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Early stage blunting causes rapid reductions in stone tool performance

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32 **Abstract**

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

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

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69 **1. Introduction**

70

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

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

93 Sharpness is not, however, solely defined by an edge's tip radius but also relates to the force applied  
94 during cutting. As Schuldt et al. (2016: 13) state, "sharpness also depends on properties of the cutting  
95 substrate, and refers to the ability of a blade to initiate a cut at low force and deformation". A  
96 straightforward example to highlight this point is a paper cut. After all, the edge of a piece of paper is  
97 not sharp and able to initiate a cut until there is sufficient force in the 'slice' motion of the paper across  
98 your skin. Although widely established within engineering research (Atkins, 2009), this aspect of  
99 sharpness has rarely been discussed within Palaeolithic literature (although see: Ackerly, 1978; Key,  
100 2016). Previous mechanical research has measured sharpness in different quantitative and qualitative  
101 terms for both geometric and force properties of edges (Maeda et al., 1989; Arcona and Dow, 1996;  
102 Komanduri et al., 1998; Szabo et al. 2001; McGorry et al., 2003; McCarthy et al., 2007; Wyen et al.,  
103 2012; Schuldt et al., 2013). Reilly et al. (2004) and Schuldt et al. (2013) discuss the co-dependence of  
104 a cutting edge's geometric and force properties in the determination of edge sharpness particularly well.

105 The latter demonstrates that force measurements may be more sensitive than measurements of edge  
106 radius in the calculation of sharpness (Schuldt et al. 2013), although as highlighted by McCarthy et al  
107 (2010), tip radius is significantly more effective in measuring sharpness than edge angle.

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

121 However, it is not known whether or not these basic mechanical principles that underlie the design of  
122 many modern cutting technologies are similarly demonstrated in Palaeolithic stone tool cutting  
123 technologies. Specifically, how are the forces required to use stone tools influenced by the sharpness  
124 (and therefore also bluntness) of their cutting edges? Further, although there has been a number of  
125 studies examining the influence of edge angle variation on stone tool cutting performance (Jobson,  
126 1986; Key and Lycett 2015; Key et al. 2016; Merritt, 2016), the relative influence that this  
127 morphological trait has on the forces required to cut materials with stone tools has never been examined  
128 in conditions absent of human actors (although also see Collins’ [2008] investigation of scraping cutting  
129 actions that, although did not record force, used a mechanised rig). Furthermore, it is not known how  
130 any influence that edge angle variation may have varies alongside differences in edge sharpness.

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

140

## 141 **2. Methods**

### 142 2.1 Stone Tool Assemblage

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

153

### 154 2.2 Sharpness

155 The complexity of measuring sharpness on cutting edges has been argued to preclude singular  
156 quantitative or qualitative measures being accurately applied during investigations into this phenomena  
157 (Reilly et al., 2004). In 2007 McCarthy et al. proposed the first dimensionless quantitative measure for  
158 calculating an edge's sharpness. The 'blade sharpness index' (BSI) is a dimensionless metric dependent  
159 on the force required to initiate a cut in a substrate, the fracture toughness and thickness of the worked  
160 material, and the indentation depth required prior to a cut being formed in the material. Although  
161 McCarthy et al (2007) did not account for an edge's geometry (and therefore tip radius), Schuldt et al.  
162 (2016) independently demonstrated that BSI is not only suitable for characterising the sharpness of a  
163 cutting edge (although this is dependent on material context), but is a linear function of an edge's tip  
164 radius and the force required at cut initiation. Further, Schuldt et al. (2016: 19) established that the cut  
165 initiation depth and force at cut initiation of an edge are suitable as "simple and fast sharpness  
166 characterization[s] for a specific cutting application." In other words, for a specific material (substrate)  
167 type and speed of cut, the material indentation (deformation/displacement) required prior to a cut  
168 initiating, and the force required to achieve the initiation of the cut, are reliable indicators of an edge's  
169 sharpness. Thus, following McCarthy et al. (2007) and Schuldt et al. (2016), we utilise mechanical  
170 records of sharpness as opposed to those defined solely from geometric attributes of cutting edges (e.g.  
171 edge radii). Specifically, we use vertical force (N), material displacement (mm) and work (J) at the  
172 point of cut initiation.

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

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

187

### 188 2.3 Cut Substrate

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

200

### 201 2.4 Indentation Cutting and Testing Station

202 Force and material displacement were recorded here using a universal testing system (Instron® 5500).  
203 Amongst other features, the Instron® allows for controlled compressive testing where the upper grip of  
204 the device lowers at a predefined speed and records both distance moved and resistance provided in the  
205 opposing direction. Both the flakes and steel blades were secured into the upper grip of the Instron®  
206 using wooden blocks (Figure 1). The cutting edge on the flakes and blades was horizontal in all

207 instances (Figure 3). The PVC was used in 100mm lengths and secured such that the cutting edges were  
208 perpendicular to the length of PVC. Each end of the PVC was secured between two wooden blocks  
209 using a vice. Coarse sandpaper attached to the blocks provided increased friction. The combination of  
210 the rough surface and the compressive force prevented any movement of the PVC during testing. A  
211 30mm gap was left between the pair of wooden blocks, across which the PVC stretched and into which  
212 the cutting edges were lowered (Figure 3).

213 The crosshead, into which the grip and flakes/blades were fixed, was lowered prior to the test initiating  
214 so that the tip of the cutting edges were in contact with the surface of the PVC at its midpoint (i.e. it  
215 was 15mm on either side to the wooden blocks) but exerting no force. At this point the displacement  
216 (distance moved) reading was set to zero. The blades were lowered into each material at a rate of  
217 20mm/min. Displacement (mm) and force (N) levels were recorded for each controlled cut, which  
218 continued until the blade passed through the PVC in its entirety. The sampling frequency in all tests  
219 was 10 Hz. All flakes and metal blades were tested six times, once with each of the sharpness conditions.

