Integrating Mechanical and Ergonomic Research within Functional and Morphological Analyses of Lithic Cutting Technology: Key Principles and Future Experimental Directions

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Abstract

The functional value of a stone tool is principally in its ability to cut, split, or otherwise deform material. The relative efficiency with which stone tools undertake cutting processes has been a point of interest to lithic archaeologists for decades, with many linking aspects of tool morphology to functional performance. Many of the questions asked by stone tool research are, however, pertinent to other disciplines. This includes mechanical engineering and ergonomic sciences where there is a substantial amount of research dedicated to understanding the mechanics of cutting and the influence exerted by tool-form attributes during use. These investigations therefore have valuable insights for lithic archaeology and our understanding of the variables that would have been influencing stone tool use in past populations. Here, the value of mechanical and ergonomic research to lithic archaeology is analyzed, key morphological and mechanical principles central to the determination of a stone tool’s cutting efficiency are reviewed, and the need for future experiments that investigate these principles within archaeological contexts is highlighted.

Key words; Stone tool, efficiency, cutting, morphology, fracture mechanics, experiment

1. Introduction

The ability to cut, split, or otherwise deform material has been a functional attribute desired in lithic technology from its origin at least 3.3 million years ago up until recent ethnographic populations (Gould et al. 1971; Toth 1985; Hiscock 2004; Gowlett 2006; Shea 2006; Eren et al. 2008; Stout et al. 2010; Holdaway and Douglas 2012; Harmand et al. 2015). Indeed, the vast majority of stone tool production procedures are undertaken with the aim of producing an edged tool capable of separating two or more aspects of a material. Stone tools are then widely linked to a range of functional behaviours, including those central to the acquisition and processing of food resources or the production and modification of items of necessity. As a result, stone tool use is often hypothesized to have been central to the survival and success of past populations.

The efficiency with which stone tools were able to undertake functional tasks is likely to have been an imperative consideration for individuals in the past (Bleed and Bleed 1987; Torrence 1989; Jeske 1992; Shea 2007). Consequently, archaeologists have conducted countless artefact analyses and experimental investigations in the pursuit of an understanding of how varying form attributes and tool-use conditions influence an individual’s ability to effectively and efficiently use stone tools (e.g., Crabtree and Davis 1968; Walker 1978; Jones 1980, 1994; Jobson 1986; Vaughan 2001; Machin et al. 2007; Collins 2008; Sisk and Shea 2009; Key and Lycett 2011, 2014). The principal aim of such undertakings is to understand how tool-form attributes affect the functional performance of specific tool types, and subsequently, to infer why past populations may have produced the tool forms that they did.

The relative ability of sharp-edged tools to cut and deform materials is, similarly, a key research theme within mechanical engineering and ergonomic sciences. Indeed, one’s ability to efficiently, effectively, and comfortably use cutting technology is of prime concern to tool producing and tool-use industries/research (e.g., Magnusson et al. 1987; Grant and Habes 1997; McGorry 2001; Aldien et al. 2005; Claudon and Marsot 2006). In much the same way as in lithic archaeology, decades of research has been dedicated to trying to understand how tool form attributes influence an individual’s ability to use modern cutting technology (e.g., McGorry et al. 2003, 2005; Atkins et al. 2004; Atkins 2006, 2009; Claudon and Marsot 2006; McCarthy et al. 2007; McCarthy et al. 2010). Contrary to many archaeological studies, however, mechanical and ergonomic literature has been able to dedicate a great deal of attention to the scientific understanding of exactly how different form attributes influence a tool’s cutting abilities. This means that the functional influence of many morphological phenomena discussed within lithic archaeology is already understood in great detail within other disciplines. To date, however, the value of this information has largely gone unnoticed, or at least under-utilized, by archaeologists. Hence, there is currently a substantial amount of information beneficial to our understanding of lithic artefacts and the functional implications of varying stone tool forms within these disciplines. Here, some of the key mechanical processes and form-dependent relationships underlying the functional capabilities of lithic technology are detailed, the value of mechanical engineering and ergonomic sciences to archaeology are highlighted, and potential future directions for experimental stone tool research are noted.

