context of use, within Palaeolithic contexts it is reasonable to conclude that each was at times likely to have had some influence on cutting performance and, consequently, may have been subject to functional selective pressures controlling for tool form variation (Torrence, 1989; Schiffer and Skibo, 1997; Key and Lycett, 2017). Quite logically, then, there has been a long history of interpreting the form of cutting edges on Palaeolithic artefacts in functional terms (Key and Lycett, 2017).

One attribute of Palaeolithic stone-tool cutting edges that has received more limited attention is sharpness. This is despite engineering and ergonomic research having repeatedly highlighted its impact on cutting processes. A particularly relevant example to studies of Palaeolithic stone tools is McGorry et al. (2003) who demonstrated that the sharpness of metal knives significantly influences the grip forces, cutting moments, and tool-use times required during the butchery of medium and large mammals. However, while lithic-related studies frequently and correctly acknowledge the importance of an edge's sharpness to its cutting performance, it is often the case that 'sharpness' is used interchangeably with the distinct morphological trait of edge angle, or no specific definition or measurement of sharpness is provided. In geometric terms, sharpness is often defined by the radius of the very tip (apex) of an edge (see: Reilly et al. 2004; Key, 2016). While tip radius and edge angle are highly correlated morphological traits, at least within modern metallic blades (Schuldt et al., 2013), the distinction between the two is important as each has distinct influences on the creation of cutting stress.

Sharpness is not, however, solely defined by an edge's tip radius but also relates to the force applied during cutting. As Schuldt et al. (2016: 13) state, "sharpness also depends on properties of the cutting substrate, and refers to the ability of a blade to initiate a cut at low force and deformation". A straightforward example to highlight this point is a paper cut. After all, the edge of a piece of paper is not sharp and able to initiate a cut until there is sufficient force in the 'slice' motion of the paper across your skin. Although widely established within engineering research (Atkins, 2009), this aspect of sharpness has rarely been discussed within Palaeolithic literature (although see: Ackerly, 1978; Key, 2016). Previous mechanical research has measured sharpness in different quantitative and qualitative terms for both geometric and force properties of edges (Maeda et al., 1989; Arcona and Dow, 1996; Komanduri et al., 1998; Szabo et al. 2001; McGorry et al., 2003; McCarthy et al., 2007; Wyen et al., 2012; Schuldt et al., 2013). Reilly et al. (2004) and Schuldt et al. (2013) discuss the co-dependence of a cutting edge's geometric and force properties in the determination of edge sharpness particularly well.

The latter demonstrates that force measurements may be more sensitive than measurements of edge radius in the calculation of sharpness (Schuldt et al. 2013), although as highlighted by McCarthy et al (2010), tip radius is significantly more effective in measuring sharpness than edge angle.

Edge angle (often referred to as the ‘included angle’ or ‘wedge angle’ in mechanical literature) impacts cutting performance, and has been demonstrated to do so to a significant extent within research using modern metal tools (Atkins, 2009; McCarthy et al., 2010). Although in certain contexts some studies with modern tools have returned more limited relationships. McGorry et al. (2005), for example, demonstrated that boning knives displaying edge angles of 20°, 30° and 45° did not display significant differences in terms of grip forces, cutting moments and cutting times during butchery processes (lamb). This is consistent with Key and Lycett (2015) who identified edge angle to be a variably influential factor on flake tool cutting efficiency (and was dependent, in part, on a stone tool’s size). In sum, although each trait influences the local stress fields of a worked material in different ways, both tip radius and edge angle have the potential to significantly impact the forces required to initiate cuts in materials with metal tools (Hirst and Howse, 1969; Arcona and Dow, 1996; Komanduri et al., 1998; Kim et al., 1999; Szabo et al., 2001; Atkins, 2009; Schuldt et al 2013), with greater measures in each increasing the forces required.

However, it is not known whether or not these basic mechanical principles that underlie the design of many modern cutting technologies are similarly demonstrated in Palaeolithic stone tool cutting technologies. Specifically, how are the forces required to use stone tools influenced by the sharpness (and therefore also bluntness) of their cutting edges? Further, although there has been a number of studies examining the influence of edge angle variation on stone tool cutting performance (Jobson, 1986; Key and Lycett 2015; Key et al. 2016; Merritt, 2016), the relative influence that this morphological trait has on the forces required to cut materials with stone tools has never been examined in conditions absent of human actors (although also see Collins’ [2008] investigation of scraping cutting actions that, although did not record force, used a mechanised rig). Furthermore, it is not known how any influence that edge angle variation may have varies alongside differences in edge sharpness.

In order to address these gaps in our understanding of the functional capabilities of Palaeolithic technologies, here we investigate the influence of edge sharpness (and, in turn, blunting) on a stone tool’s ability to cut flexible, extensible material (i.e. ‘soft-solids’, such as those seen in many biological tissues). Further, we similarly examine the role of a stone tool’s edge angle on the forces, work and displacement required to cut such material. This represents the first controlled study of how two of the most important aspects of a cutting tool’s edge influence the functional performance of Palaeolithic stone technologies. We conclude by discussing the relative importance of sharpness and edge angle in relation to each other, the influence that each trait has on cutting processes, and the extent to which behaviours may have been influenced by these factors in prehistory.

2. Methods

2.1 Stone Tool Assemblage

Initially, hundreds of flakes were knapped from Texas Fredericksburg variety chert with the aim of producing flakes displaying edges suitable for cutting. From these, ~200 were selected on the basis of displaying straight edges greater than 20mm long and no micro-flaking or fractures. The final assemblage of 50 flakes was chosen to display a range of edge angles (Figure 1). Edge angle variation was recorded here using the Caliper Method first described by Dibble and Bernard (1980). It was only necessary to record edge angle across a 10mm length of each flake's cutting edge. This edge portion was the only aspect of the tool applied during cutting and was principally chosen based on being located near the middle of the cutting edge. Six angle measurements were taken from this relatively short length of edge. Angles were recorded at three evenly spaced intervals (0mm, 5mm, and 10mm) at depths away from the edge apex of 2mm and 5mm. This produced six separate edge angle measurements (Table 1).

2.2 Sharpness

The complexity of measuring sharpness on cutting edges has been argued to preclude singular quantitative or qualitative measures being accurately applied during investigations into this phenomena (Reilly et al., 2004). In 2007 McCarthy et al. proposed the first dimensionless quantitative measure for calculating an edge's sharpness. The 'blade sharpness index' (BSI) is a dimensionless metric dependent on the force required to initiate a cut in a substrate, the fracture toughness and thickness of the worked material, and the indentation depth required prior to a cut being formed in the material. Although McCarthy et al (2007) did not account for an edge's geometry (and therefore tip radius), Schuldt et al. (2016) independently demonstrated that BSI is not only suitable for characterising the sharpness of a cutting edge (although this is dependent on material context), but is a linear function of an edge's tip radius and the force required at cut initiation. Further, Schuldt et al. (2016: 19) established that the cut initiation depth and force at cut initiation of an edge are suitable as "simple and fast sharpness characterization[s] for a specific cutting application." In other words, for a specific material (substrate) type and speed of cut, the material indentation (deformation/displacement) required prior to a cut initiating, and the force required to achieve the initiation of the cut, are reliable indicators of an edge's sharpness. Thus, following McCarthy et al. (2007) and Schuldt et al. (2016), we utilise mechanical records of sharpness as opposed to those defined solely from geometric attributes of cutting edges (e.g. edge radii). Specifically, we use vertical force (N), material displacement (mm) and work (J) at the point of cut initiation.

