Journal of Archaeological Science: Reports 16 (2017) 57–64

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

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

Mechanics of archery among Hadza hunter-gatherers

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ARTICLE INFO

Keywords:
Experimental archeology
Biomechanics
Hunting
Human ecology

ABSTRACT

The development of the bow and arrow was an important milestone in the evolution of foraging technology. Experimental approaches to interpreting lithics and other archeological evidence for early archery have led to important insights into their manufacture and use, but these studies are limited by a lack of data on the mechanics of traditional archery among living hunter-gatherers. Here, we investigated archery mechanics among the Hadza, a population of traditional hunter-gatherers living in Tanzania, who build and use their own bows and arrows to hunt wild game for food. Ten Hadza men participated in an archery competition with targets set at 15, 30, and 50 m, similar to the range of target distances during hunting. We used a spring scale to calibrate the draw force for each bow, and a high-speed digital video to record shooting mechanics and arrow velocity for each shot. Arrow velocity (45.1 ± 7.0 m/s^{-1}) and estimated kinetic energy (36.9 ± 13.4 J) were greater than typically employed in experimental archeology studies. Draw forces (311 ± 98 N) were also greater, equivalent to ~70% of men's body weight. Approximately 70% of the strain energy from the drawn bow was converted to arrow kinetic energy upon release, similar to published efficiencies for modern recurve bows. Arrow kinetic energy and draw force were similar for 15 m and 30 m targets, but increased marginally for the 50 m target, suggesting that Hadza men adjust arrow trajectory for targets at short and middle distances, but may increase draw force and hence arrow energy for distant targets.

1. Introduction

Projectile weapons are an important innovation in human cultural evolution, enabling hunters to strike their prey from a greater distance, and with more kinetic energy, than is possible with thrown rocks or spears. Bow and arrow, a successful and widespread projectile technology, is evident in the archeological record of the Levant and North Africa by ~40,000 years ago (Shea, 2006; Shea and Sisk, 2010) and may have its origins ~65,000 years ago in South Africa (Lombard and Phillipson, 2010). The development of the bow and arrow improved the effectiveness of Late Pleistocene hunters and expanded their ecological niche, reflecting an impressive degree of behavioral and cognitive sophistication (Churchill, 1993; Shea, 2006; Brooks et al., 2006; Shea and Sisk, 2010; Lombard and Wadley, 2016). The utility of early arrow technology has been demonstrated through empirical tests of lithic replicas (Pargeter, 2007; Lombard and Pargeter, 2008; Sisk and Shea, 2009). However, the mechanics of archery as practiced by living hunter gatherers is largely unstudied. Consequently, while the potential of early bow and arrow technology is well known, the kinetics and mechanical effectiveness of hunter-gatherer archery in a real world setting are not.

The Hadza, a population of traditional hunter-gatherers living in the semiarid savannah region of northern Tanzania near Lake Eyasi (Marlowe, 2010), provide an opportunity to study the mechanics of traditional archery among actively practicing hunters. Today, all the Hadza practice some hunting and gathering, and a minority of them (~200–300) subsist on foraged foods for the vast majority of their diet. We carried out the research in this paper while living in a camp whose members subsisted on wild foods for over 90% of their diet. These Hadza had no crops, domesticated animals, firearms, or vehicles. Women were gathering wild plant foods on a daily basis, mainly berries and tubers. Men foraged for honey and hunted wild game with their bows and arrows. Hadza men grow up using a bow from a very young age; small bows and arrows are commonly made and given to boys as

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http://dx.doi.org/10.1016/j.jasrep.2017.09.025
Received 4 May 2017; Received in revised form 28 August 2017; Accepted 30 September 2017

Fig. 1. Hadza bow and arrows. Arrow types shown here: A. *hi'ko*, similar to the style used in this study, B. and C. are metal tipped *//anako* arrows with two tangs. Arrow C has poison applied to the shaft of the arrow head, from below the tangs to just above the wooden shaft. D. *kasama*, with a metal tip in a symmetrical palmate shape. E. metal tipped *//ana* arrow with a single tang.

young as 3 or 4 years to play and practice with (Marlowe, 2010). Men carry a bow during most of their adult life, even on forays from camp in which hunting is not their primary objective.

Hadza men craft straight bows (i.e., without recurved ends) using branches of the *Dombeya kirkii* or *Grewia bicolor* (Woodburn, 1970; Marlowe, 2010; Fig. 1). Branches are felled with a small axe, and then carved with a knife until they are smooth and circular in cross-section, with tapered ends. The bow is then shaped by warming it in hot ashes and bending it, sometimes using the fork of a tree. Warming, bending, and carving are repeated until the bow presents a smooth, uniform, shallow arc. Animal fat or beeswax is often applied during this process to prevent the bow from cracking, and several rings of animal hide are often slid over the bow for adornment. Hadza men traditionally string the bow using processed strips of nuchal ligament of eland, buffalo, or zebra, or the sinew of giraffe. The process of making a bow can take two or three days, and they typically last for several months (Woodburn, 1970; Marlowe, 2010; Fig. 1).