220

## 221 2.5. Data Analysis

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

239 Differences in work between the six sharpness conditions for both tool types were similarly examined  
240 with Mann-Whitney U tests. Again, tests were only conducted between sequential conditions and  $\alpha =$   
241  $.01$ . Work refers to the energy (J) required to perform a cut and is calculated as the area beneath the



242 load displacement curve (Figure 5). Given that the curves were constant in shape we treated each as a  
243 triangle from the point of cut completion such that area ( $a$ ) equalled half of force ( $F$ ) multiplied by  
244 displacement ( $d$ ) ( $a = 0.5 \times (F \times d)$ ). Significant differences in work between any two conditions will  
245 indicate that the relative sharpness differences between flakes are enough to significantly influence how  
246 much energy is required during their use.

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

252

### 253 3. Results

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

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

274 Linear regressions run between edge angle and force, material displacement and work identified  
275 significant relationships on all occasions (Table 4). Thus, across all sharpness conditions examined

276 here, the angle present on the working edge of the stone flakes significantly influenced their cutting  
277 performance. Indeed, as edge angles increased, the forces, material displacement and work required to  
278 initiate cuts in the PVC also increased (Figure 7). During sharpness condition one, when the flake edges  
279 were in their ‘fresh’ condition, approximately 40% of the variation in force, displacement and work  
280 could be attributed to edge angle values. As edges became increasingly more blunt from conditions two  
281 through to six,  $R^2$  values (and therefore the force or displacement variation explained as a result of edge  
282 angle) dropped such that edge angle variation only accounted for approximately 20% of force,  
283 displacement and work in the final condition (Table 4).

#### 284 4. Discussion

##### 285 4.1 Sharpness

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

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

303 Although the attribute of sharpness has previously been mentioned within Palaeolithic literature (e.g.  
304 Jones, 1980; Buchanan, 2006; Dewbury and Russell, 2007; Braun et al., 2008), it has rarely been  
305 discussed in terms of how it influences cutting performance or its potential behavioural implications.  
306 Here, we present the first evidence indicating that it would have been of significant benefit to stone tool  
307 using individuals to maintain a sharp edge on their lithic cutting implements. This is consistent with  
308 previous mechanical and ergonomic research identifying increased cutting force requirements as metal  
309 cutting edges become increasingly more blunt and tip radii increase (Arcona and Dow, 1996; McGorry  
310 et al., 2003; Atkins, 2009; Schuldt et al., 2013). Furthermore, we demonstrate that a single abrasive

311 stroke against a tool's cutting edge is enough to significantly decrease its functional performance and,  
312 in turn, significantly increase the work required during its use. Reductions in tool performance as a  
313 result of edge blunting (i.e. reductions in sharpness) therefore have the potential to be of concern from  
314 the very start of a tool's use-life. After an initial rapid reduction in performance, however, and as  
315 demonstrated here in conditions three to six, abrasive cutting actions would have a more limited impact  
316 on cutting performance. That is, abrasive cutting actions will continue to result in increased blunting  
317 and tool-performance reductions, just at a considerably reduced rate.

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

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

347 The remaining two potential responses involve the replacement of the blunted edge with one that is  
348 sharper. This behaviour is more likely to be enacted within task-conditions that infrequently invoke  
349 cutting actions against hard, and therefore more abrasive, materials. Examples include butchery  
350 behaviours (perhaps excluding disarticulation [Braun et al., 2008]) and cutting non-domesticated green  
351 vegetation (van Gijn and Little, 2017). Essentially, if an edge is more likely to stay sharp for extended  
352 periods of use, and thus display high efficiency rates for longer, then there are greater benefits to tool-  
353 users by replacing dull edges. Specifically, there is the potential that the time and energy saved by the  
354 use of sharp edges will outweigh any costs associated with the edge's replacement. As already  
355 mentioned, there are two potential options for tool users when doing this. The first option is to replace  
356 the whole tool. This option is more likely to be enacted when using expedient tool types that display  
357 low investment costs or curation (Vaquero and Romagnoli, in press); flake and blade technologies are  
358 clear examples in this regard. That is, given the more limited raw material costs and relative ease  
359 associated with the production of such tools, the replacement of the whole tool (or a specific lithic object  
360 within a composite tool [e.g. a sickle]) would be preferential relative to the continued use of a tool  
361 displaying reduced efficiency. The second option that involves the replacement of a dull edge is the  
362 renewal, or resharpening, of a tool's cutting edge. This option is more likely to be undertaken in tools  
363 displaying greater production and transportation costs due to the associated greater requirements to  
364 maintain use-life durations and avoid the replacement of the whole tool. Certainly, functionally  
365 dependent resharpening behaviours must be balanced against raw material availability (Clarkson et al.,  
366 2015). Example technologies include scrapers, handaxes and other bifaces, and projectile points.

367 Given the frequency with which blunting events could have occurred and the significant impact this  
368 would have on stone tool performance, we argue the replacement of blunt edges would have been  
369 frequently undertaken within many Palaeolithic tool-use situations, potentially occurring multiple times  
370 during a single task (although, as already highlighted, this would be task-type dependent). There is,  
371 then, the potential for the use-life of many Palaeolithic implements to have been substantially shorter  
372 than typically thought. With regards to more expedient tool types in particular, the rapid rate at which  
373 blunting can occur would lead to a high turnover of tools and, in turn, the dense accumulation of  
374 artefacts within the archaeological record (e.g. Waters et al. 2011), occasionally even resulting in 'lithic  
375 landscapes' in which the production of stone flakes may have influenced local ecology (Foley and Lahr  
376 2015). These examples support the notion that, at times, rapid reductions in performance as a result of  
377 early stage blunting led to the rapid replacement of stone tools during use.

