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Impact of grinding technology on bilateral asymmetry in muscle activity of the upper limb

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ABSTRACT

This paper proposes and tests the idea that a major change in technology associated with the grinding of cereals may account for changes in asymmetry in the upper arms of women in the Neolithic through Iron Age across a large area of Europe. It has been observed that bilateral asymmetry in humeral strength (i.e., polar section modulus) decreased to near zero in early agricultural females, but increased again during the Iron Age. These changes in asymmetry in females have been interpreted as the direct consequence of the adoption of the saddle quern at the start of the Neolithic and its subsequent replacement by the rotary quern in the Iron Age. To test the impact of these alternative cereal grinding methods, we tested the efficiency of saddle and rotary quern grinding with 16 female volunteers and the effect of grinding on muscle activity of the upper limb with 20 female volunteers. We used electromyography to measure muscle activity in the *pectoralis*, *deltoideus*, *infraspinatus* and *triceps* muscles and adjusted muscle activity for efficiency and muscle size. Saddle quern grinding was 4.3 times less efficient than rotary quern grinding and produced a significantly higher amount of coarse- and middle-grained flour but a significantly lower amount of very fine grained flour than rotary quern grinding. Saddle quern grinding showed symmetrical muscle activity in all four studied muscles, whereas rotary quern grinding yielded consistent directional asymmetry in a majority of muscles even during bimanual rotation. Saddle quern grinding required about twice as much muscle activity per kg of grain when adjusted for muscle size than rotary quern grinding. Our results support the view that saddle quern grinding may have played a major role in the decrease in directional asymmetry in humeral strength in early agricultural females and that the adoption of the rotary quern during the Iron Age may have increased humeral directional asymmetry mainly because of increased asymmetrical loading and the reduced time needed for grinding in favor of other manipulative tasks.

1. Introduction

Major lifeway changes leave evidence not only in the form of new settlement patterns, artefacts and ecofacts, but directly on the human body as a consequence of the biocultural nature of the human adaptation (e.g., Armelagos and Cohen, 1984; Buikstra, 1977; Buikstra and Beck, 2006; Larsen, 1997, 2001). Using an experimental approach, in this paper we test the hypothesis that observed variation in one of the indicators of such biocultural changes – asymmetry in humeral strength – observed over a large geographic and temporal range is linked to changes in grinding technology.

It has been observed that female skeletal remains show a decline in bilateral asymmetry in the upper arms as indicated by decreased asymmetry in humeral robusticity and cross-sectional properties such as humeral polar section modulus (i.e., in humeral strength) between the European Mesolithic and Neolithic periods (Marchi et al., 2006; Ogilvie and Hilton, 2011; Sládek et al., 2007; Sládek et al., 2016; Sparacello and Marchi, 2008; Sparacello et al., 2011), with a resulting median directional asymmetry close to zero (Fig. 1; see also details in Sládek et al., 2012; Sládek et al., 2016). The absence of asymmetry in humeral strength of females has also been observed in the subsequent European Copper Age and Bronze Age; however, female strength asymmetry increased again up to 6% during the European Iron Age, and this asymmetry

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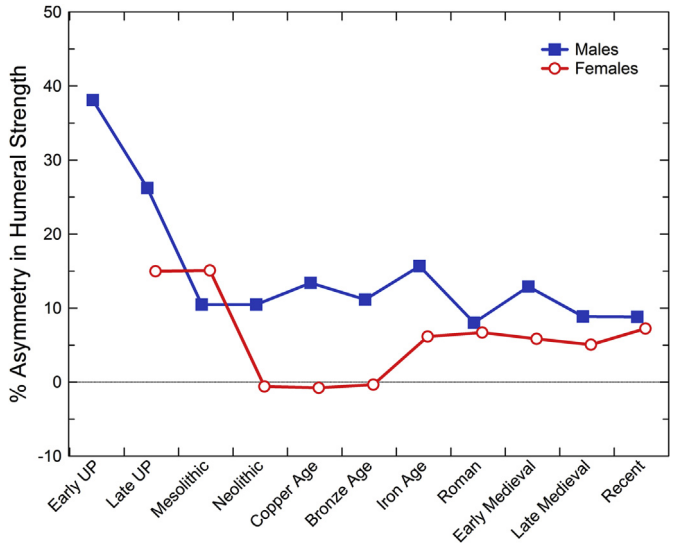

Fig. 1. Late Pleistocene and Holocene variation in median percentage directional asymmetry in humeral strength (filled (blue) = males, open (red) = females). The sample consists of 1227 matched pairs of humeri selected from sites excavated in Britain, Scandinavia, North-Central Europe, France, Italy, the Iberian Peninsula, and the Balkans. Asymmetry is computed as the percentage directional difference between right and left humeral cross-sectional strength. Positive values indicate right upper limb dominance, negative values reflect left dominance, and zero indicates an absence of asymmetry. Humeral strength was estimated using polar section modulus taken from cross-sectional shape measurements at 35% of humeral biomechanical length. Note that directional asymmetry in humeral strength declines to zero in females between the Neolithic and Bronze Age and then increases again between the Bronze Age and the Iron Age. In contrast, male directional asymmetry in humeral strength declines earlier, between the Upper Paleolithic and Mesolithic, falling to about 10%, but never falls to zero, and subsequently absolute values of male directional asymmetry show only limited variation during the Holocene. (Adapted from Sládek et al., 2016; see further details therein). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

