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Past human decision-making based on stone tool performance: Experiments to test the influence of raw material variability and edge angle design on tool function

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ABSTRACT

One of the main interests in the interpretation of the archaeological record and its variability within and through time and space is the production and use of past human stone tool technologies. Tool design and function are inevitably intertwined and strongly related to tool use. Understanding tool design provides information about early human technological adaptations and reflects human behaviour in the sense of conscious or unconscious decision-making. Nevertheless, the reason for major changes (including novelties, innovations, and loss) in past human stone tool technology is still poorly understood. A comprehensive approach focusing on tool function (What was the tool meant for?) and use (What was the tool used for?) can help to overcome this gap. While tool function (including performance) can be investigated experimentally, tool use can be addressed with use-wear analyses. These questions can be best investigated on technological systems showing little tool variability but strong evidence of maintenance and long-term use, such as Middle Palaeolithic industries.

The Late Middle Palaeolithic record of Central and Eastern Europe is marked by the emergence of an asymmetric tool-type called *Keilmesser* (bifacial backed knives). Due to their sophisticated morphology, *Keilmesser* as a case study offer the potential to address aspects of raw material selection, tool production, maintenance, and reworking.

This paper presents the results of an experiment designed to study the tool performance of *Keilmesser* from three archaeological sites, namely Balver Höhle, the Upper site of Buhlen and Grotte de Ramioul by testing raw material, edge angle and movement as independent variables. A highly controlled, sequential experiment was conducted using a mechanical device performing unidirectional cutting and carving movements on hard contact material. Results demonstrate the possibility to perform the mentioned task with 35° and 45° edge angles, maintaining function, albeit at differing levels of efficiency. The data has a direct impact on the interpretation of the archaeological assemblages regarding aspects such as stone tool morphology and resharpening. At the same time, the study highlights the importance of raw material analysis to understand the variability in the archaeological record and the implications on past human decision-making strategies.

1. Introduction

Archaeologists attempt to answer questions regarding the evolution of human behaviour through the study of material culture. In the Pleistocene, stone tools were essential to the survival of hominins. Hence, lithic artefacts provide insights into early hominin behavioural

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traits such as technological adaptations and innovations (Ambrose, 2001; Dibble et al., 2017; Key et al., 2020b; Klein, 2000; Lycett, 2015; Odell, 2000). Understanding for which purpose a tool was designed and actually used is fundamental to answer questions related to the study of human technological evolution, as for instance human decision-making processes, as well as cultural and technological dynamics, including processes of innovation, transmission and loss (e.g. Eren et al., 2023; Mullen et al., 2023; Eren et al., 2022; Mika et al., 2022; Story et al., 2019; Lycett et al., 2016). Assessing function and use of Palaeolithic tools requires profound technological and morphological knowledge, as well as suitable analogies via experimental or ethnoarchaeological observations (Fig. 1). While ethnographical comparisons are of relevance, they do not provide a one-to-one interpretation of past human technologies (Binford, 1986). Often, tool morphology (affecting typology) is solely used as a basis for the functional interpretation of the different forms visible in the archaeological record. The limitations of this selective approach have been tackled by use-wear analyses, which directly focus on the identification and interpretation of the different types of traces left on the artefacts' surfaces. In addition, experiments are fundamental: besides being necessary to build a reference collection to which archaeological artefacts are compared to, they also provide an alternative method to test hypotheses and gather new information. Experiments can also be employed to answer questions related to tool functionality (i.e. the ability to perform one or more function(s); also: Was the tool used for something different than originally intended at the time of its production?). Aspects such as tool performance, durability, effectiveness and efficiency (definitions used here: see methods for more details) are crucial in relation to tool design, function and also actual use (Abrunhosa et al., 2019; Bebber et al., 2019; Key et al., 2018; Key and Lycett, 2014, 2018; Collins, 2008). Moreover, in the context of tool performance, a more profound understanding of resharpening and recycling behaviour can be gained. Despite the assumptions and interpretations based on technological and typological studies concerning tool function, these aspects can only be tested via experiments (Clarkson et al., 2015).

With this as a prerequisite, Middle Palaeolithic lithic industries including tools indicating processes of maintenance and long-term use offer a great potential for research addressing tool function and use. Hence, also the tool design seems to play a more important role, especially towards the Late Middle Palaeolithic when regional entities occur (e.g. Mousterian of Acheulian Traditions, Keilmessergruppen; (Ruebens, 2013). The appearance of specific tools in the lithic assemblages raise the question whether such tools display a certain, additional function, an increased functional performance or instead are the result of a cultural phenomenon.

Thus, the Late Middle Palaeolithic *Keilmesser* tool type (i.e. bifacially backed knives) has been selected as a case study due to the sophisticated morphology and the highly standardised tool design. The presence of *Keilmesser* became prominent in Central and Eastern European sites (Bosinski, 1967; Mania and Toepfer, 1973; Veil et al., 1994) between late OIS 5 until mid OIS 3. *Keilmesser* display a clear asymmetric shape with a triangular or wedge-shaped cross section (Jöris, 2012, 2006, Fig. 2). *Keilmesser* are mainly produced as core tools and, less commonly, from flakes (Jöris, 2001; Jöris and Uomini, 2019). The shape characteristics of the blank chosen for the manufacture of the *Keilmesser* appear integrated into the overall tool concept (Frick and Floss, 2017; Frick and Herkert, 2019; Jöris, 2006; Wiśniewski et al., 2020). The active edge of *Keilmesser*, opposite to a natural or roughly worked back, often appears to be bipartite leading to the interpretation of *Keilmesser* as bi- or multifunctional tools suitable for task such as cutting, carving, and scraping (Frick and Herkert, 2019; Golovanova et al., 2017; Jöris, 2001, 2006, 2012; Rots, 2009).

