The role of gross-edge curvature in stone tool slicing efficiency and production during the Pleistocene

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DISSERTATION ABSTRACT

There have been various studies examining different aspects of stone flakes and their cutting edges to determine how flakes` varying characteristics affect their performance in different activities. This project is focused on one of the flake characteristics that we refer to as gross-edge curvature to investigate its role in the efficiency of stone flakes.

This project is divided into three parts: the first part which involves a controlled experiment examines the effect of the element of gross-edge curvature on the cutting efficiency of a series of experimentally produced stone flakes. The second part investigates the role of cut substrate on the effect of gross-edge curvature and edge length in several cutting activities. And the third part is focused on the role of gross-edge curvature in the Levallois reduction sequence. These studies were carried out 1) to add a component to the host of factors that influence the cutting performance of flakes 2) to shed new light on the influence of surface material type in cutting experiments, and 3) to explore the role of the gross curvature in a specific reduction sequence. How this element, i.e., gross edge curvature, interacts with the so far- known range of variables that effect stone tool efficiency remains a question for future research to investigate.

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1 DISSERTATION INTRODUCTION

Stone tools were a key component of early human adaptation without which evolution would have in all likelihood taken a different course (e.g., Carbonell et al. 2010, 1999 a; Chakrabarty 2019; Stout and Chaminade 2012). There is wide agreement that the incorporation of lithic technology into early hominins' adaptive package improved their behavioral responses to an ever-changing environment. This behavioral enhancement occurred so extensively and continuously throughout the time that the members of our own species are now obligatory tool users. Needless to say, stone tools were not the sole component of hominins` tool kit but given the archaeological invisibility of organic materials, in most cases it is difficult to discuss their roles in human evolution with high levels of certainty. The durability of stone tools, in contrast, establishes them as accessible avenues for investigation of behavioral innovations and modifications of hominins over the course of human evolution.

Stone tool use belong to the wide-ranging category of tool use which is defined as "the exertion of control over a freely manipulable external object (the tool) with the goal of (1) altering the physical properties of another object, substance, surface or medium (the target, which may be the tool user or another organism) via a dynamic mechanical interaction, or (2) mediating the flow of information between the tool user and the environment or other organisms in the environment” (St. Amant and Horton 2008). Tool use behavior occurs under various conditions to achieve a variety of objectives, but it particularly takes place to enhance the foraging activities of a broad array of organisms from early hominins to some extant species of primates to several members of bird species and aquatic animals (e.g., Beck 1980; Benney and Henkel 2006; Brown 2012; Hunt 2000, 1996; Mann and Patterson 2013; McGrew 2013; Ottoni and Izar 2008; Rutz et al. 2016; Souto et al. 2011; Weir and Kacelnik 2006). Although, tool use is not a unique characteristic of humans, the manner of tool production and use in human societies differ greatly from those in non-human foragers such that tool use/modification by other organisms is not comparable to human technology in level of variation and sophistication (Seed and Byrne 2010). This comes as no surprise as humans lack other animals` physical and behavioral adaptations, therefore tool use is their major way of coping with the daily challenges of their fluctuating environment. What has enabled humans to reach the current sophistication of tool use behavior and what has prevented other animals from rivaling humans in that domain, however, is debated. Differences in executive function skills (Coolidge and Wynn 2005), sensorimotor capabilities (Stout and Chaminade 2007), the ability to develop collective goals and intentions, i.e., shared intentionality (Tomasello et al. 2005), and cumulative culture (Tennie et al. 2009) are some of the arguments put forth to explain the gap between humans and non-humans in this matter. All that aside, the extent of variation and sophistication in human tool use behavior is indicative of its constant modification and multiple developments throughout time to better adapt humans to their dynamic physical and social habitats.

One shared feature of all tool users is their goal-oriented behavior (Ingmanson 1996) which, as noted, has developed to enhance their behavioral responses to various environmental stimuli. We ourselves as habitual tool users employ an astonishing number of various tools on a daily basis from heavy-duty machinery to the ordinary chef's knife. Ethnographic studies show hunter-gatherers use tools extensively in their foraging activities ranging from hunting to gathering (Oswalt 1976). One example of this is the !Kung San technology which consists of 1) hunting tools, (e.g., the bow and arrow), 2) gathering tools (e.g., digging stick), 3) tools for carrying water (e.g., ostrich eggshell canteens), and 4) tools for processing food (e.g., cracking stones, and mortar and pestle). For the !Kung San this is an effective tool kit which is functional in different foraging contexts and makes a wide variety of food resources accessible to individuals. It is noteworthy that the !Kung San is an example of hunter-gatherers that are highly influenced by their changing environment (Lee 1979).

A glance at the trajectory of human technology reveals that the tool-use behavior which initially developed through extensive human interaction with readily available materials such as rock nodules has undergone piecemeal, yet massive changes at both the species and genus levels. It was through this material manipulation that stone technology as a transformational phenomenon appeared and became a significant component of human existence. What led to the success of this technology was evidently its ability to generate sharp edges which facilitated the process of calorie acquisition and consumption (Ambrose 2001). As such, it led to the greater efficiency of hominin foraging since the now-modified sharp stones were unquestionably superior substitutes for hominin teeth and hands (Shea 2013). The corollary of these sharp edges was the efficiency augmentation of foraging strategies. Efficiency is defined “as maximizing the return on time or energy expended” (Bamforth 1986) or “the relationship between output and input” (Shott 1996) and it can be a complex concept as it could be measured in different ways, including time, raw material/energy costs, and body/hand pressure exerted during the production and use (Bleed 1986).

The cutting edge efficiency is one of the major elements of tool efficiency assessment and it has been focused on in studies related to the efficiency of lithic technologies (e.g., Eren, Greenspan, and Sampson 2008; Muller and Clarkson 2016). Efficiency and the cutting edge are so closely intertwined that one of the major ways to estimate the efficiency of an operational sequence is determining the amount of cutting edge it produces. This is because the more cutting edge an artifact offers the more cutting potential it carries. Flake characteristics such as edge sharpness, edge angle, size and mass, edge length, and tool shape have been shown to affect cutting edge efficiency (Key, Fisch, and Eren 2018, Biermann Gürbüz and Lycett 2021b; Bilbao et al. 2019; Key and Lycett 2014, Key and Lycett 2015; Prasciunas 2007; Collins 2008; Mika et al. 2022). This signifies efficiency is the outcome of interplay between a combination of factors. One variable that has not been addressed in previous research is what my colleagues and I refer to as the plan-view and profile-view gross-edge curvature. Edge curvature is often considered and defined from a tool’s profile-view as the extent to which the edge of a tool deviates from a straight-line profile when viewed from its side (Andrefsky 1986; Atkins 2009; Collins 1999; Key 2016; Tringham et al. 1974), but edge curvature can also be applied to a tool’s plan-view. Here, we examine the influence of both plan- and profile-view curvature as it pertains to the overall deviation from a theoretical straight line, hence our designation of ‘gross’. Suspecting that this element could impact the cutting efficiency of flakes I decided to devote my dissertation to it. With that in mind this project aims 1) to evaluate the effect of this variable on the cutting efficiency of stone flakes and 2) to examine the influence of cut substrate on the effect of this variable and cutting edge length, and 3) to track its potential change throughout core reduction using the Levallois method. To address these questions, I drew on the capabilities of experimental archaeology in opening a window into the past behavior.

Experimental archaeology has been a growing field of study that attempts to test and assess all possible archaeological hypotheses, theories, and methods by performing experiments in which a defined set of variables, or at least one variable, are/is controlled. A scientific experiment, in general, is a multi-step procedure carried out to refute or validate a hypothesis. Experiments usually consist of three types of variables including controlled, dependent (responding trait(s)), and independent (manipulated trait). A highly organized and rigorous experiment attempts to control as many variables as possible to enhance the reliability of the results (Ingersoll et al. 1997; Lin et al. 2017). Failure to do so will compromise the internal validity of the experiment which refers to whether the observed results are due to a causal relationship between dependent and independent variables. In less controlled experiments the results might derive from factor(s) other than the manipulation of the independent variable and that is where the internal validity of the research decreases. To generate reliable outcomes, controlled variables must be held constant, otherwise they interfere with assessment of the causal relationship between dependent and independent variables. One of the significant characteristics of highly controlled experiments is their “repeatable” nature, which lends support to their reliability. Amick and colleagues (1989:6-7) refer to these experiments as “confirmatory experiments”. Opposite the highly-controlled experiments are experiments in which very few variables are controlled. As Mathieu (2002:7) puts it, “these are most often performed during the first generation of experimentation on a topic”. Due to lack of control on extraneous variables, the reported relationship between dependent and independent variables in these experiments cannot be trusted. Furthermore, it renders the experimental results unrepeatable. As a result, these experiments are not useful in testing hypotheses and can be considered as “exploratory experimentation” (Amick et al. 1989:6-7) or “orientational experiments” (Malina 1983:75 in Mathieu 2002).

In his paper centered on experimental archaeology, Mathieu (2002) identifies three ways to enhance the reliability of the experimental results: 1) as was noted above, to control as many as variables as possible; 2) to enhance the contextual accuracy of the experiment (e.g., employing appropriate materials); and 3) to repeat the experiment or build on it to verify the results (Coles 1973; Ascher 1961b). However, as was already mentioned, one must keep it mind that what experiments do is to eliminate the least possible solutions to a problem, provide a range of possible answers, and discern their degree of probability; they do not decisively determine which of the possible answers are correct (Mathieu

2002 and references in it). Therefore, what experiments offer is a series of secondary data, vs. the primary data consisting of the archaeological record, awaiting the experimenter to meaningfully link them to the inferred past behavior (Saraydar 2008).

Given the above, this dissertation is based on controlled experiments designed to generate and test several hypotheses; it closely adhered to the noted principles of a scientific experiment to enhance the repeatability and reproducibility of its results. The experiments themselves were based on 1) object replication as replicas of stone tools were produced for examination and 2) behavior replication as cutting activities were carried out to understand the effect of a specific variable on the efficiency of stone flakes. It is notable that the other types of experimental archaeology are the process and system replications (Mathieu 2002) which are beyond the scope of this project.

This dissertation is divided into three parts: The first part was published in the journal *Archaeometry,* 1-13, 2022, entitled “Experimental assessment of plan-view and profile-view gross-edge curvature on stone flake slicing efficiency”. The study was carried out in collaboration with co-authors N. Desai, M. I. Eren, and G. Tostevin. We performed a controlled experiment to test a hypothesis about the influence of the plan-view and profile-view gross-edge curvature on the cutting efficiency of stone flakes. The experiment involved the recruitment of 21 human participants, replicas of stone tools, and a large number of medical gelatin blocks that participants needed to cut through based on a series of specific instructions.

The second paper, entitled “The influence of cut substrate material on the slicing efficiency effects of stone tool flake size, edge length, and gross-edge curvature,” was published in the journal *Archaeological Science: Reports* (2023, 47, 103700) . This study was also performed in collaboration with co-authors N. Desai, N., M. I. Eren, and G. Tostevin. This project was also experiment-based in which we recruited 5 participants to employ replicas of stone flakes to cut through six different surface materials (e.g., cow hide and seagrass mat). Given the specific nature of the experiment participants had to come back to the lab multiple times. The aim of the project was to evaluate how different surface materials would affect the influence of four variables (plan-view and profile-view gross-edge curvature, flake size, and edge length) on cutting efficiency. This experiment was also run in a controlled setting, and we made an attempt to control for as many variables as possible.

The third project entitled “Exploring the gross-edge curvature of experimentally produced Preferential Levallois debitage” has been submitted to a peer-reviewed journal for publication. This project involves only object replication in which five Levallois reductions were produced by M. I. Eren, one of the collaborators. The aim of this project is to determine whether gross-edge curvature remains constant throughout the reduction sequence, increases, or decreases. Given that the first two experiments were focused on stone flakes, for this project the focus was shifted onto a specific technology to examine the position of the element of gross-edge curvature in an entire reduction sequence. It is notable that this project is the first step towards assessing the efficiency of the Pleistocene major lithic technologies with regard to the potential role of gross-edge curvature in their production.

Overall, this dissertation was intentionally designed in a way that all three projects would share a similar theme (i.e., cutting efficiency and the element of gross-edge curvature). The novelty of the dissertation lies in the fact that it is the first time that the effect of both plan-view and profile-view gross-edge curvature is assessed in a cutting experiment and given the obtained results, it reliably incorporates a new component to the combination of variables that have been shown to affect the efficiency of stone flakes. We also for the first time employed a variety of surface materials in our experiment to show how different surface materials could influence the data gained in experiments. Given the time and financial constraints we were not able to test some of the generated hypotheses, but we aim to further this research in the near future.

2 PROLOGUE - PAPER ONE

This paper is the result of many hours of discussions with my collaborators in order to generate the idea of the gross-edge curvature, to design a controlled experiment, to analyze the data using appropriate methods, and to report the results in a way suitable for publication. The entire process was slightly challenging as the project was aimed to introduce a new variable into a host of already known factors that had been reported to influence the cutting efficiency of stone flakes. Thus, we had to spend many hours to devise a proper method to test our hypothesis. Given the results that we obtained and the feedback of the anonymous peer-reviewers, we are confident that the entire process was carried out correctly.

As noted, this paper is centered on the examination of the effect of the plan-view and profile-view gross-edge curvature on the cutting efficiency of experimentally produced stone flakes. We employed medical gelatins as our surface materials and recruited 21 human participants to slice through the gelatins as fast as possible using various stone flakes made by G. Tostevin that had been categorized based on size and their degree of gross-edge curvature. The whole process of the cutting activity was recorded for further analysis. The data were then analyzed by N. Desai who was specifically focused on the statistical analysis of the data and M.I. Eren helped to contextualize the results relative to the previous published studies. We successfully reported our results which were published in the journal *Archaeometry* (2022:1-13).

3 PAPER ONE

Experimental assessment of plan-view and profile-view gross-edge curvature on stone flake slicing efficiency

3.1 Paper Synopsis

Separating two or more aspects of an object via cutting was likely an important factor in the origin and evolution of flaked stone technology. In recent years experiments have demonstrated that several stone tool attributes can influence different kinds of cutting behavior: slicing, cleaving, scraping, sawing, drilling, piercing, and abrading. Here, we experimentally assessed the role of stone flake plan-view and profile-view gross-edge curvature in a controlled slicing task. We also assessed the role of edge length. Twenty-one participants, using 252 stone flakes with distinct gross-edge curvatures and edge lengths, were asked to cut through a standardized substrate and their efficiency in the task was measured in time. Flakes with longer edge lengths increased the efficiency of the cutting task but increasing either plan-view or profile-view edge curvature decreased the efficiency of the cutting task. These results have implications for the emergence of particular tool forms or reduction sequences throughout the

Pleistocene and may in part explain why certain forms were favored by Paleolithic people, leading to their convergent evolution or widespread transmission.

3.2 Introduction

Separating two or more aspects of a material (meat, tendons, hide, hair, grass, wood) or of an object composed of several materials (a carcass, a leafy branch) via cutting was an important activity for Paleolithic peoples, and likely an important factor in the origin and evolution of flaked stone technology (e.g., Ambrose 2001; Biermann Gürbüz and Lycett 2021a; Key 2016; Muller and Clarkson 2016; Rezek et al. 2018; Shea 2013). Consciously or not, early people would have plausibly favored, and then culturally transmitted, tool forms or tool form attributes that would have increased the time or energy efficiency of performing functional tasks involving cutting behaviors such as slicing, cleaving, scraping, sawing, drilling, piercing, and abrading (Key 2016:70-72). Archaeological and engineering experiments demonstrate that there are a plethora of tool forms or tool form attributes that can potentially influence cutting efficiency, including edge sharpness (Atkins et al. 2004; Key et al. 2018a), tool shape (Collins 2008; Mika et al. 2022), tool mass/size (Biermann Gürbüz and Lycett 2021b; Bilboa et al. 2019; Key and Lycett 2014), edge length (Key 2016), edge angle (Key and Lycett 2015; Prasciunas 2007), edge kerf and curvature (including serration and scalloping, Key 2016), and raw material (Bebber et al. 2019a, 2019b; Biermann Gürbüz and Lycett 2021a; Gould and Saggers 1985; Jones 1994; Key et al. 2020, 2021a). Whether a tool is hafted or not also can play an important role in a stone tool's cutting efficiency (Clarkson et al. 2015; Key et al. 2021b). How all these variables contribute to cutting efficiency in isolation and when interacting has been of frequent interest and assessment in recent years by lithic analysts.