remained practically unchanged throughout the rest of the European Holocene period (Sládek et al., 2016). A similar absence of humeral strength asymmetry in early agricultural females in the European Holocene has also been reported in studies that focused more closely on specific European regions such as Central Europe (Macintosh et al., 2014b; Sladek et al., in prep; Sládek et al., 2007) and Italy (Marchi et al., 2006; Sparacello et al., 2011). A decline in strength asymmetry in early agricultural females was also identified in the southeastern United States (Bridges, 1989; Hogue and Dongarra, 2002), and a lack of asymmetry has been described for heavily agriculturally-dependent, late prehistoric Pueblo females in the southwestern United States (Perry, 2004). Although, a decline in humeral strength asymmetry also occurs in males, the decline is observed during the Late Pleistocene, well before the adoption of agriculture, and never approaches zero (Sládek et al., 2016).

Cross-sectional geometric (CSG) properties such as the polar section modulus taken from transversal sections of long bone diaphyses have been shown to be responsive to external loading and relevant for the interpretation of mechanical environment (Ruff et al., 2006a and references therein). There is also support for the view that CSG properties of human long bones reflect the mechanical loading history of the humans during life (Ruff, 2008 and references therein) and therefore they are frequently used in bioarchaeology to reveal either mobility pattern differences among prehistoric humans (Holt, 2003; Macintosh et al., 2014a; Marchi, 2008; Ruff et al., 2015; Ruff et al., 2006b; Shaw and Stock, 2013; Sládek et al., 2006a, 2006b; Smith, 2003) or differences in manipulative behaviors (e.g., Churchill and Formicola, 1997; Churchill et al., 1996; Marchi et al., 2006; Rhodes and Knüsel, 2005; Sládek et al., 2007; Sládek et al., 2016; Sparacello et al., 2015). Given these links between CSG properties and behavior, we may hypothesize that the absence of asymmetry among early agricultural females and its reappearance in the Iron Age reflect changes in some sex-specific activity involving the upper limbs (see review in Sládek et al., 2016).

Aside from these general considerations, the factors responsible for the absence of bilateral asymmetry in humeral strength in females are unclear. It has been proposed that some role may be played by higher participation of females in domestic tasks (Sládek et al., 2007). In particular, the most frequently suggested cause is increased reliance on food grinding resulting from the adoption of querns and the introduction of new crops (see review in Sládek et al., 2016). Since food preparation is widely interpreted as a major subsistence role for females during prehistory (Murdock and Provost, 1973), it is expected that changes in grinding technologies were reflected in skeletal robusticity.

In recent years, the assignment of normative binary gender roles ("men do this, women do that") and the projection of ethnographic generalizations onto the archaeological record has received intense criticism and is recognized as an oversimplification (e.g., Bolger, 2010, 2012). Nevertheless, the vast majority of ethnographic and ethnohistoric studies remain consistent with Murdock and Provost (1973) observation that food preparation activities have most commonly been associated with women (e.g., Clay, et al., 2009; Coe and Palmer, 2013; Fratt, 1997; Joyce, 2000; McCafferty and McCafferty, 1999; Meyers, 2007; Searcy, 2011; Watts, 2014; Wrangham, 2009), and archaeological osteological studies either support such an interpretation (e.g., Eshed, et al., 2004; Molleson, 2000; Perry, 2004; Sadvari et al., 2015) or fail to identify significant sex differences (e.g., Larsen, et al., 2015; Peterson, 2002). Thus, without assuming a rigid universal and invariant gendered division of labor, the evidence supports an expectation that in the majority of cases, prehistoric women usually performed more of the food preparation tasks (such as cereal grinding) than did men. Thus, differential changes in skeletal evidence of women's activity patterns should be associated with the subsistence changes and shifts in food processing technology of the Neolithic and subsequent periods.

This assumption is supported by ethnographic observations. Generally, grinding is a gender specific task among societies which practice saddle quern grinding (e.g., Foster, 1967; Hamon and Le Gall, 2013; Chinas, 1983; Searcy, 2006). Ethnographic observations have also demonstrated that grinding on saddle querns is a time consuming task for females which results in several hours of strenuous manual activity each day (see review in Searcy, 2006 and discussion below). Experimental research on saddle querns has confirmed these ethnographic observations (Adams, 1999; Gründler et al., 1976; Holodňák, 2001; Samuel, 2010; Wright, 1993). By contrast, experimental observations have shown that grinding on rotary querns increases efficiency and substantially reduces the time needed for this specific manipulative behavior (e.g., Jorgensen, 2002).

The role of grinding on bilateral humeral asymmetry in strength is also partly supported by the European archaeological record. The transition between the European Mesolithic and Neolithic periods, as well as the transition between the European Bronze Age and the Iron Age, were both accompanied by changes in grinding technology (Crombé and Robinson, 2014; Lynch and Rowland, 2005; Watts, 2014; Wefers, 2011). European early agricultural groups intensified food grinding using the saddle quern as the main technology to prepare the new domesticated crops for consumption (Fig. 2; e.g., Watts, 2014). Archaeologists have shown that subsequently, during the intensification of agriculture during the European Iron Age,