The increase in edge angle from the distal to the proximal part of the tool reinforces this interpretation (Schunk, 2022). Additionally, *Keilmesser* are commonly seen as tools with a long tool-life-history, reflecting several stages of resharpening and reworking (Frick, 2020; Frick

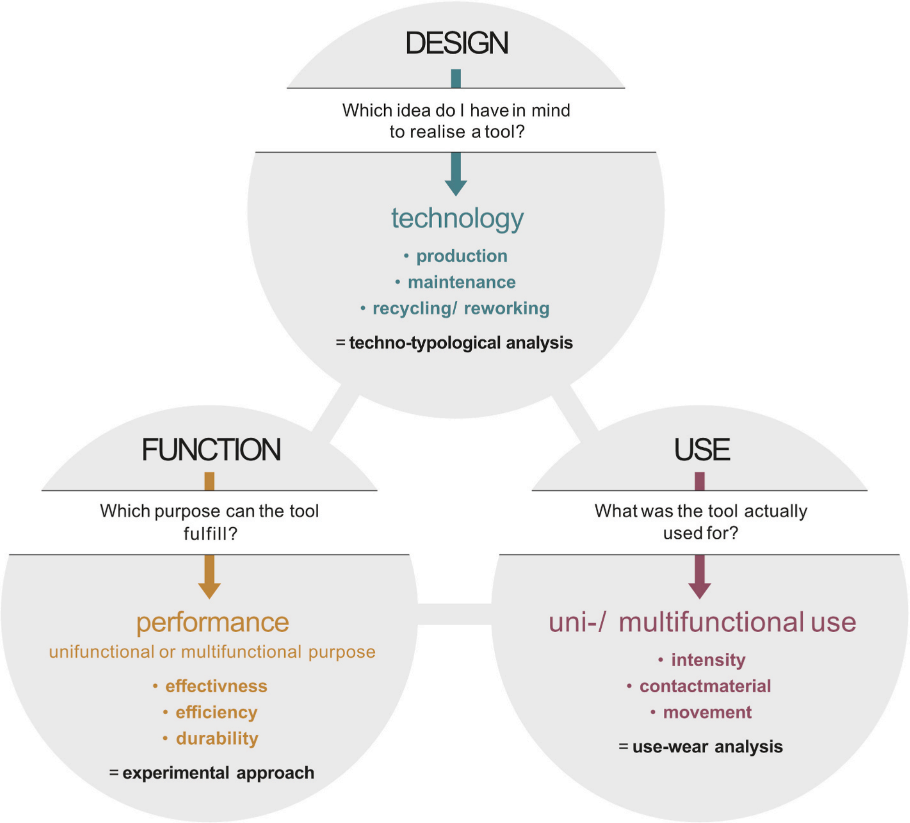

Fig. 1. Linkage between tool design, function, and use and other related terms. Illustration by Nicole Viehöver.

Fig. 2. Example of a *Keilmesser* from Buhlen (for more information about the artefact (ID BU-172) see Schunk, 2022).

et al., 2017; Frick and Herkert, 2019; Jöris, 2006; Jöris and Uomini, 2019; Pastoors, 2001). This is often indicated by an intensively retouched active edge with an emphasis on the distal part of the tool's edge. In most *Keilmesser* assemblages, flint/chert is the prevalent raw material (e.g. Sesselfelsgrotte, Lichtenberg, Pietraszyn 49a, Lichtenberg; see Delpiano and Uthmeier, 2020; Weiss, 2020; Wiśniewski et al., 2020); in others, however, local raw materials like silicified schist are predominant (e.g., Balver Höhle, Buhlen; see Schunk, 2022).

These morphological and technological aspects in *Keilmesser* provide the perfect basis to address the following research question: Why did Neanderthals employed the specific design of Late Middle Palaeolithic *Keilmesser* (choice of raw material and edge angle), and how does it affect tool functionality and tool performance? Moreover, the functionality of *Keilmesser* and the suitability of the edge design for certain tasks have only been hypothesised but have not been tested experimentally yet (except Schunk, 2022). To bridge this gap, a highly controlled, sequential *second-generation experiment* (see Marreiros et al., 2020 for more details on this approach) was conducted to investigate fundamental aspects concerning the function(s) of *Keilmesser*. Based on sensor monitoring (see methods section for more details) and the sequential character of the experiment, tool performance including effectiveness, efficiency, and durability have been analysed and evaluated in detail. This approach allowed addressing questions related to the suitability and performance of the tested edge angles for certain tasks (Schunk et al., 2023) and the influence of the raw materials involved. Together, these pieces of information help to understand the overall tool design of *Keilmesser* and Neanderthals' motives to produce such specific tools.

While the research here focusses on a tool type from the Late Middle Palaeolithic, the results have application across the Palaeolithic and can be applied to other tool types as well. Hence, the suggested approach holds the potential to change the way stone tools are studied and conclusions are drawn.

2. Materials and methods

2.1. Definitions

Tool performance, effectiveness, efficiency, and durability can be used as part of a holistic measure to assess artefact function (e.g. Schiffer and Skibo, 1997). Since definitions vary between disciplines, for the purpose of this study the following general definitions have been used: *Effectiveness* (synonym to efficacy) describes the relationship between a goal and its achievement. It therefore can also be described as a measure of effect. *Efficiency* defines the ratio between costs and benefits. In other words, it can be seen as an indicator of the consumed resources (e.g. energy, time, material) to achieve a goal. While effectiveness and efficiency are related concepts, effectiveness does not imply efficiency. *Durability* is a measure of function over use. The term describes the ability of a tool (or any other physical product) to retain function during use or throughout time in general. A decrease or loss of durability could be due to attrition from use or other factors that are not related to use such as age, natural decay, etc. Durability excludes processes of maintenance or repair. *Performance* combines all the other previously mentioned characteristics and implicates the use of a tool to process or work a given material through a specific movement. Performance describes how well a process or task was accomplished.

In the context of this study, this definition of performance can be identified as follows: The measurable features of the created cut (depth, width, material displacement) themselves are a proxy for *effectiveness*. *Efficiency* was measured as the ratio between the achieved goal, in this instance the created cut (depth) and either the applied force needed to perform the task (here constant) or the material loss of the sample (due to abrasion or breakage). *Durability* describes how often the task could be performed under the same condition before the sample was altered in a way that it could not function anymore as initially intended. Durability in this sense excludes an adjustment of the given parameters (e.g. increase in force) or tool maintenance.

Performance describes how well the sample was able to conduct the task and thus includes all prior listed measures.

The methods and materials described here only contain the workflow including key information, they are described and illustrated in detail in a protocol on protocol.io (dx.doi.org/10.17504/protocols.io.3byl4k-r6ovo5/v1).

2.2. Experimental design

To test the influence of raw material, edge angle and movement on tool performance, highly controlled, second-generation experiments (Marreiros et al., 2020) are most suitable. This way, individual variables can be eliminated, while the influence of other independent variables can be tested. Furthermore, second-generation experiments lead to reproducible, repeatable, and comparable results. To perform a highly controlled, second-generation experiment, a specific experimental design was chosen (Fig. 3) and will be detailed hereinafter.