Our interest here is in the examination of one aspect of a stone's cutting edge, which might be aptly referred to as "gross-edge curvature." Edge curvature is often considered and defined from a tool's profile-view as the extent to which the edge of a tool deviates from a straight-line profile when viewed from its side (Andrefsky 1996; Atkins 2009; Collins 1999; Key 2016; Trigham et al. 1974) (Figure 1a), but edge curvature can also be applied to a tool's plan-view (Figure 1b). Here, we examine the influence of both plan- and profile-view curvature as it pertains to the overall deviation from a theoretical straight line, hence our designation of "gross." We readily acknowledge that freshly knapped stone flakes do not frequently feature edges with neatly- and continuously-curved edges. Future experiments will explore the influence of edge curvature changes on more acute-scales along an edge (e.g., MacDonald et al. 2020, 2022; Stemp 2014; Stemp et al. 2019), rather than at the gross-scale we assess here.

In one type of cutting task – wood scraping – Collins (2008) investigated the performance of differently curved edges that were either straight, concave, or convex. The results of Collins' (2008) study showed that convex edges were the most efficient for wood scraping, followed by concave edges, and then straight edges. Collins' (2008) experiment is one of the few experiments that specifically examined the impact on efficiency of edge shape beyond edge angle. However, the direction of the action was exclusively transverse to the edge, i.e., a scraping gesture rather than a slicing gesture, or "orthogonal slicing" (*sensu* Atkins 2009:121). Given that the influence of gross-edge curvature on cutting efficiency is likely context-, and perhaps material-, dependent (Key 2016:80; also see Abrunhosa et al. 2019), Key (2016:81) notes that the "mechanical relationship between edge curvature and functional utility could profitably be

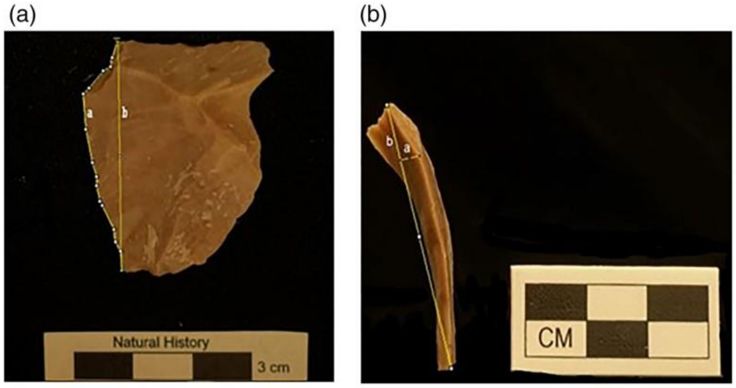

Figure 1.(a) Plan-view curvature: the length of a was divided by the length of b; and (b) profile-view curvature: the length of a was divided by the length of b.

examined by future experimental research.” Toward that end, we conducted an experiment that tested whether the increasing the plan-view and profile-view gross-edge curvature increased or decreased efficiency in a controlled slicing task. We also examined these variables in relation to edge length. We asked participants to slice through several blocks of medical gelatin as efficiently as possible using stone flakes categorized by different sizes and gross-edge curvatures.

3.3 Materials and Methods

3.3.1 Participants

We recruited 21 participants to use stone flakes in a cutting task involving a standardized substrate. None were professional butchers. The participants ranged in age from 19 through 40. Nine participants were female and 12 were male.

3.3.2 Stone Flakes

We produced more than 800 chert flakes from which we selected 252 specimens for use in the experiment. The specimens were knapped by G. Tostevin. We divided the 252 specimens into two size groups: short flakes, which were defined as flakes between 3-5 cm in size; and long flakes, which were defined as flakes >5 cm. Size was arbitrarily defined as the maximum distance of the specimen parallel to the targeted cutting edge ($flake\ size\ in\ mm$: $\bar{x} = 52.40$; $SD = 13.51$; $range = [30.52, 102.44]$; $Cutting\ edge\ length\ in\ mm$: $\bar{x} = 54.66$; $SD = 16.63$; $range = [28.545, 119.044]$).

The experimental flake specimens had a maximal thickness of 2 cm ($\bar{x} = 7.49$; $SD = 3.64$; $range = [2.02, 18.54]$), and a minimum width of 2.5 cm ($\bar{x} = 41.52$; $SD = 10.28$; $range = [25.72, 87.51]$), the latter defined as the maximum distance from one lateral edge to the other perpendicular to the cutting-edge length. All flakes possessed an edge with an angle of ≤ 50°, which was assessed via a goniometer ($\bar{x} = 25.03°$; $SD = 7.62$; $range = [16°, 49°]$), (Key and Lycett 2015; Prasciunas 2007).

The targeted edges used by participants for the cutting task were undamaged, non-cortical and marked with white-out paint on the dorsal surface, 2-3 mm from the cutting edge.

3.3.3 Cutting Substrate

Given the diverse array of materials past peoples would have cut, we chose to employ a synthetic gelatin as our experimental cutting substrate. Our use of gelatin was not specifically intended to represent any specific type of “natural” material, but instead acted as a standardized and strategic control that allowed us to assess stone flake edge curvature’s influence on cutting efficiency (Eren et al. 2016). The use of standardized modern materials as cutting substrates is common and has also employed rope, plastic tubing, and clay (e.g., Key et al. 2018b). Future experiments can further investigate the edge curvature and cutting efficiency on more “actualistic” materials (Eren et al. 2016; Jennings et al. 2021) and compare those results to the ones presented in this study.

We purchased 24 reusable “Category #0” medical gelatins from Humimic Medical Healthcare Products (https://humimic.com/). We melted the purchased gelatins so that we could insert a dog chew toy bone (14.9 cm by 3.04 cm by 4.5 cm) inside standardized blocks (18.5 cm long by 12.5 cm wide by 4.0 cm deep) (Figure 2). The bone was used as a visual guide for the participants to help aim their slicing. After each participant cut through 12 blocks the blocks were re-melted reused by subsequent participants

Figure 2. A medical gelatin block with an inserted dog chew toy bone.

3.3.4 Measuring gross-edge curvature

We calculated gross-edge plan-view curvature by dividing the length of the edge “a” by the length of “b”, the latter being a hypothetical straight line between the endpoints of the edge (Figure 1a). Thus, an index of 1 meant the edge was straight. Values above 1 denoted edges with different degrees of curvature and the higher this value, the more the plan-view edge deviated from the theoretical straight line. Following Collins (1999) and others e.g. (Eren 2012; Jennings and Smallwood 2018), we calculated gross-edge profile-view curvature by dividing the length of “b”, the straight-line distance between the distal and proximal points of contact of the interior blade surface and a flat plane, into “a”, the maximum perpendicular distance between that plane and the interior surface of the blade (Figure 1b). The lower this value, the more curved the profile-view edge. It is important to explicitly note that since we are currently investigating gross-edge curvature, we are not distinguishing between convexity, concavity, or sinuosity, but simply how much curvature exists relative to a theoretical straight line. Future efforts will aim to tease apart edge deviations on more acute levels.

We categorized the specimens into six different groups by their plan- and profile-view gross-edge curvature values. The plan-view curvature data was divided into thirds while the profile-view curvature edge was divided into halves. As such, our curvature categories were comprised of flakes with (1) low plan-view curvature and low profile-view curvature, (2) medium plan-view curvature and low profile-view curvature, (3) high plan-view curvature and low profile-view curvature, (4) low plan-view curvature and high profile-view curvature, (5) medium plan-view curvature and high profile-view curvature, and (6) high plan-view curvature and high profile-view curvature.

3.3.5 *Experimental procedure*

After watching a demonstration video on the day of the experiment, each participant was asked to slice 12 medical gelatin blocks using a different flake specimen for each block as fast as possible. The task was performed in two separate sessions on different days. In each session participants sliced six medical gelatins.

We used a random number generator (https://www.random.org/) to assign flake specimens to each participant, although each participant ended up using six flakes categorized as “short” and six flakes categorized as “long”. Each set of six short or long flakes included each of the six curvature categories. The order in which the specimens were used by participants was standardized across the experiment: (1) short flake with low plan-view curvature and low profile-view curvature; (2) long flake with low plan-view curvature and low profile-view curvature; and so on, following the curvature categorization in the previous section.

Breaks of six minutes were provided to each participant after each cutting task involving the first three blocks. Extended breaks of 10 minutes were provided after each cutting task involving the last three blocks. These breaks were provided to reduce the potential impact of fatigue on cutting performance (Key and Lycett 2014).

On the day of the experiment, we recorded participants` dominant hand grip with a hand dynamometer. There was variation in grips (measured in kg; $N\ (participants) = 21;\ \bar{x} =\ 26.4;\ SD = 9;\ range = [7, 42.7]$). We thus controlled for participant in our statistical analysis. Participants were permitted to ask any questions they had regarding the activity and the video, but the goals of the experiment were not revealed. Participants wore safety gloves to prevent any potential harm to their fingers during the activity. They were directed to then stand in front of two cameras (JVC GY-HM200U) which were set up such that a front-view and side-view of the cutting task could be recorded (Figure 3).

Participants were asked to place their non-dominant hand on the gelatin block while using their other hand to utilize the assigned flake specimen. Participants were not allowed to use their non-dominant hand to apply extra force on the gelatin and thus tear the block apart instead of slicing through it. However, we allowed participants to use their non-dominant hand to spread the slice further open so that they could assess the depth of the cut to facilitate their strategy how to proceed. This option allowed the participants to increase the rake and clearance angles of the slicing operation (Key 2016: Fig.3). Participants were also allowed to turn the gelatin around or lift it up while performing the slicing, but they were forbidden from flipping the block over as such an act would reduce the challenge of reaching the bottom surface of the gelatin.

We instructed participants to slice the gelatin on both sides (right and left) of the toy bone (Figure 4). They had to finish one side before proceeding to the other side. They were also instructed to slice the block as close to the toy bone as possible such that at least a small area, described to them to be “as small as a dime” (17.91 mm in diameter), of the bone surface was exposed since removing larger chunks would have been time-consuming.

Figure 3.Experimental set-up: the red rectangular area on the table is where the medical gelatins were placed for each participant to slice

3.3.6 *Statistical analyses*

We investigated whether gross-edge curvature and edge length played a role in slicing efficiency, controlling for other factors such as participant ID and session ID, by using an information-theoretic model selection approach. This approach allowed us to evaluate the relative strength of evidence for different models that we fit to the data, thus allowing us to compare multiple hypotheses simultaneously. Researchers commonly use information criteria such as Akaike Information Criterion (AIC) to evaluate the relative strength of evidence for different models. Since we can expect any multiple regression model to achieve a higher R^2 value by simply adding more independent variables, we need other ways to evaluate if adding any independent variable results in better inference.

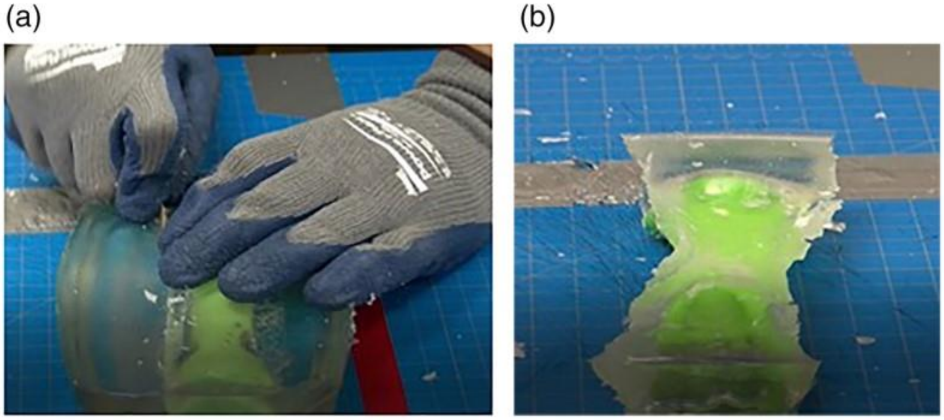

Figure 4.(a) A participant at the beginning of the slicing task; and (b) the medical gelatin after the task completion.

The AIC values help achieve this goal by measuring model performance while penalizing adding extra independent variables. The AIC value of a particular model gives a theoretical estimate for the out-of-sample performance of any model fit on a given dataset. In particular, a lower AIC value implies better performance for a given model on data that it has not seen before. Hence, this approach allowed us to evaluate if a particular independent variable is important for explaining the variation in a dependent variable.

Our independent variables were the measures of the plan-view and profile-view curvature and edge length (mm). We also included the hand strength (kg) in the analysis to determine its relative importance compared to other variables. Our dependent variable was time (in seconds) as a measure of efficiency. Since time was a count variable, we used Generalized Linear Mixed Models (GLMMs) with Poisson error structure. We controlled for any confounding effects from individual participants by including participant ID as a random effect (with random intercept) in all our models. Additionally, we added a random effect (with random intercept) of session ID to control for any gains in efficiency that may be due to learning from previous session and not due to the properties of the flakes. Since all these variables were measured in different orders of magnitude, we standardized all the variables by mean centering and scaling to a standard deviation of 1. This allowed us to compare relative effect sizes of each variable. We performed all analyses in R version 4.0.5. We fit the Poisson

GLMMs using the lme4 R-package (Bates et al. 2015) and performed the model selections using the MuMIn R-package (Bartoń 2020).

We first considered all combinations of the independent variables in different models, resulting in 16 different models (Supplementary materials, Table 1). Since our Poisson models were overdispersed, we used quasi-AICc (QAICc) instead of AIC to evaluate our models. Based on guidelines by Burnham, Anderson, & Huyvaert (2011) we used a **Δ**QAICc of less than 4 compared to the best model to consider a model to have sufficient evidence. Based on this criterion, only 2 of the best 6 models with **Δ**QAICc < 4 included hand strength (Supplementary materials, Table 1), and the 95% confidence interval of model averaged coefficients of hand strength included 0 (95% CI: [-0.23, 0.027], Supplementary materials, Table 1), suggesting that hand strength did not have a significant effect on efficiency. Hence, we performed further analyses without including hand strength. This included 8 models with different combinations of the independent variables, including the full model with all variables and the null model with just the intercept (Table 1). We report the results from these 8 models and report the model-averaged estimates and their 95% confidence intervals for inference.

3.3.7 Data Availability Statement

The data from the experiment and code to perform the analysis in this manuscript are available at https://github.com/desai-nisarg/Edge-curvature-and-efficiency and available in article supplementary material.

3.4 Results

The best model for edge performance included both edge length and curvature measures. Three of the best 4 models with a ΔQAICc < 4 included the curvature measures suggesting that edge length alone is not sufficient to explain the variation in efficiency. The top model included plan-view curvature suggesting its greater importance compared to profile-view curvature. Models that did not include edge length had no weight and a ΔQAICc > 4, implying the importance of edge length in explaining the variation in efficiency (Table 2).

Table 1: Model specifications for the eight candidate models used in the information theoretic model selections, ordered based on model weights

Model ID	Model Specification
1	Time (s) ~ Plan (std.) + Edge_length (std.) + (1|Participant) + (1|Session)
2	Time (s) ~ Edge_length (std.) + (1|Participant) + (1|Session)
3 (Full model)	Time (s) ~ Plan (std.) + Profile (std.) + Edge_length (std.) + (1|Participant) + (1|Session)
4	Time (s) ~ Profile (std.) + Edge_length (std.) + (1|Participant) + (1|Session)
5 (Null model)	Time (s) ~ (1|Participant) + (1|Session)
6	Time (s) ~ Plan (std.) + (1|Participant) + (1|Session)
7	Time (s) ~ Profile (std.) + (1|Participant) + (1|Session)
8	Time (s) ~ Plan (std.) + Profile (std.) + (1|Participant) + (1|Session)

Models were fit with a Poisson error structure since the dependent variable (time) was a count variable. Random intercepts for Participant and Session were included in all models. Plan and profile curvatures, and edge length were scaled to a mean of 0 and a standard deviation (SD) of 1 before fitting the models. This allowed us to compare the coefficients directly.

The model averaged coefficients suggest a negative relationship of edge length with time (model-averaged β = -0.149, adjusted SE = 0.012, z = 12.8, 95%

CI: [-0.172, -0.126]) and hence a positive relationship with efficiency. Models that included edge length and plan-view curvature had positive coefficients for plan curvature as opposed to negative coefficients in models without edge length included (Table 2). This suggests that plan-view curvature has a positive effect on time (and hence, a negative effect on efficiency) when keeping edge length constant (model-averaged $\beta = 0.052$, adjusted SE = 0.005, $z = 10.5$, 95% CI: [0.042, 0.062]). This effect is shown in Figure 5. The profile-view curvature also had a positive effect on time, and hence, a negative effect on efficiency when keeping edge length and plan curvature constant (model-averaged $\beta = 0.018$, adjusted SE = 0.009, $z = 2.01$, 95% CI: [0.00043, 0.036]). As standardized coefficient of edge length had a greater magnitude compared to plan-view and profile-view curvature, edge length had a comparatively stronger effect on efficiency. Similarly, plan-view curvature had a stronger effect on efficiency compared to profile-view curvature. Since none of the 95% confidence intervals contain 0, all these variables have a significant effect. Collectively, these results suggest that both the edge length and edge curvature have effects on efficiency, albeit in opposite ways, and neither should be excluded when considering slicing efficiency.