We examine the influence that sharpness has on a stone tool's cutting performance by using each flake under six different sharpness conditions. First, each flake is used in a 'fresh' condition where the edge has not been used before or subject to any kind of abrasion or damage. In the second condition, each edge was subjected to a single, light, cutting (abrasive) stroke across a soft sand stone. The third condition consisted of the edge having a further single cutting stroke across the stone (two in total). Conditions four through to six were similarly repeated until the final condition had had five strokes across the stone. Relative differences in tip geometry between conditions one and two are illustrated in Figure 2. Sand stone was chosen to intentionally examine the impact of blunting using a relatively soft material (compared to other worked materials from the Palaeolithic such as flint or bone, for example) while also controlling for material inconsistencies often observed in organic materials (e.g. wood).

In addition to the stone flakes, 10 steel 2-facet utility (razor) blades (Kolbalt®) were also used in this study (Figures 1 and 2). Each metal blade was used under the same six sharpness conditions. These were included to provide both a modern analogue against which the stone tools could be compared and to more easily facilitate comparisons with the studies by McCarthy et al (2007) and Schuldt et al. (2016).

2.3 Cut Substrate

Consistent with previous research (Marsot et al., 2007; McCarthy et al., 2007; Schuldt et al., 2013) we use an industrially produced flexible plastic (polyvinyl chloride [PVC] tubing) in place of the biological tissues that may more normally be cut by hand-held tools (including by stone tools). Principally, and as confirmed by pilot studies using strips of beef, this was due to the variable structure of animal or plant materials leading to variation in force and indentation records between cutting tests. The flexible PVC used here indents/deforms prior to cuts initiating, displays a J-shaped stress-strain curve (as observed in soft biological tissues), and is consistent in this regard with the polyurethane and ethylene propylene diene monomer rubber sheets used by McCarthy et al. (2007) and Schuldt et al. (2016). Due to the buckling observed by McCarthy et al. (2007) when polyurethane sheets were cut with blunt blade edges, we followed Schuldt et al. (2016) in using relatively thick material segments. Here we opted to use lengths of PVC tubing of 6mm O.D. (Figure 3c).

2.4 Indentation Cutting and Testing Station

Force and material displacement were recorded here using a universal testing system (Instron® 5500). Amongst other features, the Instron® allows for controlled compressive testing where the upper grip of the device lowers at a predefined speed and records both distance moved and resistance provided in the opposing direction. Both the flakes and steel blades were secured into the upper grip of the Instron® using wooden blocks (Figure 1). The cutting edge on the flakes and blades was horizontal in all instances (Figure 3). The PVC was used in 100mm lengths and secured such that the cutting edges were perpendicular to the length of PVC. Each end of the PVC was secured between two wooden blocks using a vice. Coarse sandpaper attached to the blocks provided increased friction. The combination of the rough surface and the compressive force prevented any movement of the PVC during testing. A 30mm gap was left between the pair of wooden blocks, across which the PVC stretched and into which the cutting edges were lowered (Figure 3).

The crosshead, into which the grip and flakes/blades were fixed, was lowered prior to the test initiating so that the tip of the cutting edges were in contact with the surface of the PVC at its midpoint (i.e. it was 15mm on either side to the wooden blocks) but exerting no force. At this point the displacement (distance moved) reading was set to zero. The blades were lowered into each material at a rate of 20mm/min. Displacement (mm) and force (N) levels were recorded for each controlled cut, which continued until the blade passed through the PVC in its entirety. The sampling frequency in all tests was 10 Hz. All flakes and metal blades were tested six times, once with each of the sharpness conditions.

2.5. Data Analysis

The influence that edge sharpness has on stone tool cutting performance was recorded here via vertical force (N) and displacement (mm) levels at the point of cut completion. Maximum force records always occurred immediately prior to the point at which the material was cut, and thus were easily identified within the data record (Figure 4). The matching displacement value at this point in the data record was used as the record of displacement at the point of cut initiation (Figure 4). Six different sharpness conditions were investigated here. The significance of any differences for the two dependent variables between the six conditions were investigated via Mann–Whitney *U* tests as some data sets were not normally distributed. Tests were only conducted between sequential conditions, such that only five tests were undertaken for each variable (i.e. conditions one and two, two and three, three and four, and so on, were compared). In a couple of instances during conditions three, four, five and six, stone flakes with more obtuse edges were unable to cut the PVC. Hence, the number of data values slightly drops for these conditions (n = 49, 47, 44 and 45 for conditions three through to six, respectfully). There are ten data values in all instances for the metal blades. Bonferroni Corrections were applied to control for Type I error such that $\alpha = .01$. If significant differences are identified between any two sharpness conditions it indicates that their variable measures of sharpness/bunting, as caused by a single abrasive cutting stroke, are enough to elicit significant differences in force and/or material displacement when each is used to cut.

Differences in work between the six sharpness conditions for both tool types were similarly examined with Mann-Whitney *U* tests. Again, tests were only conducted between sequential conditions and $\alpha = .01$. Work refers to the energy (J) required to perform a cut and is calculated as the area beneath the load displacement curve (Figure 5). Given that the curves were constant in shape we treated each as a triangle from the point of cut completion such that area (a) equalled half of force (F) multiplied by displacement (d) ($a = 0.5 \times (F \times d)$). Significant differences in work between any two conditions will indicate that the relative sharpness differences between flakes are enough to significantly influence how much energy is required during their use.

The influence of edge angle on force requirements and material displacement at the point of cut initiation was analysed using linear regression (n = 44-50; see above). All dependent variables were independently regressed against the mean value of the six edge angles recorded from the 10mm of utilised cutting edge. This was repeated for each of the six conditions. In order to control for Type I error a Bonferroni Correction was applied such that $\alpha = .008$.

3. Results

Descriptive data for force (N), displacement (mm) and work (J) in each of the six sharpness conditions are displayed in Table 2. These data reveal substantial shifts in all values between sharpness conditions one and two, and then again (although to a lesser extent) between conditions two and three (Table 2; Supplementary Information 1). This is repeated in both the stone flakes and metal blades (Figure 6). On average, these differences amount to 38% increases in force, 25% increases in material displacement, and 70% increases in work between conditions one and two for the stone flakes. The metal blades displayed 203%, 100%, and 533% increases in required force, material displacement and work (respectfully), between conditions one and two. Subsequent to condition three there are limited increases in these variables and it appears that additional abrasive cutting strokes do not markedly influence force or displacement requirements when cutting the PVC.

Mann-Whitney *U* tests identified that the increased force, displacement and work values between conditions one and two were significant for the stone flakes (p = .0001 in all tests). The force, displacement and work values were similarly significantly different between these sharpness conditions for the metal blades (p = .0002 in all tests). A single (light) abrasive stroke of a stone flake's cutting edge against a reasonably hard substance does, therefore, significantly affect the force, displacement and work required to cut flexible, extensible material. All other comparisons between sharpness conditions returned non-significant results (Table 3); although differences between conditions two and three approached significance for the stone flakes (p = .0268, .0784 and .0407). The addition of another abrasive stroke subsequent to the first does not, then, significantly increase force, material displacement or energy levels required when cutting with a stone tool.

Linear regressions run between edge angle and force, material displacement and work identified significant relationships on all occasions (Table 4). Thus, across all sharpness conditions examined here, the angle present on the working edge of the stone flakes significantly influenced their cutting performance. Indeed, as edge angles increased, the forces, material displacement and work required to initiate cuts in the PVC also increased (Figure 7). During sharpness condition one, when the flake edges were in their 'fresh' condition, approximately 40% of the variation in force, displacement and work could be attributed to edge angle values. As edges became increasingly more blunt from conditions two through to six, R^2 values (and therefore the force or displacement variation explained as a result of edge angle) dropped such that edge angle variation only accounted for approximately 20% of force, displacement and work in the final condition (Table 4).