378 Similarly, a requirement to frequently resharpen an edge would reduce the use-life of a tool, increase  
379 their turnover in production, and ultimately increase their prevalence within archaeological deposits.  
380 Further, the present results reemphasise that the identification of limited resharpening events on some  
381 stone tool artefacts and their discard prior to resharpening exhaustion is indicative of a short use-life  
382 (e.g. Shipton and Clarkson, 2015). Given the considerable size variation observed in some stone tool

383 types displaying modified edges (e.g. Gowlett, 2015), there is also the potential for some of this  
384 variation to have been caused by the duration of cutting tasks as this would directly influence the number  
385 of resharpening events required. While artefact size has frequently been linked to resharpening events  
386 and tool-use durations before (e.g. Dibble, 1987; McPherron, 1999; Buchanan, 2006; Iovita, 2011; Eren,  
387 2013; Lin, in press), the present results highlight that even relatively limited periods of use could lead  
388 to a substantial number of edge renewal events, and in turn, rapid alterations to tool forms. In short, the  
389 results presented here emphasise how important resharpening behaviours were likely to have been to  
390 the maintenance of functional efficiency in some stone tool types.

391 Evidence that, at times, past individuals responded to blunting events by either continuing to use dulled  
392 edges or repeatedly replacing them are, arguably, present via microwear analyses of the working edges  
393 of Palaeolithic artefacts. As demonstrated through numerous experiments (Keeley, 1980; Bamforth,  
394 1988; Evans et al., 2014; Stemp et al., 2015), the greater the duration and/or force of use a lithic edge  
395 is subject to, the more developed that wear traces on a tool are likely to be. Hence, in instances where  
396 implements with clear and functionally diagnostic microwear traces have been recovered  
397 archaeologically, there is evidence that individuals likely used these tools for extended periods and may,  
398 plausibly, have continued to use these implements subsequent to early stage blunting and its associated  
399 significant reductions in cutting performance. Particularly if wear traces or residues suggest a tool has  
400 been used to cut wood, stone, antler or bone (e.g. Hardy and Moncel, 2011; Zupancich et al., 2016;  
401 Yravedra et al., 2017). As repeatedly noted throughout >40 years of microwear analyses, however,  
402 artefact assemblages rarely display high proportions of tools with diagnostic wear traces (Keeley, 1980;  
403 Donahue et al., 2004; Lemorini et al., 2006; Solodenko et al., 2015). At times the presence of artefacts  
404 without clear wear traces has been interpreted as indicating that they were not utilised (e.g. Miller, 2014;  
405 Rots et al., 2015). The results presented here emphasise the likelihood of the alternative possibility that  
406 these tools may have been used, but were instead discarded, or their edges were resharpened, subsequent  
407 to early stage blunting events and their associated significant decreases in functional performance.

#### 408 4.2. Edge Angle

409 The angles observed on the functional edges of stone tools are of known consequence to their cutting  
410 capabilities (Jones, 1980; McCall. 2005; Collins, 2008; Key and Lycett, 2015; Key et al. 2016).  
411 Presented here is evidence identifying the impact that edge angle variation has on a stone tool's ability  
412 to cut in the absence of human actors, and how this varies in relation to sharpness. Regressions across  
413 all six sharpness conditions identified significant relationships between increasing edge angle values  
414 and greater force, material displacement and work requirements. As far as the present analyses can  
415 demonstrate, then, the angles observed on the working edges of stone tools significantly influence  
416 cutting performance irrespective of any edge sharpness variability. It should, however, be noted that  
417 although each flake performed five abrasive cutting strokes here, we can only speak to the relationship

418 between edge angle and sharpness up until this point. As highlighted by the present  $R^2$  values there is  
419 cause to believe that this relationship does vary and that as edges become progressively less sharp (i.e.  
420 more blunt), edge angle has a more limited impact on cutting. This is likely caused by sharpness levels  
421 having a greater impact on cutting forces as edges become blunter due to the associated reduction in  
422 cutting stress and, in turn, the proportionately greater amount of force that is required to perform a cut.  
423 Whether or not there is a point beyond which edges become so blunt that edge angle does not  
424 significantly contribute to cutting performance it is hard to say. It would be interesting if future  
425 experiments could investigate such matters.

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

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

449 It is important to note that the results presented here, for both sharpness and edge angle, have been  
450 determined using stone tools with straight, non-modified cutting edges and in conditions absent of  
451 human actors. Indeed, given the high internal validity provided by the methods used here (Mesouri  
452 2011; Lycett and Eren 2013; Eren et al., 2016), there are unlikely to be any variables other than those

453 investigated (sharpness and edge angle) contributing substantially to force, displacement and work  
454 variation. In turn, there is the potential for the relationships identified here to vary once more variables,  
455 such as edge scalloping, tool-size, tool-user strength, and other factors contribute to a tool's functional  
456 performance. Moreover, when tools are applied within actualistic conditions displaying high external  
457 validity, there is potential for additional task-dependent variables to influence the mechanical  
458 relationship between a tool's edge and the worked material (e.g. an accumulation of fatty tissues on an  
459 edge). It is also notable that the PVC utilised here is a relatively resistant material and did not require  
460 cuts to be performed at any great depth into the material. The former meant that on a couple of occasions  
461 very acute stone edges formed micro-fractures prior to cuts initiating, in turn, potentially increasing  
462 their required forces. The latter similarly suggests that had cuts been performed at greater depth within  
463 a material, increased friction would likely have been acting on cutting edges (Komanduri et al., 1998;  
464 Reilly et al., 2004; Atkins, 2009), in turn potentially increasing any influence that edge angle may have.  
465 Essentially, both suggest that edge angle may have had a greater impact had the material context of the  
466 task been slightly different. Future experiments may profitably investigate these points.