Table 2: Estimates of standardized coefficients, QAICc, ΔQAICc and model weights of the candidate models. Model averaged estimates and their 95% confidence intervals are included below.

Model ID	Intercept	Edge length	Plan curvature	Profile curvature	df	logLik	QAICc	ΔQAICc	weight
1	5.370	-0.157	0.0526		5	-5314.913	313.447	0	0.462
2	5.371	-0.135			4	-5372.277	314.598	1.151	0.26
3	5.370	-0.157	0.0511	0.0134	6	-5313.051	315.458	2.011	0.169
4	5.371	-0.136		0.0251	5	-5365.687	316.323	2.876	0.11
5	5.380				3	-5829.964	338.445	24.998	0
6	5.380		-0.0148		4	-5824.387	340.211	26.764	0
7	5.380			0.00903	4	-5829.089	340.477	27.030	0
8	5.379		-0.0164	0.0136	5	-5822.478	342.202	28.755	0
MAE	5.371	-0.149	0.0522	0.0180					
2.5% CI	5.203	-0.172	0.0425	0.000428					
97.5% CI	5.539	-0.126	0.0619	0.0356					

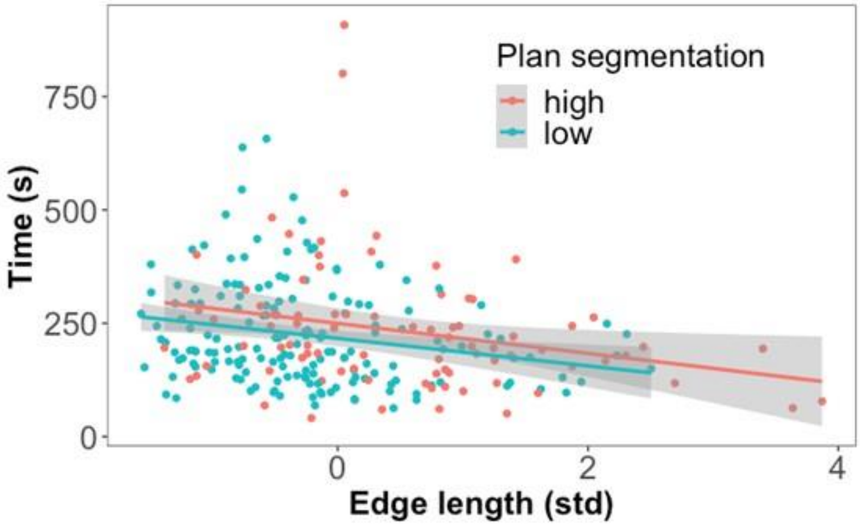

Figure 5.Effect of edge length on time for different levels of plan-view curvature. For a given edge length in standard deviations, a higher plan-view curvature results in more time.

3.5 Discussion

Several factors can influence the cutting efficiency of stone flakes (Biermann Gürbüz and Lycett 2021a, 2021b; Key 2016; Mika et al. 2022). Here, we assessed via controlled experiment the role of plan-view and profile-view gross-edge curvature on slicing a standardized material. We also examined the influence of flake edge length on efficiency. Consistent with previous results and predictions, flakes with longer edge lengths increased the efficiency of the cutting task. Increasing either plan-view or profile-view edge curvature, however, decreased the efficiency of the cutting task. While future experiments should further explore the role of these variables for cutting other materials in a multitude of ways (e.g. Collins 2008) and on more nuanced and acute scales (e.g. MacDonald et al. 2022; Stemp 2014; Stemp et al. 2019), several corollaries follow the results presented here.

The evolution of technology over the course of the Pleistocene included the emergence or adoption of elongated, flatter, or larger, specimens in various times and places either through convergent evolution or widespread transmission. All of these form variables may have potentially increased flake edge length, or decreased gross-edge curvature. For example, prismatic blades occurred time and again around the world (e.g., Bar-Yosef and Kuhn 1999; Collins 1999; Conard 1990; Eren et al. 2008; Johnson and McBrearty 2010; Muller and Clarkson 2016; Shimelmitz et al. 2011). Relative to other stone flakes, prismatic blades' length-to-width ratio and parallel lateral edges would have increased cutting edge length, and decreased plan-view edge curvature, leading to an increase in slicing efficiency. If prismatic blades were straight in profile-view as well – as occurs with some blade reduction strategies (e.g., Goring-Morris and Davidzon 2006) – then slicing efficiency would be increased further. Indeed, depending on how important slicing efficiency was to particular groups of Pleistocene people, the emergence of indirect percussion, and even pressure blade-making in the Pleistocene and Holocene may have been, in part, an attempt to reduce tool curvature to improve slicing function.

Following from above, it is interesting to note that recovered Late Pleistocene Clovis blades in North America are often highly curved in profile-view (e.g., Collins 1999). When considered relative to our results presented above, perhaps the archaeological bias toward curved Clovis prismatic blades is not because Clovis people favored and intentionally produced curved blades, but because they were discarding them at a higher rate relative to the straight, and thus more functionally efficient, blades they more often used and retouched into tools (Dibble et al. 2017). Indeed, curved vs. straight blades may have served different technological roles, a fact that may be seen differently in light of the results presented here. In the intercalated blade-bladelet sequence of the Protoaurignacian (Bon 2002), curved blades are interpreted to set up the convexity for the production of straight bladelets within a continuous sequence. The curved, plunging blades on either side of the blade core's frontal debitage surface create a distally-delimited convexity for the removal of straight bladelets. While technologically the Protoaurignacian curved blades are seen as enabling the bladelets' feathered distal terminations, the results here emphasize their role in creating their profile- and plan-view straightness as a means of increasing their slicing efficiency, as well as projectile suitability (Teyssandier et al. 2010). These arguments might also be applied to carinated blade cores of the European Upper Paleolithic.

Pleistocene users of flakes approaching the proposed “theoretical optimum” of Preferential Levallois (Lycett and Eren 2016) also would have potentially experienced increases in cutting efficiency. Preferential Levallois Flakes (PLFs) are relatively flat when compared to other flake forms (Eren and Lycett 2012), which would have reduced profile-view curvature and, based on the results presented here, increased slicing efficiency. Some PLFs can be elongated (e.g., Tryon et al. 2005), which would have further reduced plan-view curvature and increased slicing efficiency. However, even rounder PLFs may have increased cutting efficiency compared to other debitage because of their relatively larger size, which would have to some degree ameliorated plan-view curvature.

Finally, our results have potential implications for issues involving production time efficiency and expedient flakes, especially for early lithic industries like the Lomekwian and Oldowan (e.g., Braun et al. 2019; Gurtov and Eren 2014; Harmand et al. 2015; Toth and Schick 2009). One profitable avenue of future research might be to explore how often curved- vs. flat-edged flakes are produced via different reduction methods: bipolar, simple stone-on-stone percussion, discoid, biface, prismatic blade, etc. Even if one in 10 flakes is flat-edged, it is possible that knapping many stone flakes quickly produces enough of a variety from which people can select tools with preferred traits. This scenario might explain why flakes appear to be made in abundance (e.g., Foley and Lahr 2015), particularly when raw materials are readily available. However, less technological investment in core management (i.e., bipolar) may decrease the total absolute cutting-edge length of each resulting flake because bipolar and expedient flakes tend to be small. Only highly technologically difficult and/or complex sequences (e.g., Levallois, UP and Neolithic blade making, Clovis bifacial thinning) can produce long cutting edges. While the variability and number of produced bipolar and expedient flakes may allow one to select the rare good edge, their overall cutting edge length may be lower. As such, production time, the absolute cutting edge of a flake, and cutting edge length relative to tool mass are all factors that need to considered in the interpretation of archaeological assemblages (e.g. Pargeter et al. 2019; Surovell 2009; Toth and Schick 2009).

4 PROLOGUE - PAPER TWO

This project was designed to evaluate the effect of surface material on the function of plan-view and profile-view gross-edge curvature, cutting edge length, and flake size. While working on the first project which involved the use of medical gelatin, I became interested in understanding how other surface materials would operate under our experimental conditions. Given that this idea had not been tested in previous studies, I decided to design an experiment that would help understand the interaction between the above variables. Thus, six types of surface materials most of which had already been employed in other studies were selected to investigate their influence on the cutting performance of an assemblage of stone flakes produced by G. Tostevin. I recruited five participants who were required to return to the lab on five different days; this was a process that required precise arrangements and great organization. There were also discussions on how best to distribute the surface materials and stone specimens to the participants in order to satisfy the randomness requirements which resulted in a reliable experiment design.

The experiment continued for one month and a half after which the data were organized and prepared for statistical analysis by N. Desai. M. Eren, again, helped to contextualize the results relative to the previous published studies. The results which add a new aspect to the process of experimental design in terms of surface material selection, among other insights that it provides, then were reported in a paper which was published in the *Journal of Archaeological Science: Reports (*2023, 103700*).*

5 PAPER TWO

The influence of cut material on the slicing efficiency effects of stone tool flake size, edge length, and gross-edge curvature.

5.1 Paper Synopsis

Cutting actions were likely an important factor in the emergence and evolution of stone tools. In recent years, experiments have shown many factors can influence the efficiency of cutting behaviors, including tool form, tool material, and tool-user. Here, we test whether the material getting cut influences the efficiency effects of particular variables, namely flake size, cutting-edge length, and gross-edge curvature. Slicing six different materials, five participants used 300 stone flakes, with quantitatively documented differences in flake size, cutting-edge length, and gross-edge curvature. The results of our Generalized Linear Mixed Models (GLMM) provide evidence that specimen size, edge length, and edge curvature have differential effects based on the material being cut. Our results support the hypothesis that the hominin need or desire to process particular materials potentially influenced the production and selection of stone tool forms over time and to different extents.

5.2 Introduction

A continuously growing body of experiments has demonstrated that many factors can influence the efficiency of stone tool cutting behaviors, including aspects of tool form, tool material, tool-user, among others (Key 2016; see also Bebber et al. 2019; Biermann Gürbüz and Lycett 2021a, 2021b; Bilboa et al. 2019; Clarkson et al. 2015; Collins 2008; Galán and Domínguez-Rodrigo 2014; Jones 1980, 1994; Key 2013; Key et al. 2016, 2018a, 2018b, 2018c, 2020, 2021a, 2021b; Key and Lycett 2011, 2014, 2015, 2017a, 2017b, 2018, 2019, 2020; Khaksar et al. 2022; Machin et al. 2007; Marzke and Shackley 1986; Mika et al. 2022; Morrow 1996; Prasciunas 2007; Starkovich et al. 2020; Toth and Schick 2009; Walker 1978; Willis et al. 2006; also directly relevant: Atkins 2009; McCarthy et al. 2007). Understanding these factors in isolation, and while interacting, is of importance to archaeologists who wish to make inferences regarding the emergence and evolution (*sensu* Lycett 2011, 2015; Lycett and von Cramon-Taubadel 2015; Mesoudi 2011) of stone cutting tools throughout the Pleistocene and how these implements aided hominins in resource procurement, food processing, self-defense, and other activities (e.g., Key 2016). If an experiment can demonstrate a functional advantage of replica cutting tool variant

A over replica variant B, and the variant A artifact proliferated in the archaeological record while variant B artifact did not, then selection can be considered as a potential explanation for variant A's evolutionary success (Story et al. 2019). But if an experiment cannot demonstrate a functional advantage of replica variant A over replica variant B, but the variant A artifact proliferated anyway, then archaeologists are in a stronger position to consider other cultural evolutionary processes, such as transmission bias or drift (Eren et al. 2022:85; but of course selection and drift can simultaneously act on material culture, e.g. Eren et al. 2015 and references therein).

While there are many different kinds of stone cutting tools – handaxes, unifacial knives, thin bifacial knives (e.g. Lycett 2008; Mika et al. 2022; Miller 2013; Smallwood et al. 2020), etc. – our focus in the present study is on stone flakes, which were prominent, and often substantial, components of hominin toolkits throughout the Pleistocene and Holocene archaeological records (e.g. Harmand et al. 2015; Pargeter and Tweedie 2019; Semaw et al. 1997; Shimelmitz et al. 2014). Here, we build on previous cutting efficiency experiments by further examining the stone flake attributes of flake size, cutting edge length, and gross-edge curvature (Khaksar et al. 2022). By cutting efficiency, we are specifically referring to actions akin to "slicing" (Key 2016:72), and hereafter will use the terms "cutting" and "slicing" interchangeably.

Several researchers have experimentally considered the role of flake size and cutting edge length in cutting efficiency (e.g. Frison 1989; Gingerich and Stanford 2018; Huckell 1979; Jones 1980; Morrow 1996) but to our knowledge Jobson (1986) was among the first to design a systematic butchery efficiency experiment and statistically analyze the results (*sensu* Lycett and Chauhan 2010). After rabbit butchery using 24 flakes of different forms, he concluded that larger flakes had higher cutting efficiency (measured as stroke count) than smaller ones. Jobson (1986:17) reasoned this was because, relative to smaller flakes, larger flakes (1) have longer edges and can thus cut more per stroke, (2) tend to be wider and thus permit flakes to penetrate between joints and musculature more easily, (3) are generally thicker and thus possess stronger edges less apt to break or dull, and (4) can be more easily held as force is applied, which is especially important when the tool is covered in grease or other body fluids.

Prasciunas (2007) also examined the relationship between flake size, cutting edge length, and cutting efficiency via controlled experiment. She used 30 flakes of different sizes to cut through as much denim as possible within a 10-minute time period. At the end of each period, she measured the amount of material cut by each flake. Her results showed a clear trend of decreasing cutting efficiency with decreasing flake size (Prasciunas 2007:337). She postulated that this relationship could be explained by “increasing amounts of awkwardness and fatigue from intensively utilizing small flakes as opposed to larger ones, as well as an overall decrease in the amount of cutting edge of smaller flakes" (Prasciunas 2007:337). Prasciunas (2007) also documented a flake size threshold (approximately 5-10 g for flake weight and 7-10 cm^2 for flake area) beneath which flake cutting efficiency dropped off, and surmised that cutting edge length had less of an effect on the amount cutting efficiency than did flake size.

To date, Key and Lycett (2014) present one of the most important and robust experiments to analyze the relationship between the flake size and cutting efficiency. In their study, 57 participants sliced through six pieces of Hessian rope using different sized stone flakes from the following six size (length) groups: 25-30 mm, 40-45mm, 55-60 mm, 70-75 mm, 85-90 mm, and 100-105 mm. All the stone edges used for slicing were straight in morphology. Key and Lycett (2014) measured efficiency via time (seconds) and number of strokes. They also measured applied force to explore its relationship with efficiency. In sum, the results of their study demonstrated that there was a positive, significant relationship between flake size and efficiency and flake size and applied force when all six groups were assessed. However, when the two smallest size groups were removed from the analysis, the relationship between flake size and the measures of efficiency was no longer positive nor significant, but applied force still positively and significantly correlated with flake size.

Most recently, Gürbüz and Lycett (2021a) reported the results of an experiment which investigated the relationship between flake size and efficiency during wood cutting. They categorized their specimens into small (>0-70.31 mm length) and large (70.31-107.59 mm length) groups. Thirty participants were divided into two groups of 15 each, with each individual using either a small or large flake to cut a designated area on a piece of cedar shim. Based on the experimental results, Gürbüz and Lycett (2021) concluded that larger flakes required less time to finish the woodworking task and were thus more efficient.

While several experimental studies have assessed the role of flake size (and/or cutting edge length) in slicing efficiency, our recent study (Khaksar et al. 2022) examined the role of stone flake plan-view and profile-view gross-edge curvature in slicing efficiency. We quantitatively defined “gross-edge curvature” as the overall deviation from a theoretical straight line. We also analyzed the role of stone flake edge length. Twenty-one participants, using 252 stone flakes with distinct gross-edge curvatures and edge lengths, were asked to cut through a standardized material (medical gelatin) and their efficiency in the task was measured in time. Flakes with longer edge lengths increased the efficiency of the cutting task but increasing either plan-view or profile-view edge curvature decreased the efficiency of the cutting task.