1. Defining ‘Cutting’

Within mechanical engineering ‘cutting’ is a term that, although somewhat difficult to define, broadly refers to the separation of materials by means of fracturing (Atkins 2009). That is, to initiate a parting between two portions of material through the production of a ‘fracture’, or ‘crack’. This may, therefore, refer to anything from a carnivore slicing meat from a carcass with its teeth, to a rabbit splitting soil with its paws, or an arrow piecing animal hide. The process of ‘cutting’ referred to by archaeologists, and thus applied to artefacts, is more specific as by nature of the discipline it necessitates the use of a tool. Further, there is a requirement to differentiate between fracturing events that occur during stone tool flaking (i.e. ‘knapping’), and those that occur during traditional archaeological notions of ‘cutting’ (e.g., Tringham et al. 1974). Within lithic archaeology, cutting may, therefore, be defined as ‘the application of an object to a material in order to initiate the separation of two or more of its aspects by means of fracturing by indentation’. While still very broad, such a definition necessitates the use of a tool, and thus, not only would such a definition produce an artefact (which is ultimately the focus of an archaeologist’s research), but it may easily be separated from masticatory and manipulative ‘tearing’ behaviours that are of interest to zoologists, palaeoanthropologists and bio-archaeologists (e.g., Ang et al. 2006; Marzke 2015), and motion based definitions of cutting described within behavioural studies (e.g., Shumaker et al. 2011: 13). Further, a requirement to indent a worked material distinguishes ‘cutting’ from fracturing events that may occur during stone tool production. These definitions are not, however, mutually exclusive. For example, it can be argued that hammer stone strikes upon a stone core may cause indentation at the point of percussion and the cone/bulb of percussion associated with Hertzian cone fractures may cause a degree of ‘wedging’ or indentation that facilitates the production of fractures.

Within such a definition there are a number of cutting types of particular pertinence to lithic archaeology (Table 1). Here, attention is focussed upon hand-held edged tools and cutting behaviours/types undertaken by abrasive, projectile, and piercing technologies are not discussed in detail (See Cotterell and Kamminga [1990] for a lithic-centered review of abrasive fracturing and the mechanics of projectile use). In other words, it is ‘slicing’, ‘cleaving’, ‘scraping’, and ‘sawing’ cutting behaviours that are the focus of the present discussion. Many of the mechanical principles noted here are, however, applicable to forms of cutting beyond those directly referenced.

Understanding how these types of cutting are influenced by varying tool morphologies requires consideration of a number of key mechanical principles that define cutting processes. While many of these are outlined in the following discussion, it has not been possible to do so in detail in all instances and further reference to mechanical literature is recommended (e.g. Reilly et al. [2004], McCarthy et al. [2007], Atkins [2009]). The mechanical principles of cutting can, however, be broadly defined through the energy (i.e. work) required to initiate a cut and the attainment of that energy through varying input variables (Atkins 2009; see below). Thus, it is the amount of energy expended by a tool-user when producing the required ‘work’ that defines the efficiency with which a cut is performed. Identifying how tool form attributes influence the attainment of a given ‘work’ requirement is, then, key to identifying how variable stone tool forms influence cutting processes. Through the investigation of the impact that this has upon the energetic expenditure of the tool user, it then becomes possible to identify implications for understanding the tool production and tool-use choices made by past populations.

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1. Tool-Form Attributes and their Influence on Cutting

Many of the tool-form attributes exhibited by lithic cutting technology are similarly represented in modern industrial tools. As a result, archaeologists, engineers, and others concerned with the functional design of cutting tools ask similar questions in relation to how aspects of tool morphology influence cutting processes. There is, however, a stark contrast between the controlled, scientific and statistically attestable investigations carried out within engineering and ergonomic research that explicate results by means of fracture mechanics and biomechanics (e.g., Atkins et al. 2004; McCarthy et al. 2010; Rossi et al. 2014), and those conducted within archaeology that are often of more limited scientific rigour. Consequently, there is a great deal of information within this former body of work which is of pertinence to lithic archaeology, our understanding of the functional implications of variable stone tool forms, and the decision processes underlying tool production in past populations.

*Sharpness*

The sharpness of a cutting tool’s edge is widely understood to be of importance to its functional potential within lithic archaeology (e.g., Jones 1980; Dewbury and Russell 2007; Holdaway and Douglass 2012). The trait of ‘sharpness’, however, has potential to be misused, with it in some instances being used interchangeably with or alongside the morphologically distinct trait of ‘edge angle’. Although these two aspects may often be correlated, ‘edge angle’ is not necessarily tantamount to ‘sharpness’ (or vice versa) and each can be examined as an independent entity (Reilly et al. 2004; McCarthy et al. 2010). The conventional definition of ‘sharpness’ is geometrical and refers to the relative roundness of an edge at its very tip (edge apex), and thus is measurable by means of a tip’s radius (Fig. 1; McCarthy et al. 2010; Schuldt et al. 2013) Strictly speaking, sharpness is not, however, absolute, cannot be characterized by edge radius alone, and is often related to the forces measured during cutting (Reilly et al. 2004; Atkins 2009; Fig. 1). The sharpness of an edge is of influence to cutting processes due to the relative area of the tip in contact with a worked material and the forces contributing to the production of the required work (McCarthy et al. 2007). Indeed, increased edge sharpness concentrates greater cutting stresses over a smaller surface area, in turn meaning that fracture initiation (i.e. cutting) is achievable with lower applications of force. Equally, blunter tips increase the contact between a tip and worked material, diffuse the cutting stress enacted, and mean that greater force and effort is required to produce a cut.