4. Discussion

4.1 Sharpness

The presence of a sharp edge underpins the functional capabilities of a stone tool and helps explain their sustained importance to human populations for >2.6 million years. Presented here is the first evidence identifying how important the relative sharpness of these edges is and the significant impact that this attribute can have on a stone tool's cutting performance. Specifically, we have demonstrated that the applied force, material displacement, and energy expenditure required prior to a stone tool's edge cutting is significantly dependent on how sharp (or alternatively how blunt) that edge is.

In itself this may not be surprising, but the rate at which energy requirements, in particular, increase as a result of the very earliest stages of blunting appears to be rapid. Certainly, our results demonstrate that a single abrasive cutting stroke across a reasonably hard surface is enough to significantly increase how much energy is required to be expended by a stone tool user prior to a cut forming in a worked material. Here, this amounted to a 70% increase in energy (J). If considered solely in terms of the force (N) required to initiate a cut, this equated a 38% increase in the loads required to be applied by a stone tool's edge. When flake edges were exposed to additional abrasive cutting strokes there were no significant increases in energy or force requirements, in turn, emphasising that it is the earliest stages of edge blunting that have proportionately the greatest influence on stone tool cutting performance. In other words, when using a stone tool, blunting is of greatest concern to efficiency rates when the tool is at its sharpest.

Although the attribute of sharpness has previously been mentioned within Palaeolithic literature (e.g. Jones, 1980; Buchanan, 2006; Dewbury and Russell, 2007; Braun et al., 2008), it has rarely been discussed in terms of how it influences cutting performance or its potential behavioural implications. Here, we present the first evidence indicating that it would have been of significant benefit to stone tool using individuals to maintain a sharp edge on their lithic cutting implements. This is consistent with previous mechanical and ergonomic research identifying increased cutting force requirements as metal cutting edges become increasingly more blunt and tip radii increase (Arcona and Dow, 1996; McGorry et al., 2003; Atkins, 2009; Schuldt et al., 2013). Furthermore, we demonstrate that a single abrasive stroke against a tool's cutting edge is enough to significantly decrease its functional performance and, in turn, significantly increase the work required during its use. Reductions in tool performance as a result of edge blunting (i.e. reductions in sharpness) therefore have the potential to be of concern from the very start of a tool's use-life. After an initial rapid reduction in performance, however, and as demonstrated here in conditions three to six, abrasive cutting actions would have a more limited impact on cutting performance. That is, abrasive cutting actions will continue to result in increased blunting and tool-performance reductions, just at a considerably reduced rate.

In addition to the abrasive stone used here, rapid blunting events will also include a stone tool's edge being drawn across alternative hard substances, such as bone or dense plant material. Although likely to be more limited in the speed at which sharpness reduces (i.e. displays a smoother, less steeply inclined, efficiency decay curve), we predict that the cutting of softer, more extensible, materials such a meat or soft plant matter will also display an initial rapid period of blunting before levelling off. Moreover, although a tool's raw material will impact its cutting mechanics, irrespective of the stone type used the degradation of an edge will likely display a similar period of initial rapid blunting before levelling off. In other words, Palaeolithic individuals were likely to have persistently been presented with the problem of rapid performance degradation and energy expenditure increases as a result of fresh cutting edges blunting. Blunting may result from mistakes during tool-use, such as accidentally cutting bone when butchering an animal (Egeland, 2003; Braun et al., 2008) or scraping a supportive stone platform when preparing hide, or as a result of the cutting tasks itself (e.g. carving wooden, shell or bone items, digging up tubers, skinning an animal); although the relative speed and impact of sharpness decreases are likely task dependent. Given the variability of Palaeolithic tool-use contexts, individuals would have been presented with three potential behavioural responses to edge blunting, which, dependent on the tool-use context, may have been more or less likely to have been enacted. Each, in turn, has different implications for our ability to accurately interpret the archaeological record.

The first response to increased bluntness could have been to continue to use the same tool and cutting edge irrespective of initial blunting events and reductions in tool performance. At first this appears counterintuitive given the increased energetic cost, however, as has been demonstrated, the rate at which a tool's performance decreases will be more limited after the earliest stages of blunting. Under certain task conditions, the continued use of a tool after this initial phase of blunting may be a reasonable adaptive behavioural response. Specifically, during tasks that consistently produce conditions likely to blunt edges, such as when shaping wood or bone (e.g. for spear points), it would have been costly to consistently use fresh cutting edges. Certainly, if every cutting action is likely to blunt a fresh edge and significantly decrease cutting performance, then the tool production costs (time, energy, raw materials) of maintaining the constant use of very sharp edges would be high. In turn, it may be worthwhile to continue to use increasingly blunted tools up until the point that working force and work requirements increase beyond those achievable within reasonable ergonomic and energetic thresholds.

The remaining two potential responses involve the replacement of the blunted edge with one that is sharper. This behaviour is more likely to be enacted within task-conditions that infrequently invoke cutting actions against hard, and therefore more abrasive, materials. Examples include butchery behaviours (perhaps excluding disarticulation [Braun et al., 2008]) and cutting non-domesticated green vegetation (van Gijn and Little, 2017). Essentially, if an edge is more likely to stay sharp for extended periods of use, and thus display high efficiency rates for longer, then there are greater benefits to tool-users by replacing dull edges. Specifically, there is the potential that the time and energy saved by the use of sharp edges will outweigh any costs associated with the edge's replacement. As already mentioned, there are two potential options for tool users when doing this. The first option is to replace the whole tool. This option is more likely to be enacted when using expedient tool types that display low investment costs or curation (Vaquero and Romagnoli, in press); flake and blade technologies are clear examples in this regard. That is, given the more limited raw material costs and relative ease associated with the production of such tools, the replacement of the whole tool (or a specific lithic object within a composite tool [e.g. a sickle]) would be preferential relative to the continued use of a tool displaying reduced efficiency. The second option that involves the replacement of a dull edge is the renewal, or resharpening, of a tool's cutting edge. This option is more likely to be undertaken in tools displaying greater production and transportation costs due to the associated greater requirements to maintain use-life durations and avoid the replacement of the whole tool. Certainly, functionally dependent resharpening behaviours must be balanced against raw material availability (Clarkson et al., 2015). Example technologies include scrapers, handaxes and other bifaces, and projectile points.

Given the frequency with which blunting events could have occurred and the significant impact this would have on stone tool performance, we argue the replacement of blunt edges would have been frequently undertaken within many Palaeolithic tool-use situations, potentially occurring multiple times during a single task (although, as already highlighted, this would be task-type dependent). There is, then, the potential for the use-life of many Palaeolithic implements to have been substantially shorter than typically thought. With regards to more expedient tool types in particular, the rapid rate at which blunting can occur would lead to a high turnover of tools and, in turn, the dense accumulation of artefacts within the archaeological record (e.g. Waters et al. 2011), occasionally even resulting in 'lithic landscapes' in which the production of stone flakes may have influenced local ecology (Foley and Lahr 2015). These examples support the notion that, at times, rapid reductions in performance as a result of early stage blunting led to the rapid replacement of stone tools during use.

