Journal of Human Evolution 72 (2014) 52–63

Contents lists available at ScienceDirect

Journal of Human Evolution

journal homepage: www.elsevier.com/locate/jhevol

Biomechanical strategies for accuracy and force generation during stone tool production

E.M. Williams [a,*], A.D. Gordon [b], B.G. Richmond [c,d]

[a] Department of Biology, Buhl Hall, Chatham University, Woodland Road, Pittsburgh, PA 15232, USA
[b] Department of Anthropology, University at Albany – SUNY, 1400 Washington Avenue, Albany, NY 12222, USA
[c] Center for the Advanced Study of Hominid Paleobiology, Department of Anthropology, The George Washington University, 2110 G St. NW, Washington, DC 20052, USA
[d] Human Origins Program, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, USA

ARTICLE INFO

Article history:
Received 6 September 2013
Accepted 15 March 2014
Available online 18 April 2014

Keywords:
Dart-thrower's arc
Hand and wrist evolution
Kinematics
Knapping
Oldowan tool making
Wrist anatomy

ABSTRACT

Multiple hominin species used and produced stone tools, and the archaeological record provides evidence that stone tool behaviors intensified among later members of the genus *Homo*. This intensification is widely thought to be the product of cognitive and anatomical adaptations that enabled later *Homo* taxa to produce stone tools more efficiently relative to earlier hominin species. This study builds upon recent investigations of the knapping motions of modern humans to test whether aspects of our upper limb anatomy contribute to accuracy and/or efficiency. Knapping kinematics were captured from eight experienced knappers using a Vicon motion capture system. Each subject produced a series of Oldowan bifacial choppers under two conditions: with normal wrist mobility and while wearing a brace that reduced wrist extension ($\sim 30°-35°$), simulating one aspect of the likely primitive hominin condition. Under normal conditions, subjects employed a variant of the proximal-to-distal joint sequence common to throwing activities: subjects initiated down-swing upper limb motion at the shoulder and proceeded distally, increasing peak linear and angular velocities from the shoulder to the elbow to the wrist. At the wrist, subjects utilized the 'dart-thrower's arc,' the most stable plane of radiocarpal motion, during which wrist extension is coupled with radial deviation and flexion with ulnar deviation. With an unrestrained wrist, subjects achieved significantly greater target accuracy, wrist angular velocities, and hand linear velocities compared with the braced condition. Additionally, the modern wrist's ability to reach high degrees of extension ($\geq 28.5°$) following strike may decrease risk of carpal and ligamentous damage caused by hyperextension. These results suggest that wrist extension in humans contributes significantly to stone tool-making performance.

Introduction

Evidence from eastern and southern African sites indicates that multiple Plio-Pleistocene hominin species made and/or used stone tools, including *Homo habilis* sensu lato, *Homo erectus* sensu lato, and possibly *Australopithecus garhi* and *Paranthropus robustus* (Leakey et al., 1964; Clark, 1987; Susman, 1988; Semaw, 2000). Further, evidence of 3.4 million year old cut marked bones from Dikika, Ethiopia, suggests that *Australopithecus afarensis* may have practiced stone tool behaviors as well, ~0.8 million years earlier than the oldest evidence of stone tool production (McPherron et al., 2010; but see; Domínguez-Rodrigo et al., 2010; Domínguez-Rodrigo et al., 2011; McPherron et al., 2011; Domínguez-Rodrigo et al., 2012). However, the archaeological and anatomical records suggest that only later *Homo* intensified and developed stone tool behaviors, both production and use. This intensification has been attributed to the ability of later *Homo* species (i.e., beginning with *H. erectus* sensu lato) to more efficiently produce tools in terms of production time, biomechanical demands, and joint stress compared with earlier hominin species, made possible by cognitive and anatomical changes (e.g., Marzke, 1997; Susman, 1998; Stout et al., 2008; Williams and Richmond, 2012). The current study investigates the biomechanical strategies for force production and accuracy used by experienced modern human knappers during the production of Oldowan bifacial choppers.

Knapping is commonly regarded as one of the primary selective pressures that influenced the evolution of modern human upper

* Corresponding author.
E-mail addresses: ewilliams2@chatham.edu, emswill@gwmail.gwu.edu, erinmarie.williams@gmail.com (E.M. Williams), agordon@albany.edu (A. D. Gordon), brich@gwu.edu (B.G. Richmond).

