THE ROLE OF LIMB BIOMECHANICS AND TECHNOLOGICAL AID IN THE PRODUCTION OF VELOCITY DURING STONE TOOL KNAPPING

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ABSTRACT

The stone flakes produced during the Acheulean period are among the largest in the archaeological record. While acknowledging the increased strength of many hominin species, some of the large flakes produced may have required more strength to detach than modern humans can generate, leading us to question whether the hominins could also produce these flakes with handheld direct percussion. In this study, an experiment was designed to test the relationship between some of the variables pertaining to the biomechanics and kinematics of arm movements resembling a knapping motion on modern humans. Conclusions about the arm speed hominins may have generated during stone tool production and the potential use of a technological aid for increased velocity are discussed.

INTRODUCTION

For years, upper limb biomechanics and kinematics of hominins during stone tool production have been under investigation. Experiments on the arm motions of modern humans and primates while knapping have allowed researchers to test and examine upper limb and muscle mechanics as they relate to tool production. Inspired by observations of early Acheulean flakes, likely produced by hominins such as Homo erectus, this study is designed to test the relationship between variables pertaining to the biomechanics and kinematics of arm movements that resemble a knapping motion.
This study was specifically designed to attain a greater understanding of the production of velocity and the impact technological aid has on it during stone tool knapping and to help enhance our understanding of the upper limb capabilities of stone tool users and the subsequent evolution of strength and cognitive abilities within the human lineage.

EARLY STONE TOOL KNAPPING

Our production of stone tools to accomplish tasks dates to at least 3.3 Mya when hominins produced the first stone tools (Harmond et al 2018). Initially, it was widely presumed that Homo Habilis of the Homo genus was the first hominin ancestor to use stone tools. However, archaeological evidence of stone tools found at the Lomekwi 3 site in West Turkana suggests that older species may have been responsible for the earliest stone tool production. Hominin species belonging to the genus Australopithecus were present at 3.3 Mya and linked to the Lomekwi region, it is possible that at least one species of Australopithecine were the first tool makers.

Oldowan technology, often defined as simple core and flake technology (Toth 1985) was the first lithic technological industry. Hominins were likely producing flakes using direct percussion, by taking one stone and striking it against another until flakes are detached. These flakes were used for tasks such as cutting (Toth 1985).

STONE TOOL KNAPPING IN THE ACHEULEAN

The Acheulean emerged as early as 1.7 Mya (Diaz-Martin, 2015). Flakes of the Acheulean are associated with Homo erectus and are among the largest in the archeological record (Figures 1 and 2). The Acheulean archaeological industry consists of stone tools such as cleavers and handaxes (Figure 2) (Diaz-

Martin 2015). Acheulean technology was used to butcher carcasses as potential fauna (Diaz-Martin, 2015). Acheulean technology was prevalent throughout Africa, the Middle East, most of Europe and several places within Asia (Lycett and Gowlett 2008).

The bifacial, symmetrical handaxe (Figure 2), believed to have been manufactured by Homo erectus, is perhaps the most prominent stone tool of the Acheulean industry. This tool persisted for nearly two million years (Coolidge and Wynn 2016). Archaeological evidence from Rietputs 15, representing the earlier Acheulean (approximately 1.3 Mya) and the Cave of Hearths, representing the later Acheulean (about 0.5 Mya) demonstrates how Acheulean handaxes were produced in similar ways and thus had similar features across time. Handaxes produced at both sites were found to have been made through flake detachment, biracial flaking and the execution of flaking techniques meant to better shape and refine edges (Hao et al 2018). More specifically, the handaxe was typically made by "trimming around the margins of a large flake" in order to produce an edge capable of cutting (Coolidge and Wynn 2016). This type of sophistication and precision serves as a potential indicator of increased working memory capabilities of Homo erect us relative to previous hominin ancestors (ibid.).

