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1 **A Biomechanical Investigation of the Efficiency Hypothesis of Hafted Tool Technology**

2 Dominic Coe¹, Larry Barham¹, James Gardiner², and Robin Crompton²

3 ¹School of Archaeology, Classics and Egyptology, University of Liverpool, Liverpool, L69 7WZ

4 ²Institute of Life Course and Medical Sciences, University of Liverpool, Liverpool, L7 8TX

5

6 **Abstract**

7 The transition from hand-held to hafted tool technology marked a significant shift in conceptualising
8 the construction and function of tools. Amongst other benefits, hafting is thought to have given users
9 a significant biomechanical and physiological advantage in undertaking basic subsistence tasks
10 compared with hand-held tools. It is assumed that addition of a handle improved the (bio)mechanical
11 properties of a tool and upper limb by offering greater amounts of leverage, force, and precision.

12 This controlled laboratory study compares upper limb kinematics, electromyography and physiological
13 performance during two subsistence tasks (chopping, scraping) using hafted and hand-held tools.
14 Results show that hafted tool use elicits greater ranges of motion, greater muscle activity, and greater
15 net energy expenditure compared with hand-held equivalents. Importantly, however, these strategies
16 resulted in reduced relative energy expenditure compared with the hand-held condition in both tasks.
17 More specifically, the hafted axe prompted use of two well-known biomechanical strategies that help
18 produce larger velocities at the distal end of the limb without requiring heavy muscular effort, thus
19 improving the tool's functional efficiency and relative energy use.

20 The energetic and biomechanical benefits of hafting arguably contributed to both the invention and
21 spread of this technology.

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26

27 **Keywords | Energetics**

28 Hafting | Handle | Biomechanics | Palaeolithic | Chopping | Scraping | Energetics | Efficiency

29

30 Introduction and Research Context

31 Humans are distinctive among primates and the wider animal kingdom for dependency on technology
32 to meet basic physiological needs and the close integration of technology in many aspects of their
33 social and personal lives (Biro et al., 2013; Guindon, 2015:79-80). Since its appearance between
34 500,000 to 250,000 years ago (Wilkins et al., 2012; Barham, 2013), the invention of hafted (composite)
35 tool technology represents a key technological transition that has shaped human social, cognitive, and
36 biological capabilities. This new additive technology, with tools made of multiple parts combined into
37 a working whole, has generated considerable interest in its cognitive implications, including the
38 development of language and extended planning (Ambrose, 2001; 2010; Barham, 2010; 2013; Wynn,
39 2009; Wadley, 2010; Haidle, 2010; Hodgskiss, 2014; Sykes, 2015; Fairlie and Barham, 2016; Fairlie,
40 2017).

41 Of the advantages hafting is proposed to have conferred over non-hafted tools (killing power (Wilkins
42 et al., 2014), raw material efficiency (Thieme, 1997; 2003) and reduced contact with biological hazards
43 (Barham, 2013)), the underlying advantage lies in the greater leverage offered by placing working
44 edges in a handle or shaft compared with hand-held tools that typified the Lower Palaeolithic
45 (Oldowan and Acheulean). A hafted tool is generally assumed to increase the energetic efficiency,
46 force and precision that can be applied to a task (Firth, 1925: 286; Odell, 1994; Morrow, 1996; Cowan,
47 1999; Churchill, 2001; Rots et al., 2011; Rots, 2015b). These largely untested assumptions have been
48 consolidated into the 'efficiency hypothesis' of hafted tool technology (Barham, 2013) which argues
49 that the increased biomechanical performance that can be applied to a task reduces energy
50 expenditure and muscular force used. These reductions in physiological and biomechanical demands,
51 as well as demands on energy and time budgets, would enhance both individual and group survival.

52 Despite speculation about the adaptive benefits of hafting and the proposed efficiency hypothesis,
53 very little effort has been made to compare human-hafted and hand-held tool use performance.
54 Morrow (1996) investigated the efficiency (in minutes) of three sizes (small, medium, large) of
55 bifacially flaked knives to saw a hardwood dowel. Hafting a knife blade to a handle improved the
56 functional efficiency of small and medium sized knives over their non-hafted counterparts (Morrow,
57 1996). Reece et al. (1997) recorded muscle recruitment patterns whilst using end-scrapers (hafted)
58 and side-scrapers (hand-held), finding that some thenar muscles (flexor pollicis brevis and opponens
59 pollicis) were recruited at higher levels during hand-held scraping compared with hafted scraping.
60 Conversely, hypothenar musculature (e.g. abductor digiti minimi) was more active during the hafted
61 end-scraping condition. They link the variation in recruitment patterns to morphological differences
62 observed in Neanderthal hands, which provided a greater mechanical advantage to thumbs in
63 precision gripping hand-held tools compared to hands of anatomically modern humans (Niewoehner,
64 2007: 182). Claud et al. (2015) found late Middle Palaeolithic flake cleavers functioned more
65 effectively than hand-held cleavers in both tree felling and carcass butchery tasks as measured by
66 number of blows and time required. More recently, Key et al. (2021) compared the cutting
67 performance of replicated hafted flint knives with effectiveness of non-hafted flint flakes and hand-
68 held large flint bifacial tools across two standardised cutting tasks. They examined ergonomic
69 differences between the tool types using electromyographic (EMG) analysis of nine upper limb
70 muscles involved in gripping (first dorsal interosseous, flexor pollicis longus, abductor digiti minimi,
71 flexor pollicis brevis), and movements of the wrist, elbow, and shoulder (flexor pollicis brevis,
72 brachioradialis, flexor carpi radialis, biceps brachii, triceps brachii, anterior deltoid). The results show
73 that addition of a handle reduces the activity of muscles involved in gripping compared with cutting
74 tools held directly in the hand. Hafted knives also involved greater muscle activity in the upper body

75 with the potential to generate extra force in cutting. The ergonomic and functional advantages of
76 hafted knives support the predictions of the efficiency hypothesis.

77 This study establishes a controlled experimental methodology for comparing both proposed
78 advantages of hafted technology using human dominant-side kinematics, tool velocity (chopping
79 only), selected electromyography and whole body respirometry. The methodological approach
80 combines the advantages of controlled experimentation that allows for repeated trials that minimise
81 variation between variables, with a large sample of participants which enables us to record human
82 interaction with the tools and materials giving the study archaeological relevance (Eren et al. 2016).
83 We test the hypothesis that hafted tool use, and the mechanical lever advantage of a handle, will
84 result in a kinematic pattern of reduced motion across the upper limb. In addition, we test the
85 propositions that hafted tool-use will exhibit a pattern of reduced muscle activity in selected upper
86 limb muscles and that energy use will be significantly reduced as a result.

87 **Materials and Methods**

88 The experiments compared differences in movement, muscle use and oxygen consumption
89 in the context of two different activities that reflect basic subsistence and maintenance activities
90 common in the past: chopping and scraping. Participants with a high level of physical fitness (see
91 Shaw et al., (2012)) were recruited to undertake controlled experiments using hand-held and hafted
92 axes and scrapers.

93

94 **Participants**

95 A total of 40 participants (24 male and 16 females) with no known upper limb musculoskeletal
96 disorders were recruited for this study. The mean participant age was 26.0 (± 4.0) years, mean height
97 173.60 (± 27.36) cm and mean weight 75.26 (± 15.15) kg. All experiments took place in the Evolutionary
98 Morphology and Biomechanics Research Group Gait Laboratory, University of Liverpool over seven
99 months. Each participant's data was collected in a single data collection session. All participants
100 received a verbal and written description of the protocol prior to participation. Following this, each
101 participant provided written informed consent to the lead author (DC). No participants opted to
102 withdraw. All participants were required to wear a glove on their dominant hand during both tasks
103 and safety glasses during the chopping task. The study was approved by University of Liverpool
104 Research Ethics Council (RETH1967).