\*\*\*Figure 2 to be inserted near here\*\*\*

The impact that sharpness has upon cutting processes highlights the fact that cutting only occurs when the stress generated by a tool’s edge exceeds the strength of the material it is in contact with and the forces provide work of separation at an appropriate rate. Since cutting stress ($σ$) is calculated as force ($N$) per unit area ($m$2), so $σ=N/m$2, all cutting processes require a force input. The amount of force (i.e. loading) able to be enacted through a tool is then central to the cutting capabilities of lithic technology. The presence of a sharper edge would, therefore, be of benefit to individuals concerned with the efficiency of, or forces enacted during, stone tool use. Indeed, all other variables being equal, sharper edges create relatively greater cutting stresses, which in turn facilitate quicker and larger fracture initiations (and by association more efficient cutting processes) and the cutting of materials of greater strength (i.e. resistance). This is illustrated in Figure 2, where a cut ($h$) only initiates when stress ($σ$) is greater than the material’s strength ($φ$). Up until that point, loading can create an indented deformation ($δ$) in some materials (e.g., animal tissues), however, it is only when $σ>φ$ that a cut is initiated, the material opens, and the tool’s edge can move into the resultant fracture.

Sharpness is of particular importance during stone tool use as plant and animal tissues are highly extensible and flexible, meaning that the deformation (i.e. compression, bending, etc.) they allow prior to cut initiation is relatively high (Mai and Atkins 1989). This means that if a cutting edge is dull, then plant and animal tissue is likely to deform prior to there being enough stress to initiate a cut. The importance of this can be seen during the reaping of crops where a dull blade would not sever the stem of a plant, but instead knock it to one side. The influence of edge sharpness during the cutting efficiency of biological tissues has been extensively investigated within mechanical engineering literature (e.g., McGorry et al. 2003; Shergold and Fleck 2004; Claudon and Marsot 2006; McCarthy et al. 2007; McCarthy et al. 2010), with all noting that increased measures of edge sharpness result in reduced loading requirements and force input during tool use. For instance, McGorry et al. (2003) investigated the influence of edge sharpness during the cutting of meat with metal knives. Specifically, they tested its impact upon cutting moments, grip forces and cutting times, identifying that in all instances sharper blades required significantly lower measures. The sharpness of a cutting edge is, therefore, of significance to the efficiency of, and required force input during, butchery.

If future experimental research was able to test similar measures with lithic technology there is the potential to address numerous avenues of inquiry relating to the relative importance of cutting edge ‘sharpness’ during prehistory. This includes discussion relating to the relative necessity of sharp edges during different tool use contexts, how frequently re-sharpening behaviours may have been required to be undertaken, and whether there are any sharpness ‘thresholds’ beyond which re-sharpening becomes essential to efficient tool use.

*Edge Angle*

Generally defined as the angle produced between two intersecting planes on a tool’s edge (Dibble and Bernard 1980; McCarthy et al. 2007; Key and Lycett 2015), the variable of ‘edge angle’ (often referred to as the ‘included’ or ‘wedge’ angle in engineering literature; Figs. 1 and 3) is one of the most heavily investigated morphological phenomena with regards to its influence on the efficiency of lithic cutting technology. Indeed, since Wilmsen’s (1968) influential examination of the varying edge angles observed on Paleo-Indian flake tools it is often investigated in light of its functional implications (e.g., Gould et al. 1971; Broadbent and Knutsson 1975; Crabtree 1977; Siegel 1985; Jensen 1986; Jobson 1986; Gowlett 2006; Borel et al. 2013; Eren 2013; Iovita 2014). It is only very recently, however, that the impact of edge angle variation has been considered within the context of fracture mechanics. Contrary to expectations, there is no automatic relationship between more acute edge angles and greater time efficiency in flake cutting tools as individuals have the potential to counteract any detrimental influence that more obtuse edges may have by increasing the load applied during use (Key and Lycett 2015).