467

## 468 5. Conclusion

469 The calculation of the BSI detailed by McCarthy et al (2007) and Schuldt et al. (2016) may be beyond  
470 many without an engineering background. As demonstrated here (and elsewhere [Schuldt et al., 2016])  
471 a straightforward and relatively accessible method for archaeologists to test stone tool sharpness and its  
472 impact on cutting performance is the measurement of force, material displacement and work. We have  
473 shown that sharpness not only significantly influences these three variables when using a stone tool, but  
474 any impact caused by blunting occurs rapidly, with as little as a single abrasive cutting stroke causing  
475 ~38% increases in force requirements and 70% increases in work (energy expenditure). The impact of  
476 edge angle variation on cutting performance has also been shown to co-vary with edge sharpness, with  
477 edge-angle variation having greater influence on cutting performance the sharper the cutting edge. As  
478 discussed, there is the potential for these mechanical relationships to have impacted on the tool-  
479 production and use behaviours of Palaeolithic individuals and, in turn, have left morphologically visible  
480 traces in the artefact record. Certainly, the rapid rate at which stone tools blunt, and their cutting  
481 performance consequently decreases, indicates that the use-lives of lithic artefacts (or more specifically  
482 their cutting edges) may have been far shorter than typically thought. Rapid reductions in tool  
483 performance as a result of blunting may, in turn, account for the abundance of lithic artefacts recovered  
484 from some archaeological sites, the speed with which resharpening behaviours altered tool forms, and  
485 the lack of microscopic wear traces on many lithic implements.

486

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494

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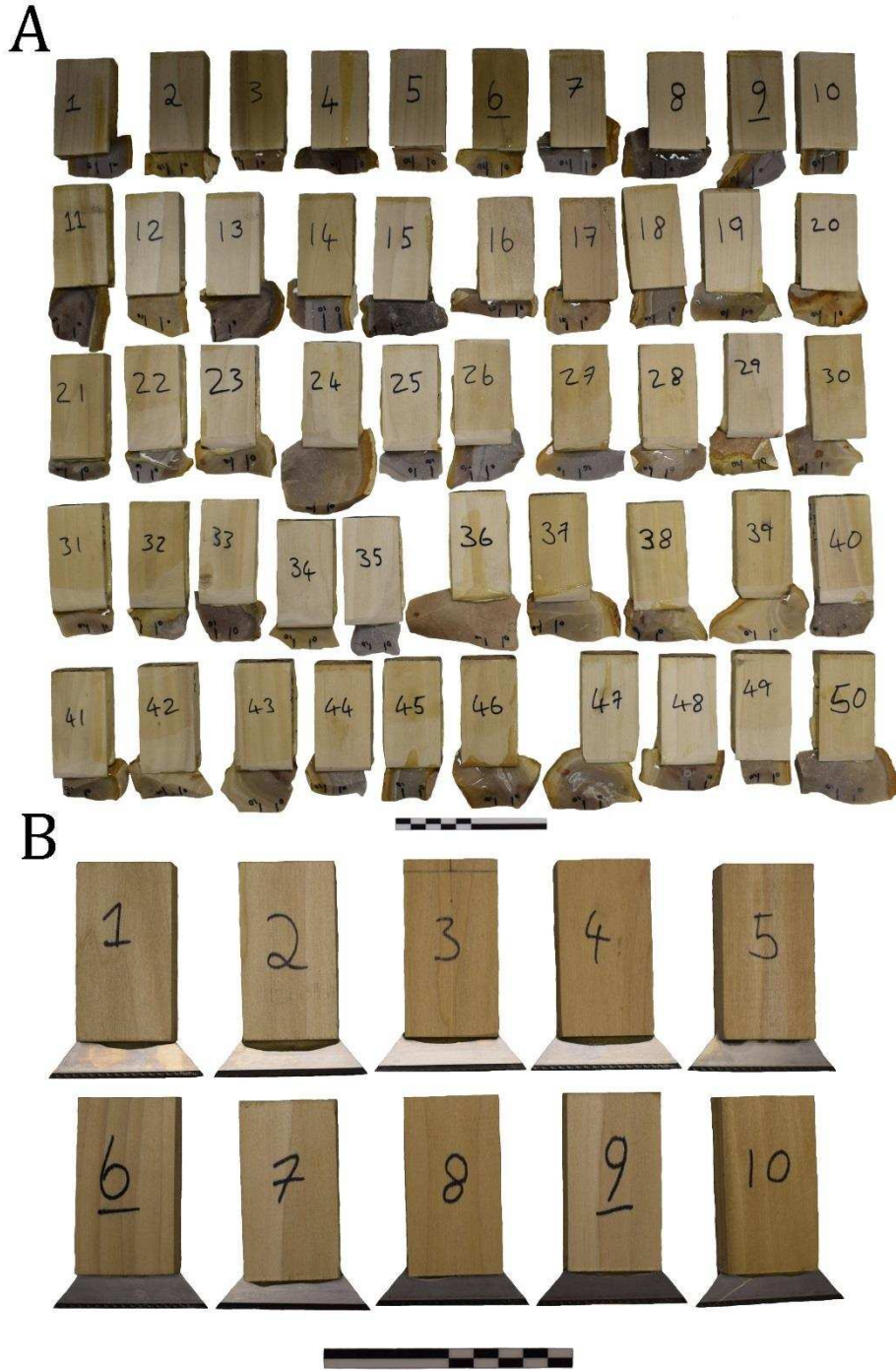
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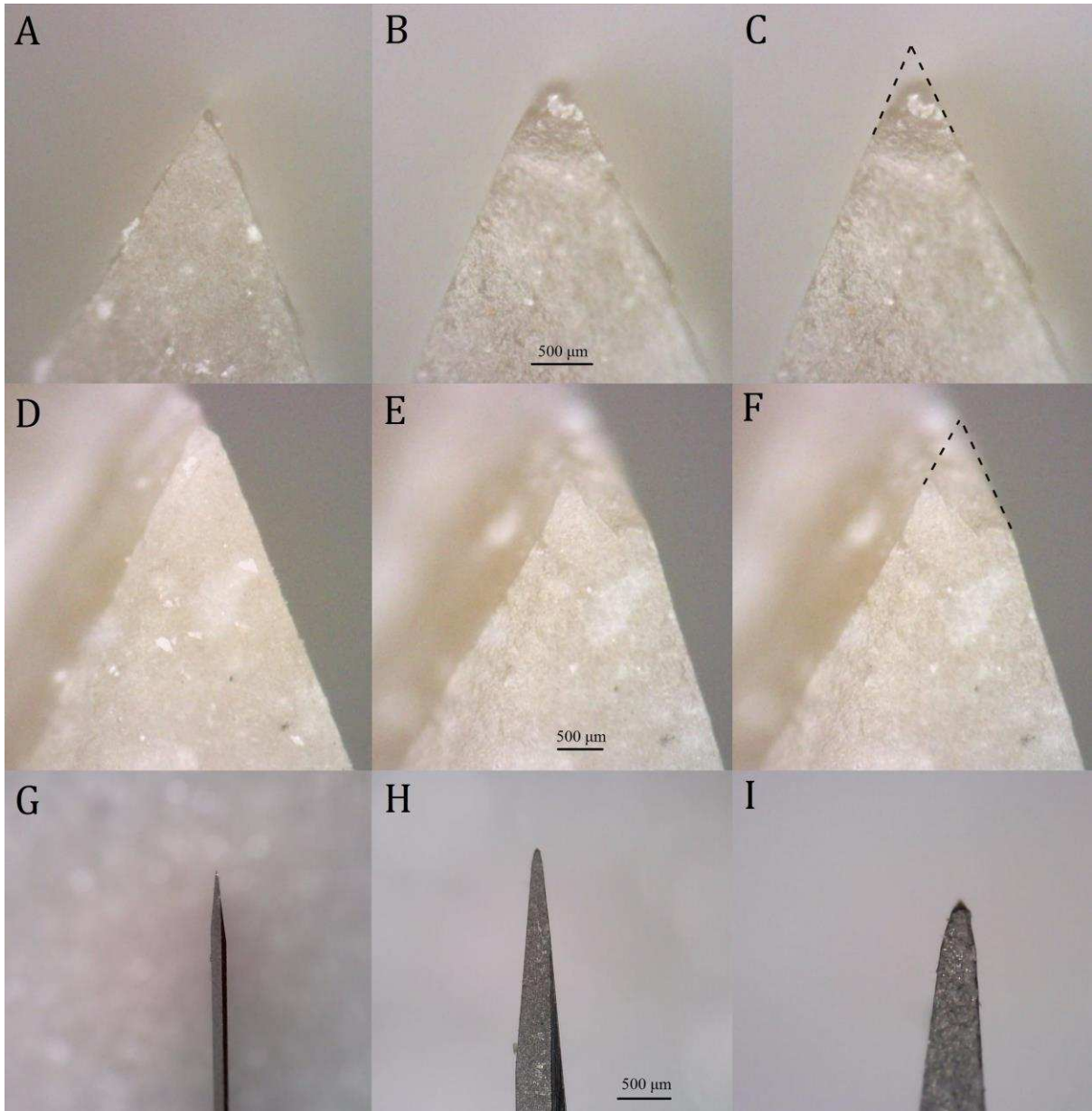
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663 Figures