Here, we will expand on our own experimental work and that of others by presenting the results of a study designed to assess the influence of different cut materials on flake size, cutting edge length, and gross-edge curvature efficiency effects. In other words, how are variables that influence slicing efficiency affected when they interact via the slicing of different materials? Is an increase in slicing efficiency due to changes in stone flake size, cutting edge length, or gross-edge curvature in one cut material duplicated in another cut material? Or do different cut materials encounter disproportional changes in slicing efficiency as specimen size, cutting edge length, or gross-edge curvature vary?

5.3 Materials and Methods

5.3.1 Stone Flake Specimens

G. Tostevin knapped 300 chert stone flakes. Following Khaksar et al. (2022), we categorized the flakes into five size groups: 3-4 cm, 4-5 cm, 5-6 cm, 6-7 cm, and > 7 cm. We defined size as the maximum distance of the flake parallel to the cutting edge to be used in the slicing task ($\bar{x} =$56.6 mm; *SD* = 15.9; *range* = [30.36, 106.2]). All flakes possessed a width of at least 2.5 cm as measured perpendicular to the targeted cutting edge ($\bar{x} =$43.0 mm; *SD* = 11.3 ; *range* = [25.02, 94.45]) and a thickness of maximum 2.5 cm (($\bar{x} =$ 8.3 mm; *SD* = 4.3; *range* = [2.39, 23.12]) in order to ensure that an overly small handhold (of less than 2.5cm width) would not affect the cutting performance. The stone flake edge to be used by the participants was marked with white-out to stand out from adjacent edges. None of the selected edges were cortical or retouched, but all had an angle of ≤ 50° as measured with a manual goniometer. We recorded the cutting edge length using the ImageJ software ($\bar{x} = 60.1$ mm; *SD* = 20.9; *range* = [23.795, 162.784]). Following Khaksar et al. (2022), the plan- and profile-view gross-edge curvature of each stone flake's selected edge was measured. In each size group there were two flakes in each category of (1) low plan-view curvature and low profile-view curvature, (2) medium plan-view curvature and low profile-view curvature, (3) high plan-view curvature and low profile-view curvature, (4) low plan-view curvature and high profile-view curvature, (5) medium plan-view curvature and high profile-view curvature, and (6) high plan-view curvature and high profile-view curvature. In other words, on each material every participant used two flakes per size group.

The range of the plan-view curvature values was divided into equal thirds to represent "low", "medium" and "high" values. The profile-view curvature values were divided by the median value into "low" and "high" categories. All of the above attributes were measured (and analyzed below) as continuous variables but were apportioned ordinally as above to ensure that each participant was given flakes with the same range of attributes to cover the variability of interest. As such, each participant was given, per a randomization process (see below), 60 specimens, consisting of five size groups, with two specimens per 6 curvature groups within each size group (see Table 3). All recorded data on the stone flake specimens is available in the supplementary online materials.

Table 3. Distribution of specimens and cut substrates for one of the participants. Other participants received identical distributions.

	Material	***Denim***	***Hide***	***Grassmat***	***Cardboard***	***Medical Gelatin***	***Hemp Rope***	***Flake sample per size group***
Participant A	**Size Group 3-4 cm**	2	2	2	2	2	2	12
	Size Group 4-5 cm	2	2	2	2	2	2	12
	Size Group 5-6 cm	2	2	2	2	2	2	12
	Size Group 6-7 cm	2	2	2	2	2	2	12
	Size Group >7 cm	2	2	2	2	2	2	12
	Flake sample per material	10	10	10	10	10	10	60

5.3.2 Cut materials

Using stone flakes, each participant cut the following six materials: corrugated double-walled cardboard (thickness 9/32 inch or 7.1mm); natural Jute twine rope of 8 mm thickness; indigo 11 oz denim cloth; natural seagrass mat (0.5 inch high or 12.7mm); medical gelatin (Humimic Medical Healthcare Products, rigidity category #0 to match muscle tissue, https://humimic.com/; block size ,8 inch * 5 inch *1.18 inch or 203mm * 127mm * 30mm); and 3-4 oz vegetable-tanned cowhide. We constructed six wooden frames, each 9.84 inch by 9.05 inch (250mm *230mm), and attached each material to them with heavy-duty clamps (Figure 6).

Following Khaksar et al. (2022), we note that our use of these six materials was not specifically intended to represent any specific type of “natural” material, but instead acted as standardized and strategic controls that allowed us to assess how different materials interact with particular flake variables to influence slicing efficiency (Eren et al. 2016).

On the day of the experiment, we recorded participants` dominant hand grip with a hand dynamometer. There was variation in grips (measured in kg; N (participants)=5; $\bar{x}$= 33.064; SD=10.09; range= [23.66 - 45]). We thus controlled for participant strengths and other qualities in our statistical analysis.

5.3.3 Experimental Procedure

We recruited five participants in their early and mid-twenties. Four were female and one was male, and none had experience using stone tools. Each participant received 12 flakes from each of the five size categories. Each participant then used two flakes from each size category to slice through each of the six materials (Table 3). Thus, in total each participant used 60 stone flakes to cut through 10 pieces of each material type. To avoid order effects, we presented each participant with a flake of curvature-size-material combination in an order that was randomized using the following procedure. We first created a vector of length 60 representing the edge curvature combinations that each participant is supposed to receive (Plan curvature: low, med, high; Profile curvature: low, high). We then randomly sampled without replacement from this vector using the sample() function in R. This allowed us to first randomize the edge curvature combinations that the participants would receive. Next, since each participant was supposed to receive 2 flakes from each size-material combination, we created a vector of length 60 representing each size material combination twice as depicted in table 1 above. We created a random order of 60 flakes by randomly sampling without replacement from this vector using the sample() function in R. We performed this sampling three times to ensure proper randomization. This resulted in a presentation order that was random in terms of curvature, size, and material.

Each participant came to the lab five times, over the course of five different days, to carry out the slicing tasks. We provided participants 120 US dollars for their participation and time. On the first session, verbal instructions were given to each participant; participants started the slicing task right away during the subsequent four sessions.

Each slicing task was interspersed with recovery times of three minutes. However, the natural seagrass mat was more difficult to cut, and thus if two seagrass mats slicing tasks occurred in a row due to the randomization process, we allowed a six-minute recovery after the first piece and another six-minute break after the second one. We required participants to wear safety gloves to prevent any injuries. The sessions were recorded using two cameras (JVC GY-HM200U) which were set up on both sides of the participant. We marked on each material the area where the cuts were to be placed and allowed participants to place their non-dominant hand on the frame during the slicing task (Figure 7).

For the materials of denim, hide, seagrass mat and corrugated cardboard we asked each participant to slice through the material such that a straight, long and open cut was visible at the end of their activity. Given the varying type of materials and level of difficulty involved in cutting through them, we determined a priori cuts of different lengths for each material: a 19 cm cut for denim (Figure 6**,** b); a 17 cm cut for hide (Figure 6**,** c); a 22 cm cut for the corrugated cardboard (Figure 6**,** d); and a 10 cm cut for the seagrass mat(Figure 6**,** f).

For hemp rope, we asked participants to cut the rope as it was attached to the wooden frame into two pieces (Figure 6**,** a). We allowed participants to hold the rope while cutting it.

For the medical gelatin, we instructed participants to cut through the block along its length (Figure 6, e). We allowed them to place their hands on the block while cutting through it, although we ensured that participants did not tear the block open with their hands. They were not allowed to flip the gel block around.

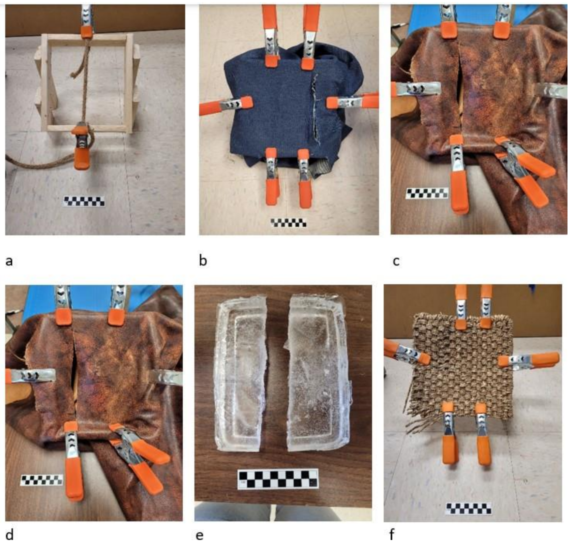

Figure 6**.** (a-f) show the wooden frames and different cut materials attached to them.

5.3.4 Statistical Analyses

We tested whether the effects on efficiency of gross-edge curvature (plan-view or profile-view) and size (edge length or specimen size) varied for different materials using Generalized Linear Mixed Models (GLMMs). As our response variable was time measured in seconds, we used GLMMs with a Poisson error structure. We fitted separate models for plan and profile edge curvatures, for each of edge length and specimen sizes, resulting in a total of four models with formulas described in Table 4. Each model tested the 3-way interaction of material, edge length (or specimen size), and plan (or profile) edge curvature. We controlled for the individual variation among participants using a random intercept for participant ID. We performed all analyses in R version 4.0.2 and fitted GLMMs using the lme4 R-package (Bates et al. 2015).

All raw data and code are available at https://github.com/desai-nisarg/Cut-material-and-efficiency.

Figure 7. A participant cutting through the natural seagrass mat.

Table 4. Model specifications for the interaction models used to test whether an artifact's size, edge length, or edge curvature had differential effects based on the material used.

Model ID	Model Specification
1	Time (s) ~ Material * Edge_length (std.) * Plan_curvature + (1|Participant)
2	Time (s) ~ Material * Edge_length (std.) * Profile_curvature + (1|Participant)
3	Time (s) ~ Material * Artifact_size * Plan_curvature + (1|Participant)
4	Time (s) ~ Material * Artifact_size * Profile_curvature + (1|Participant)

5.4 Results

We found significant three-way interactions in all four models, i.e. among specimen size, material, and plan curvature (Figure 8 and Table 5); specimen size, material, and profile curvature (Figure 9 and Table 6); edge length, material, and plan curvature (Figure 10 and Table 7); and edge length, material, and profile curvature (Figure 11 and Table 8).

Results from model 1 suggest that the effects of specimen size and plan curvature on efficiency vary based on the material for all material and specimen size combinations except for specimen sizes of 4 to 6 cm on gel, 7 cm and above on hide, and 6 to 7 cm on rope (Table 5). Similarly, results from model 2 suggest that the effects of specimen size and profile curvature on efficiency vary based on the material for all material and specimen size combinations except for specimen sizes of 4 to 5 cm on denim, and 7 cm and above on rope (Table 6). Edge length and plan curvature also have differential effects on efficiency for different materials as the three-way interactions are significant for all materials (Table 7). For profile curvature, the three-way interactions are significant for all but gel and grassmat (Table 8). Collectively, these results provide evidence that specimen size, edge length, and edge curvature have differential effects based on different materials.

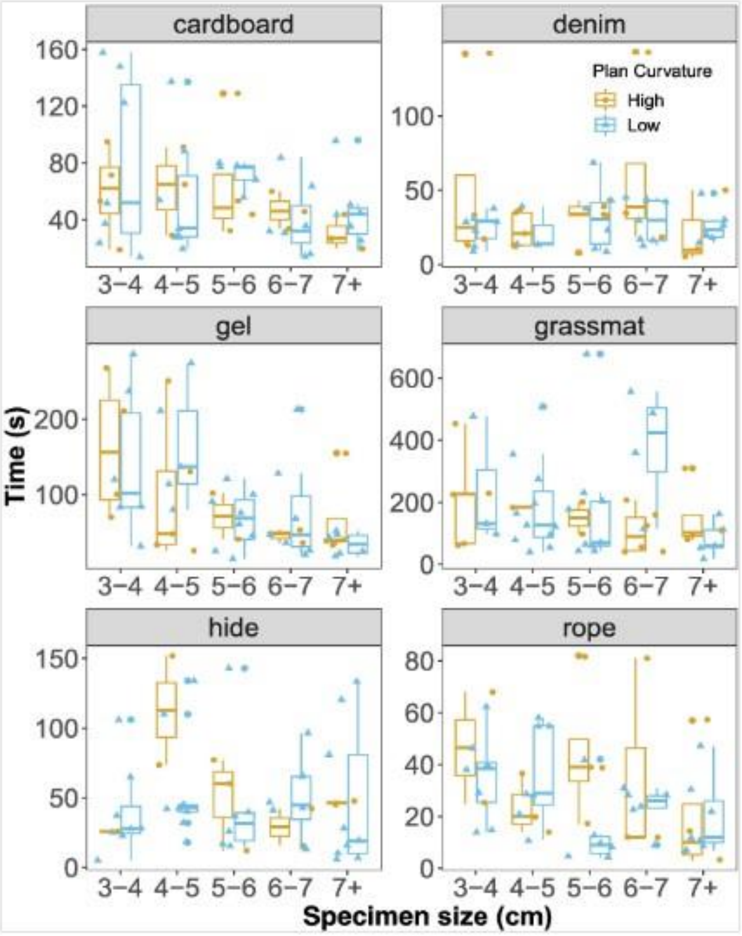

Figure 8**.** Raw data showing the interactions among Specimen size group, Material, and Plan-view curvature.

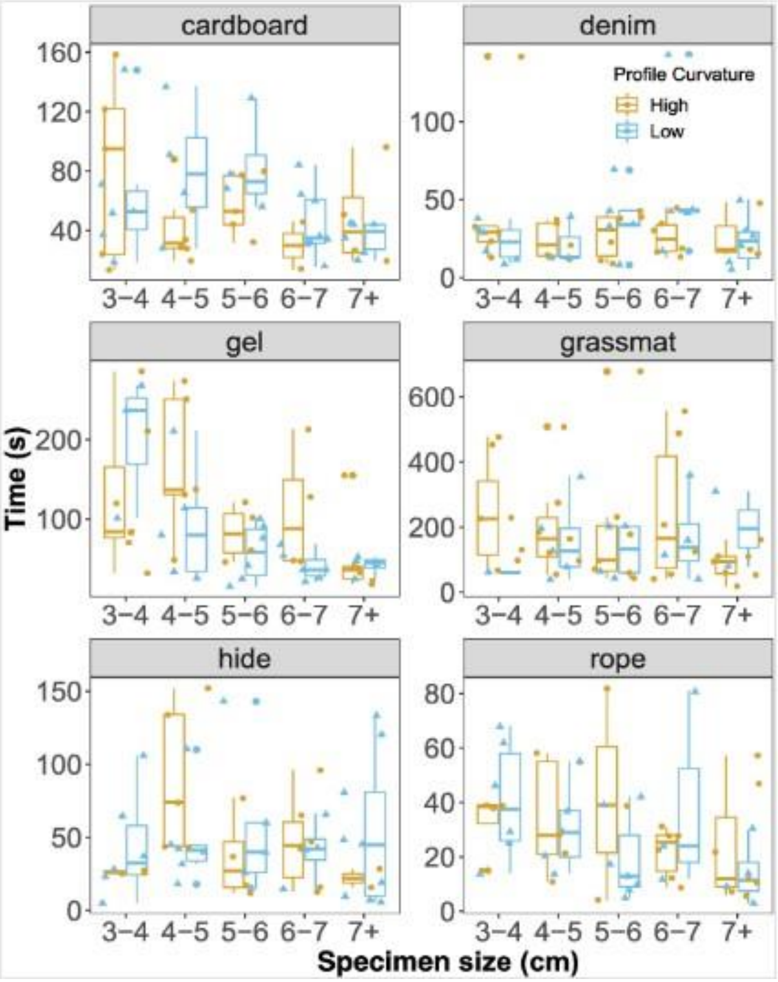

Figure 9. Raw data showing the interactions among Specimen size group, Material, and Profile-view curvature.