\*\*\*Figure 3 to be inserted near here\*\*\*

This underlines the fundamental impact that edge angle variation has within the mechanics of cutting; that is, it determines how much resistance a worked material enacts upon a tool’s edge. Indeed, as Figure 3 details, the more obtuse the edge angle, the greater the vertical resistance enacted upon a tool’s cutting surfaces and thus the greater the input forces required to initiate a cut. This is why it has been found that individuals are able to counteract the increased resistance of more obtuse edge angles by increasing their working load during cutting tasks using stone tools (Key and Lycett 2015). Load increases are, of course, of influence to energy use, and energetic efficiency may be improved through the use of more acute edges. Importantly, however, such statements need to be considered in light of an edge’s predisposition to fracture and blunt under high loading (Tringham et al. 1974; Cotterell and Kamminga 1990), and as a result any preferentiality for more acute working edges during wood and bone modification (for example) would be balanced against a requirement to withstand high working loads. Indeed, as recently recorded by Eren and Lycett (in press, 17), an optimization between “providing a viable cutting edge, yet not being so acute as to be weak and friable upon application” may help explain why Levallois flakes were preferentially produced despite their edge angle ranges typically being higher than that of debitage flakes. Notably, these considerations (and those relating to abrasion/blunting rates) are also likely to have to a variable relationship with the type of raw material that tools are produced from. While the risk of edge fracturing is reduced in metallic blades, such considerations are similarly applied within engineering literature (Atkins 2009).

The edge angle on a cutting tool is of varying consequence to cutting efficiency. If an individual is able to counteract the increased resistance experienced by an obtuse edge by increasing working loads or by producing a gap between the cutting edge and the material being deformed, then more obtuse edges are likely to have a minimal effect in terms of time efficiency (Fig. 3). If either of these are not possible, however, then edge angle is likely to be of consequence to cutting efficiency, in terms of both time and energy, and more acute edges may preferentially be produced. Similarly, more obtuse edges may be preferred in some scraping technology in order to minimize the chances of material being cut (e.g. Gould et al. 1971).

An investigation by McGorry et al. (2005) tested the impact that edge angle variation has upon the efficiency of butchery processes using modern metal knives with angles of 20°, 30° and 45°. They compared their relative cutting proficiency by means of the grip force, cutting moments and time taken during the butchery task and showed that edge angle had little to no influence upon any of the three dependent variables. Indeed, butchery times were roughly equal irrespective of the edge angle used. When compared to another similar experiment in terms of edge angle ranges and materials, but lacking the possibility of creating a recess/gap between the tool’s surface and the worked material (see ‘rake’ and ‘clearance’ angles; Figure 3), it was noted that all edge angles could initiate a cut, however the more obtuse the angle then the greater the force required to do so (McCarthy et al. 2010).

The examples of McGorry et al. (2005) and McCarthy et al. (2010) highlight the complex interactions that may be present between any given morphological aspect of a cutting tool and the mechanical processes underlying measures of tool-use efficiency. Moreover, this specific example goes to highlight the context dependent relationship between some tool-form attributes and their relative importance during cutting processes. In absence of the context in which archaeological cutting tools were used, it may, therefore, be difficult to hypothesize accurate functional and behavioral implications for specific stone tool forms or attributes. Hence, it is vital for future experimental and functional research to take into consideration the context in which stone tools may have been used.

*Edge Scalloping/Serration/Kerf*

Modifications made to the edge of a freshly produced flake or contiguous flake removals from the edge of a core tool will create irregularities along its profile (typically referred to as ‘denticulated’ or ‘notched’ edges [e.g., Binford and Binford 1966; Rosen 1982; Picin et al. 2011]). Strictly speaking, such edges are either ‘scalloped’ or ‘serrated’ (Atkins 2009), with the former being when the depth of the recess is smaller than the pitch and the latter being when the pitch is smaller than the depth (Fig. 4). Edges can then be further separated by means of their sideways splay. This is the extent to which the sharp edge of a tool deviates from a straight line profile when viewed from its side (Fig. 4). Within engineering literature this is referred to as the edge’s kerf (Atkins 2009). Within archaeological literature, the ‘sinuosity’ of a lithic tool may similarly be used to define an edge’s deviation from linearity (e.g., Shelley 1990; Boldurian 1991; Jennings 2013). Sinuosity is, however, determined by the relative relationship between an edge’s length and its deviation from linearity, while kerf is not defined relative to the length of the cutting edge.