2.3. Archaeological tools and their edge angles

To investigate tool performance of Late Middle Palaeolithic *Keilmesser,* artefacts (n = 157) from three different sites, namely Balver Höhle (Germany; n = 65 (Andree, 1928; Bahnschulte, 1940; Günther, 1964);), the Upper site of Buhlen (Germany; n = 83; (Bosinski, 1969; Bosinski and Kulick, 1973; Jöris, 2001) and Grotte de Ramioul (Belgium; n = 9; (Ulrix-Closset, 1975; Vandebosch, 1921) were selected (Fig. 4). The artefacts from these three sites are made of two raw materials: some are made of flint (n = 15), while the clear majority is made of silicified schist (n = 142).

Although flint is generally the more common raw material in *Keilmesser* assemblages, the three sites were selected for a reason: The mainly silicified schist inventories of Balver Höhle and Buhlen can be

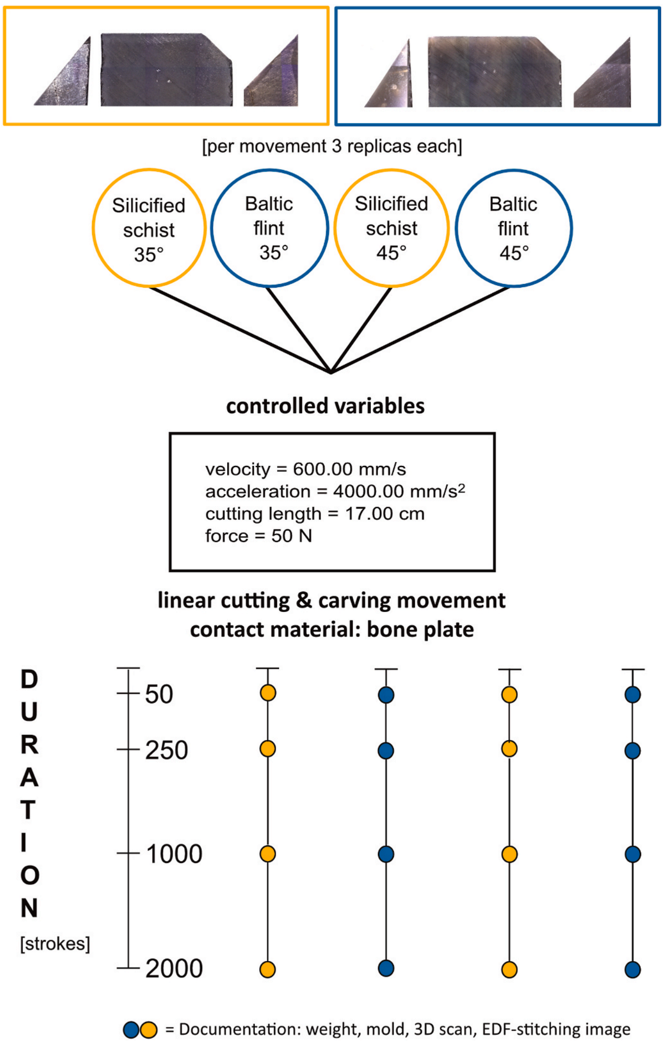

Fig. 3. Experimental design.

described as representing one of the largest *Keilmesser* assemblages in central Europe and are therefore especially suitable for the analysis of the artefact category itself. Ramioul however, is a small assemblage but the artefacts mirror the opposite situation – some are made of silicified schist, but the majority are flint artefacts.

To study the effect of the edge angle on tool functionality and performance, the angle was measured multiple times along the active edge of all *Keilmesser*. By doing so, it should be guaranteed that edge angle variations due to changes in the tool morphology are included in the average value. The measurements were not taken on the original artefacts but digitally on their 3D models (Schunk, 2023), using a smartScan-HE R8 structured-blue-light-scanner (Hexagon, Germany) with the software OptoCat. The field of view (FOV) S-150 used has a minimum point-to-point distance of 33 μm. Identical settings were used for all artefacts. Approximately 20–27 scans per tool were needed to create a complete model. After scanning, the resulting STL file was imported into GOM Inspect, a free software for 3D measurement data to edit the model. For calculating the edge angle values of the artefacts' active edges, the '2-lines' procedure (2 mm length of the line) of the 3D-EdgeAngle method was applied (see Schunk et al., 2023 for more details on the applied method). The measurements were taken at 10 mm distance to the intersection of the dorsal and ventral surface (active edge). Due to the bipartite edge morphology of *Keilmesser*, two mean arithmetic average values per active edge were calculated. The first average was based on the measurements from the sections two to four and the second average on the sections five to nine (https://doi.org/10.5281/zenodo.7564605; Fig. 5). Following this scheme for all analysed *Keilmesser*, 35° for the distal and 45° for the proximal part of the tools were calculated.

2.4. *Experimental sample preparation*

To eliminate confounding factors in the experimental design and tackle independent variables individually, the samples for the experiment were standardised (Marreiros et al., 2020; Eren et al., 2016). The standard samples are machine-cut to a predefined shape to isolate the effects of raw material and edge angle. Baltic flint as well as silicified schist (in the experimental context: lydite) served as raw materials, reflecting the raw material variability of the sampled *Keilmesser*. Blocks of silicified schist were collected near the small streams in the surrounding areas of the two sites Buhlen and Balver Höhle Eren et al., n.d.. Raw-material intra-variability was controlled by the use of as few raw material nodules/blocks as possible. Using a lapidary slab saw, these were first cut into slices of 10 mm thickness, and then further into size-defined blank of 30 mm standard width and varying length: In this way, the slices were cut into as many blanks as possible to reduce raw material variation. In the next step, one end of each blank was unifacially cut along the 30 mm width with a diamond band saw to produce an edge with a given edge angle (35° and 45°, mimicking edge angle data of the archaeological artefacts, see above). The leading side of the active edge was modified by adding a 45° chamfer (transitional edge, bevel, between two faces of an object; here used on samples for cutting only), reducing the length of the edge, accordingly. The chamfered edge allowed for dispersal of the acting forces when critical interaction with the contact material was initiated. Purpose of this modification was to spread the applied force across a larger surface area, therefore minimising the risk of immediate or catastrophic fracture. This cut was also executed with the diamond band saw. In total, 24 standardised samples have been prepared: 12 of these samples were produced out of flint nodules and the other 12 from silicified schist blocks. Each set was split in two groups with six samples each: 35° and 45° edge angles. Due to the high degree of standardisation, the experiment could be conducted with a comparably small sample size without venturing validity.