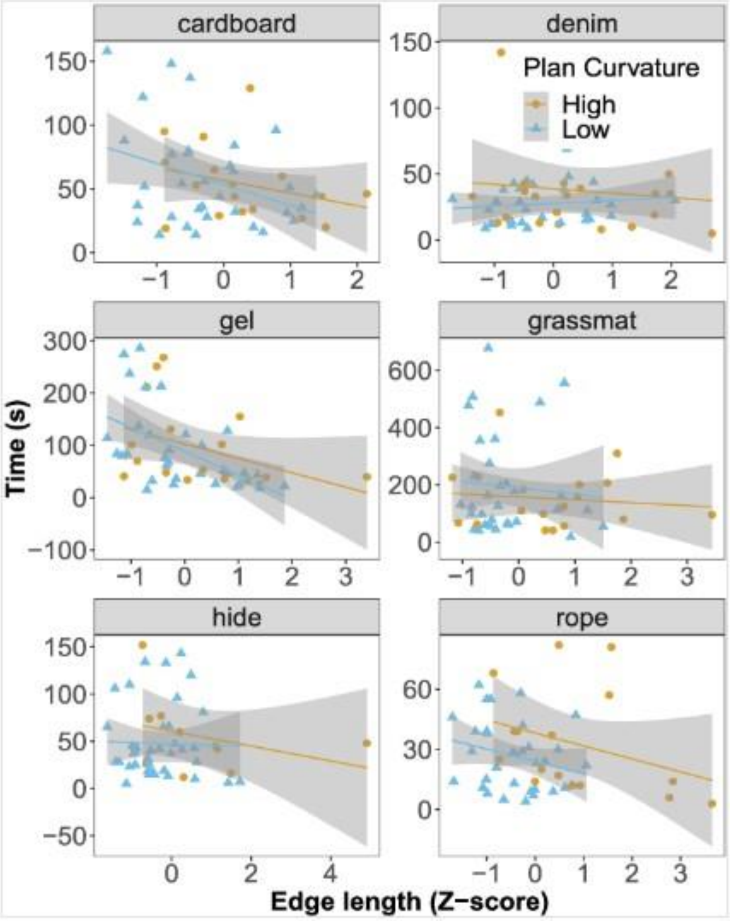

Figure 10. Raw data showing the interactions among Edge length, Material, and Plan-view curvature

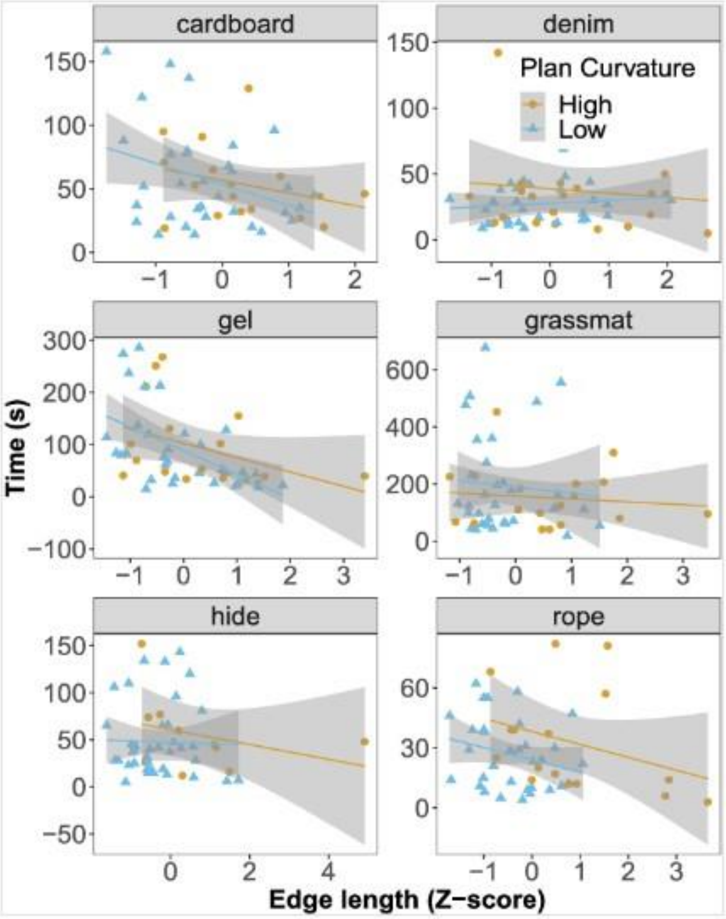

Figure 11. Raw data showing the interactions among Edge length, Material, and Profile-view curvature.

Table 5: Results from the Poisson GLMM testing the interaction among Specimen size group, Material, and Plan curvature.

	Estimate	Std. Error	z value	P (>|z|)
(Intercept)	5.4	0.41	13.14	0
Specimen size group (cm): 4-5	0.32	0.62	0.51	0.61
Specimen size group (cm): 5-6	0.53	0.61	0.87	0.38
Specimen size group (cm): 6-7	-1.31	0.57	-2.3	0.02
Specimen size group (cm): 7+	-3.1	0.87	-3.57	0
Material: denim	-8.61	0.85	-10.09	0
Material: gel	-1.18	0.58	-2.03	0.04
Material: grassmat	-0.9	0.42	-2.14	0.03
Material: hide	3.13	1.04	3.02	0
Material: rope	-4.85	1.03	-4.72	0
Plan Curvature	-0.99	0.31	-3.2	0
Specimen size group (cm): 4-5 * Material: denim	4.5	1.09	4.13	0
Specimen size group (cm): 5-6 * Material: denim	4.3	1.2	3.58	0
Specimen size group (cm): 6-7 * Material: denim	7.71	1.02	7.53	0
Specimen size group (cm): 7+ * Material: denim	7.78	1.5	5.17	0
Specimen size group (cm): 4-5 * Material: gel	0.9	0.81	1.12	0.26
Specimen size group (cm): 5-6 * Material: gel	0.4	0.96	0.41	0.68
Specimen size group (cm): 6-7 * Material: gel	5.03	0.94	5.37	0
Specimen size group (cm): 7+ * Material: gel	1.79	1.11	1.61	0.11
Specimen size group (cm): 4-5 * Material: grassmat	4.62	0.83	5.55	0
Specimen size group (cm): 5-6 * Material: grassmat	1.74	0.69	2.52	0.01
Specimen size group (cm): 6-7 * Material: grassmat	6.3	0.66	9.56	0

Specimen size group (cm): 7+ * Material: grassmat	2.49	0.92	2.72	0.01
Specimen size group (cm): 4-5 * Material: hide	-5.1	1.3	-3.93	0
Specimen size group (cm): 5-6 * Material: hide	-9.91	1.44	-6.88	0
Specimen size group (cm): 6-7 * Material: hide	-3.75	1.39	-2.7	0.01
Specimen size group (cm): 7+ * Material: hide	-0.41	1.35	-0.3	0.76
Specimen size group (cm): 4-5 * Material: rope	3.82	1.27	3.02	0
Specimen size group (cm): 5-6 * Material: rope	-5.94	1.38	-4.31	0
Specimen size group (cm): 6-7 * Material: rope	1.28	1.19	1.08	0.28
Specimen size group (cm): 7+ * Material: rope	6.34	1.5	4.23	0
Specimen size group (cm): 4-5 * Plan Curvature	-0.53	0.54	-0.99	0.32
Specimen size group (cm): 5-6 * Plan Curvature	-0.62	0.53	-1.17	0.24
Specimen size group (cm): 6-7 * Plan Curvature	0.61	0.49	1.24	0.22
Specimen size group (cm): 7+ * Plan Curvature	2.19	0.78	2.82	0
Material: denim * Plan Curvature	6.75	0.73	9.27	0
Material: gel * Plan Curvature	1.59	0.5	3.2	0
Material: grassmat * Plan Curvature	1.61	0.36	4.54	0
Material: hide * Plan Curvature	-3.63	0.95	-3.83	0
Material: rope * Plan Curvature	3.65	0.9	4.03	0
Specimen size group (cm): 4-5 * Material: denim * Plan Curvature	-4.04	0.92	-4.41	0
Specimen size group (cm): 5-6 * Material: denim * Plan Curvature	-3.58	1.03	-3.48	0
Specimen size group (cm): 6-7 * Material: denim * Plan Curvature	-6.01	0.87	-6.88	0

Specimen size group (cm): 7+ * Material: denim * Plan Curvature	-6.55	1.31	-5	0
Specimen size group (cm): 4-5 * Material: gel * Plan Curvature	-0.67	0.7	-0.96	0.34
Specimen size group (cm): 5-6 * Material: gel * Plan Curvature	-0.88	0.84	-1.05	0.29
Specimen size group (cm): 6-7 * Material: gel * Plan Curvature	-4.58	0.81	-5.62	0
Specimen size group (cm): 7+ * Material: gel * Plan Curvature	-1.99	0.98	-2.03	0.04
Specimen size group (cm): 4-5 * Material: grassmat * Plan Curvature	-4.01	0.74	-5.45	0
Specimen size group (cm): 5-6 * Material: grassmat * Plan Curvature	-1.47	0.6	-2.46	0.01
Specimen size group (cm): 6-7 * Material: grassmat * Plan Curvature	-4.87	0.56	-8.63	0
Specimen size group (cm): 7+ * Material: grassmat * Plan Curvature	-2.24	0.81	-2.76	0.01
Specimen size group (cm): 4-5 * Material: hide * Plan Curvature	5.53	1.17	4.71	0
Specimen size group (cm): 5-6 * Material: hide * Plan Curvature	9.31	1.3	7.19	0
Specimen size group (cm): 6-7 * Material: hide * Plan Curvature	4.22	1.25	3.39	0
Specimen size group (cm): 7+ * Material: hide * Plan Curvature	1.37	1.22	1.12	0.26
Specimen size group (cm): 4-5 * Material: rope * Plan Curvature	-3.27	1.11	-2.95	0
Specimen size group (cm): 5-6 * Material: rope * Plan Curvature	4.89	1.19	4.1	0
Specimen size group (cm): 6-7 * Material: rope * Plan Curvature	-0.97	1.03	-0.94	0.35
Specimen size group (cm): 7+ * Material: rope * Plan Curvature	-5.59	1.32	-4.24	0

Table 6: Results from the Poisson GLMM testing the interaction among Specimen size group, Material, and Profile curvature.

	Estimate	Std. Error	z value	P (>|z|)
(Intercept)	3.89	0.21	18.11	0
Specimen size group (cm): 4-5	0.52	0.11	4.83	0
Specimen size group (cm): 5-6	0.69	0.11	6.47	0
Specimen size group (cm): 6-7	-0.18	0.12	-1.48	0.14
Specimen size group (cm): 7+	-0.55	0.12	-4.49	0
Material: denim	-1.52	0.15	-10.39	0
Material: gel	1.38	0.1	13.77	0
Material: grassmat	1.65	0.13	13.07	0
Material: hide	0.03	0.13	0.24	0.81
Material: rope	-0.47	0.11	-4.07	0
Profile Curvature	6.1	1.18	5.19	0
Specimen size group (cm): 4-5 * Material: denim	0.06	0.21	0.27	0.79
Specimen size group (cm): 5-6 * Material: denim	0.89	0.2	4.51	0
Specimen size group (cm): 6-7 * Material: denim	1.92	0.21	9.34	0
Specimen size group (cm): 7+ * Material: denim	1.6	0.22	7.35	0
Specimen size group (cm): 4-5 * Material: gel	-1.45	0.14	-10.72	0
Specimen size group (cm): 5-6 * Material: gel	-2.02	0.15	-13.45	0
Specimen size group (cm): 6-7 * Material: gel	-1.49	0.15	-9.65	0
Specimen size group (cm): 7+ * Material: gel	-1.28	0.17	-7.55	0
Specimen size group (cm): 4-5 * Material: grassmat	-0.98	0.15	-6.39	0

Specimen size group (cm): 5-6 * Material: grassmat	-1.65	0.16	-10.61	0
Specimen size group (cm): 6-7 * Material: grassmat	-1.09	0.16	-6.65	0
Specimen size group (cm): 7+ * Material: grassmat	0.17	0.17	0.98	0.33
Specimen size group (cm): 4-5 * Material: hide	-0.59	0.18	-3.35	0
Specimen size group (cm): 5-6 * Material: hide	-0.69	0.16	-4.22	0
Specimen size group (cm): 6-7 * Material: hide	-0.22	0.18	-1.2	0.23
Specimen size group (cm): 7+ * Material: hide	-0.09	0.19	-0.49	0.63
Specimen size group (cm): 4-5 * Material: rope	-0.58	0.17	-3.39	0
Specimen size group (cm): 5-6 * Material: rope	-1.63	0.17	-9.75	0
Specimen size group (cm): 6-7 * Material: rope	0.66	0.2	3.33	0
Specimen size group (cm): 7+ * Material: rope	-0.38	0.22	-1.73	0.08
Specimen size group (cm): 4-5 * Profile Curvature	-16.19	1.89	-8.55	0
Specimen size group (cm): 5-6 * Profile Curvature	-16.79	1.82	-9.25	0
Specimen size group (cm): 6-7 * Profile Curvature	-8.22	2.4	-3.42	0
Specimen size group (cm): 7+ * Profile Curvature	0.75	2.21	0.34	0.73
Material: denim * Profile Curvature	10.98	1.97	5.56	0
Material: gel * Profile Curvature	-11.99	1.52	-7.89	0
Material: grassmat * Profile Curvature	-10.34	1.81	-5.72	0
Material: hide * Profile Curvature	-17.23	2.59	-6.65	0

Material: rope * Profile Curvature	-3.72	1.82	-2.05	0.04
Specimen size group (cm): 4-5 * Material: denim * Profile Curvature	1.27	3.15	0.4	0.69
Specimen size group (cm): 5-6 * Material: denim * Profile Curvature	-10.65	3.19	-3.34	0
Specimen size group (cm): 6-7 * Material: denim * Profile Curvature	-20.36	3.78	-5.39	0
Specimen size group (cm): 7+ * Material: denim * Profile Curvature	-26.57	3.97	-6.7	0
Specimen size group (cm): 4-5 * Material: gel * Profile Curvature	29.59	2.26	13.07	0
Specimen size group (cm): 5-6 * Material: gel * Profile Curvature	26.78	2.64	10.15	0
Specimen size group (cm): 6-7 * Material: gel * Profile Curvature	20.95	2.7	7.75	0
Specimen size group (cm): 7+ * Material: gel * Profile Curvature	12.52	2.97	4.22	0
Specimen size group (cm): 4-5 * Material: grassmat * Profile Curvature	22.03	2.5	8.83	0
Specimen size group (cm): 5-6 * Material: grassmat * Profile Curvature	30.1	2.44	12.34	0
Specimen size group (cm): 6-7 * Material: grassmat * Profile Curvature	30.49	2.88	10.57	0
Specimen size group (cm): 7+ * Material: grassmat * Profile Curvature	-5.93	2.77	-2.14	0.03

Specimen size group (cm): 4-5 * Material: hide * Profile Curvature	33.59	3.5	9.61	0
Specimen size group (cm): 5-6 * Material: hide * Profile Curvature	24.56	3.1	7.92	0
Specimen size group (cm): 6-7 * Material: hide * Profile Curvature	22.1	3.59	6.16	0
Specimen size group (cm): 7+ * Material: hide * Profile Curvature	26.08	4.21	6.19	0
Specimen size group (cm): 4-5 * Material: rope * Profile Curvature	13.75	2.9	4.74	0
Specimen size group (cm): 5-6 * Material: rope * Profile Curvature	24.79	2.46	10.08	0
Specimen size group (cm): 6-7 * Material: rope * Profile Curvature	-7.27	3.78	-1.92	0.05
Specimen size group (cm): 7+ * Material: rope * Profile Curvature	4.38	3.6	1.22	0.22

Table 7: Results from the Poisson GLMM testing the interaction among Edge length, Material, and Plan curvature.

	Estimate	Std. Error	z value	P (>|z|)
(Intercept)	3.84	0.28	13.59	0
Edge Length (mm)	-0.91	0.2	-4.55	0
Material: denim	-2.88	0.38	-7.59	0
Material: gel	-1.04	0.3	-3.53	0
Material: grassmat	1.67	0.24	6.89	0
Material: hide	-0.4	0.39	-1.02	0.31
Material: rope	-3.97	0.4	-9.98	0
Plan Curvature	0.05	0.18	0.25	0.81
Edge Length (mm) * Material: denim	2.25	0.3	7.37	0
Edge Length (mm) * Material: gel	1.15	0.26	4.36	0
Edge Length (mm) * Material: grassmat	0.94	0.22	4.31	0
Edge Length (mm) * Material: hide	0.78	0.24	3.21	0
Edge Length (mm) * Material: rope	0.65	0.35	1.85	0.06
Edge Length (mm) * Plan Curvature	0.54	0.17	3.17	0
Material: denim * Plan Curvature	2.07	0.33	6.31	0
Material: gel * Plan Curvature	1.35	0.26	5.28	0
Material: grassmat * Plan Curvature	-0.39	0.21	-1.86	0.06
Material: hide * Plan Curvature	0.28	0.35	0.79	0.43
Material: rope * Plan Curvature	2.87	0.34	8.36	0
Edge Length (mm) * Material: denim * Plan Curvature	-1.68	0.26	-6.56	0

Edge Length (mm) * Material: gel * Plan Curvature	-1.14	0.23	-5.03	0
Edge Length (mm) * Material: grassmat * Plan Curvature	-0.64	0.18	-3.52	0
Edge Length (mm) * Material: hide * Plan Curvature	-0.52	0.2	-2.56	0.01
Edge Length (mm) * Material: rope * Plan Curvature	-0.58	0.29	-1.97	0.05

Table 8: Results from the Poisson GLMM testing the interaction among Edge length, Material, and Profile curvature.