Similarly, a requirement to frequently resharpen an edge would reduce the use-life of a tool, increase their turnover in production, and ultimately increase their prevalence within archaeological deposits. Further, the present results reemphasise that the identification of limited resharpening events on some stone tool artefacts and their discard prior to resharpening exhaustion is indicative of a short use-life (e.g. Shipton and Clarkson, 2015). Given the considerable size variation observed in some stone tool types displaying modified edges (e.g. Gowlett, 2015), there is also the potential for some of this variation to have been caused by the duration of cutting tasks as this would directly influence the number of resharpening events required. While artefact size has frequently been linked to resharpening events and tool-use durations before (e.g. Dibble, 1987; McPherron, 1999; Buchanan, 2006; Iovita, 2011; Eren, 2013; Lin, in press), the present results highlight that even relatively limited periods of use could lead to a substantial number of edge renewal events, and in turn, rapid alterations to tool forms. In short, the results presented here emphasise how important resharpening behaviours were likely to have been to the maintenance of functional efficiency in some stone tool types.

Evidence that, at times, past individuals responded to blunting events by either continuing to use dulled edges or repeatedly replacing them are, arguably, present via microwear analyses of the working edges of Palaeolithic artefacts. As demonstrated through numerous experiments (Keeley, 1980; Bamforth, 1988; Evans et al., 2014; Stemp et al., 2015), the greater the duration and/or force of use a lithic edge is subject to, the more developed that wear traces on a tool are likely to be. Hence, in instances where implements with clear and functionally diagnostic microwear traces have been recovered archaeologically, there is evidence that individuals likely used these tools for extended periods and may, plausibly, have continued to use these implements subsequent to early stage blunting and its associated significant reductions in cutting performance. Particularly if wear traces or residues suggest a tool has been used to cut wood, stone, antler or bone (e.g. Hardy and Moncel, 2011; Zupancich et al., 2016; Yravedra et al., 2017). As repeatedly noted throughout >40 years of microwear analyses, however, artefact assemblages rarely display high proportions of tools with diagnostic wear traces (Keeley, 1980; Donahue et al., 2004; Lemorini et al., 2006; Solodenko et al., 2015). At times the presence of artefacts without clear wear traces has been interpreted as indicating that they were not utilised (e.g. Miller, 2014; Rots et al., 2015). The results presented here emphasise the likelihood of the alternative possibility that these tools may have been used, but were instead discarded, or their edges were resharpened, subsequent to early stage blunting events and their associated significant decreases in functional performance.

4.2. Edge Angle

The angles observed on the functional edges of stone tools are of known consequence to their cutting capabilities (Jones, 1980; McCall. 2005; Collins, 2008; Key and Lycett, 2015; Key et al. 2016). Presented here is evidence identifying the impact that edge angle variation has on a stone tool's ability to cut in the absence of human actors, and how this varies in relation to sharpness. Regressions across all six sharpness conditions identified significant relationships between increasing edge angle values and greater force, material displacement and work requirements. As far as the present analyses can demonstrate, then, the angles observed on the working edges of stone tools significantly influence cutting performance irrespective of any edge sharpness variability. It should, however, be noted that although each flake performed five abrasive cutting strokes here, we can only speak to the relationship between edge angle and sharpness up until this point. As highlighted by the present R^2 values there is cause to believe that this relationship does vary and that as edges become progressively less sharp (i.e. more blunt), edge angle has a more limited impact on cutting. This is likely caused by sharpness levels having a greater impact on cutting forces as edges become blunter due to the associated reduction in cutting stress and, in turn, the proportionately greater amount of force that is required to perform a cut. Whether or not there is a point beyond which edges become so blunt that edge angle does not significantly contribute to cutting performance it is hard to say. It would be interesting if future experiments could investigate such matters.

Given that up to ~40% of force, material displacement and work requirements during stone tool use has been shown to be attributed to edge angle variation, it would be reasonable to conclude that individuals concerned with the performance of their cutting tools should select or produce tools with more acute edges. However, as identified both here and previously (Key and Lycett, 2015; Key et al., 2016), other factors such as edge sharpness, tool size, and ergonomic considerations can alter the otherwise straightforward relationship between more acute stone tool edges equalling increased performance. While we would refer you to the aforementioned articles for discussion on tool-size and manual ergonomics, it is evident here that the role that edge angle plays in stone tool performance is dependent on how sharp the working edge is. There would, then, be less incentive for an acute angled working edge if the tool is going to be used for a task that consistently produced conditions to blunt the tools edge, such as wood working tasks. Conversely, those tasks that would less frequently present conditions that could rapidly blunt a tool's edge, such as cutting muscle tissue, there is increased incentive to select tools with acute edges as it will have a greater influence on tool performance for longer.

Whether the mechanical relationships identified here *actually* influenced Palaeolithic individual's behaviour and, in turn, lead to visible variation in the archaeological record it has yet to be seen. Nonetheless, presented here is evidence identifying the significant impact that sharpness and edge angle variation can have on a stone tool's cutting performance and, as such, there is cause to reason that Palaeolithic tool users would likely have been under pressure to select for different tool forms in response to these mechanical relationships (Key and Lycett, 2017). Certainly, raised here are new and interesting possibilities for interpreting the tool production and selection choices of past stone tool using populations and, as has been highlighted elsewhere (e.g. Terradillos-Bernal and Rodríguez, 2012; Iovita, 2014; Key and Lycett, 2017; Hoggard, 2017; Sánchez-Yustos et al., 2017), there is the potential for artefacts to shed light on these matters.

It is important to note that the results presented here, for both sharpness and edge angle, have been determined using stone tools with straight, non-modified cutting edges and in conditions absent of human actors. Indeed, given the high internal validity provided by the methods used here (Mesouri 2011; Lycett and Eren 2013; Eren et al., 2016), there are unlikely to be any variables other than those investigated (sharpness and edge angle) contributing substantially to force, displacement and work variation. In turn, there is the potential for the relationships identified here to vary once more variables, such as edge scalloping, tool-size, tool-user strength, and other factors contribute to a tool’s functional performance. Moreover, when tools are applied within actualistic conditions displaying high external validity, there is potential for additional task-dependent variables to influence the mechanical relationship between a tool’s edge and the worked material (e.g. an accumulation of fatty tissues on an edge). It is also notable that the PVC utilised here is a relatively resistant material and did not require cuts to be performed at any great depth into the material. The former meant that on a couple of occasions very acute stone edges formed micro-fractures prior to cuts initiating, in turn, potentially increasing their required forces. The latter similarly suggests that had cuts been performed at greater depth within a material, increased fiction would likely have been acting on cutting edges (Komanduri et al., 1998; Reilly et al., 2004; Atkins, 2009), in turn potentially increasing any influence that edge angle may have. Essentially, both suggest that edge angle may have had a greater impact had the material context of the task been slightly different. Future experiments may profitably investigate these points.

5. Conclusion

The calculation of the BSI detailed by McCarthy et al (2007) and Schuldt et al. (2016) may be beyond many without an engineering background. As demonstrated here (and elsewhere [Schuldt et al., 2016]) a straightforward and relatively accessible method for archaeologists to test stone tool sharpness and its impact on cutting performance is the measurement of force, material displacement and work. We have shown that sharpness not only significantly influences these three variables when using a stone tool, but any impact caused by blunting occurs rapidly, with as little as a single abrasive cutting stroke causing ~38% increases in force requirements and 70% increases in work (energy expenditure). The impact of edge angle variation on cutting performance has also been shown to co-vary with edge sharpness, with edge-angle variation having greater influence on cutting performance the sharper the cutting edge. As discussed, there is the potential for these mechanical relationships to have impacted on the tool-production and use behaviours of Palaeolithic individuals and, in turn, have left morphologically visible traces in the artefact record. Certainly, the rapid rate at which stone tools blunt, and their cutting performance consequently decreases, indicates that the use-lives of lithic artefacts (or more specifically their cutting edges) may have been far shorter than typically thought. Rapid reductions in tool performance as a result of blunting may, in turn, account for the abundance of lithic artefacts recovered from some archaeological sites, the speed with which resharpening behaviours altered tool forms, and the lack of microscopic wear traces on many lithic implements.