Due to the accumulation of residues from the contact material, and to allow a clear analysis, all samples were cleaned after cutting. First the samples were rinsed with tap water and then individually packed in a plastic bag filled with ~100 ml of distilled water and a non-ionic detergent. The sample bags were placed in a preheated ultrasonic bath for 10 min at 45 °C and 100 kHz. Subsequently, the detergent solution was exchanged with tap water. This was repeated two more times. In a final step, the sample bags were filled with ~100 ml distilled water to rinse off any detergent residue adsorbed onto the sample surface. Samples were air dried with the aid of an oil-free compressor.

2.5. *Hardness measurements*

The hardness of the two involved raw materials was measured to evaluate the possible influence of the raw material itself on tool morphology (e.g. knappability; see Magnani et al., 2014) and also to predict potential efficiency and durability during the use-life of the tool (Key et al., 2020a; Key et al., 2020b; Braun et al., 2009). These data are also relevant to gain internal experimental validity.

The hardness was measured on the experimental sample blanks with a Leeb rebound hardness tester (Proceq Equotip 550, Leeb C probe). Here, an impact body, a small ball, is dropped with a defined energy onto the surface of the sample. The velocity of the impact body before and after the impact is measured. Based on these measurements, the ratio between the impact velocity and rebound velocity defines the Leeb hardness (in HL; here in HLC = Leeb rebound hardness measured with probe C). The advantage of the hardness test conducted with the Leeb rebound is that the measurements can be carried out rapidly and are

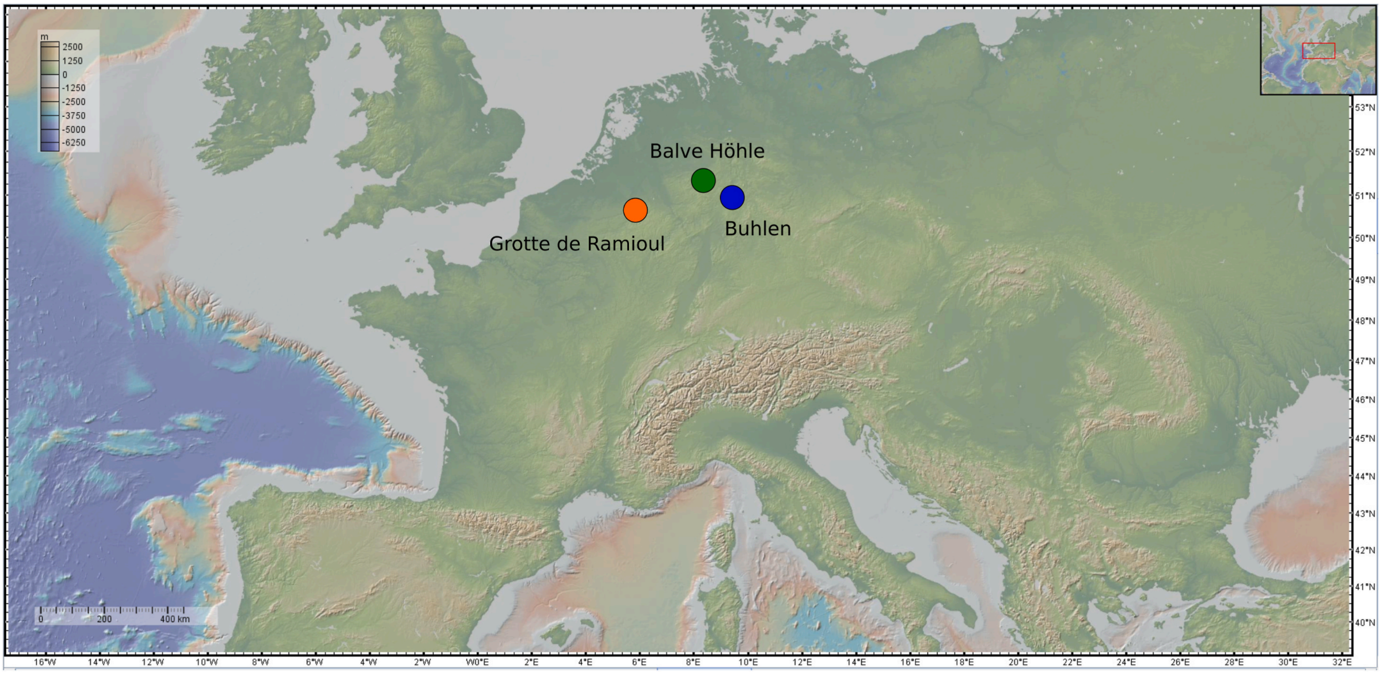

Fig. 4. Location of the three Middle Palaeolithic sites mentioned in the text: Buhlen (blue dot), Balver Höhle (green dot) and Ramioul (orange dot). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

virtually non-destructive (hard rock). The disadvantages are the required flat surface and mandatory minimum size and mass of the object. While the standardised samples provide ideal flat surfaces, they do not fulfil the minimum size/mass requirement. Thus, the samples had to be placed on a stable supporting base (here a flat, polished granite slab of about 20 kg) and connected with an additional coupling paste. To insure and test intra-variability in each sample, ten measurements per sample were taken. The number of measurements not only ensures the inclusion of the raw material variability within the result but also identifies potential outliers (i.e. internal fractures, mineral inclusions etc.).

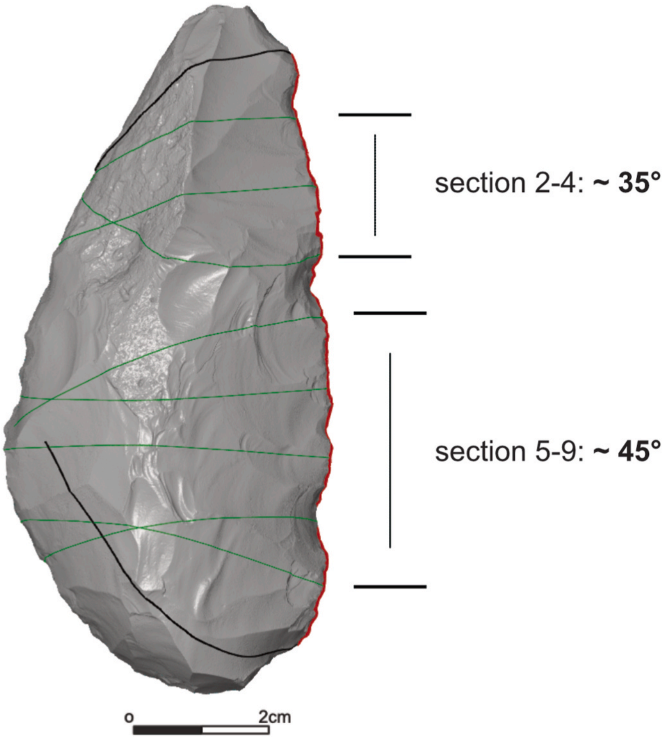

Fig. 5. Calculation of the edge angles, illustrated here on a 3D model of a *Keilmesser* from Ramioul. The perpendicular lines are the sections. The sections used to calculate the edge angles are shown in green and the ones excluded for the calculation in black. The edge angle values have been calculated with the ‘2-lines’ procedure following Schunk et al., 2023. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.6. *Sample coordinate system*