http://dx.doi.org/10.1016/j.jhevol.2014.03.004
0047-2484/

limb anatomy (Susman, 1994; Marzke, 1997). Though there is a growing body of research on upper limb kinematics and biomechanics during stone tool behaviors (Marzke and Shackley, 1986; Marzke et al., 1998; Bril et al., 2010; Nonaka et al., 2010; Williams et al., 2010; Rein et al., 2013), only one feature, thumb robusticity, has experimentally been shown to confer a functional advantage during stone tool behaviors (Rolian et al., 2011). Otherwise, we have yet to experimentally demonstrate a functional advantage to any of the derived upper limb features present in the genus *Homo* relative to the primitive condition in regard to the basic knapping swing. This research gap is likely due in part to the inherent difficulty of isolating and testing the biomechanical effects of many of the relevant features. The derived ability of modern humans to obtain high degrees of wrist extension [$\sim$70°(Almquist, 2001)] offers a unique exception to this problem. The effects of the hypothetical ancestral condition can be approximated with the use of a simple brace, which limits extension to $\sim$30°–35°. Though by no means an exact analog for the hypothetical ancestral condition, the use of such an extension-limiting brace enables researchers to begin exploring some of the biomechanical parameters of early hominins that may have influenced stone tool behaviors. This motion range is the mean extension limit of extant chimpanzees (Tuttle, 1967, 1969; Richmond, 2006) and potentially that of early hominins such as *Australopithecus anamensis* and *A. afarensis*, two species that exhibit components of the wrist locking complex seen in extant African apes (e.g., an osteological projection on the dorsal surface of the distal radius, Richmond and Strait, 2000). The modern human ability to obtain high degrees of wrist extension is hypothesized to contribute to effective stone tool production, and potentially to activities such as throwing and clubbing (Marzke, 1971; Ambrose, 2001; Richmond et al., 2001; Williams et al., 2010). For example, wrist extension has been shown to contribute to the generation of high velocities and strike forces among amateur knappers (Williams et al., 2010). Here we expanded on this research by investigating the wrist's contribution to target accuracy, and by examining experienced rather than amateur stone tool makers. We hypothesized that knappers would be significantly more accurate when able to utilize their full range of wrist extension and that the use of higher degrees of wrist extension would result in significantly greater velocities at the second metacarpal (MC) head and greater angular velocities at the wrist compared with knapping trials when the wrist was restrained.

The inclusion of data from experienced tool makers, compared with the novice knappers that participated in our earlier study (Williams et al., 2010), enabled us to investigate whether the acquisition of skill would have an effect on upper limb kinematic patterns (Rein et al., 2013). We further hypothesized that when the wrist was not restrained, more experienced knappers would use a full proximal-to-distal joint sequence in terms of joint motion initiations, peak linear and angular velocities, and the onset of angular velocities in order to make full use of the proximal-to-distal joint sequence.

Materials and methods

Sample

Data were captured from eight subjects, six males (Subjects A – F) and two females (Subjects G and H). All subjects were familiar with Oldowan stone tool types. Subjects A – E were highly skilled knappers, proficient in knapping techniques spanning the Oldowan, Acheulean, and the Middle and Late Stone Ages. Subjects F – H were proficient in making Oldowan and Acheulean tools, but not yet as skilled in some of the more complex tool traditions. Subjects were all right-hand dominant and free from muscular and/or osteological conditions. Informed consent was obtained under guidance by The George Washington University Institutional Review Board (IRB # 100631).

For the analysis of upper limb motions, each subject produced a total of four Oldowan bifacial choppers using nodules of raw English flint (selected for its relatively homogeneous composition and uniform material properties) that were largely free of cortex. Each subject produced two bifacial choppers under normal, non-restrained conditions. All subjects other than Subject C made two additional choppers while wearing the extension-limiting brace, resulting in a total of 30 choppers (Fig. 1). The reduction sequence for each bifacial chopper started with a chunk of material approximately the size of an American football that had been removed from a larger nodule. Subjects were instructed to produce 'rough' bifacial choppers with no more than five flake removals per side in order to create a single chopping edge. A total of 510 swings were recorded, 265 when subjects' wrists were unbraced, and 245 when subjects' wrists were braced. Subjects produced four additional bifacial choppers using a fine-grained Oregon basalt, two under normal conditions and two while braced. In total, each subject produced four choppers under normal conditions and four while wearing the extension-limiting brace (except for Subject C, who produced choppers in basalt and flint only in the unbraced condition), resulting in 60 choppers total.

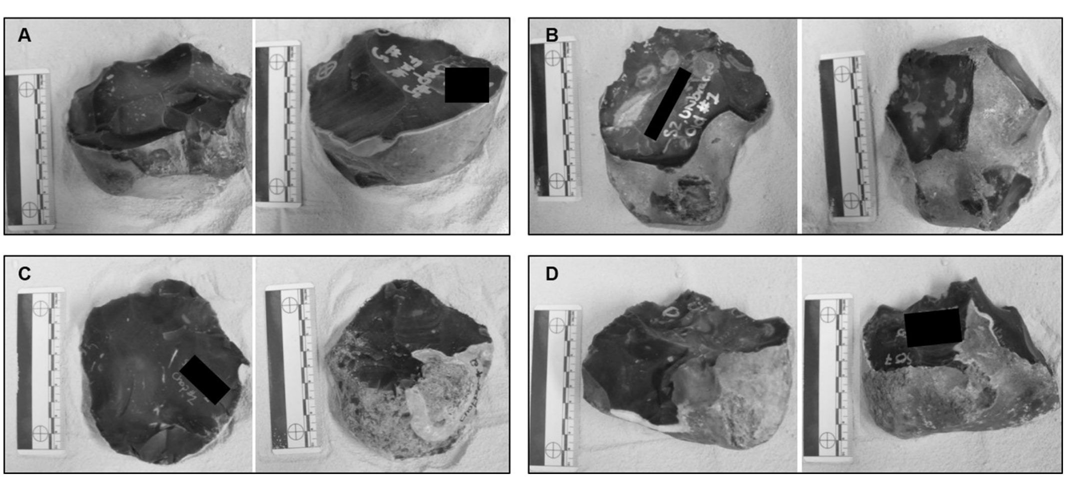

Figure 1. Experimentally produced Oldowan choppers. Both faces of Oldowan bifacial choppers produced under normal knapping circumstances (i.e., unbraced) by Subject A (A), Subject C (B), Subject F (C), and Subject G (D).