Acknowledgements

We are grateful to the anonymous reviewers for their feedback and helpful suggestions on an earlier version of this article. AK gratefully acknowledges the British Academy for supporting his research through a Postdoctoral Fellowship (pf160022). MIE is supported by the College of Arts and Sciences at Kent State University and the National Science Foundation (NSF Award ID: 1649395). AK would like to thank the Department of Anthropology at Kent State University for hosting him in spring 2017, during which this study was undertaken, and Barbara Davis for her help during this visit.

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Figures

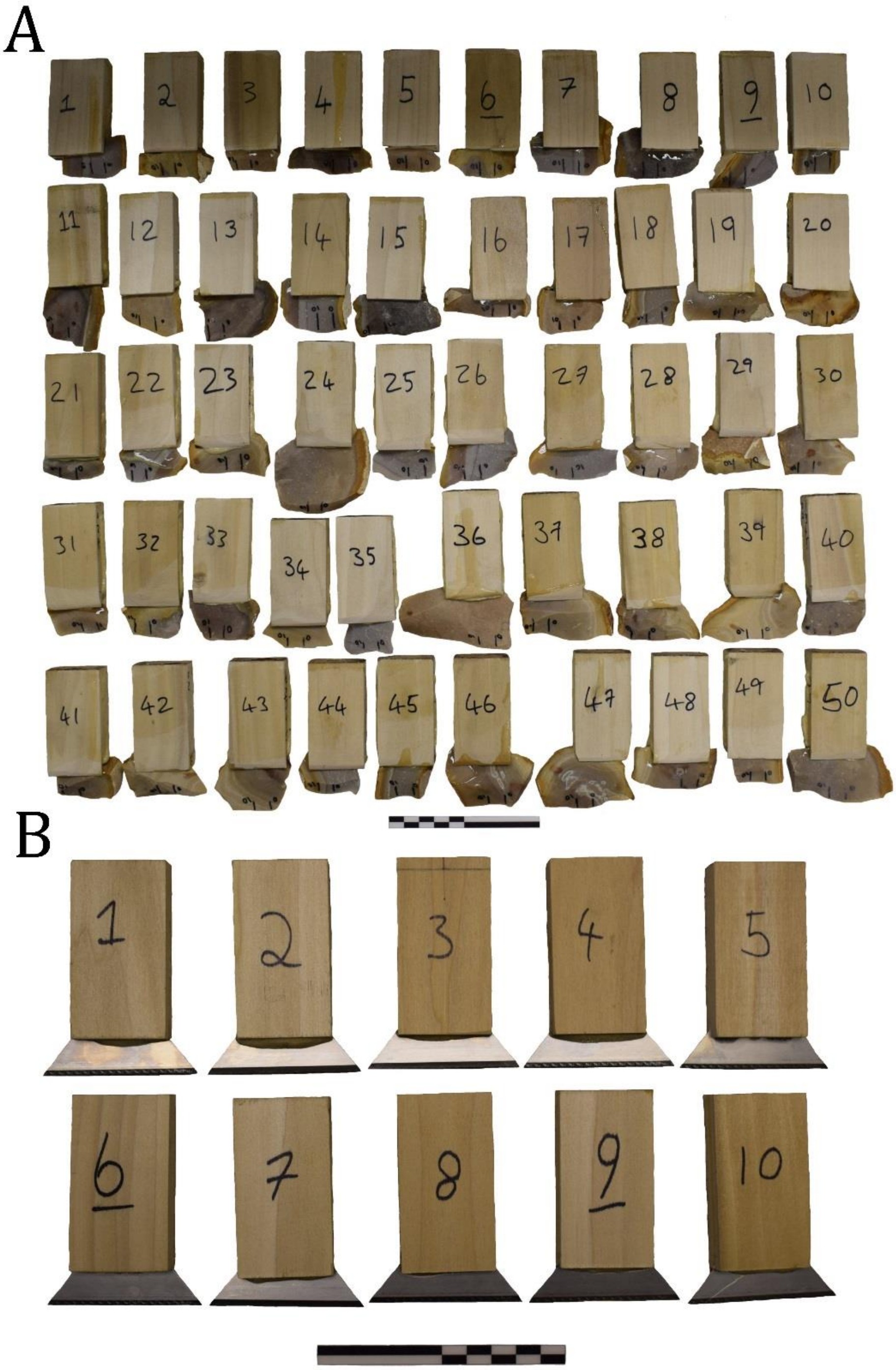

Figure 1: The 50 stone flakes (A) and 10 metal blades (B) used during the cutting tests. Each has been secured into a wooden block so that it can be securely held by the upper grip of the Instron®.