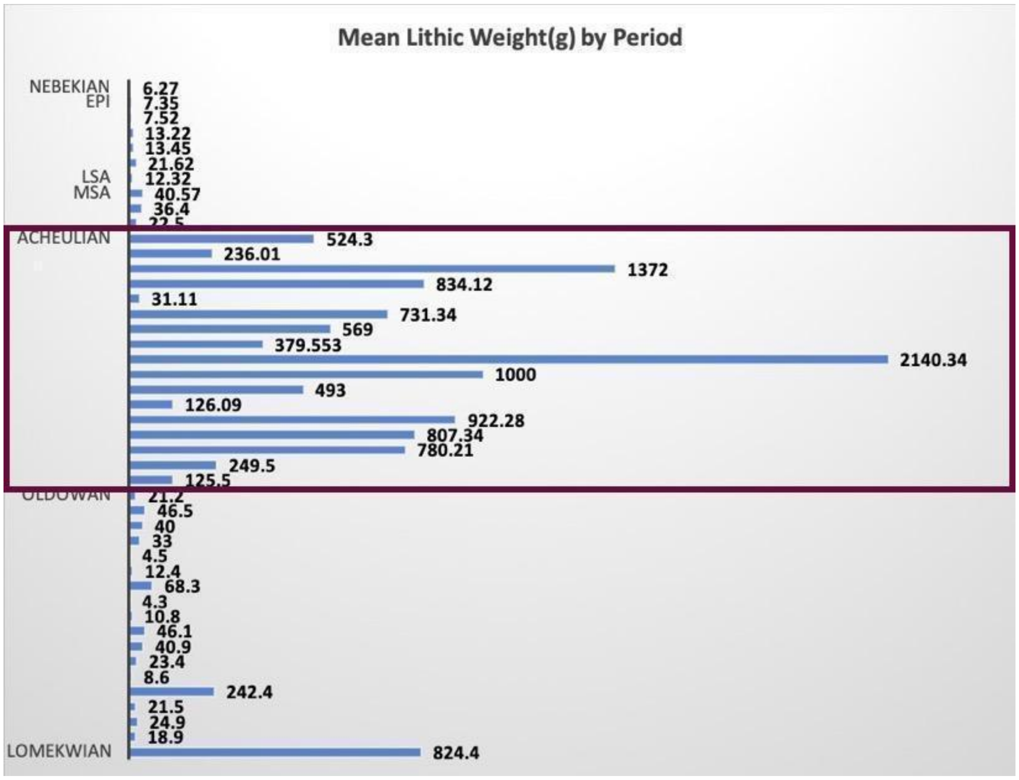

Figure 1. Acheulean flake size at known sites (Li et al 2019).

Figure 2. Large Acheulean flakes from the site of Canteen Kopje, South Africa.

HOMINIM STRENGTH AND MORPHOLOGY

Humans share common ancestral ties with primates, particularly African apes. Modern humans are weaker than most primates. Case in point, modern humans have weaker shafts relative to femoral head size in comparison to African apes (Ruff et al 1999). The strength of earlier hominins, on the other hand, was a closer match to the strength of primates. Cross-sectional cortical bone analysis has revealed that Australopithecine and Homo *habilis* had femora as strong as those of chimpanzees (ibid.). The idea of human ancestors once being as strong as primates suggests a decline in hominin strength over time.

The decline in strength within the human lineage is further depicted by the change in hominin stature and body mass. Case in point, early Homo erectus were generally slightly stronger than modern humans (Ruff et al 1999). An increased decline in hominin strength is further supported by the decline in diaphyseal robusticity from hominins of the Pleistocene compared to modern day humans (Ruff et al 1993). Case in point, shaft robusticity of early modern Homo sapiens is more similar to archaic Homo sapiens than modern humans today (ibid.). Higher robusticity in early Homo species is attributed to increased mechanical loading on the skeletons (Trinkaus et al. 1994). One commonly believed and tested hypothesis is that increases in robusticity, particularly thumb robusticity, as well as thumb length and the air muscle mass allowed hominins of the Homo genus to produce more force, as well as endure higher joint stress, during stone tool production (Campbell 2011). The identification of patterns and the change in factors such as body mass and structure throughout the lineage serve as an indicator of the evolution of human strength. After drawing 254 mass and 204 stature estimates from 311 hominin specimens, all of which were dated from 4.4 Ma to the start of the Holocene, an analysis of the mass and structure estimates suggests that, with considerable variability, early hominin were of larger body mass and structure in comparison to australopithecine (Will et al 2017). Generally speaking, many hominin species. Furthermore, a decline in stature and body mass is present in Homo sapiens during the later portion of the Pleistocene and Holocene (ibid.). During the later Pleistocene when modern human-like limb propositions started to appear in Homo ergaster (Richmond et al 2002).