	Estimate	Std. Error	z value	P (>|z|)
(Intercept)	3.99	0.19	21.35	0
Edge Length (mm)	-0.15	0.05	-2.85	0
Material: denim	-0.69	0.06	-10.82	0
Material: gel	0.19	0.05	3.93	0
Material: grassmat	1.03	0.04	23.62	0
Material: hide	-0.18	0.05	-3.53	0
Material: rope	-1.03	0.06	-17.28	0
Profile Curvature	-2.04	0.7	-2.89	0
Edge Length (mm) * Material: denim	0.54	0.07	7.41	0
Edge Length (mm) * Material: gel	-0.18	0.07	-2.68	0.01
Edge Length (mm) * Material: grassmat	0.1	0.06	1.71	0.09
Edge Length (mm) * Material: hide	0.01	0.06	0.17	0.87
Edge Length (mm) * Material: rope	-0.04	0.07	-0.61	0.54
Edge Length (mm) * Profile Curvature	-2.72	0.9	-3.03	0
Material: denim * Profile Curvature	3.12	1.14	2.75	0.01

Material: gel * Profile Curvature	5.63	0.86	6.55	0
Material: grassmat * Profile Curvature	3.52	0.8	4.42	0
Material: hide * Profile Curvature	2.12	0.95	2.23	0.03
Material: rope * Profile Curvature	7.51	0.97	7.71	0
Edge Length (mm) * Material: denim * Profile Curvature	-4.37	1.31	-3.34	0
Edge Length (mm) * Material: gel * Profile Curvature	1.3	1.1	1.17	0.24
Edge Length (mm) * Material: grassmat * Profile Curvature	1.37	1	1.37	0.17
Edge Length (mm) * Material: hide * Profile Curvature	4.47	1.27	3.5	0
Edge Length (mm) * Material: rope * Profile Curvature	3.36	1.17	2.87	0

5.5 Discussion

Stone flake size, cutting edge length, and gross-edge curvature have all previously been shown to play a role in slicing efficiency (e.g., Jobson 1986; Key et al. 2014; Khaksar et al. 2022; Prasciunas 2007). In this study, we asked whether the type of material sliced – the cut material – interacted with these stone tool variables such that these latter variables' relationship with slicing efficiency changed. We designed an experiment that directed five participants to use 300 stone flakes, varying in our key variables of interest, in a slicing task involving six distinct materials. Overall, our results were consistent with the hypothesis that different materials interact with stone tool variables such that these variables’ precise effects on efficiency can be altered or, in some cases, overwhelmed. In other words, for example, our analysis suggests that a strong inverse relationship between slicing efficiency and flake size in one material may be less strong or less steep in another material.

Following Key and Lycett (2017b) and Gürbüz and Lycett (2021), our results support the hypothesis that the need or desire to process *particular* materials potentially influenced the production and selection of stone tool forms over time and to different extents. Indeed, Key and Lycett (2017b, emphasis added) state in their functional reassessment of flakes versus handaxes that their results identify that the *material context in which these tools are used* is key to their relative functional efficiencies, with flake cutting tools being significantly more efficient than handaxes when undertaking relatively small, precise cutting tasks. Alternatively, we identify that handaxes are significantly more efficient than basic flake cutting tools when tasked with cutting relatively large, resistant portions of material. Thus, these results provide evidence that the adoption and widespread production of handaxes was motivated by requirements to undertake this type of task.

Along these lines, our experimental results allow us to tentatively propose that where we see particular stone tool sizes and curvatures, we might see specific materials being worked, a prediction potentially testable via microwear. As a simple example, suppose an archaeologist finds an assemblage with several flakes between 4-5 cm in size and possessing high plan-view curvature. Based on our experiment results, that archaeologist should be more likely to find via microwear (or some other form of archaeological evidence) that those flakes were used to work a material akin to gel or rope, since those materials interact with that flake form in such a way as to reduce cutting time and thus increase cutting efficiency (Figure 9). Of course, exactly what past materials would have been similar to gel or rope is currently poorly understood and speaks to the need for further material science comparisons between "traditional" materials and modern "proxy" materials (e.g., Clarkson et al. 2022; Eren et al. 2022; Key et al. 2018; Lowe et al. 2019; Wilson et al. 2021). And one must not forget that flakes and other stone tools can be (usually are?) multifunctional implements – why spend time and energy to knap a certain flake form when the same amount of time or energy can be spent putting a little more "elbow grease" into one's slice?

We feel it necessary to emphasize the word "particular" when we refer to cut materials in the previous paragraph because our results also clearly show that some sliced materials interacted with our experimental stone tools in such a way that predicted increases or decreases in slicing efficiency due to changes in flake size, cutting edge length, and gross-edge curvature appear to be eliminated (which also follows Key and Lycett [2017b]). We note that these eliminations of predicted form-efficiency relationships arose most often in the easiest (denim) and most difficult materials (seagrass mat) to cut. Intuitively, this makes sense.

An easy-to-slice material would ameliorate the negative efficiency effects of small flakes, short cutting edges, or high gross-curvature values. And materials that are intractable to cut may render useless the advantages of large flakes, long cutting edges, and low gross-curvature values. Put another way, materials that are too easy or too difficult to slice are essentially material thresholds that equalize the effect that stone tool form variables have on efficiency (see also Key and Lycett 2015). Nevertheless, we feel it important to emphasize that the majority of materials showed an interaction with stone tool variables such that efficiency changed. As such it is entirely possible that our documented results for the denim and the seagrass mat are false negatives. Future experiments should further assess this possibility. One reason for such re-testing – beyond standard scientific practice – is that one could easily expect that stone tool variables should be amplified, rather than eliminated, for materials that are hard to cut.

Concerning thresholds, Key and Lycett (2014) found that the relationship between the flake size and cutting efficiency entered a plateau once flake size was above 50 mm. As an additional analysis, we tested whether there existed a threshold beyond which the specimen size had no effect on the efficiency. We performed a Threshold regression using the chngpt R-package (Fong et al. 2017). We performed a ‘segmented’ threshold regression with Poisson error structure to estimate and test the existence of a threshold in the specimen size (Fong et al. 2017). However, we found no evidence of a threshold flake size beyond which size had no effect on efficiency from our threshold regression models. The best estimate of a possible threshold point in the regression was at the specimen size group of 6 to 7 cm, but it was not statistically significant. Similarly, there was no evidence of a threshold edge length beyond which it had no effect on efficiency. The best estimate of a possible threshold point in the regression was at an edge length of 43 mm, but it was not statistically significant.

The presence (in Key and Lycett 2014) or absence (in the present study) of flake size efficiency thresholds should come as no surprise given that the experiments differ in several important ways. For instance, Key and Lycett's (2014) stone flakes possessed straight edges while ours varied in gross-edge curvature. While Key and Lycett (2014) used a cut material similar to our jute rope, namely hessian rope, other variables differed, such as rope thickness, participant sample size, and experimental setting. We also did not record loading and thus could not assess that variable following Key and Lycett (2014). But the differential existence of thresholds in one study versus another speaks to the question of exactly which variables, or combination of variables, produce flake size thresholds in slicing efficiency experiments. Future research can address this question.

Finally, while our focus in this study was primarily on the influence of cut materials on stone tool form efficiency effects, it is not lost on us that distinct stone tool variables can also interact with each other to produce disparate efficiency results (Tables 5-8). Distinct optimal or sub-optimal combinations of flake size, cutting edge length, and gross-edge curvature may have arisen at various times and places in the archaeological record (e.g., Eren and Lycett 2012; Khaksar et al. 2022). Moreover, when "optimal" combinations in flake form do not arise, archaeologists should be mindful that the perishable materials (e.g., wooden handles) may be playing a role in overcoming deficiencies that could potentially arise from use of the stone tool form alone (Barham 2013; Coe et al. 2022; Key et al. 2021). For example, prismatic blades and microliths are often smaller than Preferential Levallois Flakes (PLF) (decreasing the former's slicing efficiency) but could conceivably possess edges with lower gross-edge curvature values (increasing the former's slicing efficiency). However, the insertion of prismatic blades and microliths into a handle essentially increases their size, perhaps elevating their efficiency to a level equal to, or beyond, that of a handheld PLF.

6 PROLOGUE - PAPER THREE

Given that this paper is the last of the trio, my collaborators and I decided to shift our focus from isolated, controlled stone flakes onto a specific stone technology. Thus, for this project we focused on the Levallois reduction strategy. One of the collaborators, M.I. Eren, who is a well-known Levallois producer and his experimental Levallois collections have been cross- validated against archaeological examples (Eren and Lycett 2012, 2013b), performed five Levallois reductions which led to the production of a total of 462 flakes including 12 preferential Levallois flakes (PLFs). Similar to the first two papers this project was also centered on the concept of efficiency, cutting edge, and the element of plan-view and profile-view gross-edge curvature; specifically, this project aimed to understand how gross-edge curvature changes during the reduction process; whether it remains constant throughout the reduction sequence, increases, or decreases. Detecting any of these patterns contributes to ongoing discussions involving the standardization and economization of Levallois debitage.

This undertaking provided me with an opportunity to take the results of my earlier experiments which involved production of stone flakes to the next level which consisted of the examination of an entire reduction process. The results of this work have been submitted to a peer-reviewed journal and it is currently under review.

7 PAPER THREE

Exploring the gross-edge curvature of experimentally produced Preferential Levallois debitage

7.1 Paper Synopsis

Flaked stone reduced via a Levallois, or Levallois-like, sequence potentially provided benefits to hominins in terms of flake morphology and economy relative to other sequences. But such benefits did not come without costs. Here, we contribute to ongoing debates regarding Levallois technology by assessing the gross-edge curvature of experimentally produced Levallois debitage and Preferential Levallois Flake (PLF) edges. Previous experiments have shown that as gross-edge curvature increases, cutting efficiency decreases. As such, our results allow us to evaluate standardized gross-edge curvature throughout multiple Preferential Levallois Core reduction stages. Also, among several results, we show that as Levallois debitage size decreases, so too does gross-edge curvature, suggesting that knappers pursuing a Levallois core to exhaustion will not be penalized in terms of this feature.

7.2 Introduction

Levallois stone technology is often considered to be a hallmark of the African, Near Eastern, and European Middle Stone Age (MSA) or Middle

Paleolithic (MP) (e.g. Blinkhorn et al. 2021a, 2021b; Centi and Zaidner 2021; Dibble and Bar-Yosef 1995 and references therein; Eren et al. 2014; Groucutt et al. 2019; Lycett 2007, 2009; Lycett and von Cramon-Taubadel 2010; Moncel et al. 2011, 2020; Picin 2018; Rose et al. 2011; Shipton 2022; Tryon 2006; Tryon et al. 2005; Usik et al. 2013). Yet in recent years the presence of Levallois, or Levallois-like, technology has been proposed or described in both earlier and later temporal periods, as well as in geographic regions such as South Asia, East Asia, North America, and South America (Adler et al. 2014; Akhilesh et al. 2018; Bradley et al. 2010; Davis and Willis 2018; Eren et al. 2019; Hu et al. 2019; Pallo 2022; Scerri et al. 2021; Shipton et al. 2013; White and Ashton 2003). Such proposals or descriptions, however, have not always been met with acceptance (e.g., Li et al. 2019), and much recent work on Levallois has focused on recognizing its archaeological presence (e.g., Delpiano et al. 2021; Gonzalez-Molina et al. 2020; Ranhorn et al. 2019). One potential reason for disagreement over Levallois proposals or descriptions may have to do with whether a researcher conceives classic, volumetric, or technical definitions of Levallois stone technology, as put forth by Boeda (1988, 1994, 1995) and others (Bordes 1968; Chazan 1997; Commont 1909; De Mortillet 1883; Inizan et al. 1999; Schlanger 1996; Van Peer 1992), as a *theoretical model* against which real archaeological artifacts can be compared (Clarke 1968; Eren and Lycett 2016; Lycett and Chauhan 2010). By approaching Levallois as a theoretical model, rather than as a categorical reality to be recognized, the question “*is this specimen (or assemblage) Levallois?*” shifts to “*how closely does this artifact (or assemblage) resemble the Levallois model?*” (Eren and Lycett 2016; Lycett and Eren 2013a; Ranhorn et al. 2019). Some artifacts or assemblages may more closely resemble that model, some less so, some not at all.

By better understanding the potential economic and functional benefits and costs of the Levallois theoretical model, conceivably archaeologists can better infer why artifacts or assemblages conforming to or approximating that model emerged, were transmitted, evolved, or were abandoned and replaced with an alternative technology. Toward this end of understanding Levallois’ benefits and costs, lithic analysts have employed both experimental stone tool replication and mathematical modelling. This work suggests that Levallois reduction produces a variety flake forms with a variety of edge angles (Eren and Lycett 2012, 2016; see also archaeological examples, e.g., Shimelmitz and Kuhn 2018). This variety may be more standardized than some alternative reduction strategies, but less standardized than others (Muller and Clarkson 2022). However, Levallois knapping has the capacity to produce flakes that result in core morphologies that archaeologists recognize as “Preferential” or “Lineal” Levallois (Eren and Bradley 2009; Lycett and Eren 2018; Sandgathe 2004). As a population these latter flakes, what archaeologists call “Preferential Levallois Flakes” (PLFs), possess several statistical tendencies that feasibly would have been beneficial to hominins, including a flatness that would have facilitated resharpening; a thickness that would have augmented durability; a center of mass that would have enhanced cutting efficiency and ergonomics; and edge angles that would have balanced sharpness with robusticity (Eren and Lycett 2012; Eren and Lycett 2016).

Mathematical modelling and replication experiments have also suggested that Levallois reduction possesses economic benefits. For example, Brantingham and Kuhn (2001) used a geometric two-dimensional model that depicted the reduction process of ovoid stone cobbles. Their work showed that steep angled cores resembling what archaeologists consider to be Levallois cores have the advantage of maximizing usable blanks and cutting edge while minimizing raw material loss during the preparation and reduction. Following Brantingham and Kuhn (2001), Lycett and Eren (2013b) assessed the former's mathematical model via experimental replication, which allowed for the assessment of real, three-dimensional chert cores, possessing all the knapping challenges therein (cortex, inclusions, etc.). Lycett and Eren (2013b) produced a total of 3957 Levallois debitage flakes including 75 PLFs to examine six measures of reduction economy. Their experimental work confirmed the main conclusions underlying Brantingham and Kuhn`s (2001) mathematical work and suggested that after the initial shaping of the Levallois core mass loss is stabilized in the subsequent episodes of core repreparation. Together, Brantingham and Kuhn's (2001) and

Lycett and Eren’s (2013b) assessments do not support a characterization of Levallois as a wasteful or inefficient reduction strategy.

There are other potential benefits to Levallois suggested by experimental replication. For example, in another assessment of economy, cutting edge amount per unit mass (mm/g), Muller and Clarkson (2016) demonstrated via stone tool replication that Levallois reduction produced statistically as much cutting edge, or more, than bipolar, multiplatform, discoidal, biface, and prismatic blade reduction strategies. And once learned, current experimental evidence is consistent with the hypothesis that Levallois reduction may be easily knapped on a variety of stone raw materials, ranging from flints, to basalts, to obsidian, and so on (Bar-Yosef et al. 2011; Eren et al. 2011a).

Lithic analysts often laud the benefits of Levallois; the challenges and costs less so. For example, results from modern stone tool replication suggest that flake removals resulting in what archaeologists recognize as Preferential Levallois cores require a particular and restricted core morphology (Eren and Bradley 2009; Lycett and von Cramon-Taubadel 2013). Experiments also suggest that the consistent production of such core morphologies and PLF removals are relatively more complex than what may be required in other types of reduction sequences (e.g. discoid, biface, prismatic blade, Muller et al. 2017) and therefore may have demanded a substantial time investment to learn, rock to practice on, and, possibly, teachers to learn from (Eren et al. 2011a, 2011b;

Lycett 2019; Lycett et al. 2016; Muller et al. 2022). Moreover, although Levallois debitage is more standardized, and produces more cutting edges, than several other types of lithic reduction, experiments suggest that certain types of blade reduction (e.g., punch, pressure) surpass Levallois in these parameters (Muller and Clarkson 2016, 2022).