105

106 **Task Apparatus**

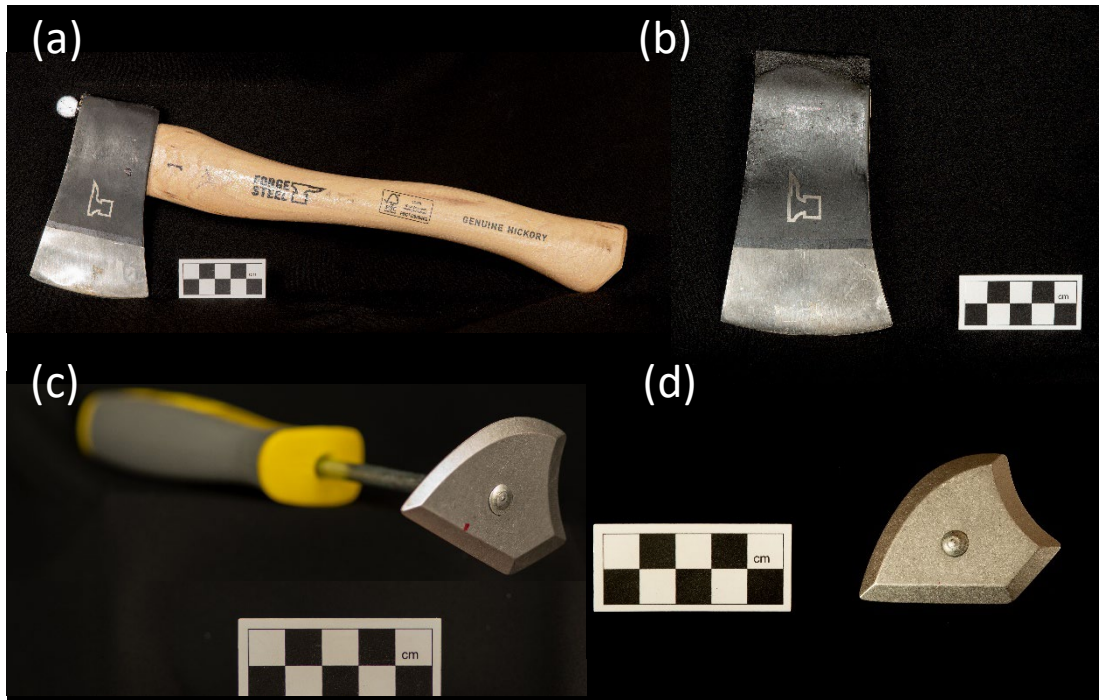
107 The tools selected for the experiments were commercially manufactured, functionally
108 effective and, importantly, allowed for the control of several variables important to the study's
109 primary focus of isolating the biomechanical effect of the handle (tool weight, edge length, edge
110 sharpness, handle length). In both ergonomics (McGorry, 2001; McGorry et al., 2003; 2005) and
111 experimental archaeology (Walker, 1978; Morrow, 1996; Key et al., 2018) the weight and sharpness
112 of a tool has been shown to affect performance and productivity and these were prioritised here.

113

114 The chopping tool was a hatchet (referred to passim as axe) with a forged steel head and hickory
115 handle (Screwfix, UK). In the hafted condition (Fig. 1a), no modifications were made. In the hand-held
116 condition (Fig. 1b), the handle was removed at the base of the axe head. The scraping tool
117 ('Combination Shavehook', Wickes, UK) was designed to be used uni-manually in an anteroposterior
118 pulling motion. No modification was made to the tool used in the hafted condition (Fig. 1c). For the
119 hand-held condition (Fig. 1d), the handle was removed to leave just the scraper head.

120

121 For the chopping task, commercial ash (*Fraxinus spp.*) dowels, 60mm in diameter and 350mm in length
122 (G&S Specialist Timber, UK) were selected for their uniform size and material properties. The diameter
123 selected reduced the risk of being chopped through completely in both hafted and hand-held
124 conditions, whilst still providing a perceived achievable goal. They were also comparable in diameters
125 to wooden implements from the Palaeolithic record (Thieme, 1997; Oakley, 1977; Allington-Jones,
126 2015) and other experimental studies of chopping tasks (Claud et al., 2015). For the scraping task,
127 carpet (80% wool, 20% polyester, Carpet Options, UK) from a single roll was selected to provide a
128 consistent, uniform surface. Carpet is considered a good substitute for large ungulate hide and has
129 been used in previous studies investigating the biomechanical impact of scraping (Shaw et al., 2012).
130



131
132 *Figure 1: Hafted (a) and hand-held (b) chopping tools and hafted (c) and hand-held (d) scraping tools used in experimental*
133 *conditions.*

134 Kinematics

135 Twelve Oqus 7 (Qualisys, Gothenburg, Sweden) motion capture units (MCUs) recording at 200
136 Hz were used to collect three-dimensional motion of the thorax and dominant upper arm, forearm,
137 and hand. A total of thirteen reflective markers were attached to anatomical landmarks of the torso
138 and dominant upper limb, following ISB (International Society of Biomechanics) recommendations
139 (Wu et al., 2005) (Table 1). In addition, two, four-marker cluster plates were placed in the upper arm
140 and forearm to track upper and forearm movement. An additional marker ('Axe') was placed on the
141 top of the axe head in the hafted condition to assess velocity of the tool. No 'Axe' marker was attached
142 in the hand-held condition to avoid an obstacle in grasping the tool as well as concerns with accurate
143 visibility of the marker throughout the task. Given the proximity of the MCP3 marker (~2cm) to the
144 axe-head, we consider this a reasonable substitute to measure velocity.
145

Segment definitions			
Segment	Geometry	Defining Markers	Tracking Markers
Trunk	Cylinder	C7, IJ, midC7IJ (calc) T8, PX, midT8PX (calc) RAC LAC	C7 T8 IJ PX
Upper Arm	Cone/Cylinder	Proximal: GHJC (calc) Distal: EM, EL, EJC (calc)	UAPP, UAPA, UADP, UADA
Forearm	Cone/Cylinder	Proximal: EM, EL, EJC Distal: RS, US, WJC (calc)	FAPP, FAPA, FADP, FADA
Hand	Sphere	Proximal: RS, US, WJC Distal MCP3, MCP5 HJC (calc)	WJC (calc), MCP3, MCP5
Joint Coordinate System (JCS) definitions			
Joint	Segment	Reference Segment	Axes: Motions
Trunk	Trunk	Virtual Lab	X: Flexion/Extension Y: Lateral Flexion Z: Axial Rotation
Glenohumeral	Upper Arm	Trunk	X: Flexion/Extension Y: Abduction/Adduction Z: Internal/External Rotation
Elbow	Forearm	Arm	X: Flexion/Extension
Wrist	Hand	Radius	X: Flexion/Extension Y: Ulnar/Radial Deviation Z: Pronation/Supination
Key: C7 – Spinous process of 7 th cervical vertebrae; T8 – Spinous process of 8 th thoracic vertebrae; IJ – Suprasternal notch; PX – Most caudal point on the sternum; RAC/LAC – Right and left acromioclavicular joint; EM – Medial epicondyle; EL – Lateral epicondyle; RS – Radial styloid; US – Ulnar styloid; MCP3 – 3 rd metacarpophalangeal joint; MCP5 – 5 th metacarpophalangeal joint; UAPP, UAPA, UADP, UADA – Upper arm plate; FAPP, FAPA, FADP, FADA – Forearm plate.			

147
148

149 Electromyography

150 Eleven Trigno (Delsys, Boston, MA, USA) sensors were placed on the dominant side over the
 151 latissimus dorsi, upper trapezius, anterior deltoid, medial deltoid, posterior deltoid, pectoralis major
 152 (clavicular), biceps brachii, triceps brachii, brachioradialis, forearm extensor bundle (extensor
 153 digitorum, extensor carpi radialis, extensor carpi ulnaris), forearm flexor bundle (flexor digitorum,
 154 flexor carpi radialis, flexor carpi ulnaris). Placement of each sensor followed guidelines set out by
 155 Criswell (2010). Before electrode placement, the skin over each muscle was prepared by shaving hair
 156 and cleaning with alcohol. Before data collection, participants performed eight maximal tests
 157 developed by Boettcher et al. (2008) and Ginn et al. (2011) to produce maximum voluntary
 158 contractions (MVCs) for each muscle. Each MVC test was performed in a random order three times,
 159 each lasting five seconds. Between repetitions, participants were given a thirty second rest and
 160 between each test a minimum of one-minute. These data were used to normalise participant EMG
 161 data relative to their peak MVC activity (%MVC).