\*\*\*Figure 4 to be inserted near here\*\*\*

The mechanical influence of a scalloped or serrated edge during cutting is a moot point within engineering literature (Atkins 2009). Indeed, in terms of cutting performance (excluding sawing) the two are generally comparable to straight edges; although, there are a few hypothesized differences. Firstly, greater irregularity increases the length of a tool’s edge, and thus, during a slicing cut, a scalloped/serrated edge would have a relatively greater length of edge pass over a material. In turn, this would increase the horizontal force input of the slice-push ratio that describes the work required to initiate a cut (Atkins 2006; see below), and theoretically should increase the ease with which a cut is initiated. In reality this does not always happen as dependent upon the spacing and depth of the scalloping/serration, materials may not fill the concavity and make contact with all of the edge. Furthermore, any material which does fill a concavity is likely to be subject to snagging and tearing due to the variable loading distribution along a scalloped/serrated tool’s edge. Subsequently, this would decrease the potential velocity able to be gained during the slicing motion of a cut and thus the cutting stress enacted. The use of a scalloped or serrated edge may, therefore, be linked to broad, heavy duty cutting actions that can be undertaken with forces larger than the cohesion forces of the material into which the peaks are embedded. Correspondingly, this means that the relative ‘neatness’ (i.e. uniformity and consistency in terms of depth and direction) of a cut is likely to be far greater during the use of a straight edge than a scalloped one. This suggests that when undertaking a relatively refined, delicate cutting task a straight edged stone tool may be preferred. Scalloped or serrated edges do have the benefit of increasing the longevity of an edge as any damage incurred is concentrated upon the ‘peaks’ between each serration (Atkins 2009). This means the rest of the edge remains relatively damage free for longer, a matter of particular relevance to butchery activities (*c.f.,* Dewbury and Russell 2007; Braun et al. 2008).

Relative to scalloping and serration, the influence exerted by a tool’s kerf is well understood. In essence, a tool’s kerf dictates whether material is removed as waste during a cutting action (and thus whether it is a sawing action [Table 1]), and just how big a recess/gap is produced within the worked material. A particularly clear example is a modern handsaw, where a 2mm cut between two portions of wood is produced because the width of the alternating teeth is 2mm. This is why a straight edge with no notable sideways splay, such as those observed on fresh blades, does not remove waste material during a cut and only causes material severance (i.e. a ‘slicing’ cut). Within lithic technology, kerf may be produced through a number of edge modifications (e.g., denticulation, bifacial flaking) so long as there is a degree of sideways splay to the edge (Fig. 4).

Individuals might opt to produce cutting edges with a notable kerf dependent upon whether they were required to undertake a sawing or slicing cut. For example, when cutting brittle materials such as bone or wood with a flake, as a cut increases in depth there is ever increasing resistance/friction acting upon the surface of the tool, so that at a certain point the finite force a hand can exert will no longer move the tool. A flake displaying kerf would remove waste material and produce a void into which the tool’s edge could continue to cut with reduced resistance. Kerf may be produced as a by-product of a tool’s production methods (e.g., bifacial flaking) and thus may be present in a class of tools irrespective of the functional tasks in which they are being employed. In bifaces and other tools it may, therefore, be desirable to limit kerf, because the larger the kerf the more material is wasted during cutting and greater energetic input is required due to greater resistance and friction.

The edge profile of a lithic cutting tool impacts its ability to be used efficiency. Moreover, varying degrees of serration/scalloping and kerf differ in effectiveness dependent upon the context of use. Consequently, past populations are likely to have controlled for or actively pursued these morphological features to varying degrees. To date, experimental undertakings have only touched upon the influence that these attributes may have upon stone tool performance (e.g. Walker 1978; Jones 1980, 1994; Merritt 2012; Key and Lycett in press). Experiments specifically investigating such tool form attributes have the potential to provide informed functional commentary upon the edge form choices made in past societies.

*Edge Curvature*

The main impact of edge curvature is that it alters localized slice-push ratios along the edge of a tool (Atkins 2006). During most cutting behaviors, there is both a force normal to the cutting edge and a force parallel to the cutting edge. The slice-push ratio specifies the relative energetic input required by both the pressing and slicing motions of a tool when achieving a specific cutting stress between a tool’s edge and worked material (Atkins et al. 2004; Atkins 2006). This means that the ease of cutting is influenced by both the speed with which an edge is drawn across a material perpendicular to the cut and the loading enacted on the tool (Atkins et al. 2004; Atkins 2006).