BIOMECHANICS OF ARM SWING MOVEMENTS

Upper-limb biomechanics of tool production have impacted hominin evolution and stone tool production. The study and analysis of these various factors offer potential explanation of how hominin strength may have evolved over the course of thousands or millions of years relative to tool production.

The biomechanics and kinematics of hominin stone tool production can be simulated by modern humans during knapping activities. However, this can also be studied when modern humans partake in activities such as hammering, pitching and throwing, as these are examples of modern day upper-limb activities that are similar to stone tool knapping (Williams et al 2010). Since the upper-limb movement required for knapping is identical to the upper-limb movement required for these activities, studying the biomechanics and kinematics of the modern upper arm when engaged in such activities can help draw conclusions pertaining to the biomechanics and kinematics of the hominin arm during stone tool production.

One aspect of upper-limb biomechanics found to influence upper-limb kinematics is humoral torsion. Low humeral torsion results in high-speed throwing, as individuals with lower humeral torsion have more elastic energy stored in the soft tissues of their shoulder which helps to produce faster throws (Roach et al 2013) and (Roach and Lieberman 2014). Humeral torsion has been linked to high-speed throwing in the hominin record, as some Homo Erebus had incredibly low humeral torsion which allowed for them to store more elastic energy and thus produce the fastest throws (Roach and Richmond 2015). Humeral torsion is thus an example of one biomechanical factor that increases arm velocity.

Wrist flexion and extension are also found to influence strike velocity. Upper-limb movements typically occur in proximal-to-distal sequences, culminating in extreme and rapid wrist flexion right before strike (Williams et al 2010). The higher angular velocities that are reached via the proximal-to-distal sequence during knapping. Having the ability to obtain high degrees of wrist extension enables the hand and hammerstone to reach significantly higher linear velocities and thus higher strike forces (ibid.). In an experiment in which expert knappers produced Oldowan bifacial choppers where half the subjects maintained normal wrist extension and the other half wore a brace that reduced wrist extension simulating a likely condition of early hominins, it was found that when the wrist was unrestrained, the subjects achieved greater target accuracy, angular velocities, and hand linear velocities (Williams et al 2014). Wrist extension evidently affects accuracy and efficiency in tool production. Angular and linear velocity and force reaches a peak during the downswing phase of knapping (ibid.).

METHODS

For this study, we developed an experiment designed to test the relationship between variables pertaining to upper biomechanics and kinematics when performing motions that mimics that of tool knapping.

Participants

This study consists of a total of 21 participants (n = 21) recruited from The College of New Jersey. Participants included both undergraduates and faculty, ranging in age from 18 to 53 years with a mean age of 24.762 years and standard deviation of 11.081 years (Table 1). Participant height ranged from 147.218 centimeters to 190.500 centimeters with a mean height of 167.634 centimeters and a standard deviation of 11.147 centimeters (Table 1).

Table 1. Descriptive Statistics for Participant Measurements

	Mean	S.D.	Min	Max
Age (years)	24.762	11.081	18	58

Height (cm)	167.634	11.147	147.218	190.500
Forearm Length (cm)	34.814	3.757	26	44
Bicep Circumference Measurement (cm)	28.095	4.300	20	38

Participant Measurements

A standard tape measure was used to obtain various arm length measurements of each participant's dominant arm. The forearm length of each participant was measured by measuring the length from the midpoint of the elbow to the first flex of the wrist just below the distal end of the radius. Participant forearm length ranged from 26 centimeters to 44 centimeters with a mean forearm length of 34.814 centimeters and a standard deviation of 3.757 centimeters (Table 1). The measurement of the bicep circumference was obtained by placing the measuring tape around the participant's bicep and recording the result. Participant bicep circumference ranged from 20 centimeters to 38 centimeters with a mean bicep circumference of 28.095 centimeters and a standard deviation of 4.300 centimeters (Table 1).