162

163 Respirometry

164 A Cosmed K5 (Cosmed, Rome, Italy) pulmonary gas exchange system that uses indirect
 165 calorimetry to estimate energy expenditure (EE) was used to measure participants' energy use during
 166 hafted and hand-held tool use. The K5 system used oxygen consumption (VO₂) and carbon dioxide
 167 production (VCO₂), converted to EE using formulae developed by Weir (1949) (Levine, 2005). Before
 168 data collection, participants' resting metabolic data was collected. Participants were required to lie

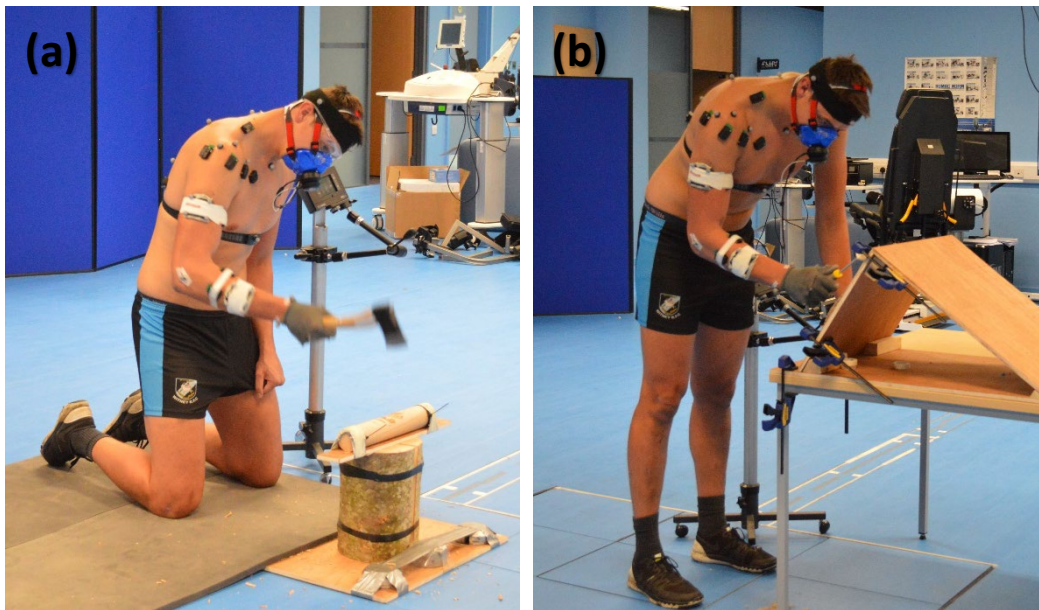
169 prone for fifteen minutes after a period of at least two hours fasting. These data were used to
170 normalise respirometry data by calculating net energy expenditure for each task and condition.

171

172 Experimental Protocol

173 The Cosmed K5 was fitted first and resting EE collected. EMG electrodes were applied,
174 followed by MVC trials from the eight muscle tests. Next, kinematics markers were affixed to
175 participants and a static trial performed. Last, the data collection protocol commenced in a random
176 order. For each task and condition, participants completed the activity continuously for five minutes
177 at a pace they deemed capable of maintaining. Participants were provided with at least ten minutes'
178 rest between task conditions to ensure fatigue was not a factor in task performance. The chopping
179 task was to remove as much wood as possible from the wooden dowel within five minutes. The task
180 was completed kneeling a comfortable distance from the wooden dowel, secured horizontally in front
181 of them(Fig. 2a). Kneeling was selected for the chopping task as the safest posture to use, significantly
182 reducing the risk of injury. In this position, miss-strikes would follow through into the ground rather
183 than into participants' feet, legs, or torso. For the scraping task, participants were instructed to
184 remove as much carpet fibre as possible in five minutes without damaging the carpet base. This task
185 required participants to be in a standing position, supported by their non-dominant arm if preferred.
186 The carpet tile was attached to a board at an oblique angle (60°) (Fig. 2b).

187



188
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Figure 2: Study participant performing hafted conditions of chopping (a) and scraping (b) tasks.

190

191 Data Processing

192 Initial processing of kinematics data used Qualisys Track Manager 2.17 (QTM) software.
193 Markers were identified, labelled, and 10 motion cycles were isolated in the 2nd, 3rd and 4th minute
194 of activity. These motion cycles were then exported to Visual3D (C-Motion, Germantown, Maryland,
195 USA) where motion data was filtered using a low pass, 4th order Butterworth filter and local
196 coordinate systems were defined for each body segment (trunk, arm, forearm and hand). A kinematic
197 model was created using a hybrid approach that included both Gates et al. (2016) and Rab et al. (2002)
198 methods. Kinematic data was time-normalised from the highest point in the Z axis of the MCP3 marker
199 (0%) to the subsequent highest point in the Z axis (100%). All normalised motion cycles were combined
200 for each participant to create a mean representative cycle waveform for each intersegmental angle.

201

202 To assess velocity characteristics, 3D co-ordinates for the 'Axe' and 'MCP3' markers from the hafted
203 trial and 'MCP3' from the hand-held trial were exported from QTM. In Matlab, the co-ordinate data
204 were filtered using the same low pass 4th order Butterworth filter in line with the kinematics data.
205 Marker co-ordinates were used to calculate marker displacement and marker velocity, expressed as
206 meters per second (m/s). Participant data were averaged to produce mean participant velocity for
207 each marker across the chop cycle and action cycles (0 – 100%) created using the same method as for
208 kinematics data.

209
210 Raw MVC and trial EMG data was high pass filtered (40Hz, [zero lag], 4th order Butterworth), full wave
211 rectified, then low pass filtered (5Hz, [zero lag], 4th order Butterworth) using Matlab 2019b (The Math
212 Works, Natick, MA). The peak value for each muscle from the MVC trials was identified to determine
213 maximum activation for each muscle. This value was used to normalise trial data to %MVC across the
214 motion cycle. The EMG data were time normalised in the same manner as kinematics data.

215
216 Respirometry data were automatically converted and expressed as energetic expenditure per minute
217 by the K5 device. All further processing was completed in Matlab 2019b. Data were low pass filtered
218 (5Hz, [zero lag], 4th order Butterworth) following recommendations of Robergs et al. (2010). Mean
219 resting energetic expenditure was calculated from the last twelve minutes of the 15-minute rest
220 period. Mean trial energetic expenditure was calculated from the last four minutes of the task
221 condition. Net energy expenditure (EE) was calculated by subtracting resting EE from mean trial EE.
222 Last, 'cost of activity' EE (CoA EE) was calculated by dividing net EE in with 'measure of performance
223 (MoP) for each participant. MoP was a quantifiable measure of a participant's performance in each
224 task and condition. For chopping, the volume of wood removed from the wooden dowel was
225 calculated by subtracting post-chopping volume of the dowel from original volume of the dowel using
226 models created using a DAVID SLS-2 scanner (Hewlett-Packard, Palo Alto, Cali., USA) (Fig. 3). To
227 calculate original volume, custom Matlab code that applied convex hull methodology was used. To
228 calculate post-chopping volume, each model was imported into Geomagic Studio 10 (3D Systems,
229 N.C., USA) and volume was calculated using a built-in function. MoP for the scraping task was
230 calculated as weight of fibre removed from the carpet tiles.

231

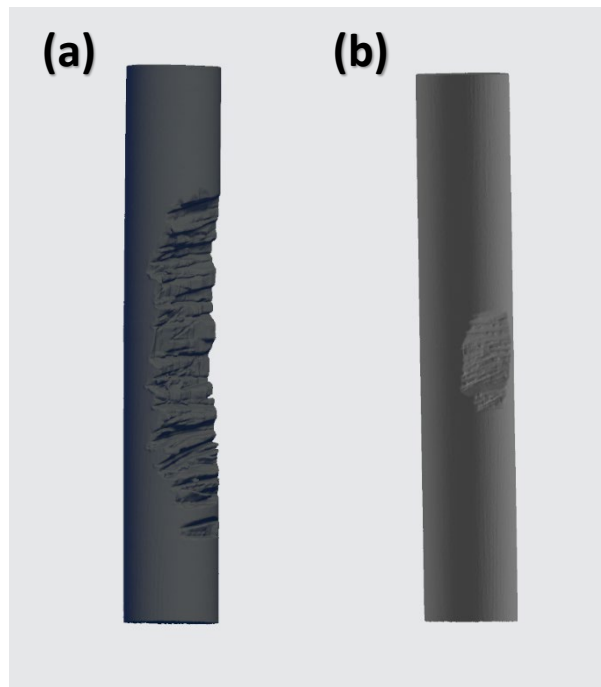


Figure 3: Example 3D models of wooden dowels chopped during the hafted (a) and hand-held (b) chopping conditions.