A coordinate system was created directly on the sample surface (Calandra et al., 2019). For this, three ceramic beads 100–200 μm diameter were adhered with epoxy resin on the dorsal and ventral side of the tool, respectively. The coordinate system was not applied for the purpose of this study but for potential, subsequent use-wear analysis to enable analysis of the exact same surface throughout the sequential experiment.

2.7. *Experimental setup*

The experimental setup of the conducted second-generation experiments involved a modular mechanical device, SMARTTESTER®, which allows for repeatable, precise, and sensor-monitored movements (Calandra et al., 2020). The setup with linear drives was used to perform two different movements: unidirectional cutting and carving (Figs. 6 and 7). Artificial bone-like polyurethane plates served as contact material (Schunk et al., 2023). The cutting and carving length was 17 cm in both cases. Three samples per raw material and per edge angle were tested for each movement (i.e. n = 12 for each movement). The experiment was built up as a sequential experiment (material removal at a relatively large angle of attack contrary to an abrasive scraping movement at a lower angle of attack; Fig. 3). Four cycles defined by number of strokes were executed. The first cycle included the strokes 1 to 50, the second strokes 51–250, the third strokes 251–1000 and the final cycle strokes

Fig. 6. Standard sample (here FLT8-2) used for cutting movements clamped into the Inotec SMARTTESTER ® sample holder. The edge of the sample presents a 90° angle (angle of attack) to the contact material (artificial bone plate).

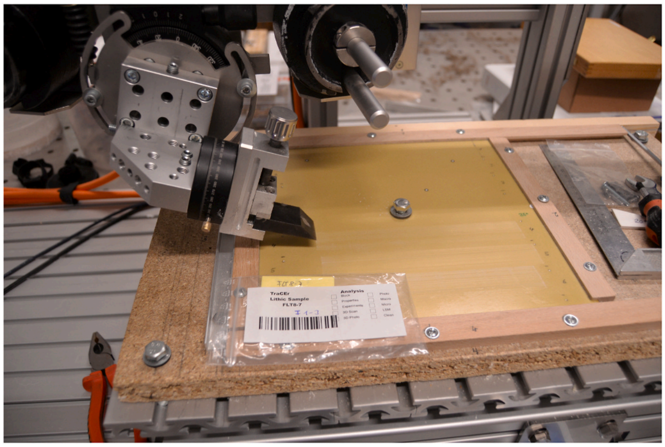

Fig. 7. Standard sample (here FLT8-7) used for carving movements clamped into the Inotec SMARTTESTER ® sample holder. The flat surface of the sample constitutes a 20° angle (angle of attack) with the contact material (artificial bone plate).

1001–2000. Some parameters were kept constant during the experiment, while others were measured by sensors only. The peak velocity with 600.00 mm/s and the acceleration with 4000.00 mm/s^2 belonged to the predetermined factors. The force of 5 kg m/s^2 was also defined by the mass of the dead weights mounted onto the sample holder. In total five sensors were activated during the entire duration of the experiment. Three sensors monitored the predetermined factors velocity, acceleration and force as measured by the drive's current or an additional sensor as in case of the force. The other two sensors recorded the penetration depth in mm and the friction in N. The sampling rate was in a frequency of 10 Hz per sensor. The samples were clamped straight into the sample holder in a 90° angle of attack between sample and contact material for the cutting movement (Fig. 6), whereas the samples were adjusted differently for the carving movement (Fig. 7). With the plane-parallel, rectangular end, the samples were clamped into the sample holder in a 20° angle towards the contact material (angle of attack). Consequently, the carving movement was performed in a flat and unidirectional movement. The sample holder guaranteed that the samples were always clamped and orientated in an identical way. A program (template) per sample was created to ensure the constancy of the programmed settings as for instance the position of the sample on the x-, y- and z-axes.

2.8. Documentation

All samples were documented before and after each cycle to note how and at which point in the course of the sequential experiment the samples have changed. The documentation followed a protocol involving four steps: The samples were weighed to measure material loss due to edge damage. To obtain a robust value, each sample was measured three times. The surfaces of the samples were scanned with a smartScan-HE R8 featuring the S-150 FOV. All scans were taken at identical settings. The scans were taken to measure the volume and to localise, visualise and compare potential material loss along the samples' cutting edges. In addition, the 3D models also served for the edge angle calculation (as described for the archaeological artefacts). Calculating the edge angle of the experimental samples allowed for the quantification of the change in edge angle due to use.

Three of the four surfaces per sample (one lateral and the two main surfaces) were documented with the Smartzoom 5 digital microscope (Carl Zeiss Microscopy GmbH). The PlanApo D 1.6×/0.10 objective was used to create EDF-stitched images, which served as visual documentation of the samples' surfaces. Moulds (Provil® novo, Kulzer GmbH) were taken from the two cutting surfaces covering the edge for possible future use-wear analyses.

In a nearly identical way to the samples, 3D models of the contact material (artificial bone plates) were generated before and after the experiment. Here, the larger object size necessitated a different FOV (M-450, point-to-point distance = 108 μm) to scan the objects entirely.

After the experiment, the contact material documentation was augmented with a Sensofar S wide (Sensofar Metrology, Spain), a 3D optical metrology system. Based on the data acquired with the S wide and processed in ConfoMap (a derivative of MountainsMap Imaging Topography; https://doi.org/10.5281/zenodo.7565158), the depth and the width of the cuts and scratches were quantified (https://doi.org/10.5281/zenodo.7564605). Together with the decrease in material volume, this allowed for a broad evaluation of the contact material.