Hadza men make their arrow shafts from branches of *Dombeya kirkii* or *Grewia bicolor* trees (Fig. 1). The arrow shaft is made from a single piece of wood, sinew or cotton string is used to wrap the fletching (typically four or five feathers) to the base, and a knife is used to carve a nock. The style of the head depends on the arrow's intended function. In some (*hik'o*; Fig. 1A), the end of the shaft is sharpened and serves as the head of the arrow. These wooden-tipped arrows are used for small game, and are typically used for archery competitions. Several styles of metal arrow heads are also made (Fig. 1B–E), the heads cold forged from metal scrap (e.g., heavy framing nails) using a metal hammer, field stone anvil, and cold chisel. Metal arrow heads are made with a thin shaft at the base which is slotted into a hole drilled into the end of the wooden shaft. Sinew wrapping is used to prevent the shaft from splitting. For many metal-tipped arrows, poison, derived from botanical sources, is applied like putty to the shaft just below the arrow head (Fig. 1C). Hadza men manufacture poison from two different botanicals, *panjube* (*Adenium obesum*) and *shanjo* (*Strophanthus eminii*). Hadza have also been observed using a third type of poison, *kalakasy*, a botanical-based poison not manufactured by Hadza and acquired through trade with neighboring groups (Marlowe, 2010).

The available measurements of Hadza bows suggest they develop considerable draw forces. Marlowe reported a mean draw weight of 309 N ± 55.6 N (range: 216–420 N, $n = 30$); Woodburn (1970) reports maximum draw weights of 445 N (45 kg), and Bartram (1997) reports a maximum draw weight of 588 N (60 kg). By comparison, mean self-reported draw weight for a sample of 22 male Olympic archers (recurve bows) was 211 ± 16 N (Table S1). However, arrow kinematics and bow efficiency for the Hadza have not been studied and thus it is not known whether the high draw forces of Hadza bows translate to high arrow velocities. Reported draw weights were not measured at a set draw length or during actual shooting events, and some have suggested that traditional straight bows are relatively inefficient at converting stored elastic strain energy to arrow kinetic energy (Miller et al., 1986; but see Kooi, 1991; Tuijn and Kooi, 1992). Further, it is unknown whether draw mechanics are related to body size, or whether Hadza men adjust their draw length or the trajectory angle to accommodate differences in target distance.

Bow and arrow mechanics in living hunter-gatherers are needed to inform experimental studies of Paleolithic archery. The effectiveness of different arrowhead designs, materials, and hafting techniques, as well as the magnitude and nature of use wear and impact damage, are all dependent upon arrow velocity and impact force, which are in turn constrained by elastic energy storage and efficiency of the bow. Draw forces are often unreported, but a recent paper by Sisk and Shea (2009) examining the performance of triangular lithic arrowheads reported a draw force of approximately 180 N. Experimental studies of lithic design, hafting material, and impact damage have generally employed arrow velocities between 28 and 36 m/s (Pargeter et al., 2016; Sano and Oba, 2015; O'Driscoll and Thompson, 2014) although Gaillard et al. (2016) examined velocities as high as 50 m/s. Arrow kinetic energies are typically unreported, but mean arrow mass and velocity reported by Pargeter (2007) and Sano and Oba (2015) produce values below 14 J. Draw forces and arrow velocities are based largely on replication studies of Paleolithic bows and arrows. For example, Miller et al. (1986) report arrow velocities of 35 m/s using a wooden replica straight bow. Nonetheless, without measurements from living populations actively using these technologies, it is difficult to assess whether and to what extent experimental studies replicate real world conditions.

In this study, we investigate the mechanics of archery among Hadza men during a target shooting competition. We measured the dimensions and draw forces for each participant's bow and arrows, and used high-speed video to record shooting kinematics and arrow flight. We then tested the hypothesis that bow mechanics were correlated to body size and arm dimensions of the archer, the distance from the archer to the target, or both. Using data from Olympic archers for comparison, we examine the effectiveness of Hadza bow and arrow technology. Finally, we discuss the implications of these results in reconstructing hunting ecology in Late Pleistocene and Holocene hunter-gatherers.

2. Materials and methods

2.1. Participants

Ten Hadza men participated in an archery competition that HP, DAR, and BMW organized at Sengeli camp in June 2010. This competition took place on one afternoon, during a two-month field season focused on measuring daily energy expenditure and physical activity (Pontzer et al., 2012; Pontzer et al., 2015; Raichlen et al., 2017). We provided a prize for the most accurate archer (most target hits): a large, empty coffee tin (Africafe 250 g) that is useful as a storage tin. The participants appeared happy and eager to compete, and a small,