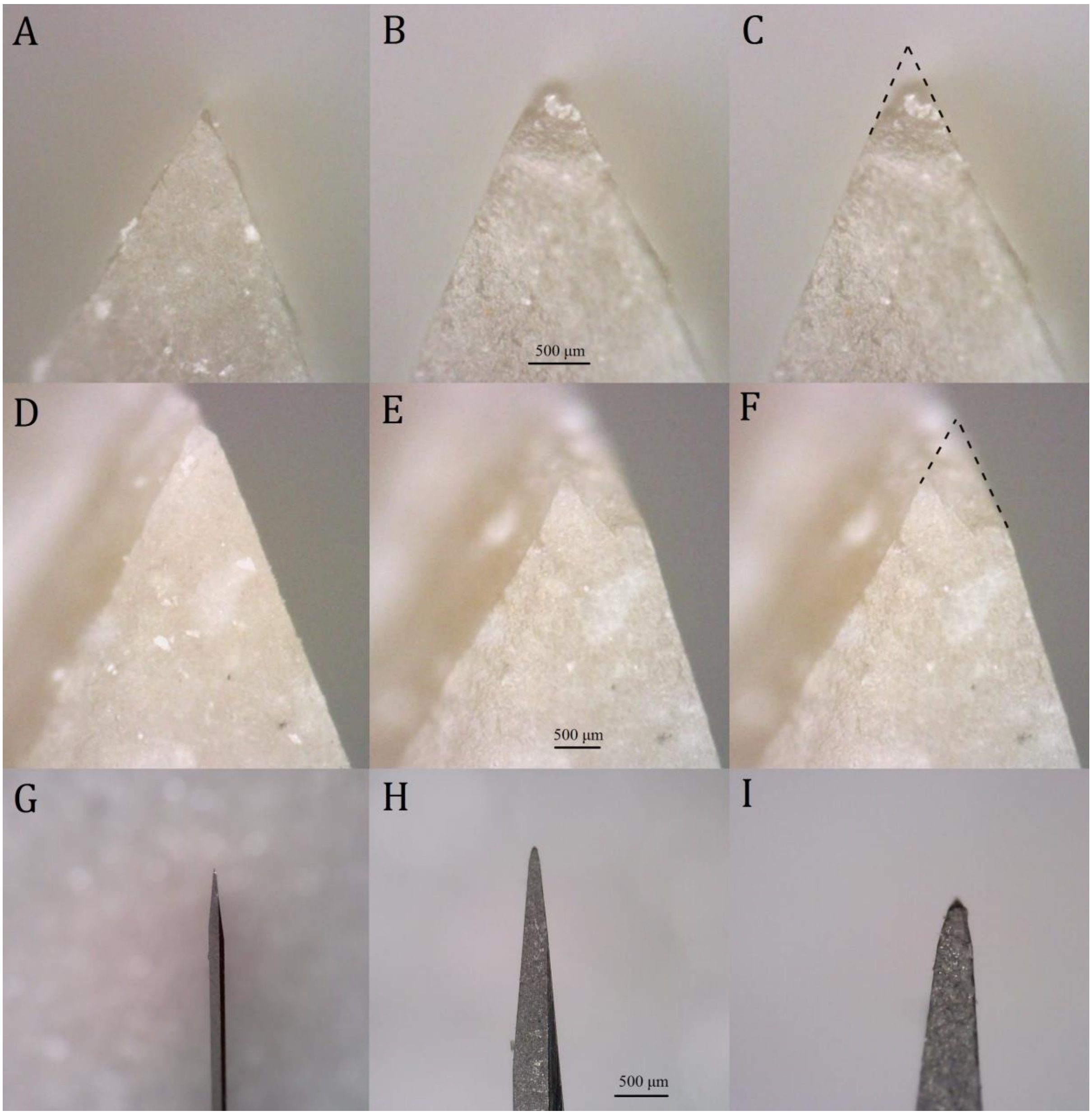

Figure 2: Differences in tip geometry resulting from an abrasive cutting stroke against a 'fresh' flake edge. Comparisons between (A) and (B), and (D) and (E), reveal increases in edge radii and microfracturing. As demonstrated by Schuldt et al. (2013), tip offset increases as edges become more blunt and edge radii increase (C, F). Also depicted (G, H, I) is the cutting edge of the metal blade. Much of the difference in force and displacement between the two tools is likely due to the more acute edges observed on the blade edges. Scales are approximate and only refer to the central three images.

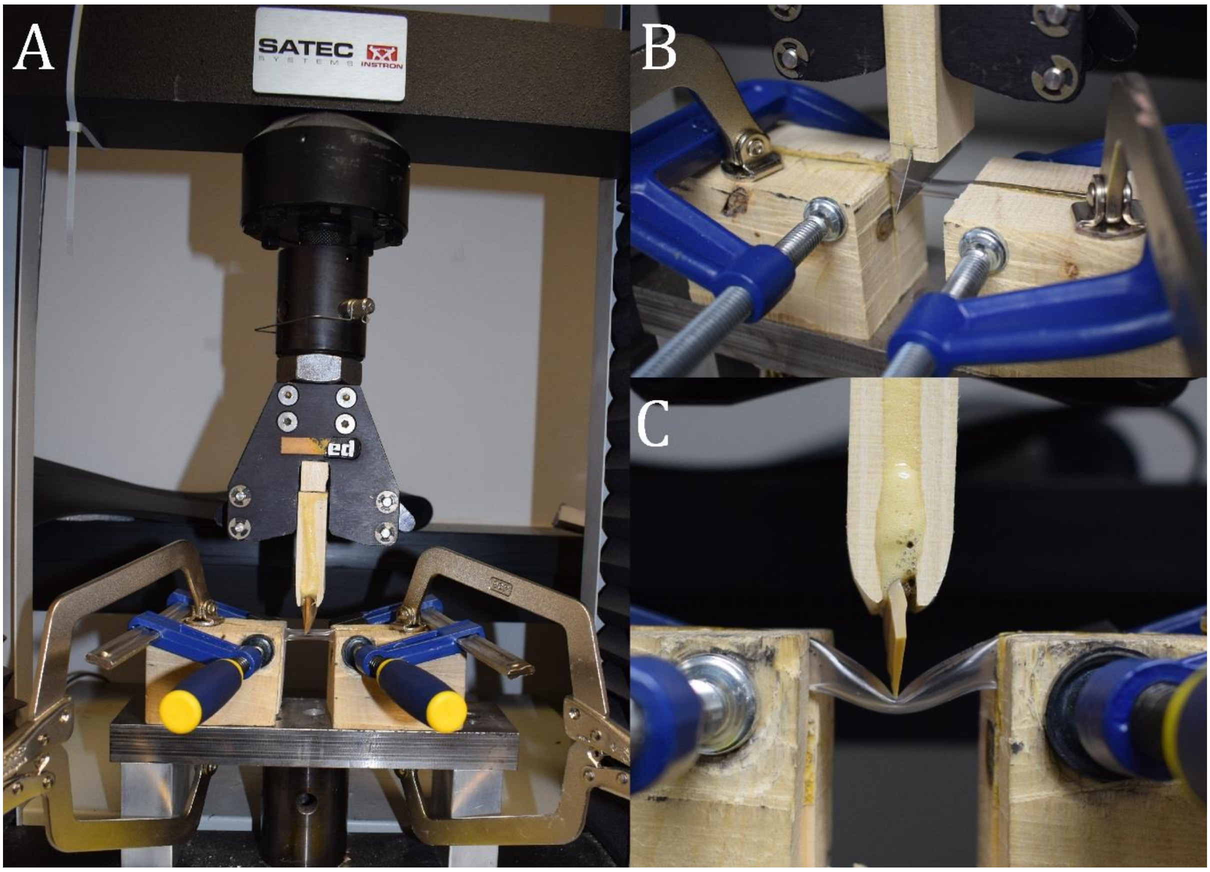

Figure 3: The material set-up and Instron® testing station. Depicted are two of the stone flakes (A, C) and one metal blade (B). Image (C) illustrates the displacement of the PVC prior to a cut initiating.