Participant Tasks and the Production of Velocity

Participants were instructed to complete several tasks designed to obtain the measurements of velocity produced by the biomechanics of tool knapping motion. Velocity was measured using a Speed CheckR™ brand 7500 dual laser speed indicator. Participants repeated each velocity related task twice. The two swings were averaged and recorded in an excel sheet.

Participants were first asked to move their forearm in a chopping motion while keeping their upper arm (shoulder to elbow) pressed tightly against their body. The only part of the arm that was in motion for this task was the forearm (elbow to wrist). In this study, this velocity is referred to as the "chop swing velocity". Participant chop swing velocity ranged from 2.655 meters per second to 13.2 meters per second with a mean chop swing velocity of 8.307 meters per second and a standard deviation of 2.950 meters per second (Table 2).

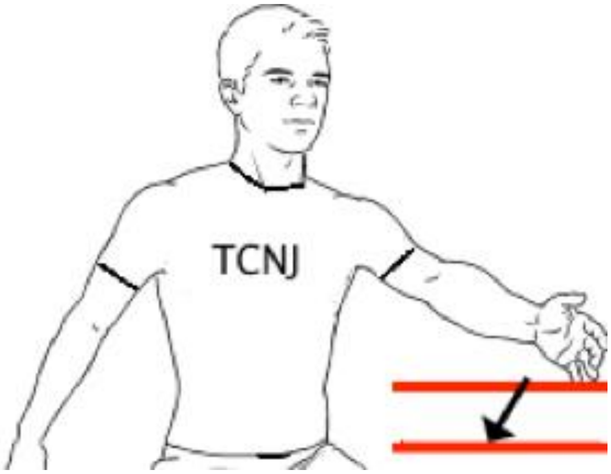

Figure 3. Example of participant performing a chop swing, where the red lines indicate laser locations.

Participants then repeated the chopping motion while holding a 10-centimeter-long rod, which, for the purposes of this study, was treated as a hafting tool extension or a technological aid. We refer to the resulting velocity as the "chop swing velocity with technological aid". Participant chop swing velocity with technological aid ranged from 4.98 meters per second to 18.35 meters per second with a mean of 12.796 meters per second and standard deviation of 3.077 meters per second (Table 2).

While we acknowledge that testing the described relationships and impact of technological aid on participants performing a full arm swing would have added greatly to this study, we were unable to do so, as participants consistently missed the target when holding technological aid.

Table 2. Descriptive Statistics for Participant Chop Swing Velocity

	Mean	S.D.	Min	Max
Chop Swing Velocity (m/s)	8.307	2.950	2.655	13.2
Chop Swing Velocity with Technological Aid (m/s)	12.796	3.077	4.98	18.35
Chop Swing Velocity Difference (m/s)	4.488	2.384	-0.215	8.855

Statistical Approach
We used ordinal least squares (OLS) regression models to examine the relationship between bicep circumference measurements and the resulting chop swing velocity, holding forearm length constant. We used the following OLS regression equation to examine these relationships as well as predict the resulting chop swing velocity both with and without the presence of technological aid: $Y = a + \beta 1X1 + \beta 2X2$ where a = constant (intercept), β1 = Beta for bicep circumference and β2 = Beta for forearm length.

RESULTS

Two regression models were developed and used to analyze the relationship between bicep circumference, forearm length and chop swing velocity while simultaneously exploring the possibility of whether the addition of technological aid acts as an equalizer in velocity production.