Following the research described above, in the present study we further explore functional and economic aspects of Levallois reduction and debitage. Our focus here is on an aspect of Levallois that has not been addressed in previous research, namely the plan-view and profile-view gross-edge curvature of debitage flakes. In two previous controlled cutting experiments Khaksar et al. (2022, 2023) showed that increases in gross-edge curvature broadly and significantly decreased the efficiency of slicing. To better to understand gross-edge curvature in Levallois debitage, we replicated a large debitage sample and tracked gross-edge curvature throughout the reduction process. Our central question is whether gross-edge curvature remains constant throughout the reduction sequence, increases, or decreases. Detecting any of these patterns contributes to ongoing discussions involving the standardization and economization of Levallois debitage.

7.3 Materials and Methods

7.3.1 Levallois Replication

M.I.E. knapped five Preferential Levallois reductions on Texas Georgetown chert using hard hammer direct percussion (Figures 12-13). This knapping produced 462 debitage flakes (inclusive of 16 PLFs) **(**Data S1, Table 9**)**. As M.I.E. knapped flakes he numbered them according to their core number, stage number, and reduction sequence removal number and bagged them. Levallois reduction “stages” were defined by the creation of PLFs. For example, core #1’s *first* stage included all the debitage removed in the creation of the first PLF, plus that first PLF. Core #1’s *second* stage then included all the debitage removed after the first PLF up to and including the second PLF.

M.I.E. knapped the Preferential Levallois reductions “blind,” in that he was not aware of the goals of the experiment, nor what was being measured on the flakes. These reductions were also knapped well-before he was made aware of Khaksar’s focus on gross-edge curvature in other experiments (Khaksar et al. 2022, 2023).

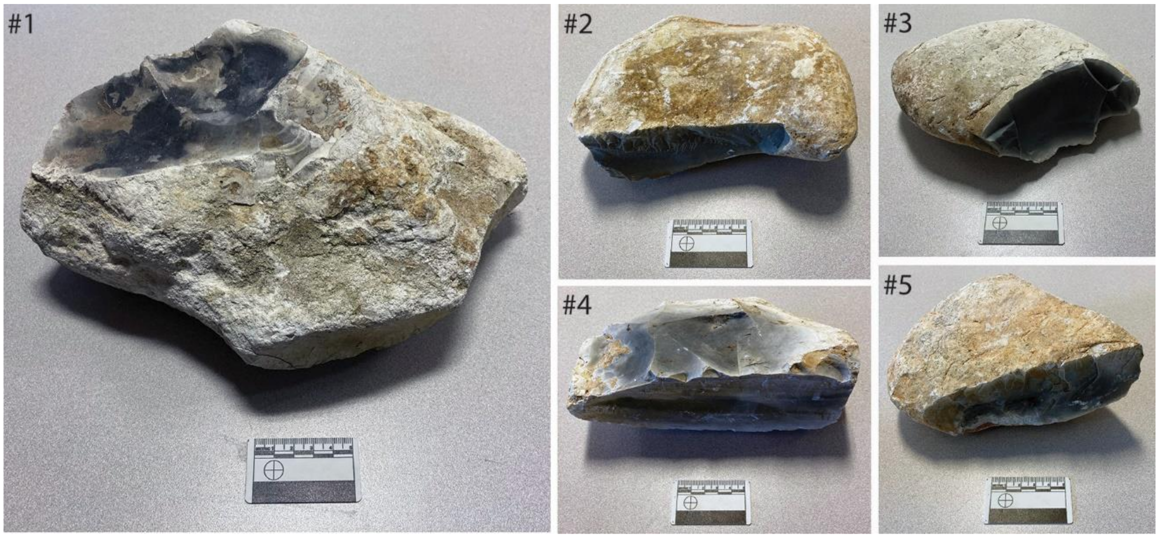

Figure 12. The experimental nodules prior to Preferential Levallois reduction.

7.3.2 Quantifying Gross-Edge Curvature

We quantitatively defined “gross-edge curvature” as the overall deviation from a theoretical straight line. As detailed by Khaksar et al. (2022, 2023), and reproduced here, we calculated gross-edge plan-view curvature by dividing the length of the edge “a” by the length of “b”, the latter being a hypothetical straight line between the endpoints of the edge (Figure 14 a). A value equal to 1 indicates a straight plan-view edge and values above 1 denote curved plan-view edges such that the higher the value above 1, the more the plan-view edge deviates from a straight line. Following Collins (1999) and others (e.g., Eren 2012; Jennings and Smallwood 2018), we calculated gross-edge profile-view curvature by dividing the length of “b”, the straight-line distance between the distal and proximal points of contact of the interior flake/blade surface and a flat plane, into “a”, the maximum perpendicular distance between that plane and the interior surface of the flake/blade (Figure 14 b). A value equal to 0 indicates a straight profile-view edge and values above 0 (but never above 1), denote increasingly curved profile-view edges. It is important to note that since we are currently investigating gross-edge curvature, we are not distinguishing between convexity, concavity, or sinuosity, but simply how much curvature exists relative to a theoretical straight line. Future efforts will aim to tease apart edge deviations on more detailed levels. These future efforts will be important because, following Khaksar et al. (2022), we readily acknowledge that freshly knapped stone flakes do not frequently feature edges with neatly- and continuously-curved edges. Future experiments will explore the influence of edge curvature changes on more acute-scales along an edge (e.g., MacDonald et al. 2020, 2022; Stemp 2014; Stemp et al. 2019), rather than at the gross-scale we assess here.

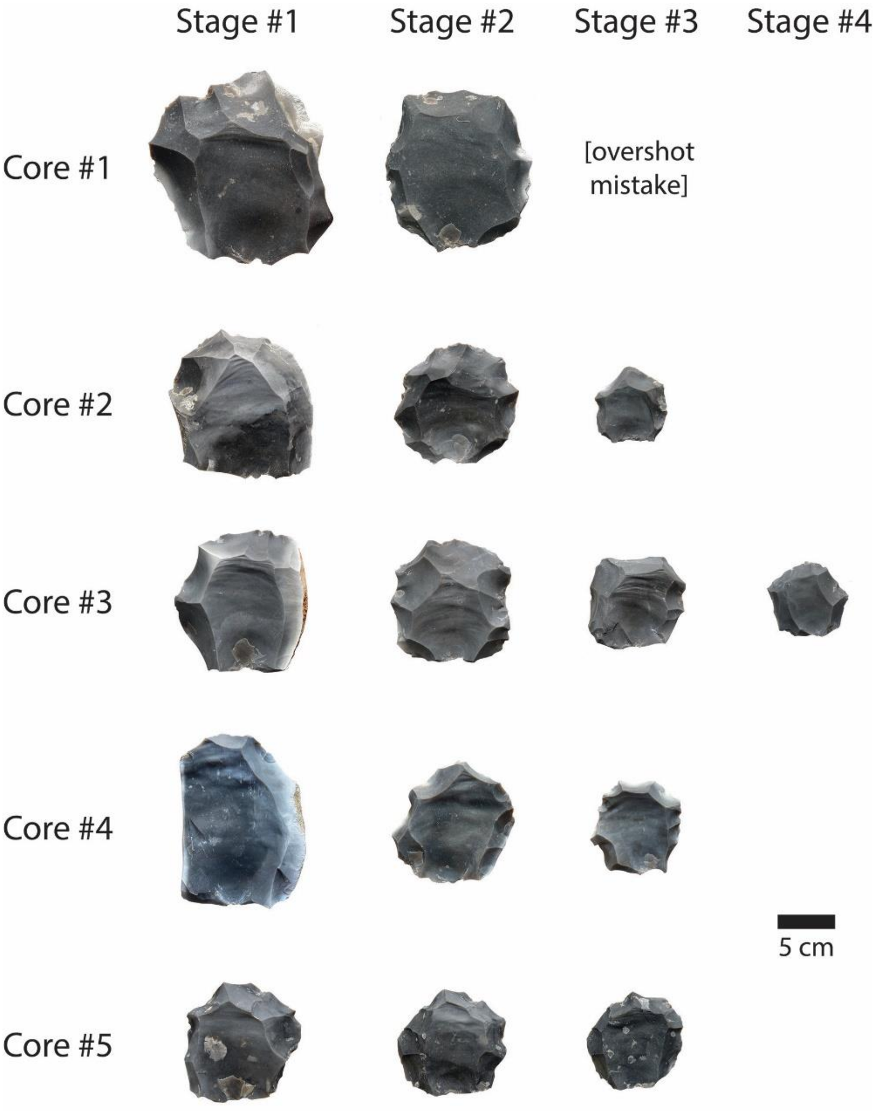

Figure 13. The experimental Preferential Levallois Flake removals per core and stage.

Table 9. Experimental core mass data, as well as debitage mass, chips mass, and Preferential Levallois Flake (PLF) mass. A piece of debitage was defined as a flake removal; chips resulted from platform preparation. We recorded mass in grams (g).

Core	Original Nodule Mass	Stage	Debitage Mass	Total Chips Mass	PLF Mass
1	6732.94	1	4099.15	204.1	319.8
		2	845.49	52.3	158.7
		3	702.3	41.1	310
2	2225.33	1	1126.53	35.2	174.3
		2	498.2	18.6	63.9
		3	256.5	26.7	25.4
3	2247.5	1	1170.5	49.5	131.2
		2	361.9	19.1	58.6
		3	150.4	16.3	57.8
		4	203.9	13.8	14.5
4	2388.3	1	1054	43.8	300.4
		2	596.1	41.2	95.7
		3	192.7	12.3	52.1
5	1855.1	1	1345.7	62	110.2
		2	134.5	14.9	41.4
		3	97.6	7.5	41.3

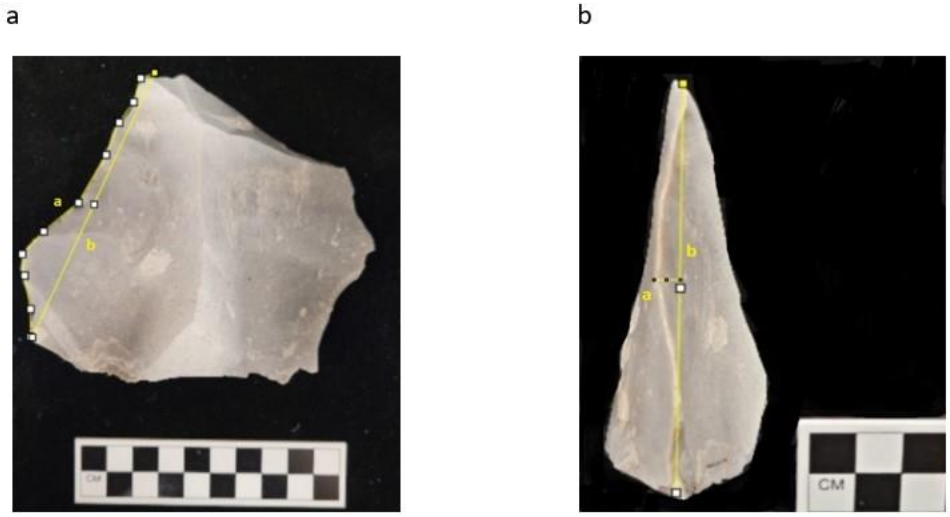

Figure 14. Measurement of plan-view (a) and profile-view (b) gross-edge curvature.

7.3.3 Recording Gross-Edge Curvature

A flake can have multiple suitable cutting edges (defined simply here as an edge angle < 50°), especially since a flake can be grasped in different ways. As such, we decided to assess the plan- and profile-view gross-edge curvature of each flake’s longest maximum cutting edge. We defined this longest maximum cutting edge as the longest section of a flake’s edge that could be used while being grasped. This edge was often easily defined because cortex, a right angle or even obtuse edge, or a sharp inflection point provided a natural cut off. In some instances, however, we were forced to define an edge’s boundaries more subjectively because the inflection point was along a gradual edge curve.

Once the longest maximum cutting edge was defined on a flake, we measured and recorded its gross-edge curvature following Khaksar et al. (2022). In sum, we photographed each specimen and used *ImageJ* software to record gross-edge curvature.

7.3.4 Statistical Analysis

We carried out two sets of analyses of gross-edge curvature and mass of the flakes in our experimental dataset. The first set of analyses focus on the plan-view and profile view gross-edge curvature variables by reduction stage. We examine the degree to which the samples conform to underlying normality and use Kruskal-Wallis nonparametric tests to compare plan-view and profile view gross-edge curvature of flakes by reduction stage. We conduct post-hoc analyses using paired Wilcoxon tests for Kruskal-Wallis tests that return significant results. Next, we use Levene’s tests to evaluate the variation among the reduction stages for plan-view and profile view gross-edge curvature measures. Levene’s test is an alternative to Bartlett’s test that is less sensitive to departures from normality. Lastly, we investigate the correlation between plan-view and profile-view gross-edge curvature and flake mass using the nonparametric Spearman’s rank test.

In the second set of analyses, we compare the PLFs to the non-PLF flakes. We follow the same protocol as above, except we use the Wilcoxon two-sample test instead of the Kruskal-Wallis test.

All raw data and R-scripts are available in the supplementary online material.

7.4 Results

Average plan-view gross-edge curvature for the flakes in our sample increases slightly from stage 1 to stage 4 (Table 10). The box plot (Figure 15) and skewness measures by reduction stage (Stage 1=1.95; Stage 2=1.11; Stage 3=1.0; Stage 4=0.5) indicate long tails in the samples and a significant Shapiro-Wilk test of normality (W=0.893, $p<0.000$) together warrants a nonparametric approach. The nonparametric Kruskal-Wallis test comparing plan-view gross-edge curvature by stage rejects the null hypothesis that the samples come from the same population and suggests that one or more pairs of medians are statistically different (KW $\chi^2=11.61$, df=3, p=0.009). Post-hoc pairwise analyses indicate that only stage 1 and stage 4 (the small sample of flake removals associated with core 3) are significantly different (Table 11). Levene's test indicates there is no significant difference in variation of plan-view gross-edge curvature among the four stages (F=0.184, p=0.907).

Table 10.Summary statistics for plan-view gross-edge curvature.

	n	mean	sd	min	Q1	median	Q3	Max
Stage 1	184	1.20	0.18	1.00	1.05	1.15	1.29	2.30
Stage 2	122	1.22	0.17	1.00	1.08	1.20	1.30	1.84
Stage 3	137	1.23	0.18	1.00	1.09	1.19	1.33	1.89
Stage 4	17	1.30	0.15	1.05	1.19	1.29	1.41	1.69

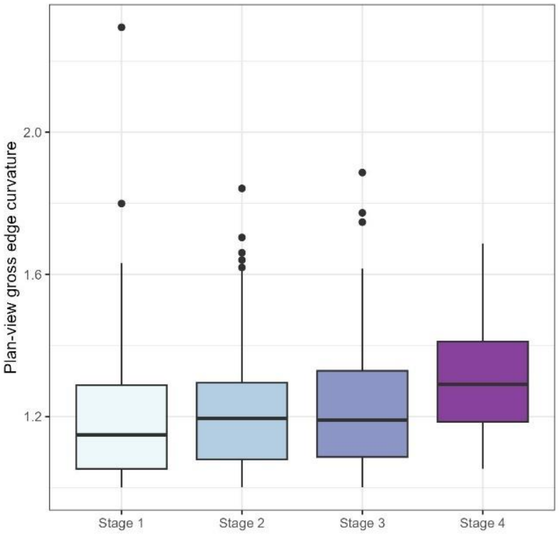

Figure 15. Box plot of plan-view gross-edge curvature by reduction stage.

Table 11. Pairwise comparisons of plan-view gross-edge curvature by stage using Wilcoxon rank sum test with continuity correction. Bonferroni correction used as the p-value adjustment method.

	Stage 1	**Stage 2**	**Stage 3**
Stage 2	0.396	-	-
Stage 3	0.442	1.000	-
Stage 4	0.014*	0.166	0.178

*Significant difference after Bonferroni correction.