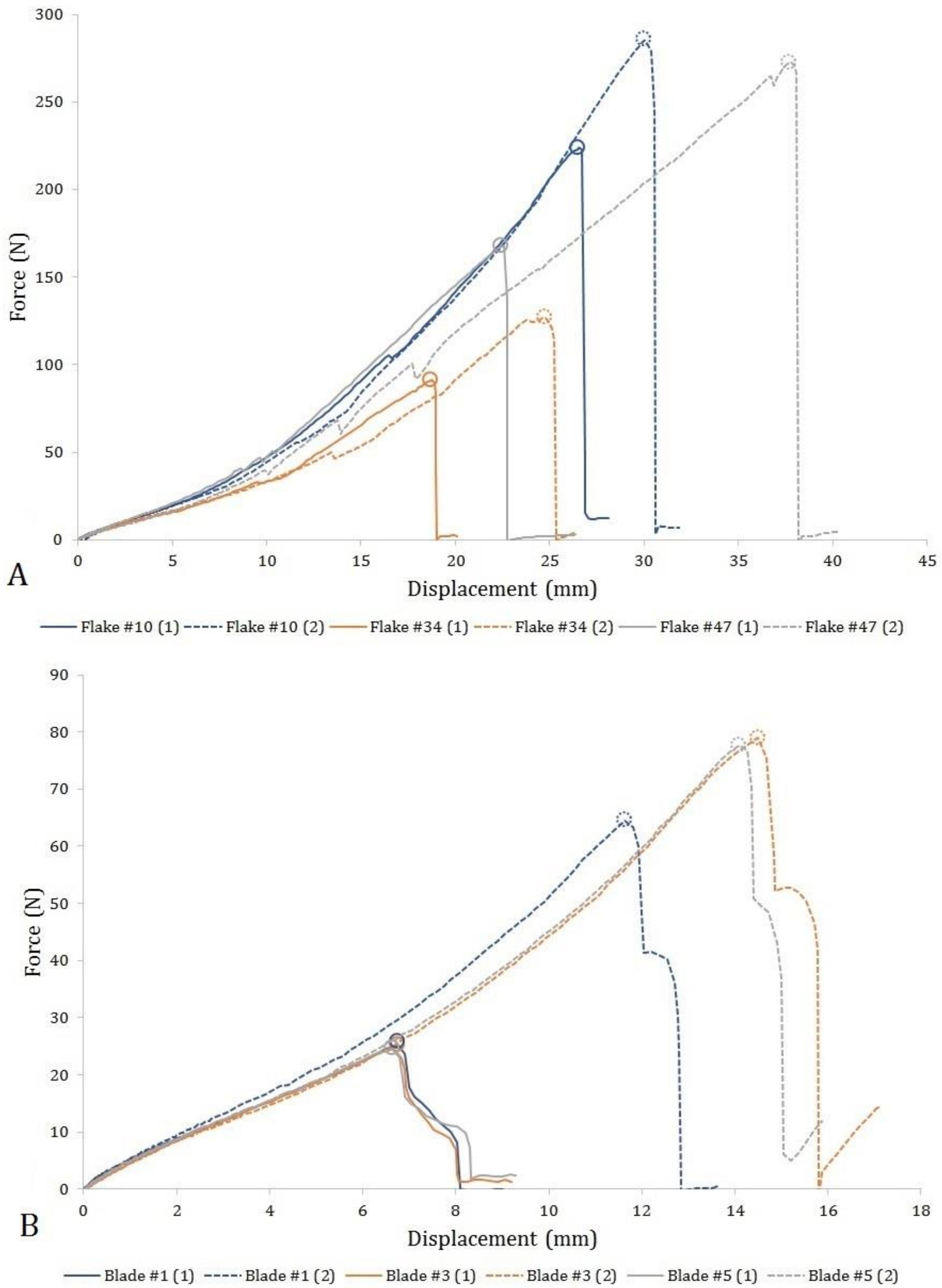

Figure 4: Load displacement curves depicting typical tests with stone flakes (A) and metal blades (B). Data for each tool has been plotted for both conditions one (1) and two (2). Data values highlighted by circles indicate that point at which force (N) and displacement (mm) were recorded.

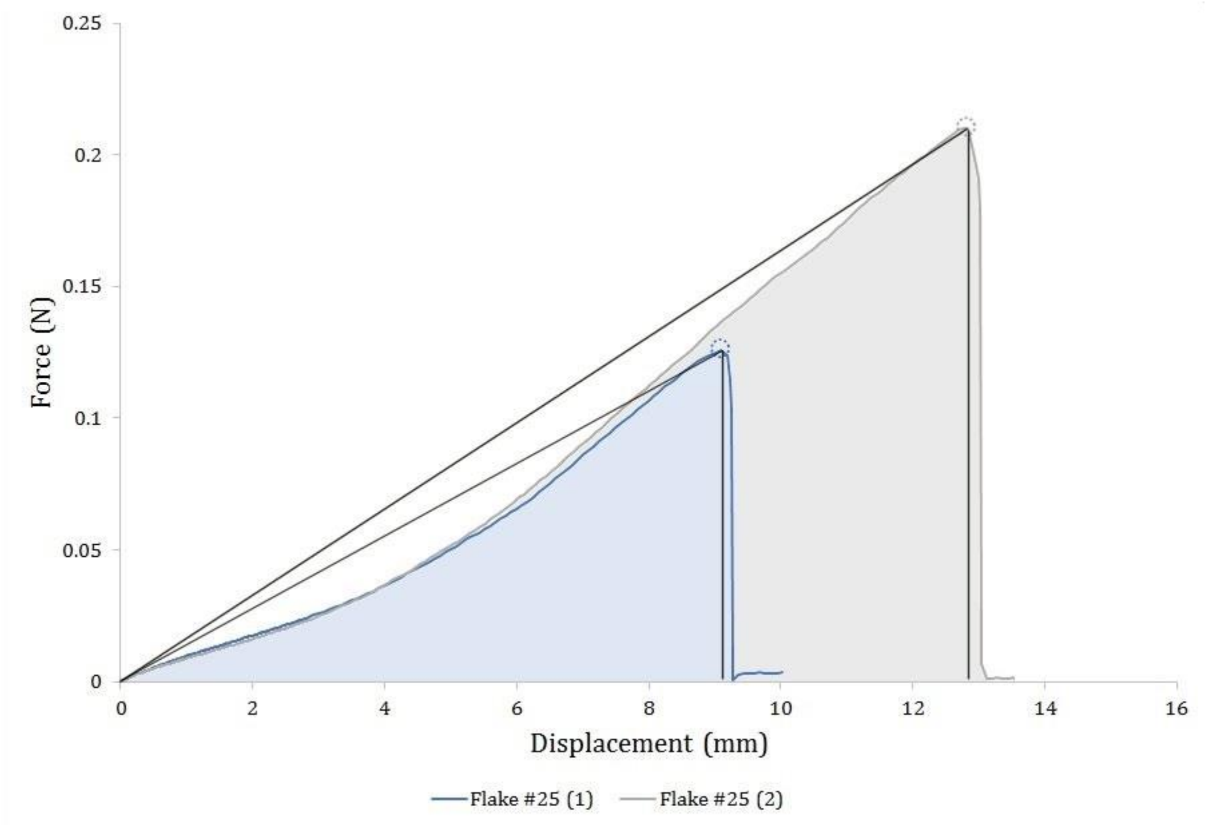

Figure 5: Load displacement curves identifying the area used to calculate work (J) during a cut. Depicted here are conditions one (1) and two (2) for stone flake #25, the actual area of work for these cutting tests, and the work calculated here ($a=0.5\times(F\times d)$).

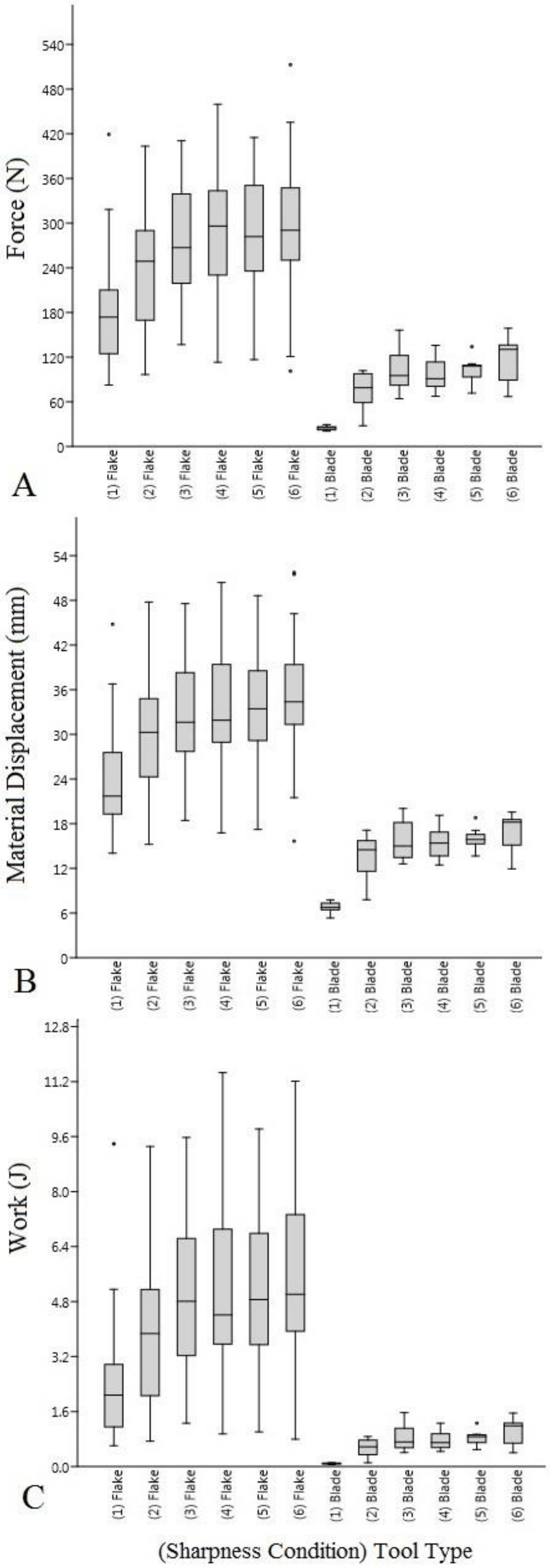

Figure 6: Depicted here are the clear differences in force (N), displacement (mm) and work (J) (A, B and C, respectively) between conditions one and two, and conditions two and three, along with the more limited increases thereafter. The notable differences in each variable between the stone flakes (left) and metal blades (right) are also clear.