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235 Data Analysis

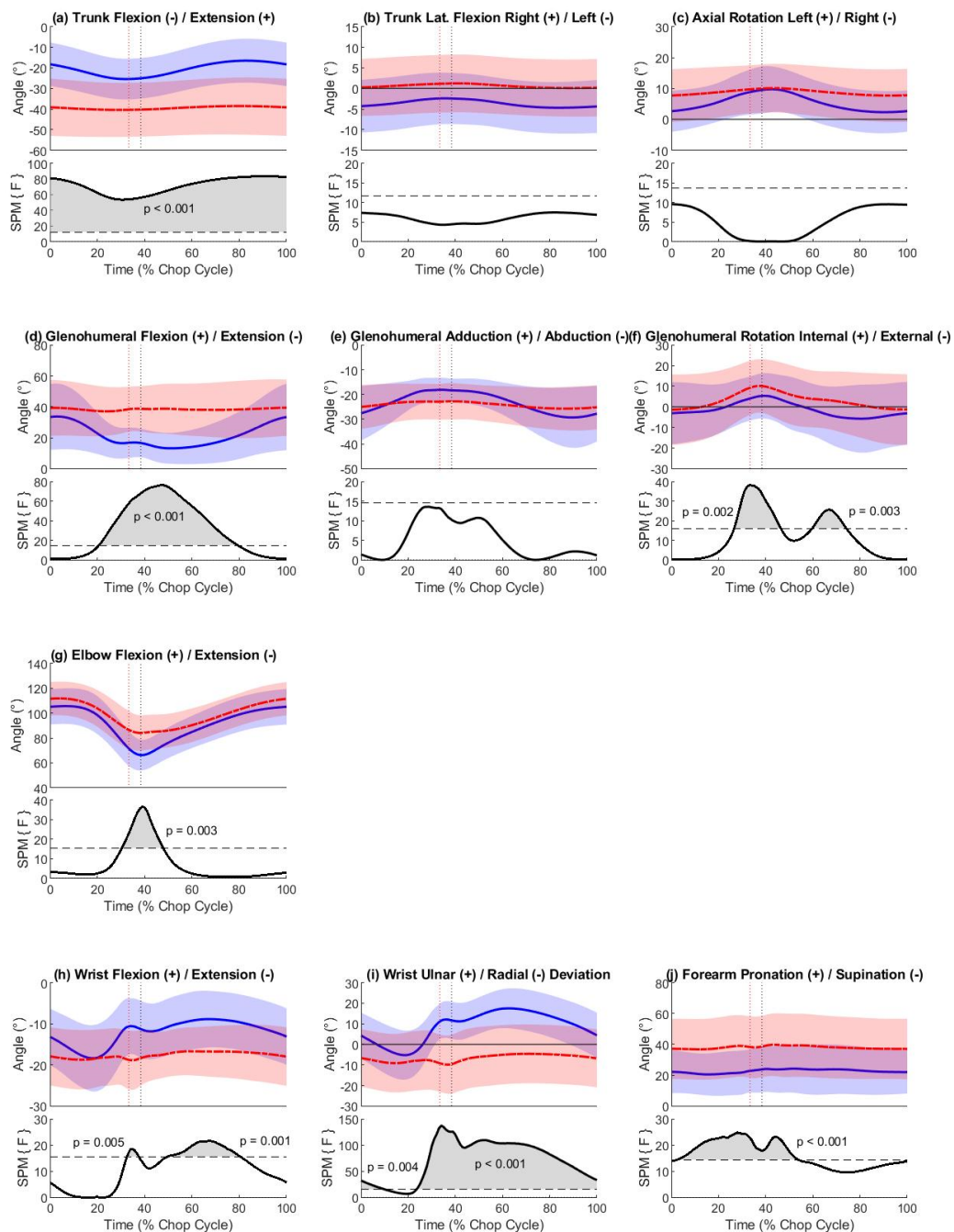
236 One-dimensional statistical parametric mapping (SPM) was used to detect differences in
237 intersegmental angles and muscle activity conditions (hafted vs. hand-held) across normalised action
238 cycle curves (Pataky, 2010; 2012). SPM works by providing a topological analysis of smooth continuum
239 associated with experimental intervention (Pataky, 2010; 2012). Using open-source Matlab code
240 (www.spm1d.org), a series of Bonferroni-corrected analyses of variance (ANOVA) variables were used
241 to determine differences between conditions for each intersegmental angle, velocity marker, and
242 muscle. The SPM method distinguished all specific time points in the motion cycle time-series where
243 statistically significant differences between groups existed. ANOVA was used to compare energetic
244 performance (Net EEmin and CoA) condition ($\alpha = 0.05$) using SPSS V25 (SPSS Inc. Chicago, IL, USA).

245

246 Results

247 Chopping – Kinematics

248 Differences in motion were noted between experimental conditions (hafted vs hand-held) in
249 trunk, glenohumeral, elbow, and wrist angles (Fig.4). Across the full chop cycle, the torso was
250 positioned in a less flexed ($p < 0.001$) posture during hafted chopping (Fig. 4a). In both downswing and
251 upswing phases, hafted chopping elicited greater flexion ($p < 0.001$) and external rotation ($p = 0.002$
252 & $p = 0.003$) at the glenohumeral joint (Fig. 4d & f). In hafted chopping, the elbow was flexed to a
253 greater degree ($p = 0.003$) during termination of downswing and initiation of upswing (Fig. 4g).
254 Participants also held their wrist in a less extended position at termination of downswing in hafted
255 chopping ($p = 0.005$), this continued into the upswing phase ($p = 0.001$) (Fig. 4h). A similar motion
256 pattern was noted in wrist deviation, although the degree of difference was greater: the wrist
257 positioned in significantly more ulnar deviation at initiation and termination of downswing and during
258 all of upswing ($p = 0.004$ & $p < 0.001$) (Fig. 4i). Although the time series graph shows a lack of overall
259 forearm rotation across the chop cycle, during most of the downswing and initial phase of upswing,
260 participants held their forearm in a less pronated position ($p < 0.001$) in hafted chopping (Fig. 4j).

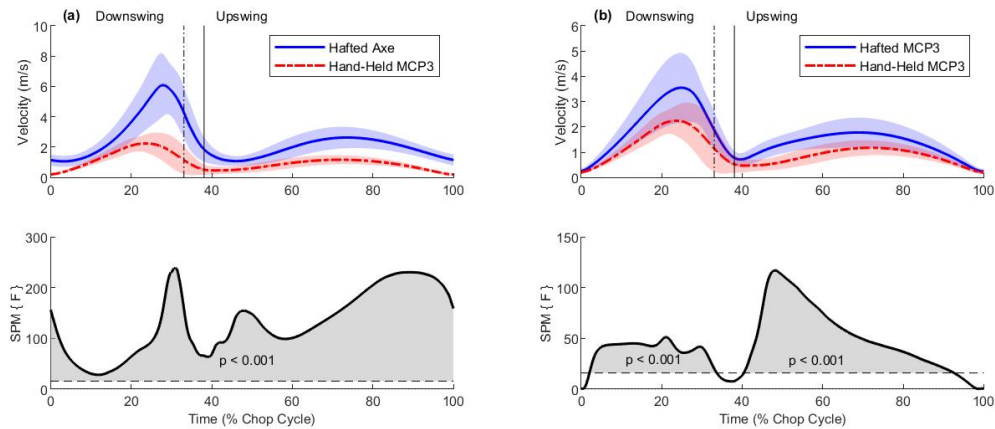


261

262 *Figure 4: Averaged participant group trunk, glenohumeral, elbow, and wrist intersegmental angles for hafted (blue) and*
 263 *hand-held (red) conditions, time normalized to a full chop cycle. Downswing and Upswing for each condition are separated*
 264 *by colour coordinated, vertical dashed lines. One standard deviation for each group is represented by shading in the*
 265 *corresponding colour. Associated SPM F-scores are reported below the average waveforms. Where F-scores exceed the*
 266 *critical value (black horizontal dashed line), significant differences between groups are recognised and labelled.*

267 Chopping – Velocity

268 Velocity comparisons for both hafted axe marker vs hand-held MCP3 marker and hafted MCP3
 269 marker vs hand-held MCP3 marker reveal significant differences. The hafted axe marker had a
 270 significantly higher velocity ($p < 0.001$) across the full chop cycle (Fig. 5a). Comparison of MCP3 marker
 271 velocity during both conditions, again showed the hafted condition produced significantly greater
 272 velocities in both downswing ($p < 0.001$) and upswing ($p < 0.001$) (Fig. 5b).



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Figure 5: Averaged participant groups velocity of condition markers, time normalised to a full chop cycle. (a) velocity of the hafted axe head (blue) and hand-held MCP3 (red, dashed) condition markers. (b) velocity of the hafted MCP3 (blue) and hand-held MCP3 (red, dashed) condition markers. One standard deviation for each group is represented by shading in the corresponding colour. Associated SPM F-scores are reported below the average waveforms. Where F-scores exceed the critical value (black horizontal dashed line), significant differences between groups are recognised and labelled.