664

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



667

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

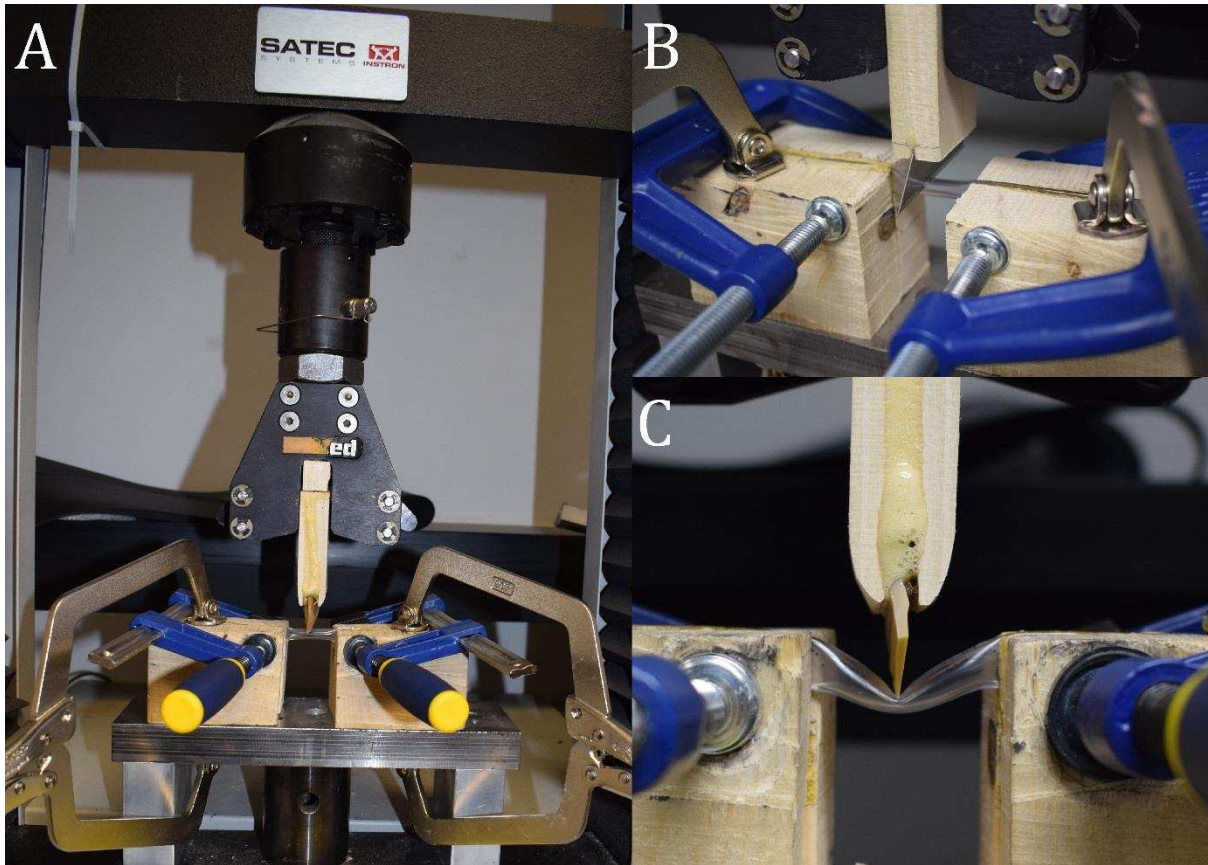
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679 Figure 3: The material set-up and Instron® testing station. Depicted are two of the stone flakes (A, C)  
680 and one metal blade (B). Image (C) illustrates the displacement of the PVC prior to a cut initiating.