2.9. Data analysis

To examine tool effectiveness, efficiency, and durability, the samples were reviewed in terms of their morphological changes: location, type and quantity of material loss, fractures, and retouch, as well as changes in the edge angle were documented. To begin with, the 3D models were inspected visually. GOM Inspect allows for a comparison of 3D meshes. Based on a colour scale, the differences between two 3D meshes can be visually highlighted but also quantified.

Furthermore, the sensor data recorded throughout the experiments with the SMARTTESTER® were analysed. Three of the five sensors were predetermined factors: velocity, acceleration and force. This means, the sensor data act as a quality control mechanism - the analysis of these sensor data shows how controlled the experiment indeed was in terms of repeatability and accuracy. The other two sensors recorded penetration depth and friction, although friction was not considered here. The penetration depth is of interest because it is one measure of tool efficiency and performance. During the experiment, sensor data were saved per strokes and per sensor individually as TXT files. By means of R (version 4.0.2 through RStudio version 1.3.1073, RStudio Inc., Boston, USA) the data generated throughout the experiment were statistically analysed and plotted. Reports of the analysis created with knitr (v. 1.33; (Xie, 2021) and rmarkdown (v. 2.9.1; (Allaire et al., 2021) in HTLM format are available on Zenodo (https://doi.org/10.5281/zenodo.7564605). The derived data, the scripts and the RStudio project can also be found in the same repository. In this way, outliers due to erroneous recordings could be detected. The SMARTTESTER® software caused in occasional instances recordings for single strokes that were outside the possible moving radius of the mechanical device. Thus, these clearly identifiable outliers were excluded from the data analysis. The statistical analysis (descriptive statistic) focused on calculating the relative penetration depth reached per sample, i.e. by subtracting the initial depth from the maximal depth. The relative penetration depth can be used as a measure of effectiveness.

Based on the recorded and measured data, tool performance (resulting from effectiveness, efficiency, and durability) can be evaluated. A measure of effectiveness was based on the characteristics of the cuts/scratches. Characteristics were defined by the regularity, the uniformity and the width of the cuts and scratches. Additionally, the material displacement (penetration depth) was assessed to estimate effectiveness. Since the force was constant throughout the experiment, the ratio between the achieved penetration depth and the material loss of the sample was a determinant for efficiency. The retention of function over time without tool maintenance or increase of force was relevant for assessing durability. The overall tool performance was evaluated and compared between samples based on the combination of effectiveness, efficiency, and durability.

3. Results

3.1. Raw material hardness

Based on the tested samples, flint has a higher HLC value than silicified schist (Fig. 8). The arithmetic mean for the flint is 958.9 HLC while the one from silicified schist is 909.9 HLC. The variability in HLC for silicified schist is considerably higher compared to the flint: the flint hardness ranges from 944.1 HLC to 965.4 HLC, while the range for the silicified schist is 785.9–951.5 HLC. The likely reason for that can be seen in the structure of the silicified schist. Silicified schist is a finely layered (schistose), brittle sedimentary rock that fractures conchoidally (Floss, 1994). The raw material is also characterised by small internal cracks. When the impact body of the Leeb rebound hardness test hits a less compact area of the surface (e.g. due to a crack underneath the surface), rebound energy is dissipated and the Leeb hardness value will be smaller. This might be more frequently the case for silicified schist than for flint.

3.2. Durability: function over time

All n = 24 standard samples completed the four cycles totalling 2000 strokes each. Thus, none of the samples completely lost their function over time although the tool edges changed. Durability is therefore equal for all tested standard samples.

3.3. Effectiveness: characteristics of the cuts/scratches and penetration depth

The characteristics of the cuts and scratches produced on the bone plates were used to evaluate tool effectiveness. The cuts produced with the flint samples visually differ slightly from the ones produced with the silicified schist samples (Fig. 9). After a comparison of the twelve cuts, the flint cuts appear as thin lines, whereas the silicified schist cuts seem wider and less regular, in particular the cuts produced with the 35° silicified schist samples. These observations could be verified with the width measurements based on the S wide data (Fig. 10).

For most of the traces left on the bone plates after carving, no major difference is noticeable between those caused by flint or by silicified schist samples. On average, however, the silicified schist samples penetrated slightly deeper. All scratches produced during carving have something in common: they have a more or less pronounced undulating pattern. This pattern is caused by a mechanical phenomenon involving friction called “stick-slip” that occurs when one object/surface slides over a second object/surface and is subject to experimental parameters such as pressing force and relative velocity (Daams and Herting, 2012; Wen and Huang, 2017). However, the impact of this stick-slip effect is constant throughout the experiment and thus is not affecting the results.

Penetration depth data was constantly recorded with the depth sensor and the depth of each performed stroke can be analysed individually (Figs. 11and12). This allows for a clear understanding of effectiveness and efficiency based on the calculated relative depth per sample (i.e. difference in depth between each value and the starting value) and measured depth after 2000 strokes on the bone plates. In general, the maximum penetration depth reached during carving was comparable between samples with a 35° and a 45° edge (Fig. 10). One exception is the trace left by the flint sample FLT8-10. This sample achieved a comparatively high penetration depth (1648.3 μm; see **Appendix_A**). During the first cycle, the sample was not held firmly in the sample holder and was able to move slightly. Thus, the active edge of the sample and the bone plate were not exactly parallel to each other. During the second cycle, this problem was rectified, and the sample could not move anymore in the sample holder. Due to the sample misalignment of the first cycle, the surface of the bone plates (the scratch, i.e. the carving track) presented more resistance and friction in the subsequent cycle which in turn caused more alteration on the tool (**Appendix_B**). The sample FLT8-10 therefore has to be treated as an outlier. For cutting, the 35° samples achieved a comparatively higher