279

Chopping – Electromyography

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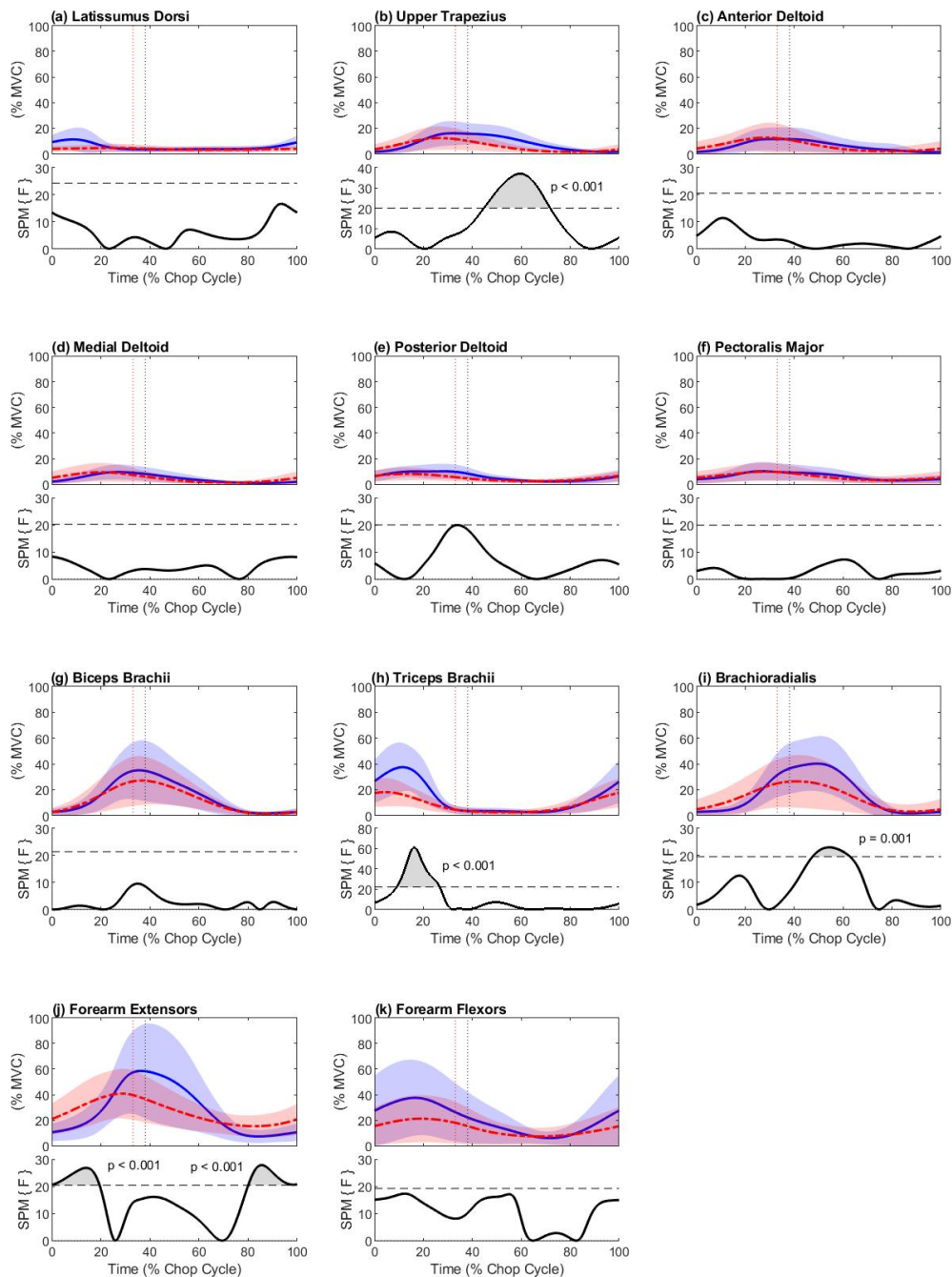
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As in the motion results, significant differences occur between experimental conditions (Fig. 6). During the downswing phase, triceps brachii ($p < 0.001$) amplitude was higher in the hafted condition (Fig. 6h), whereas forearm extensors ($p < 0.001$) amplitude was higher in the hand-held condition for the same phase (Fig. 6j). Forearm extensor ($p < 0.001$) amplitude was also higher in late upswing during hand-held chopping. During the early upswing phase, the hafted condition produced higher amplitudes for both the upper trapezius ($p < 0.001$) and brachioradialis ($p = 0.001$) (Fig. 6b & i). Moreover, muscles acting primarily on the glenohumeral joint appeared to be used only minimally in both conditions (Fig. 6c – f), with only the upper trapezius (Fig. 6b) approaching 20% MVC.

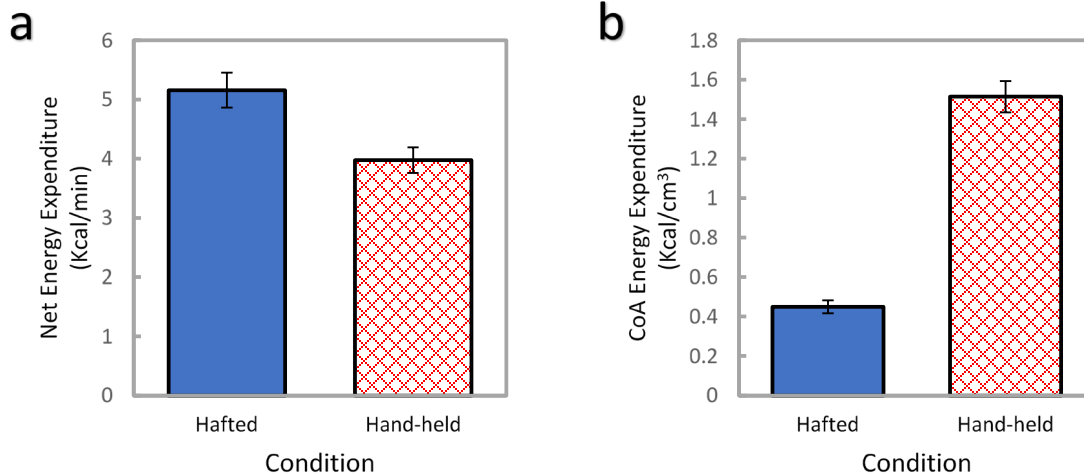


288

289 *Figure 6: Averaged participant group normalized (% MVC) muscle amplitudes for hafted (blue) and hand-held (red), time*
 290 *normalized to a full chop cycle. Downswing and Upswing for each condition are separated by the colour coordinated,*
 291 *vertical dashed lines. One standard deviation for each group is represented by shading in the corresponding colour.*
 292 *Associated SPM F-scores are reported below the average waveforms. Where F-scores exceed the critical value (black*
 293 *horizontal dashed line), significant differences between groups are recognised and labelled.*

294 Chopping – Respirometry

295 Significant differences were also revealed in absolute (hereafter ‘Net’) energy use between
 296 hafted and hand-held conditions ($p < 0.001$), with participants using more energy in the hafted
 297 condition compared with the hand-held condition (Fig. 7a). Importantly, this difference was reversed
 298 when energy use was assessed relative to the MoP. Participants used significantly ($p < 0.001$) fewer
 299 kilocalories to remove a cm^3 of wood in the hafted condition than the hand-held (Fig. 7b).