Thus, depending on the position of the tool’s edge in respect to the worked material, the cutting motion employed, and the stability provided by the hand and worked material, varying degrees of vertical or horizontal force may result from variation in the curvature of a cutting edge. The forces on a straight edged tool are more consistent and have consequently been found to require significantly lower maximal grip force during use (McGorry et al. 2004). The benefits provided by a straight or curved edge are likely to be highly context dependent. For example, if a cutting task only facilitates the use of a relatively small length of cutting edge, such as when cutting tendons/ligaments during joint disarticulation, it may be preferable to employ a concave edge where the distal length of edge enacts particularly high cutting stresses for a short portion of the cut. Alternatively, when performing long cuts through large portions of material, it may be preferable to employ the relatively long length of a straight edge due to its greater cutting consistency.

For tasks where there is no perpendicular motion of a tool relative to the direction of the cut being produced, such as during scraping activities, then varying degrees of curvature have a different impact. Principally, curvature would dictate the amount of edge that makes contact with a worked material, and thus, the amount of cutting stress enacted relative to loading. In turn, this influences the efficiency with which scraping would be undertaken. Collins (2008) examined this during a wood scraping experiment and found that flint flakes with a convex edge were most efficient. Collins (2008) concluded that this was due to the convex edge having a smaller area of contact with the worked material, thus exerting greater pressure during use. A straight edged scraper would have had the same loading levels distributed over a greater area. Had the loading levels been high enough for straight edged flakes to enact greater stress, or had the worked material been softer and provided less resistance, then it is highly likely that Collins’ (2008) experiment would have returned different results.

Only a limited number of lithic technologies are characterized by the regular or predetermined production of uniformly straight or curved cutting edges (e.g. blades). Most of the edges present upon stone cutting tools have both straight and variably curved aspects. There are, then, important questions relating to 1) why some stone tool production sequences are specifically geared towards the production of either curved of straight edges and 2) how the variable edge curvature observed upon other stone tool forms influences their ability to be used and why individuals may not have chosen to standardize these edge forms to a greater extent. Examination of these (and other) aspects of the mechanical relationship between edge curvature and functional utility could profitably be examined by future experimental research.

*Tool Size (Including Edge Length and Mass)*

The size of a stone tool has a number of implications in terms of its cutting mechanics and functional utility. Firstly, tool size increases are often correlated with alterations to other morphological attributes (Gowlett and Crompton 1994), particularly cutting edge length. A number of previous experimental undertakings link relatively longer edges to increased cutting efficiency (e.g., Jones 1980; Jobson 1986). Mechanically, the relative efficiency of a cut within a given unit measurement of edge length will be the same on two edges of varying length (i.e., if all else is equal, 10mm of edge will cut the same amount of material irrespective if it is on an edge 30mm in length or 100mm). The main influence of varying edge lengths is in the amount of cutting edge drawn across a material during one cutting stroke (*c.f*. Tringham et al. 1974: 188). Moreover, greater edge lengths have the potential to increase the velocity of a cutting stroke, in turn increasing the horizontal force input of the slice-push ratio (Atkins et al. 2004). This has clear implications in terms of cutting efficiency and energetic expenditure, with greater edge lengths reducing the time and number of cutting strokes required to cut a given portion of material. Past peoples would then have had reason to maximize the length of edge able to be used during cutting tasks. In practice, however, there is neither an exponential relationship between edge length increases and greater cutting efficiency, nor a universal ability for relatively long edges to be used in all cutting contexts. Indeed, for all stone tool and worked material types, there is a point beyond which size and edge length becomes too great for the tool to be effectively utilized. Thus, the relative benefits of maximizing a cutting tool’s edge length are task dependent.

A second implication is that a tool’s size attributes have substantial ergonomic consequences for tool users, and as a result there are implications in terms of an individual’s ability to apply high loads during cutting tasks. Since loading directly contributes to the calculation of a tool’s cutting stress, any influence that tool size has upon an individual’s ability to exert force through the hand may substantially alter the efficiency of cutting. Further, the application of a tool’s edge to a worked material creates torque, a force which attempts to rotate the tool about the point at which it is gripped. Thus, the requirement to apply a secure, forceful grip upon stone tools during their use is two-fold. While the relative ability of certain tool forms to facilitate high manipulative and cutting forces has previously been noted by lithic archaeologists (e.g., Jobson 1986; Tomka 2001; Key and Lycett 2014), it is within engineering and ergonomic research that detailed investigations have been undertaken.