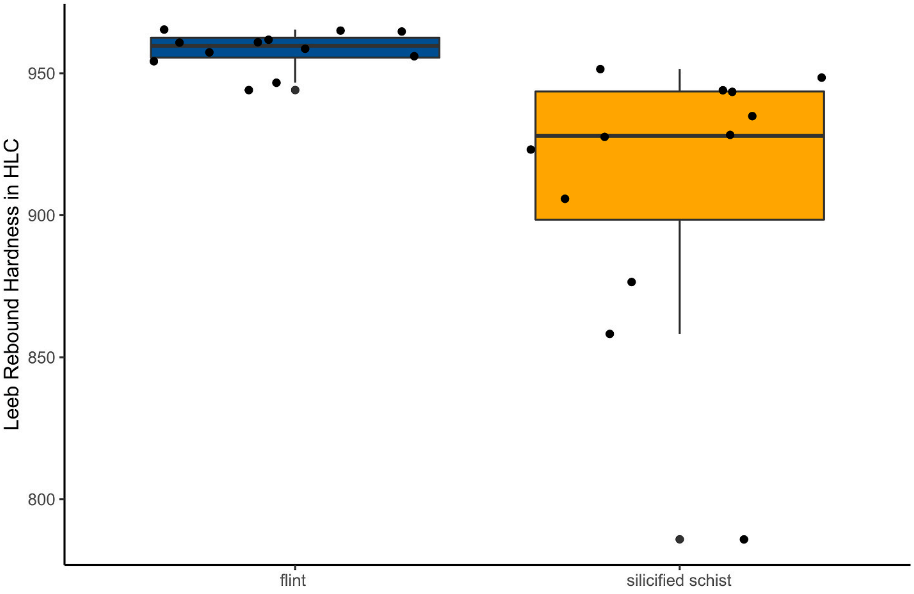

Fig. 8. Leeb Rebound Hardness in HLC measured for the two raw materials flint and silicified schist.

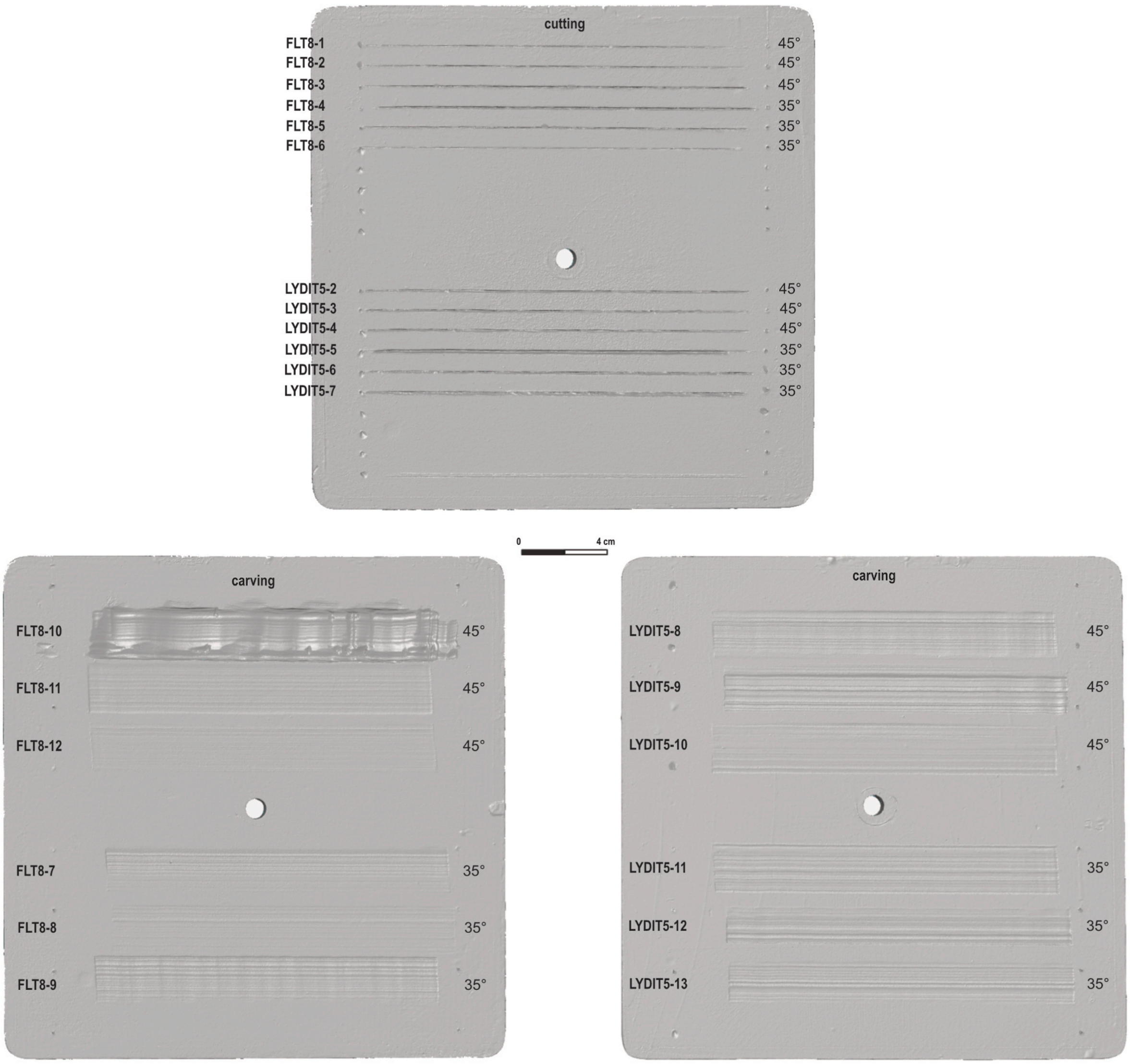

Fig. 9. Images of the 3D models of the artificial bone plates used during the experiment after 2000 strokes. The upper scan shows the plate used for cutting, the lower left 3D model the plate used for carving with flint samples. The lower right image illustrates the 3D model of the bone plate used for carving with silicified schist samples.

penetration depth than the 45° samples (Fig. 10). More importantly, the depth data revealed a difference in penetration depth related to the raw material of the standard samples. The silicified schist samples tended to penetrate deeper into the contact material than the flint samples throughout the course of the experiment. Consequently, the biggest penetration depth was reached with a silicified schist sample (LYDIT5-7).

3.4. *Efficiency: volume, weight, and edge angle change*

Efficiency was measured by the ratio between the achieved relative penetration depth of the cut/scratch (goal) and the material loss of the sample. While the documentation of the penetration depth was addressed prior, the volume of each standard sample and the corresponding volume loss throughout the experiment was calculated based on 3D models. On average, silicified schist samples experience a volume loss of 0.43% (~36.6 mm^3; 1.70–205.8 mm^3) (Fig. 13 and Table 1, note the values in the table separate between the samples used for the scraping and cutting movement). Flint samples display a slightly higher average volume loss of 0.51 % (~50.36 mm^3, 2.70–150.7 mm^3). While the 35° flint samples show less volume loss than the 35° silicified schist samples for cutting as well as carving, the opposite is true for the 45° samples (even when excluding FLT8-10 as an outlier). These values are mirrored by the weight measurements (weight loss silicified schist 35°: 0.17 g, 45°: 0.02; flint 35°: 0.01 g, 45°: 0.12 g; Fig. 13). Although the silicified schist samples fractured more and thus experienced more frequent damage, on average, the material loss is in most cases only minor (Fig. 14). However, the silicified schist samples appear more fragile and tiny particles break away (Fig. 15), which is reflected in the edge angle measurements. By contrast, the flint samples display more often material loss comparable to micro edge scarring or retouch but not fractures. The retouch-like material loss might be more invasive towards the surface (like thinning/shaping through retouch) and could explain the bigger loss in volume and weight. Moreover, this type of material loss might not change the edge angle in a way that the breaking particles do on the silicified schist.