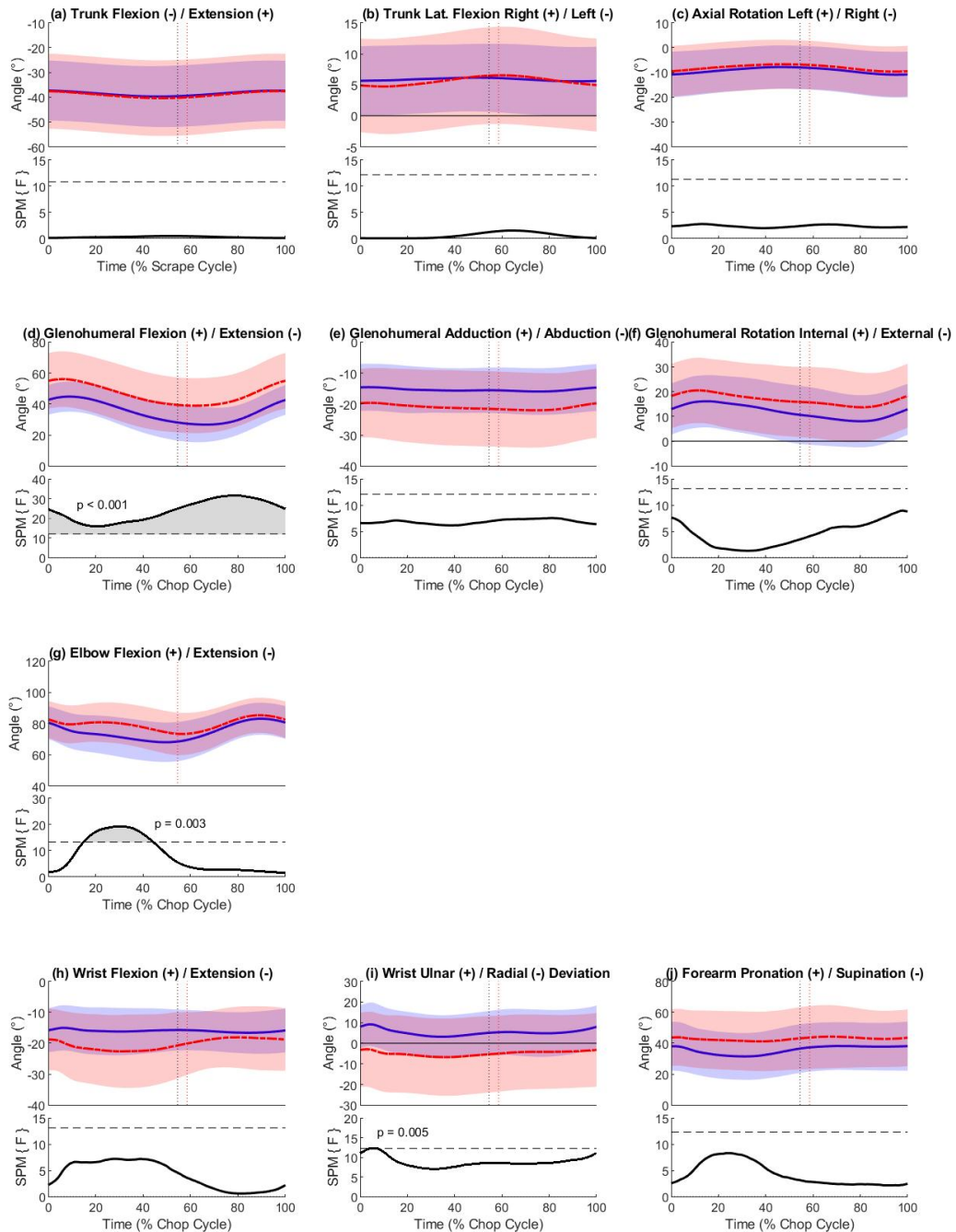
301

302 *Figure 7: Averaged participant group for (a) net energy expenditure (EE) and (b) cost of activity (CoA) EE for hafted (blue)*
 303 *and hand-held (red, crosshatch) conditions in the chopping task. Results show that hafted chopping had a statistically*
 304 *higher net energy demand compared with hand-held chopping. Only when energy use is assessed to a measure of*
 305 *performance, to create a cost of activity energy expenditure, is the energetic efficiency of a handle realised.*

306

307 Scraping – Kinematics

308 For the scraping tasks, differences in intersegmental angle were noted between experimental
 309 conditions (hafted vs. hand-held) in glenohumeral and elbow joint angles (Fig. 8) representing subtle
 310 differences at specific regions of the upper limb. Although the motion pattern at the glenohumeral
 311 joint and elbow followed a similar pattern, participants in the hafted condition had a less flexed
 312 glenohumeral position ($p < 0.001$) across the full scrape cycle (Fig. 8d) and a less flexed elbow ($p =$
 313 0.003) during the downstroke of the scrape cycle (Fig. 8g). Though not significant, the hafted condition
 314 also positioned the wrist in a less extended and ulnar deviated position throughout the scrape cycle
 315 (Fig. 8h & i).

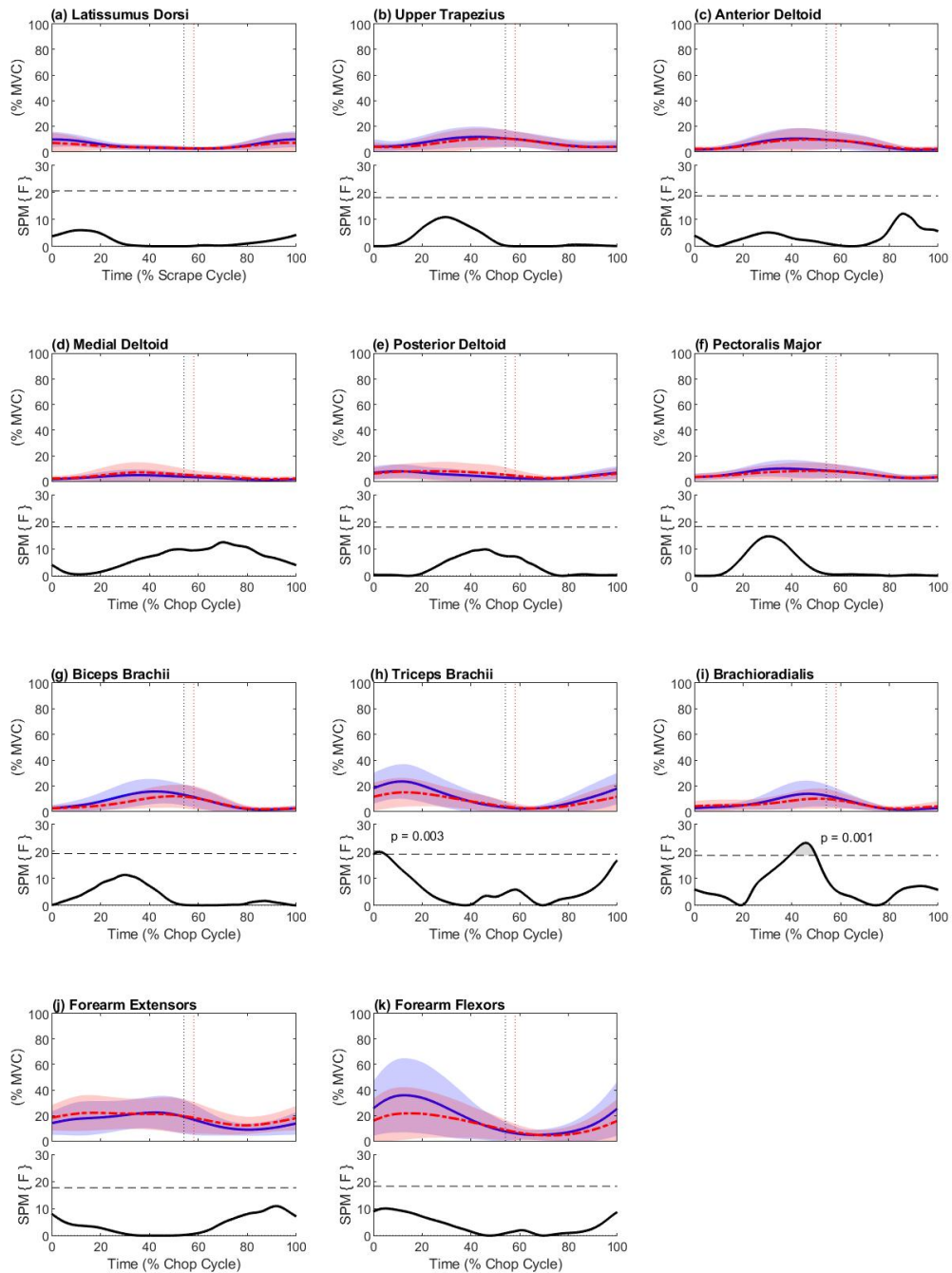


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317 *Figure 8: Averaged participant group trunk, glenohumeral, elbow, and wrist intersegmental angles for hafted (blue) and*
 318 *hand-held (red) conditions, time normalized to a full scrape cycle. Downstroke and Upstroke for each condition are*
 319 *separated by the colour coordinated, vertical dashed lines. One standard deviation for each group is represented by shading*
 320 *in the corresponding colour. Associated SPM F-scores are reported below the average waveforms. Where F-scores exceed*
 321 *the critical value (black horizontal dashed line), significant differences between groups are recognised and labelled.*

322 **Scraping – Electromyography**

323 Despite an overall similarity in muscle magnitude patterns across the upper limb, significant
 324 differences in muscle magnitude exist between experimental conditions (Fig. 9). During downswing,
 325 triceps brachii ($p = 0.003$) and brachioradialis ($p = 0.001$) amplitude was higher in the hafted condition
 326 (Fig. 9i & h). Further, muscles acting on the glenohumeral and elbow joints also seem to be minimally
 327 used in both conditions, with only forearm flexors (Fig. 9k) substantially exceeding 30% MVC.



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Figure 9: Averaged participant group normalized (% MVC) muscle amplitudes for hafted (blue) and hand-held (red), time normalized to a full scrape cycle. Downstroke and Upstroke for each condition are separated by the colour coordinated, vertical dashed lines. One standard deviation for each group is represented by shading in the corresponding colour. Associated SPM F-scores are reported below the average waveforms. Where F-scores exceed the critical value (black horizontal dashed line), significant differences between groups are recognised and labelled.