Most notably, it has been demonstrated that there are certain grip sizes and shapes that maximize gripping forces during tool use (e.g., Hall 1997; Blackwell et al. 1999; Freund et al. 2002; Edgren et al. 2004; Seo and Armstrong 2008; Rossi et al. 2014) and thus, may aid in maximizing cutting stress. For example, it is known that handle diameters between 31mm – 40mm (Hall 1997; Freund et al. 2002; Edgren et al. 2004; Seo and Armstrong 2008) are optimal in terms of maximizing the gripping force exerted during power grips. Such studies are important as they highlight that tool sizes can be optimized in terms of facilitating the transfer of high forces through the hand and into the tool. Hence, there are likely to be stone tool sizes that optimize the amount of force applied during cutting behaviors and thus would have been preferred by prehistoric individuals. Ergonomic differences between tools of different sizes and shapes are, however, complex and include factors such as the relative surface area available to grip and the biomechanical positioning of digits (i.e., moment arms, muscle lengths, etc.) (Fowler et al. 2001; Seo and Armstrong 2008; Vigouroux et al. 2011; Goislard de Monsabert et al. 2014). Notably, attributes that have the greatest influence on force transferal are going to be those that influence the relative positioning of the thumb and fingers in respect to each other and the palm (Seo and Armstrong 2008; Rossi et al. 2014).

The optimization of a tool’s size in relation to force output is, however, also likely to be dependent upon the manipulative proportions of the individual using the tool (Eksioglu 2004; Seo and Armstrong 2008). Hence, the farther into the evolutionary record that questions relating to the ergonomic nature of stone tools go, the greater the consideration we need to give to the morphology of the species using the tools. For example, prior to the origin of modern human-like digit proportions (Ward et al. 2014; Lorenzo et al. 2015), optimal grip spans, and thus optimal tool sizes, were likely to have been smaller (Eksioglu 2004).

With regard to the manipulation of particularly small objects, it is known that not only does the use of precision grips enact substantially greater pressures upon the digits relative to larger ‘power’ grips, but they facilitate the exertion of substantially lower forces (Goislard de Monsabert et al. 2014). Hence, one’s ability to exert and resist forces through a tool are likely to alter as a result of the relative ‘precision’ of the grip used, with very small tools enacting particularly high manipulative stresses relative to their restricted force output. This further increases the likelihood that small (i.e. ≤ 2cm) stone tools (e.g., Agam et al. 2014) were restricted in their functional value, perhaps being best suited to cutting materials that require limited force or are of limited volume (Key and Lycett 2014). Moreover, the hafting of small stone tools to larger handles may often have been related to relatively high force requirements during use.

Finally, increases to a stone tool’s size results in the cubic growth of a tool’s mass (Crompton and Gowlett 1993). It may be presumed that the increased mass of a tool should result in increased loading force and cutting stress as, after all, gravitational force is a direct product of an object’s mass. The impact of a tool’s mass during use is not, however, so straight forward. The dynamic nature of most tool use requires both varied and intricate movements and extended tool use durations. Increases to a tool’s mass can directly counteract the ease with which a cutting tool can be controlled during use and increase the rate at which fatiguing occurs. Indeed, such is the impact of a tool’s mass that Grant and Habes (1993, 199) conclude minimizing ‘mass’ to be the “primary objective for reducing the risk of fatigue and injury during hand tool use”. Similar statements have been made for Acheulean handaxes, where allometric changes controlling for cubic growth in a tool’s mass are hypothesized to be derived for functional reasons (Crompton and Gowlett 1993). While the requirement to control for mass in hand-held stone tools is of particular relevance to larger tool types, it is a consideration applicable to all and likely to be of increased importance in more intricate cutting (*c.f*., McGorry et al. 2004).

Morphological aspects relating to ‘size’ (e.g., ‘mass’, ‘length’, ‘thickness’, ‘edge length’) are perhaps the most widely discussed of stone tool attributes. Rarely, however, have the underlying causes of any functional differences between stone tools of varying size been examined. Mechanical and ergonomic investigations examining the use of stone tools of varying size would then make a valuable contribution to our understanding of exactly why past populations produced tools of specific sizes, and why tool sizes varied within and between artefact assemblages.

1. Conclusion

To date, archaeological research has not widely employed the use of mechanical principles when explaining how cutting processes may efficiently be undertaken by stone tools. As a result, theoretical explanations into the varying functional utility of stone cutting tools are not only substantially behind tool-form analyses in mechanical and ergonomic research, but are limited relative to other areas of lithic research (e.g., Ackerly 1978; Cotterell and Kamminga 1987, 1990; Dibble and Pelcin 1995; Stemp and Stemp 2003; Ollé and Vergès 2008; Jennings 2011; Lin et al. 2013; Key et al. 2015; Hutchings 2015; Stemp et al. 2015). Here, a series of key principles and morphological attributes within the mechanics of cutting have been detailed, identifying the complex array of variables influencing cutting processes. While this discussion is by no means exhaustive and there are a considerable number of mechanical aspects to cutting that could not be discussed (see: Atkins 2009), including the influence of variable task conditions (e.g., Grant and Habes 1997; Aguilera and Martin 2001; McGorry et al. 2004), it is nonetheless evident that there are a substantial number of variables that may influence the efficiency of cutting tasks using stone tools.