Table 3. OLS Regression Models Predicting Chop Swing Velocity

	Model 1: Predicting Chop Swing Velocity			Model 2: Predicting Chop Swing Velocity with Technological Aid	
	Beta	(Std. Error)		Beta	(Std. Error)
Intercept	3.854	(6.238)		9.423	(6.716)
Bicep Circumference	0.296	(0.164)*		0.248	(0.177)
Forearm Length	-0.111	(0.188)		-0.103	(0.202)
R Squared	0.155			0.099	
Note: p < 0.10: *					

Model 1 represents the relationship between bicep measurement, forearm length and chop swing velocity without the presence of technological aid. According to the model, as the bicep circumference increases by 1 centimeter, the chop swing velocity is expected to increase by 0.296 meters per second, holding forearm length constant ($p < 0.1$) (Table 3, Figure 4). However, as the forearm measurement increases by 1 centimeter, the chop velocity is expected to decrease by 0.111 meters per second, holding bicep circumference constant (Table 3, Figure 4). There is a 0.155 proportion of variance in the chop swing velocity that can be explained by both bicep circumference and forearm length (Table 3).

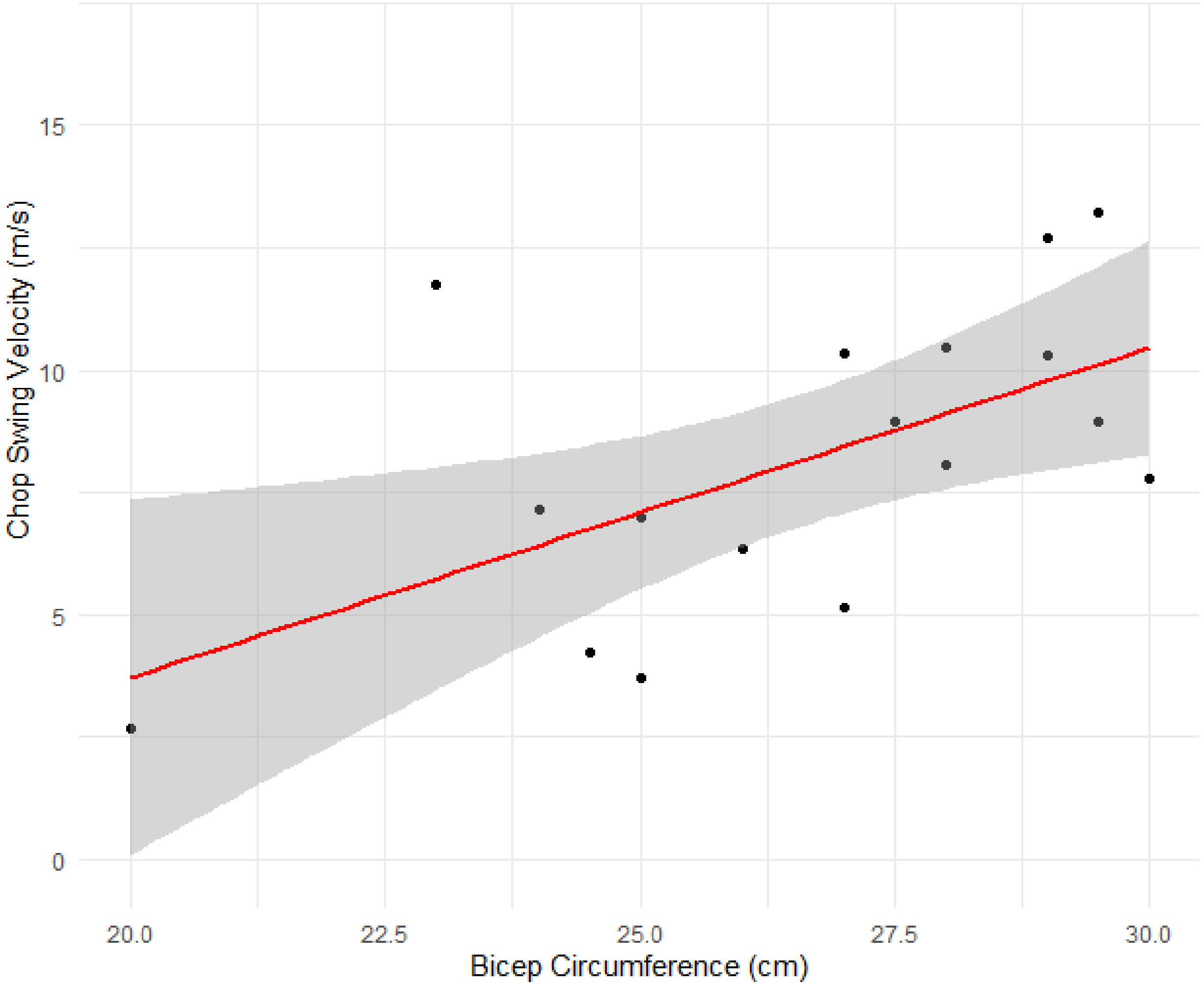

Figure 4. The graph displays the OLS regression prediction line and confidence intervals of participant bicep circumference measurements and chop swing velocity without the presence of technological aid.

Model 2 displays the relationship between bicep measurement, forearm length and chop swing velocity with technological aid. The model reveals that as the bicep circumference increases by 1 centimeter, the chop swing velocity with technological aid is expected to increase by 0.248 meters per second, assuming that the forearm length is held constant (Table 3, Figure 5). However, when