334

Scraping – Respirometry

335

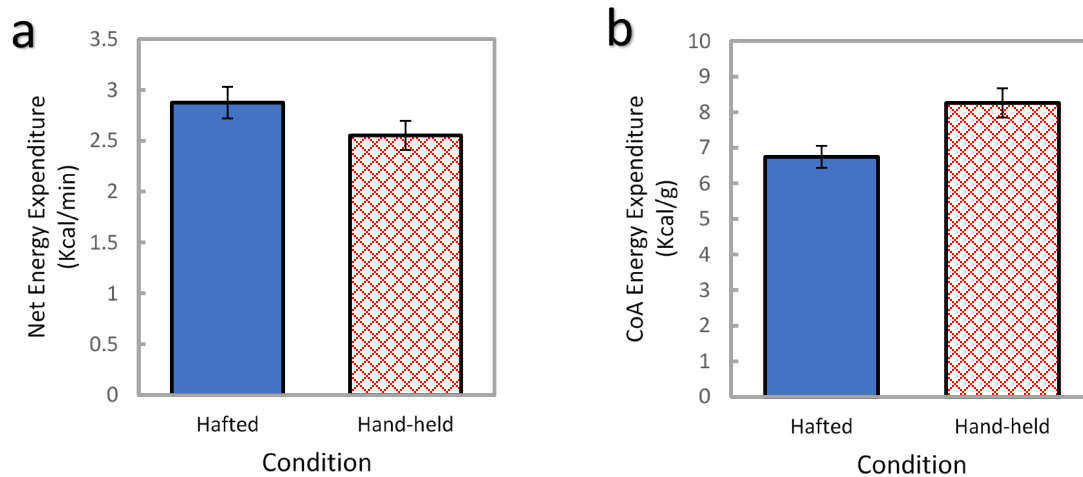
336

337

A similar pattern of results for scraping respirometry was noted as for chopping respirometry. Results for Net EE reveal that participants used more energy in the hafted condition ($p = 0.006$) compared with the hand-held condition (Fig. 10a).

338 Again, once a measure of performance for scraping is combined with Net EE (CoA EE), analysis shows
339 participants used fewer kilocalories to remove a gm of fibre in the hafted condition ($p < 0.001$) than
340 hand-held (Fig. 10b).

341



342

343 *Figure 10: Averaged participant group for (a) net energy expenditure (EE) and (b) cost of activity (CoA) EE for hafted (blue)*
344 *and hand-held (red, crosshatch) conditions in the scraping task. Results show that hafted scraping had a statistically higher*
345 *net energy demand compared with hand-held scraping. Only when energy use is assessed to a measure of performance, to*
346 *create a cost of activity energy expenditure, is the energetic efficiency of a handle realised.*

347

348 **Discussion**

349 **Chopping Task**

350 Results of kinematics (Fig. 4) and EMG (Fig. 6) analyses highlight important differences,
351 representing functionally different motion and muscle-activity strategies which affect the efficiency
352 of each tool. Contrary to expectations, the hafted condition is characterised by an overall more open
353 posture (less crouched) (Fig. 4a), significantly greater range of motion throughout the chop cycle and
354 across each segment (Fig. 4), and greater muscle magnitudes in both upswing and downswing. Overall,
355 motions and muscles acting in the sagittal plane (flexion/extension) showed the most noteworthy
356 differences, corresponding to greater levels of extension in the hafted condition.

357 The large differences recognised between chopping conditions are best understood by comparing
358 joint angular velocities (Fig. 11), identification of a proximal-to-distal joint sequence (PDJS) (Putnam,
359 1991) and Dart Thrower's Motion (DTM) (Palmer et al., 1985). PDJS describes the coordinated
360 movement of a multi-joint system in which motion follows a proximal-to-distal sequence whereby the
361 most proximal joint (trunk) begins its motion first and reaches its peak angular velocity before more
362 distal joints (glenohumeral, elbow, wrist) (Putnam, 1991; Williams et al., 2010; 2014; Feuerriegel,
363 2016). In this motion, the arm moves in a similar fashion to a whip resulting in greater angular
364 velocities at the most distal joint than would be achieved without benefit of passive interactive
365 torques (torque at the glenohumeral joint contributes to final hand velocity). This is known as a
366 velocity summation effect.

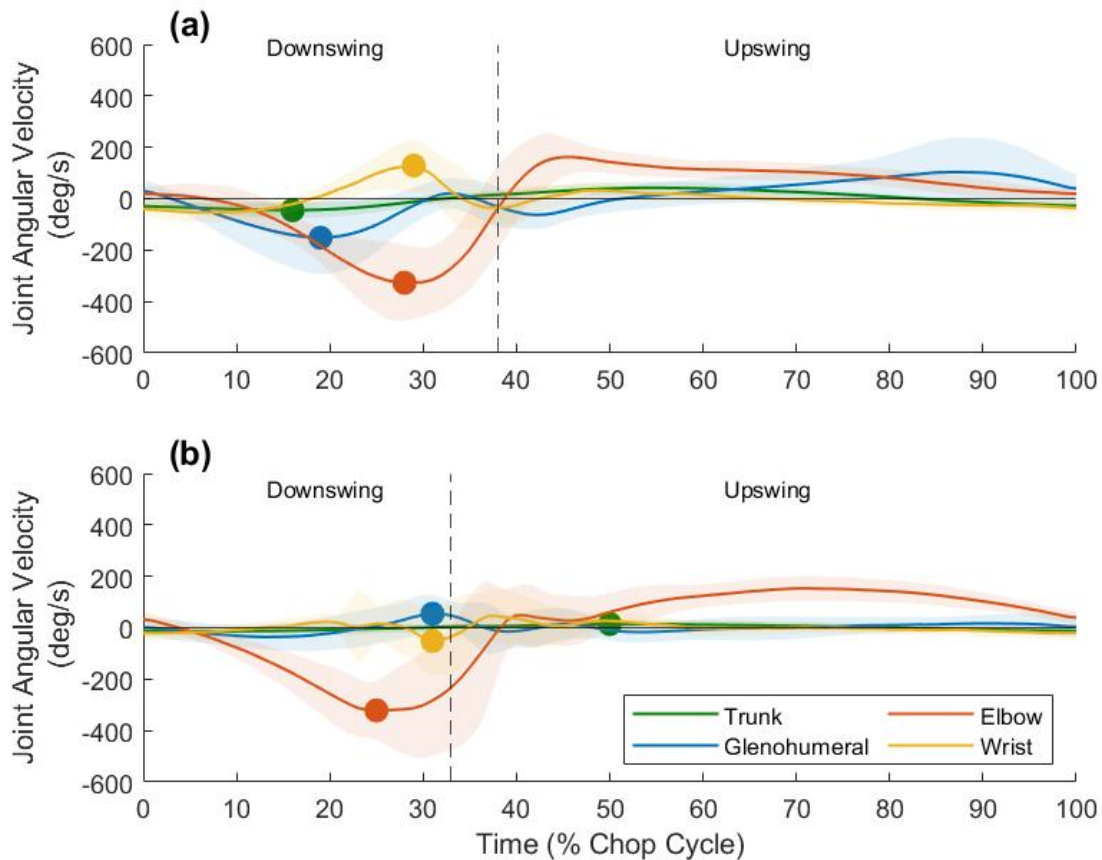


Figure 11: Angular velocities of glenohumeral flexion/extension (blue), Elbow flexion extension (orange) and wrist flexion/extension (yellow), time normalised to full chop cycle during the hafted (a) and hand-held (b) chopping task. Coordinated coloured dots represent peak joint angular velocity for each joint motion in X-axis. Downswing and Upswing phases are separated by vertical dashed lines.

Table 2: Peak angular velocities for each joint and condition during the chopping task.

Joint	Joint Angular Velocity (deg/s)	
	Hafted	Hand-held
Trunk	-44.81	14.27
Glenohumeral	-152.10	54.10
Elbow	-327.04	-321.86
Wrist	128.85	-51.58

Studies of contemporary hammering activities identified a full PDJS (Côté et al. 2005), however, advantages of a summation effect were not recognised, with the elbow producing greater peak angular velocity (Côté et al., 2005: table 1). We also found hafted chopping peak angular velocities occur in a PDJS, also extending the PDJS to include the trunk (Fig. 11a). Furthermore, hafted chopping failed to utilise the full summation effect (Fig. 11a; Table 2), with elbow angular velocities peaking higher than at the wrist (Table 2). Why high impact activities employ a modified PDJS motion remains poorly understood but this may represent a strategy to avoid high joint reaction forces, ensuring joint stability at wrist and elbow (Williams et al., 2014). The complete absence of a PDJS during hand-held chopping (Fig. 11b) supports this hypothesis. It is possible that in high-impact, percussive activities such as hammering and chopping, traditional PDJS is not the best model to produce maximum linear velocity of the tool head, or that in these activities, elbow motion represents a more important joint motion compared with other activities (i.e. knapping) where reactive forces are substantially reduced.

386 During hafted chopping, the wrist moved from an extended, radially deviated position to a flexed,
387 ulnar-deviated position known as the Dart Thrower's Motion (DTM) (Palmer et al., 1985) (Fig. 4h and
388 i). Motion during hafted chopping aligns well with that identified in studies of hammering which have
389 shown whilst hammering follows a typical DTM path, there is an offset in extension (Fig. 3h; Palmer
390 et al, 1985; Curran et al., 2008; Leventhal et al., 2010). The importance of this motion appears two-
391 fold. First, it offers an improvement in radio-carpal joint stability relative to pure anatomical motions
392 of extension-flexion and radial-ulnar deviation (Crisco et al., 2005). Secondly, the highly mobile wrist
393 enables cocking of the wrist, which aids in dealing with the inertial resistance of the axe during
394 upswing and early downswing. Furthermore (in conjunction with a PDJS), an uncoiling and rapid ulnar
395 flexion of the wrist at the end of downswing maximises axe velocity just before the strike, without
396 requiring heavy use of forearm musculature (Williams et al., 2014; Marzke et al., 1998; Pigeon et al.,
397 1996). Lack of wrist mobility (Fig. 4h, i) and corresponding reduction in velocity (Fig. 5) of the axe head
398 in hand-held relative to hafted chopping indicates the importance of such motions during behaviours
399 which utilise power grips, including hafted chopping (Wolfe et al, 2006).