Principally, the efficiency of cutting with stone tools is influenced by variables that affect the stress enacted between the edge of the tool and the material being cut. This may either be through alterations to the forces enacted or aspects of the tool that contact the worked material. The extent to which prehistoric individuals exploited mechanical and ergonomic principles to maximise efficiency rates during cutting is, however, a point that requires further examination. Indeed, there is both a need to provide lithic-centric evidence for these principles through the experimental use of stone tools, and a requirement to analyse lithic tool-forms and production methods in light of the principles presented here. Further, there is need to explore how the mechanical and ergonomic principles outlined here may appropriately be applied within the behavioral and technological complexities of archaeological contexts. Certainly, the dynamic interactions observed between stone tool-users, variable task conditions, adjustable tool forms, and the life-history of stone tools provide intricacies beyond those frequently observed in mechanical and ergonomic research. In this sense, while the information detailed here provides theoretical foundations that can profitably be applied within archaeological contexts, there is a great deal yet to be investigated regarding mechanical and ergonomic influences during stone tool production and use. It is hoped that the discussion provided here may go some way to encouraging such undertakings.

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Table 1. Types of cutting with particular relevance to lithic archaeologists. Definitions, tool form attributes of particular influence, and example technologies with which they may be associated are noted. Note that these are not behavioral or movement defined definitions (e.g. Tringham et al., 1974; Keeley, 1980), but rather, detail differences in the mechanical relationship between the tool and worked material. While the tool form attributes noted here have particular importance to the efficiency of certain types of cutting, note that all morphological aspects have the *potential* to influence a tool’s cutting efficiency (some are more likely to realize this potential than others dependent upon the context of use and the form attributes of the tool in question [Key 2015]).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Cutting Type | Definition | Functional Example | Tool Form Attributes or Particular Relevance  | Example Technology |
| Slicing  | The severance of two portions of material via the lineal movement of an edged tool across a material concurrent with the perpendicular pressing of the tool into the material. No waste material is created and separation is caused by material severance. | The severing of animal tissue with a flake or blade. |  Edge Angle, Sharpness, Edge Curvature, Tool Size, Edge Length | ‘Basic’ Flake, Biface, Blade, Levallois Flake |
| Sawing | The severance of two material portions via the removal of ‘waste’ material (e.g. sawdust). Undertaken by the lineal movement of an edge tool across a material concurrent with its pressing into the material. | Wood modification with a biface or ‘chopper’. | Sharpness, Edge Angle, Scalloping, Serration, Kerf, Edge Curvature, Tool Size, Edge Length | Denticulate Blade, Denticulate Flake, Biface |
| Cleaving | The production of a cut without lineal movement of the tool across the material’s surface. Force is solely enacted in the direction of the cut and typically severs a portion of material from a greater material mass.  | Chopping wood with a stone axe head. | Sharpness, Edge Angle, Tool Size | Stone Axe (of various types), ‘Basic’ Flake, Blade  |
| Scraping | The forceful, orthogonal separation of a portion of material from the surface of another. Little to no movement perpendicular to the motion of material removal is undertaken. | A ‘scraper’ removing fat from an animal hide or a surface layer of wood. | Sharpness, Edge Angle, Edge Curvature, Mass, Edge Length | ‘Scrapers’ of Various Types |
| Drilling | Forceful indentation and deformation of a material at a specific point. Includes tool rotation and motion into a material’s surface, but no lineal motion across the material’s surface.  | An Awl producing circular holes in wood or ivory. | Sharpness, Edge Angle, Tool Size, Mass | Drill Point, Awl |
| Piercing | Forceful indentation and deformation of a material at a specific point. Includes motion into a material’s surface, but little to no tool rotation or lineal motion across the material’s surface. | Projectile point embedding into a material. | Sharpness, Edge Angle, Tool Size, Mass | Spear Point, Arrow Head |
| Abrasion | The creation of ‘grooves’, ‘scratches’, or surface microfractures via the sliding of an object over another. Indentation is at the micro-level. | Creation of a polished axe head or the use of grinding stone during grain processing.  | Tool Size, Mass | Pestle and Mortar, Abrading Stone |