Table 12. Summary statistics for profile-view gross-edge curvature.

	n	**mean**	**sd**	**min**	**Q1**	**median**	**Q3**	**max**	**% Zero**
Stage 1	184	0.05	0.04	0.00	0.03	0.04	0.06	0.22	4.35
Stage 2	122	0.05	0.03	0.00	0.02	0.04	0.06	0.22	7.38
Stage 3	136	0.04	0.03	0.00	0.02	0.04	0.06	0.16	8.09
Stage 4	17	0.06	0.03	0.02	0.03	0.05	0.06	0.14	0.00

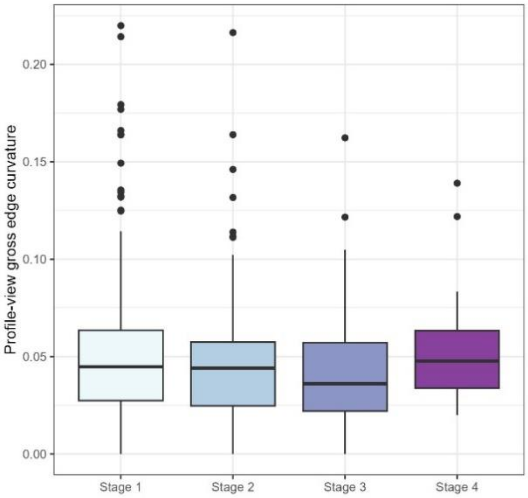

Figure 16. Box plot of profile-view gross-edge curvature by reduction stage.

Table 13. Pairwise comparisons of profile-view gross-edge curvature by stage using Wilcoxon rank sum test with continuity correction. Bonferroni correction used as the p-value adjustment method.

	Stage 1	Stage 2	Stage 3
Stage 2	1.000	-	-
Stage 3	0.020*	0.500	-
Stage 4	1.000	1.000	0.138

*Significant difference after Bonferroni correction

Table 14. Summary statistics for flake mass.

	n	mean	sd	min	Q1	median	Q3	max
Stage 1	184	53.39	80.43	0.90	6.58	24.90	60.25	444.46
Stage 2	122	23.36	27.91	0.60	5.15	14.55	31.45	163.30
Stage 3	136	13.74	29.12	0.50	2.70	6.25	14.13	310.00
Stage 4	17	12.85	14.77	1.10	3.60	9.40	14.50	62.00

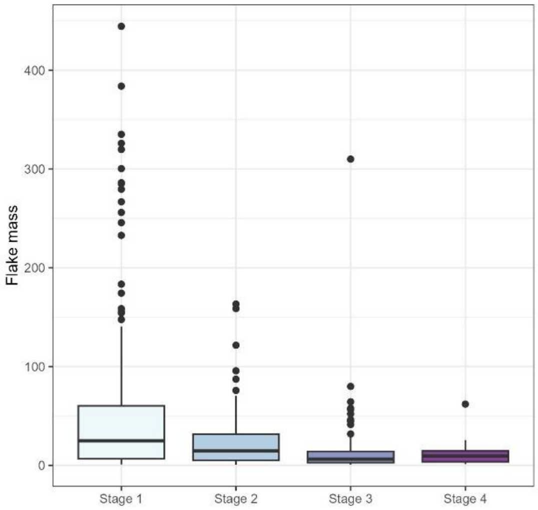

Figure 17. Box plot of flake mass by reduction stage.

Table 15. Summary statistics for the preferential Levallois flakes (n=16) and the other non-preferential Levallois flakes (n=443) for plan-view gross-edge curvature, profile-view gross-edge curvature, and flake mass.

Plan-view gross-edge curvature							
	mean	**sd**	**min**	**Q1**	**median**	**Q3**	**max**
flake	1.21	0.18	1.00	1.07	1.17	1.31	2.30
plf	1.31	0.14	1.11	1.22	1.28	1.36	1.64
Profile-view gross-edge curvature							
flake	0.05	0.04	0.00	0.02	0.04	0.06	0.22
plf	0.05	0.02	0.01	0.03	0.05	0.06	0.09
Flake mass							
flake	28.91	53.07	0.50	4.20	11.90	30.20	444.46
plf	122.21	103.79	14.50	49.43	79.80	162.60	319.80

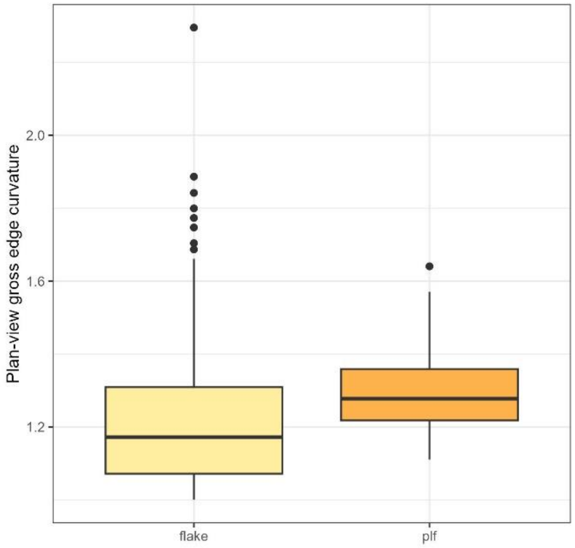

Figure 18. Box plot of plan-view gross-edge curvature by flake type

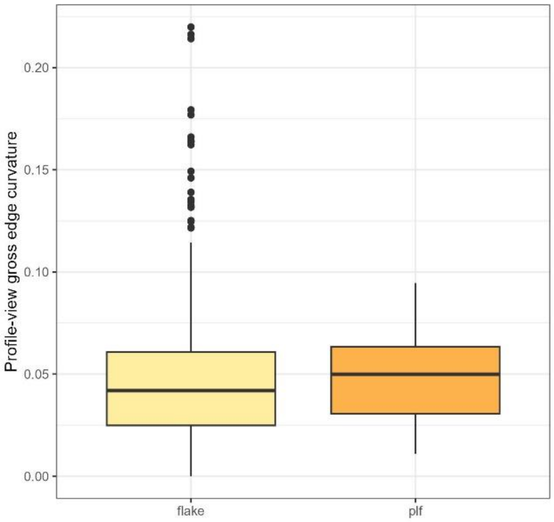

Figure 19. Box plot of profile-view gross-edge curvature by flake type.

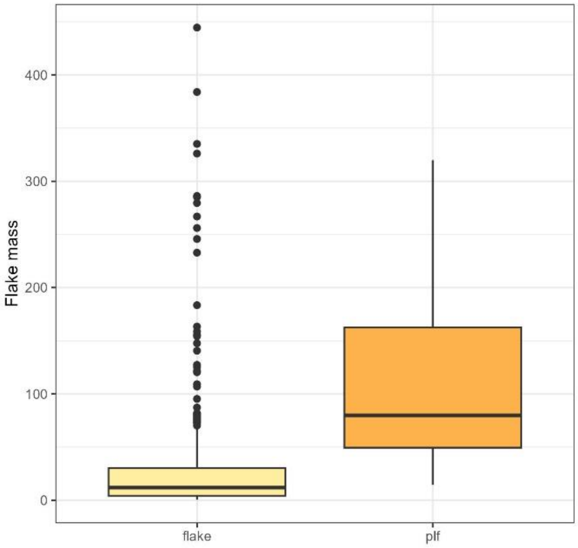

Figure 20. Box plot of flake mass by flake type.

7.5 Discussion

Relative to several other lithic reduction strategies, assessment of the Levallois theoretical model suggests that it would have provided many benefits to hominins in terms of flake function and reduction economy. So many benefits, in fact, that the Levallois theoretical model could potentially be considered as a theoretical optimum (Brantingham and Kuhn 1999; Eren and Lycett 2016). If true, then the widespread transmission and convergent evolution of Levallois and Levallois-like reduction sequences around the world and in different time periods is easily explained, even perhaps predictable (Lycett and Eren 2013b).

Here, we explored a feature of Preferential Levallois debitage that to our knowledge has yet to be quantitatively assessed: gross-edge curvature. Our results broadly show that when considering several cores together Levallois debitage plan- and profile-view gross-edge curvature is broadly consistent – one might say standardized – across reduction stages in terms of central tendency and variation. Such regularity in gross-edge curvature could easily be framed by archaeologists as a benefit to past hominins in that this feature is more or less predictable, and does not persistently increase in value thereby decreasing the overall cutting efficiency of flake populations per reduction stage.

Yet the cores we analyzed were not consistent in form. Thus, the debitage from a larger core’s first reduction stage was mixed with the debitage from a smaller core’s first reduction stage. In other words, the reduction stage analysis could possibly be aggregating different flake sizes in each stage in unusual ways that mostly result in “no difference” with respect to gross-edge curvature per stage. Thus, to investigate the issue further, we conducted an analysis of flake size and gross-edge curvature. As flake size decreases, so too does gross-edge curvature, and to a significant degree. Given that we also show flake size decreases per Preferential Levallois core stage, this latter result suggests that as Levallois reduction proceeds, increasingly smaller flakes are becoming more efficient cutting-wise with respect to both plan-view and profile-view gross-edge curvature. These positive, significant correlations are particularly interesting given that smaller flakes have been shown to be less efficient for certain cutting tasks relative to larger flakes (Biermann Gürbüz and Lycett 2021; Jobson 1986; Key and Lycett 2014; Khaksar et al. 2022, 2023; Prasciunas 2007). As such, it is possible that the decreasing gross-edge curvature of smaller Levallois debitage may to some degree offset the cutting deficiencies that come with smaller flake size, and thus be an additional motivating factor for carrying on with Levallois reduction, or creating small flake products (e.g., Dibble and McPherron 2006), rather than abandoning a core early in the sequence. At the very least, flakes created toward the end of a Levallois reduction sequence do not appear to possess the coinciding nadirs of small size and high gross-edge curvature (Brantingham and Kuhn 1999; Lycett and Eren 2013b).

Flake removals that result in what archaeologists recognize as Preferential Levallois Cores possessed significantly higher gross-edge curvatures relative to other Levallois debitage. While we should be cautious about this result given our small sample size of PLFs (n=16), any decrease in PLF cutting efficiency attributed to increased gross-edge curvature may perhaps have been compensated for, or overwhelmed by, other variables attributed to PLFs that increase cutting efficiency like increased flake size, longer cutting edges, ergonomic shape, and robust edge angles (Eren and Lycett 2012, 2016). We also should not be surprised by significantly larger plan-view gross-edge curvature in PLFs relative to other debitage given that successful PLF removals from rounder Levallois cores – like the ones produced for this present study – means that an equally round flake will be removed, mirroring the core’s upper surface and round plan-view outline (Khaksar et al. 2022). A group of elongated PLF cores (e.g., Tryon et al. 2005) may provide different plan-view gross-edge curvature values. We documented no difference between debitage and PLF flakes in terms of profile-view gross-edge curvature, which might be considered surprising given that PLFs generally possess a flat morphology overall. But to reiterate, caution should be exercised with respect to any conclusions drawn here regarding our PLF assessment given the small sample size.

Moving forward, in addition to further testing involving the relationship between gross-edge curvature and cutting efficiency, fruitful analyses of gross-edge curvature would ideally follow the work of Muller and Clarkson (2016, 2022) and Muller et al. (2017, 2022) whereby multiple reduction sequence types (e.g. Levallois, prismatic blade, bifacial) are compared via experimental replication. Understanding central tendencies and variation of gross-edge curvature – and thus one aspect of cutting efficiency – across a diversity of experimental reduction sequence options would further help archaeologists interpret potential benefits and costs and thus why, in particular contexts, certain knapping sequences were invented, adopted, or discarded (Eren et al. 2022). Another future research avenue would be to begin measuring gross-edge curvature on archaeological specimens and assemblages, although such work is likely to be fraught with difficulty given the biases of the archaeological record.

Finally, to conclude we would like to note that nowhere in this study did we employ the terms "predetermination," "intention," or "design": concept staples in the Levallois literature (e.g., Dibble and Bar-Yosef 1995; Eren and Lycett 2012 and references therein; Schlanger 1996; Shipton 2022; Wynn et al. 2017). These word omissions were a deliberate choice merely to illustrate that – depending on the question being asked – fruitful discussions of past technologies, and their potential costs and benefits to their hominin makers and users, can still be had without any sort of reference to hominin intent, producer design, or conscious awareness of those costs and benefits. Introductory textbooks on evolution make a distinction between "function" and "purpose" (e.g., Futuyma 2013), focusing on the former. Similarly, an evolutionary understanding of stone tools and other past technologies may benefit in some specific instances by focusing on tool function rather than assuming, or attempting to divine, the “purpose” predetermined, intended, or designed by its hominin maker.

8 DISSERTATION CONCLUSION

This dissertation explored in the form of 3 papers the theme of stone tool cutting edge efficiency. The major goal of the entire project was to evaluate the role of the plan-view and profile-view gross-edge curvature in the cutting efficiency of stone flakes. As previously noted, different characteristics of flakes e.g., edge angle, edge length, flake size, and flake shape have been the subject of research, however, the effect of the element of gross-edge curvature on edge efficiency has not been addressed in experimental studies. Suspecting that it might play a role I decided to design experiments to assess its potential influence.

The first paper was produced to directly address the above question. My colleagues and I designed and conducted an experiment to collect data on the relationship between the gross edge curvature and slicing efficiency. The collected data were then statistically analyzed, the result of which showed that the plan-view and profile-view gross-edge curvature had in fact an effect on the cutting efficiency of flake stones and that this element was as important as a variable such as edge length in the efficiency performance of cutting edge. These results have implications for the emergence of particular tool forms or reduction sequences throughout the Pleistocene and may in part explain why certain forms were favored by Paleolithic people, leading to their convergent evolution or widespread transmission.

The second paper was focused on the influence of surface material on the effect of flake size, edge length, and the plan-view and profile-view gross-edge curvature on the cutting edge efficiency. I carried out another experimental study to evaluate the role of different surface materials on edge performance. Statistical analyses that were conducted on the experimental data indicated that variance in surface material can lead to differential effects of flake size, edge length and gross-edge curvature on the cutting efficiency of flakes. This means that depending on the type of surface material the relationship between edge length and edge efficiency could be either strong or weak. All of this suggests that the need and preference of hominins for a specific type of surface material could have affected the production and selection of stone artifacts throughout time. This paper also shows that depending on the type of surface material employed in lab settings experimental studies can produce different results that might influence current thinking on a particular subject.

The third paper was focused on the element of gross-edge curvature in Levallois reduction. We produced a lithic assemblage consisting of five Levallois reductions to study the potential changes of gross-edge curvature during the process. The results showed that when the five cores were considered together the plan and profile view gross-edge curvatures were consistent across the reduction stages in terms of central tendency and variation. When flake size was factored into the analysis, the results indicated that smaller flakes had lower gross-edge curvature which is a factor that could offset the decreasing efficiency that comes with small size. Our analyses also showed that the PLFs had higher gross-edge curvature compared to the group of debitage. This is a disadvantage that could be offset by the larger size of the PLFs, their longer cutting edge, robust edge angles ,and ergonomic shape all of which contribute to the efficiency of these products.

With the last paper comes the end of my entire PhD work, however, there is still a lot to be done. Designing experiments with the aim of examination of the effect of the element of gross-edge curvature on the cutting efficiency of different technologies including the Levallois would be a large-scale project that is left for the future. We may never know the complete host of variables that interact with each other to produce a specific outcome but every single study that is carried out is a step towards identifying a new variable. And with each new identification comes the necessity of conducting further research to unravel the exact nature of interaction between the newly-identified and already-known variables. This makes building on previous research necessary, otherwise one might become entrapped into repetitive processes that squander resources while producing not much benefit. Variable identification, in our field, is not an easy process as it is in some other fields since in the former, actions and reactions are examined in a context that is remarkably different from the original settings that gave rise to them. Thus, there is always an element of uncertainty in our inferences, the extent of which increases or decreases based on the robusticity of our research. However, given the limitations of our field in terms of accessibility of the subjects` intentions and perceptions, we always have the option of conducting controlled experiments to create a spectrum of behavioral possibilities and impossibilities and hence, to generate alternative hypotheses that can illuminate the reasons underlying an archaeologically observed behavior. That is the direction that this dissertation took; by performing controlled experiments my project aimed to determine whether the variable of plan-view and profile-view gross-edge curvature impacts the slicing performance of stone flakes. Although the statistical tests indicated it indeed affects the cutting-edge efficiency, we may never know whether the Paleolithic hominins intentionally adjusted that variable but we now know, through the experiments, that could have been a “behavioral possibility”. On the importance of performing experiments, one should also mention Francis Bacon`s stimulating thinking on it. “He taught that not only must we observe nature in the raw, but that we must also ‘twist the lion's tail’, that is, manipulate our world in order to learn its secrets.’ (Hacking 1983, p.149). As noted, our field, compared to some other research areas, is limited in its capabilities in twisting the lion`s tail but it has increasingly been successful in revealing the past world` secrets through conducting vigorous research and robust experiments. My dissertation, based on controlled experiments was my effort to “twist the lion`s tail” and add a piece to the complex puzzle of the Pleistocene hominin behavior.

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