400 PDJS and DTM motion strategies employed during hafted chopping allow the upper limb to produce
401 higher velocities (Côté et al, 2008) at the axe head (Fig. 5). This results in greater kinetic energy being
402 transferred into the wood, and more effective removal of material. PDJS and DTM motion strategies
403 also help provide stable joint motions capable of coping with reactive forces produced during striking
404 of axe onto wood. In line with results expected from the utilisation of PDJS and DTM, velocity results
405 (Fig. 5a) show hafted chopping produced significantly higher axe head velocity (a proxy for kinetic
406 energy) for the entire chop cycle and most importantly during the period around axe strike. During
407 hafted chopping participants were able to impart significantly greater kinetic energy into the wood to
408 split fibres compared with hand-held chopping. The latter employs a fundamentally different motion
409 sequence that ultimately cannot produce the same velocity (and therefore kinetic energy) as the
410 hafted axe head. This resulted in hand-held chopping denting and mincing rather than splitting the
411 wood fibres (Fig. 3b). That participants did not employ PDJS (Fig. 11b) and DTM motions (Fig. 3h and
412 i) in hand-held chopping reflects a compromise between producing the levels of kinetic energy needed
413 to split wood fibres whilst minimising reactive forces caused by striking to avoid injury. The proximity
414 of hand to axe head in hand-held chopping and the direct transfer of forces into the upper limb
415 probably inhibited wrist mobility and exploitation of the full range of motion at elbow and
416 glenohumeral joints seen in hafted chopping.

417 The greater motion and muscle amplitude seen in hafted chopping translate to an overall increase in
418 Net energy expenditure (EE) (Fig. 7), with hafted chopping using ~20% more total energy during the
419 task (Fig. 7a). Only when Net EE is calculated relative to a measure of performance (MoP) is the handle
420 efficiency realised, our analysis showing hand-held chopping uses three times more kilocalories to
421 remove a cubic centimetre of wood than hafted chopping (Fig. 7b).

422 Scraping Task

423 Results of kinematics (Fig. 8) and EMG (Fig. 9) analyses represent subtle differences at specific regions
424 of the upper limb which ultimately resulted in significant energetic efficiency during a scraping task
425 (Fig. 10b). A similar motion pattern is observed in both scraping conditions across the upper limb, with
426 differences often relating to different starting and ending positions in the cycle. In flexion/extension,
427 the glenohumeral follows the same path in both conditions, although hand-held scraping is
428 permanently held in ~12° greater flexion compared with hafted scraping (Fig. 8d). Whether this
429 difference places alternative demands on flexion and extension musculature is not revealed but could
430 result in differences in other, deep lying musculature, such as the coracobrachialis or teres major.
431 Although similar in much of the scrape cycle, hand-held scraping deviates from continuous slow

432 extension of the elbow, instead undergoing a period of stasis before continuing to extend briefly at
433 the end of downstroke (Fig. 8g). This difference is potentially a strategy to limit motion at elbow and
434 wrist to provide greater control of the force exerted during hand-held scraping. In hafted scraping, the
435 mechanical leverage of the handle may enable continued pressure to be exerted through the scraper,
436 allowing extension to continue unimpeded throughout downstroke. In line with continued extension
437 of the elbow in hafted scraping, the triceps brachii is significantly more active during this period (Fig.
438 9h).

439 Reece et al. (1997) and Key et al. (2021) identify differences in muscle activity and recruitment in
440 scraping and cutting tasks respectively when using hafted and hand-held tools. Similarly, the present
441 study shows that hafted scraping elicits greater activity in muscles around the elbow (Fig. 9h, i)
442 compared with hand-held scraping. As in the chopping task, the hafted scraper enables more use of
443 the upper limb in terms of both motion and muscle use, ultimately providing it with greater functional
444 capabilities. This is likely linked to the different grips used in the two conditions. Barham (2013:10)
445 suggests, “the precision-grip used to hold a blade limits the amount of force that can be applied to the
446 cutting motion when compared to a power-grip used to grasp a handle”. In this study and that of Key
447 et al. (2021), use of a power grip affords a greater use of the upper arm compared with the precision
448 grip, which appears to limit use of these muscles and motions, reducing forces placed through the
449 tool.

450 As in the chopping task, increased motion and muscle activity in hafted scraping resulted in a greater
451 absolute (Net) EE compared with hand-held scraping (Fig. 10a). This result was reversed once the MoP
452 for scraping was applied, revealing an energetic efficiency to this task whilst using a hafted scraper
453 (Fig. 10b). Unlike the chopping task, the mechanisms driving this greater efficiency are difficult to
454 establish for scraping. We hypothesise that the amount of pressure that can be exerted through the
455 scraper head is key to the greater effectiveness of a hafted scraper. As above, the difference in force
456 production is likely based on the precision grip used in hand-held scraping compared with the power
457 grip used in hafted scraping (Barham, 2013).

458 Hafting Biomechanics and the Efficiency Hypothesis

459 The results of this study support previous research highlighting functional efficiency advantages of
460 hafting in a variety of tasks and experimental settings (Morrow et al., 1996; Reece et al., 1997; Claud
461 et al., 2015; Key et al., 2021). The adaptive benefits and motivations behind the invention and
462 proliferation of hafted tool technology are likely to be complex and multifaceted (Rots 2013). This
463 study shows that two subsistence activities, ubiquitous in the prehistoric past, are significantly
464 improved in both tool functionality and energetic efficiency when undertaken using a hafted tool
465 compared with the hand-held equivalent.

466 This study has shown that to gain energetic advantage, a complex set of interactions occurs between
467 motions and postures which ensure the tool remains functionally effective (e.g. axe-head velocity),
468 while likely minimising reactive forces and risk of injury. The finding that a high-impact activity such
469 as chopping, which is very difficult to complete hand-held, benefits greatly from hafting is unsurprising
470 and has been predicted (Rots 2010; Barham 2013). However, that hafting also offers a biomechanical
471 and physiological advantage to a scraping task, in which hafting is not functionally a requirement of
472 acceptable performance, supports previous assumptions that hafting confers a universal advantage
473 (Barham, 2013). This could increase the general fitness of the individual and groups reliant on basic
474 subsistence activities (Rots, 2013; Mateos et al., 2018). Experimental evidence of adaptive advantages
475 offered by hafting contributes to our understanding of the invention of this technology at a time of
476 increased ecological resource variability during the Middle Pleistocene (Potts et al. 2020).

477 As noted earlier, this study employed an internal experimental model in its use of commercial tools,
478 as a result, further validation work with more naturalistic arrangements would be a valuable direction
479 for future research to help embed this research into other studies that employed an external model.
480 Following this study and the work of Key et al. (2021), further experimental research is needed to
481 assess the impact of hafting on other basic activities (drilling and piercing) as well as a variety of haft
482 forms (cleft and juxtaposed etc.) to help model the spread and amplification of hafted technologies.

483

484 **Conclusion**

485 Hafted tool technology marked a significant shift in conceptualising the construction and
486 function of stone tools. As well as representing an important shift in cognition of hominin groups that
487 produced them (Ambrose, 2010; Barham, 2013; Wynn, 2009; Wadley, 2010; Hodgskiss, 2014; Sykes,
488 2015; Fairlie and Barham, 2016; Fairlie, 2017), hafting is often cited for the biomechanical and
489 physiological benefits it offers the individual over hand-held equivalents (Firth, 1925; Odell, 1994;
490 Morrow, 1996; Cowan, 1999; Churchill, 2001; Rots et al., 2011; Rots, 2015b; Barham, 2013). This study
491 has shown that in two subsistence tasks, hafting results in significantly different biomechanical
492 strategies, that ultimately works to offer an energetic benefit compared with hand-held equivalent
493 tools. Most notably, during the chopping task it has shed light on the mechanism whereby the
494 energetic benefit is achieved through increases in joint motions and muscle use which resulted in an
495 increase in velocity and force that ultimately made the hafted tool used more effective per unit of
496 energy applied to a task. Further research focussed on specific upper limb segments and muscle
497 groups (e.g. the wrist joint and forearm musculature), as well as role of the grips employed would be
498 of value to understanding the adaptive value of this key technological transition.

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504

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