the forearm length increases by 1 centimeter, the chop swing velocity with technological aid is expected to decrease by 0.103 meters per second, holding the bicep circumference constant (Table 3, Figure 5). There is a proportion of 0.099 variance in the predicted chop swing velocity with technological aid in relation to bicep circumference and forearm length measurements (Table 3).

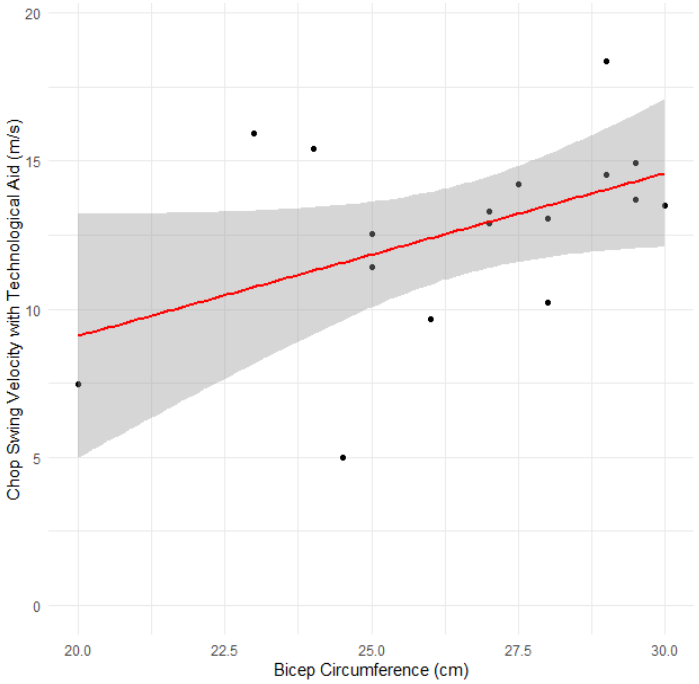

Figure 5. The graph displays the OLS regression prediction line and confidence intervals of participant bicep circumference measurements and chop swing velocity with the presence of technological aid.
We find that technological aid acts as an equalizer for those with smaller bicep circumferences. Using the prediction equation from earlier, we found that without the presence of technological aid, those with a bicep circumference one standard deviation above the mean are expected to produce a chop swing velocity of 9.71 meters per second (Table 3, Figure 4), holding forearm length constant at the mean (34.81 centimeters). On the other hand, those with a bicep circumference one standard deviation below the mean are expected to produce a chop swing velocity of 7.13 meters per second (Table 3, Figure 4), holding forearm length constant at the mean (34.81cm). With the presence of technological aid, participants with a bicep circumference one standard deviation above the mean are expected to produce a chop swing velocity of 13.93 meters per second (Table 3, Figure 5), holding forearm length constant at the mean (34.81cm). Those with a bicep circumference one standard deviation below the mean are expected to produce a chop swing velocity of 11.78 meters per second (Table 3, Figure 5).