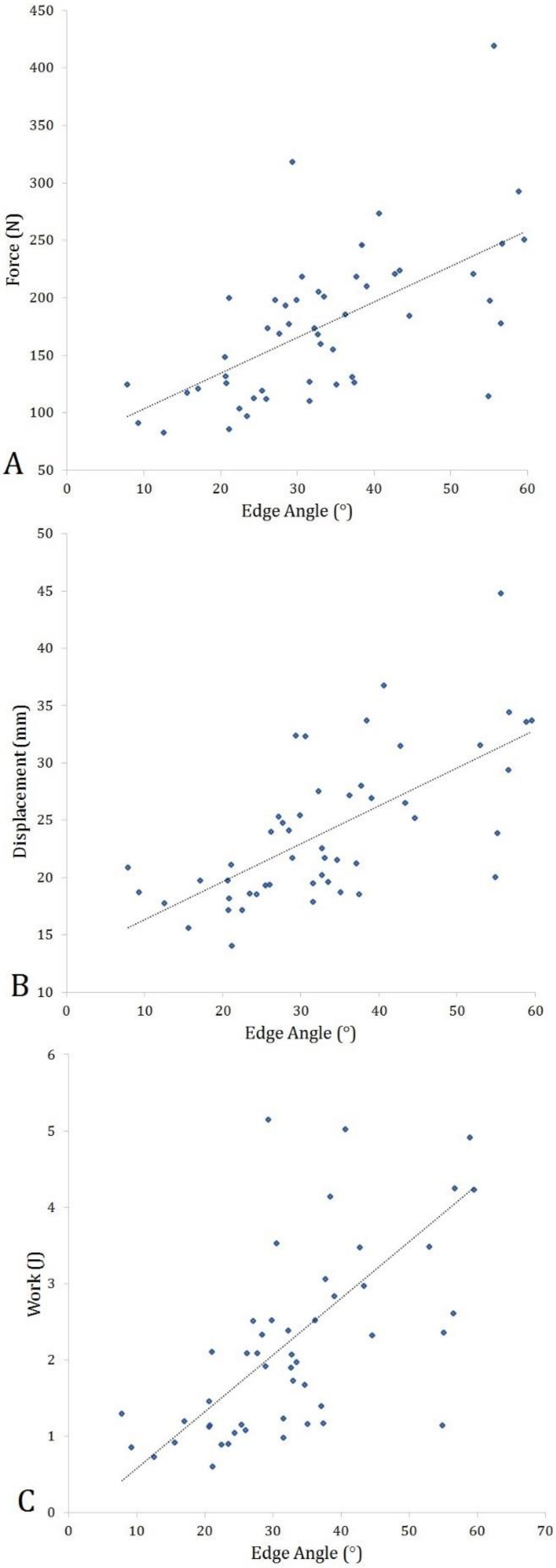

Figure 7: Linear regressions between mean edge angle and force (N), displacement (mm), and Work (J) (A, B and C respectively for flakes during condition one). Each regression was significant (p = .0001 in each instance) and displayed R^2 values of .378, .449 and .377 (respectfully). A single outlier in ‘C’ is not present as a flake with an angle of 55° had work equalling 9.4.

Tables

Table 1: Descriptive data for the six edge angle measurements recorded from the stone flakes.

Depth of Caliper Measurement	2mm Depth (n = 50)			5mm Depth (n = 50)			Mean (n = 360)
10mm Segment Position (mm)	0	5	10	0	5	10	
Mean (^{o})	32	33	34	33	34	34	33
S.D. (^{o})	14	13	15	13	13	14	13
C.V. (%)	45	41	43	41	40	40	39

Table 2: Descriptive data for force (N), displacement (mm) and work (J) values during each of the six sharpness conditions for both the stone flakes and metal blades.

Sharpness Condition (# of abrasive strokes)	**Stone Flakes**								
	Force (N)			Displacement (mm)			Work (J)		
	Mean	S.D.	C.V. (%)	Mean	S.D.	C.V. (%)	Mean	S.D.	C.V. (%)
1 (0)	175.7	65.9	37.5	24.0	6.4	26.8	2.3	1.6	68.4
2 (1)	242.8	79.8	32.9	30.1	7.6	25.3	3.9	2.1	54.6
3 (2)	280.9	74.0	26.3	32.8	7.1	21.6	4.8	2.2	45.1
4 (3)	284.5	78.8	27.7	33.5	7.3	21.9	5.0	2.3	46.3
5 (4)	285.8	73.5	25.7	33.9	7.1	21.0	5.1	2.2	42.5
6 (5)	301.5	80.9	26.8	34.9	7.1	20.2	5.5	2.5	44.8
	Metal Blades								
	Force (N)			Displacement (mm)			Work (J)		
	Mean	S.D.	C.V. (%)	Mean	S.D.	C.V. (%)	Mean	S.D.	C.V. (%)
1 (0)	24.6	2.8	11.2	6.7	0.7	10.6	0.084	0.017	20.6
2 (1)	74.5	24.1	32.4	13.4	2.9	21.7	0.532	0.254	47.7
3 (2)	102.2	28	27.4	15.7	2.5	16.1	0.832	0.366	44.0
4 (3)	97.9	23.2	23.7	15.6	2.2	14.4	0.787	0.296	37.6
5 (4)	102.9	16.6	16.1	16.0	1.4	8.7	0.830	0.204	24.5
6 (5)	120.2	29.2	24.3	17.2	2.4	14.1	1.063	0.366	34.5

Table 3: Results of the Mann–Whitney *U* tests run between force (N), displacement (mm) and work (J) values for each of the six sharpness cutting conditions. Highlighted in **bold** are significant *p* values subsequent to the conservative Bonferroni Correction applied here (α = .01).

Stone Flakes			
Sharpness Conditions	Force	Displacement	Work
1 → 2	**.0001**	**.0001**	**.0001**
2 → 3	.0268	.0784	.0407
3 → 4	.7415	.6234	.6028
4 → 5	.9146	.7120	.8148
5 → 6	.4189	.5302	.4727
Metal Blades			
Sharpness Conditions	Force	Displacement	Work
1 → 2	**.0002**	**.0002**	**.0002**
2 → 3	.0756	.1620	.0890
3 → 4	.7337	.9699	.9699
4 → 5	.6232	.7913	.6776
5 → 6	.1620	.1859	.1620

Table 4: Linear regressions between force (N), displacement (mm) and work (J) at cut initiation and flake edge angle (°) across all six sharpness conditions. All results are significant despite the conservative Bonferroni Correction applied here ($\alpha = .008$). It is clear that as edges become increasingly more blunt, edge angle has a more limited influence on cutting performance.

Sharpness Condition (# of abrasive strokes)	**Force**		**Displacement**		**Work**	
	p	**R^2**	***p***	**R^2**	***p***	**R^2**
1 (0)	.0001	.378	.0001	.449	.0001	.377
2 (1)	.0001	.311	.0001	.296	.0001	.355
3 (2)	.0001	.263	.0001	.257	.0001	.288
4 (3)	.0001	.282	.0004	.243	.0002	.266
5 (4)	.0012	.222	.0041	.180	.0016	.214
6 (5)	.0033	.184	.0028	.190	.0042	.175