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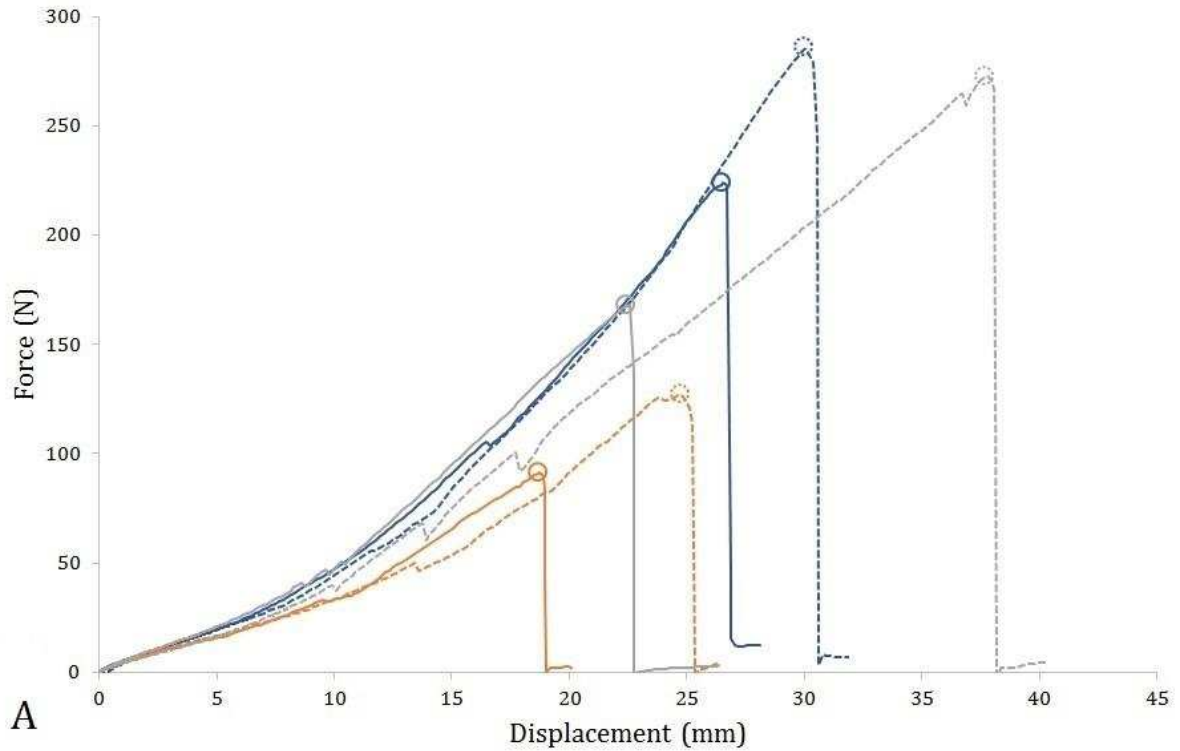
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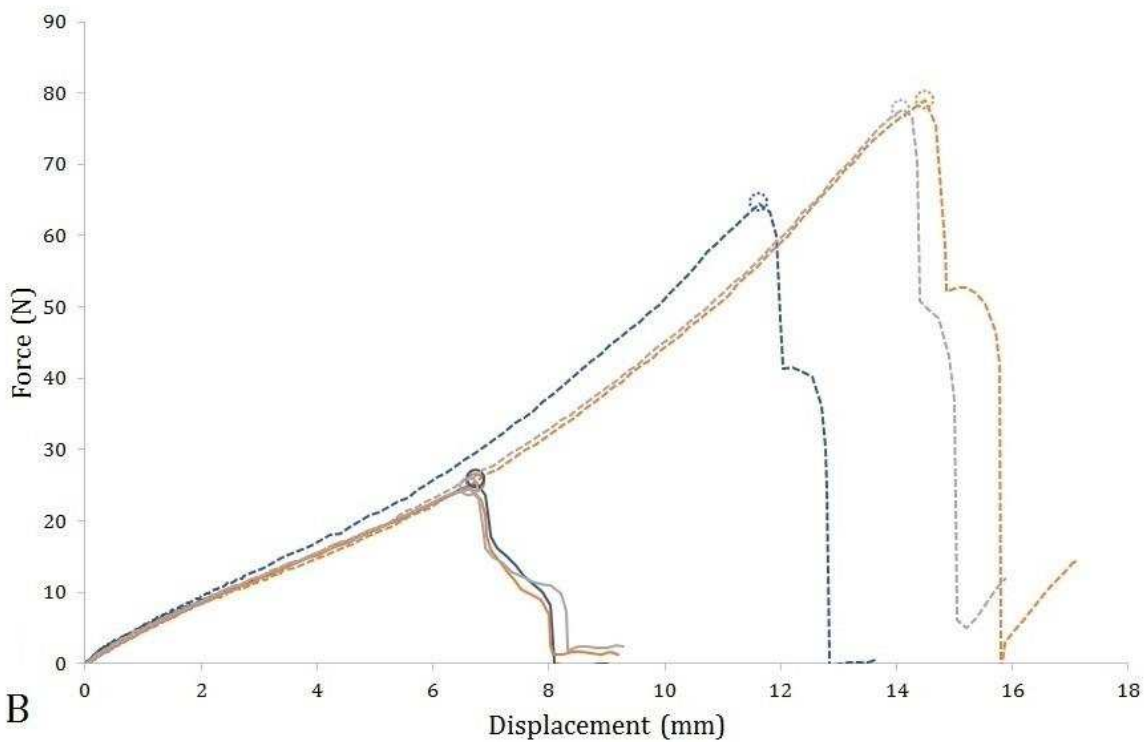
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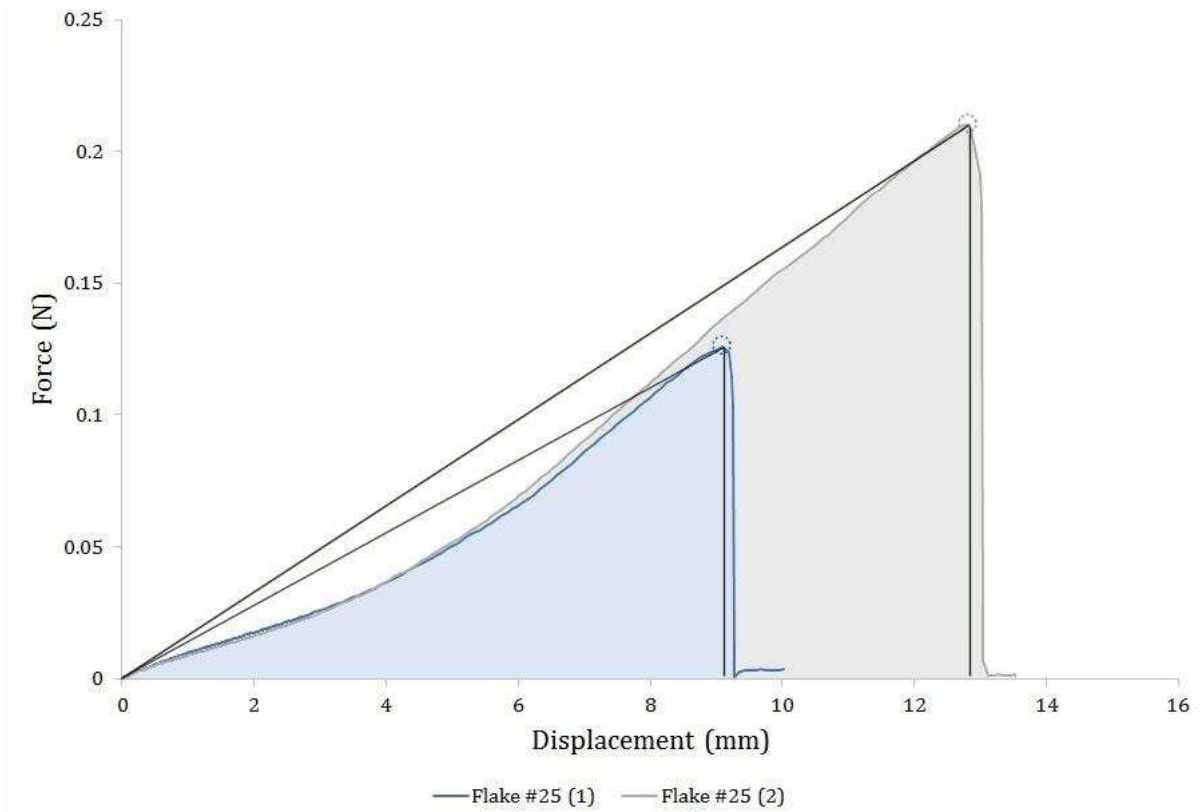
— Flake #10 (1) - - - Flake #10 (2) — Flake #34 (1) - - - Flake #34 (2) — Flake #47 (1) - - - Flake #47 (2)