Without technological aid, those with bicep circumferences that are one standard deviation above the mean are expected to swing about 36% faster than those with a bicep circumference one standard deviation below the mean: 9.71/7.13 = 1.36 ~ 36%. When technological aid is present, those with a bicep circumference one standard deviation above the mean are predicted to swing 18% faster than those with a bicep circumference one standard deviation below the mean: 13.93/11.78 = 1.18 ~ 18%. In other words, without technological aid, individuals with larger bicep circumferences are expected to swing about 36% faster than those with smaller bicep circumferences. However, when using a technological aid, those with larger bicep circumferences are expected to swing 18% faster than those with smaller bicep circumferences. The presence and use of technological aid bridges the gap between bicep circumference disparities, as having a larger bicep circumference ceases to be advantageous.

DISCUSSION

The archaeological record identifies Acheulean hominins, likely Homo erectus and their contemporaneous variations, as producers of the largest flakes. This may suggest that Homo erectus produced a greater amount of velocity during stone tool knapping, as such velocity and strength likely would have been needed for the production of large flakes. However, Homo erectus are also known to have been smaller in body size and stature. We suggest that Homo erectus may have been using technological aid to assist in stone tool production.

The transition from held-hand to hafted tool technology, which consists of a handle attachment to the original hand-hand tool acting as a technological aid, improved the functions, capability and effectiveness of tool technology by increasing leverage, force production and precision (Coe et al 2022). In terms of velocity, when both these types of tools and their capabilities were tested against each other during chopping and scraping tasks, it was found that the use of the hafted technology resulted in the production of greater velocities at the distal end of the limb with very little reliance on muscle movement (ibid). Similarly, we find that arm velocity increases relative to bicep circumferences in the presence of technological aid (Table 3, Figure 5). However, our findings also suggest that technological aid would have served as an equalizer for hominin species with smaller bicep circumference measurements, as having larger bicep circumference measurements were not advantageous in the presence of technological aid (Table 3, Figures 4 and 5). This may have been especially beneficial for stone tool producing hominins of smaller size and stature, such as Homo erectus.

Given that the complex and sophisticated design of the Acheulean bifacial handaxe is associated with increased hominin cognition (Coolidge and Wynn 2016) and (Diaz-Martin 2015), it is reasonable to conclude that Homo erectus may have had enhanced cognitive abilities compared to previous stone tool producers. In fact, Homo erectus had a brain size of about 1000cc, exceeding that of the "ape range" corresponding to the size of previous hominin brains (Coolidge and Wynn 2016). With such advanced cognitive abilities, it is possible that Homo erectus intentionally used technological aids to enhance the efficiency and effectiveness of stone tool knapping, since an increased use in technological aid is linked to an increase in cognitive ability (Ruff et al 1999). The potential increased use of technological aid is also linked to decline in reliance on physical strength (ibid.).

It should be noted that while the relationship between bicep circumference and chop swing velocity is statistically significant ($p < 0.1$) without the presence of technological aid (Table 3 Model 1), it is not statistically significant with the presence of technological aid (Table 3 Model 2). Nonetheless, the latter relationship is practically significant, as it demonstrates the influence of technological aid may have on arm velocity and strength. As demonstrated above, the data and statistical analyses is practically significant, as it reveals the potential impact of technological aid on Acheulean technology and hominin evolution.

Conducting additional studies with larger sample sizes will allow for the impact and influence of technological aid on Acheulean technology to be explored further. It's role as an equalizer may be applicable to other upper limb biomechanical variables in addition to bicep circumference measurements.

CONCLUSION

Holding all else constant, when modern humans perform a chop swing motion that replicates the stone tool knapping motion, their chop swing velocity is expected to increase as their bicep circumference measurements increase. The use of technological aid acts as an equalizer for those with smaller bicep circumferences. When a technological aid is used, having a larger bicep circumference is not advantageous in the higher production of chop swing velocity.

Therefore, producers of Acheulean technology who were smaller in stature and body mass may have benefited from making and using technological aids, such as hammerstones hafted onto the ends of sticks, to increase their swing velocity for the production of large flakes. Homo erectus were perhaps manufacturing and using technological aids to assist in the production of some of the largest known flakes in the archaeological record. This possibility leaves room for further exploration of hominin strength and cognitive development throughout the Acheulean period and beyond.

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