— Blade #1 (1) - - - Blade #1 (2) — Blade #3 (1) - - - Blade #3 (2) — Blade #5 (1) - - - Blade #5 (2)

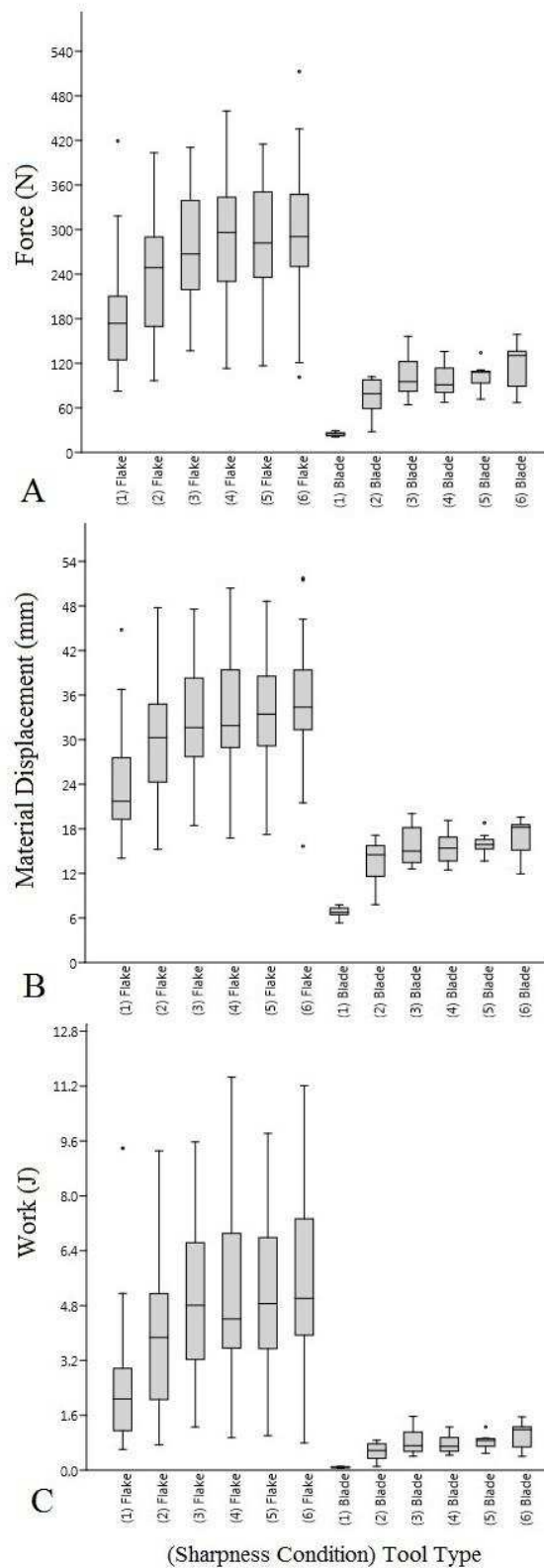
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694 Figure 4: Load displacement curves depicting typical tests with stone flakes (A) and metal blades (B).  
 695 Data for each tool has been plotted for both conditions one (1) and two (2). Data values highlighted by  
 696 circles indicate that point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



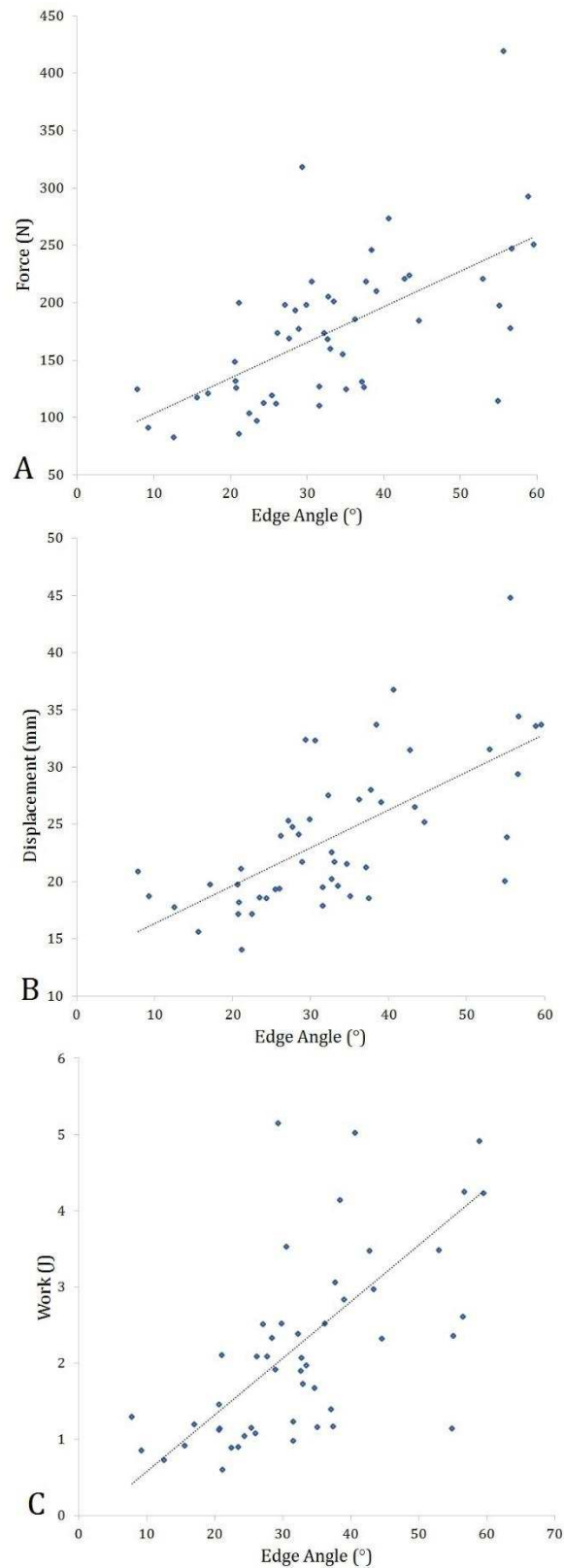
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698 Figure 5: Load displacement curves identifying the area used to calculate work (J) during a cut. Depicted  
 699 here are conditions one (1) and two (2) for stone flake #25, the actual area of work for these cutting  
 700 tests, and the work calculated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



701

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



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

711 **Tables**

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

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

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737 Table 2: Descriptive data for force (N), displacement (mm) and work (J) values during each of the six  
 738 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. (%)
<b>1 (0)</b>	175.7	65.9	37.5	24.0	6.4	26.8	2.3	1.6	68.4
<b>2 (1)</b>	242.8	79.8	32.9	30.1	7.6	25.3	3.9	2.1	54.6
<b>3 (2)</b>	280.9	74.0	26.3	32.8	7.1	21.6	4.8	2.2	45.1
<b>4 (3)</b>	284.5	78.8	27.7	33.5	7.3	21.9	5.0	2.3	46.3
<b>5 (4)</b>	285.8	73.5	25.7	33.9	7.1	21.0	5.1	2.2	42.5
<b>6 (5)</b>	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. (%)
<b>1 (0)</b>	24.6	2.8	11.2	6.7	0.7	10.6	0.084	0.017	20.6
<b>2 (1)</b>	74.5	24.1	32.4	13.4	2.9	21.7	0.532	0.254	47.7
<b>3 (2)</b>	102.2	28	27.4	15.7	2.5	16.1	0.832	0.366	44.0
<b>4 (3)</b>	97.9	23.2	23.7	15.6	2.2	14.4	0.787	0.296	37.6
<b>5 (4)</b>	102.9	16.6	16.1	16.0	1.4	8.7	0.830	0.204	24.5
<b>6 (5)</b>	120.2	29.2	24.3	17.2	2.4	14.1	1.063	0.366	34.5

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

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

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

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

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