Based on the 3D scans, the edge angles of the standard samples have been calculated. To illustrate the edge angle values and changes, one mean value per sample was calculated ('3-point' procedure; mean value of section 2 to 8 and distance 3 to 6; see Schunk et al., 2023; Fig. 16). Thereby, the correlation of the resulting data with the raw material of the samples as well as the performed task is of interest. In cutting, the

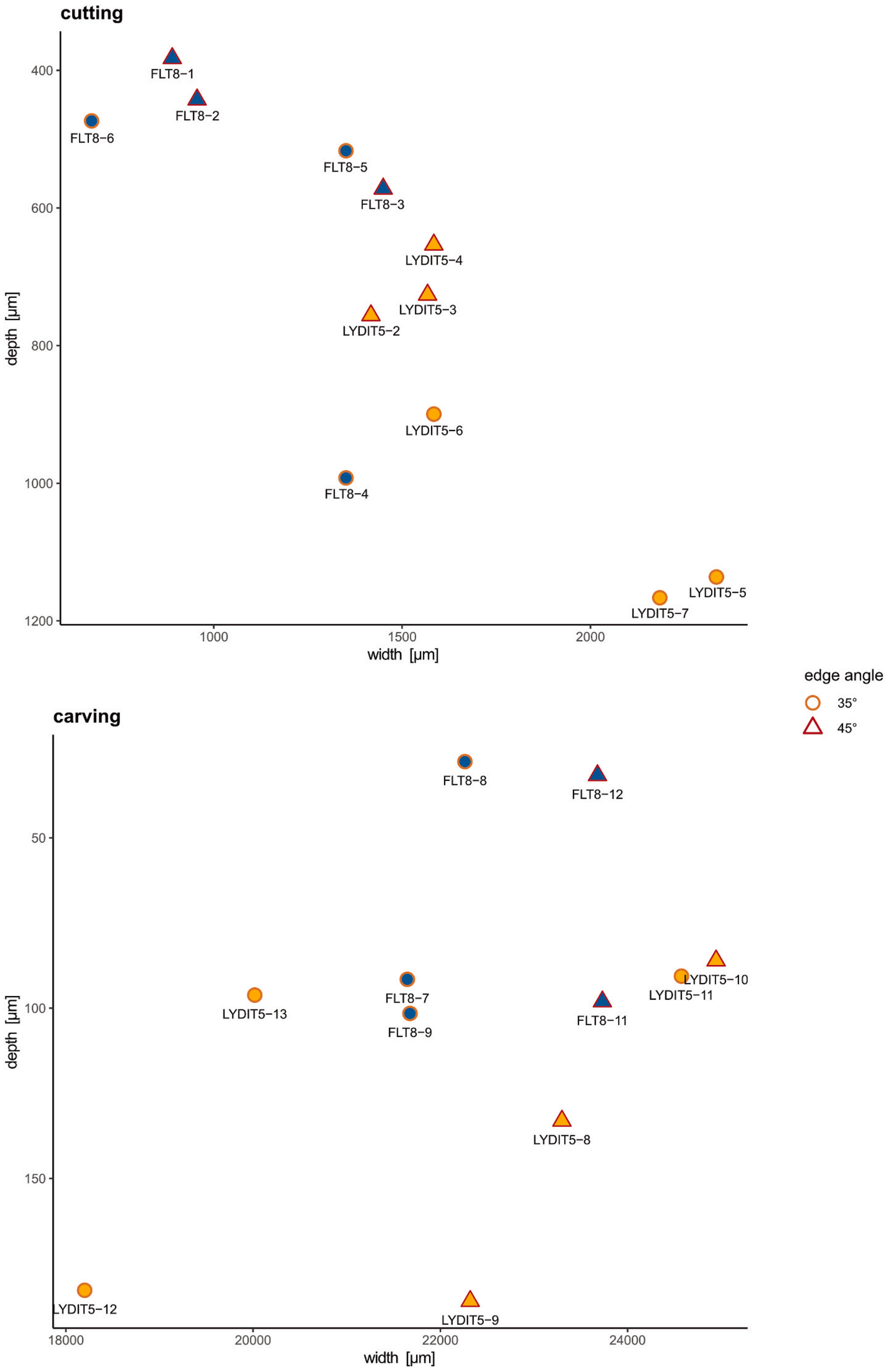

Fig. 10. Measurements of the cuts in the contact material (top) produced during the cutting movements and the scratches produced during the carving movement (bottom), each after 2000 strokes. The plot shows the maximum width and maximum depth of each cut/scratch. The y-axes are reversed so that deeper cuts/scratches are towards the bottom of the plots. The data point from sample FLT8-10 (outlier) was excluded from the plot. A plot including all samples is available as supplementary data (Appendix_A; or on Zenodo https://doi.org/10.5281/zenodo.7564605).

results differ depending on the initial edge angle of the samples. While the shift in edge angle is only minor for the 45° flint (<2°) and silicified schist (2x < 2°, 1x ~5°) standard samples, it is different for the 35° samples. The flint samples still display only negligible changes. For the three silicified schist samples with a 35° edge angle, a decrease in acuteness is clearly visible and illustrated by continuous material loss throughout the experiment. This is reflected by an edge angle change of about 5° for two of the samples. The third sample (LYDIT5-5) changed from 35° to approximate >100° due to fracture in the third cycle (between 250 and 1000 strokes). Remarkably, the six samples (flint and silicified schist) with a 35° used for carving did not change appreciably. The same counts for a majority of the 45° samples used for carving. Nevertheless, two samples, one flint (FLT8-10) and one silicified schist sample (LYDIT5-9) experienced some alteration after 50 strokes, leading in both cases to a slow, but continuous increase in edge angle.

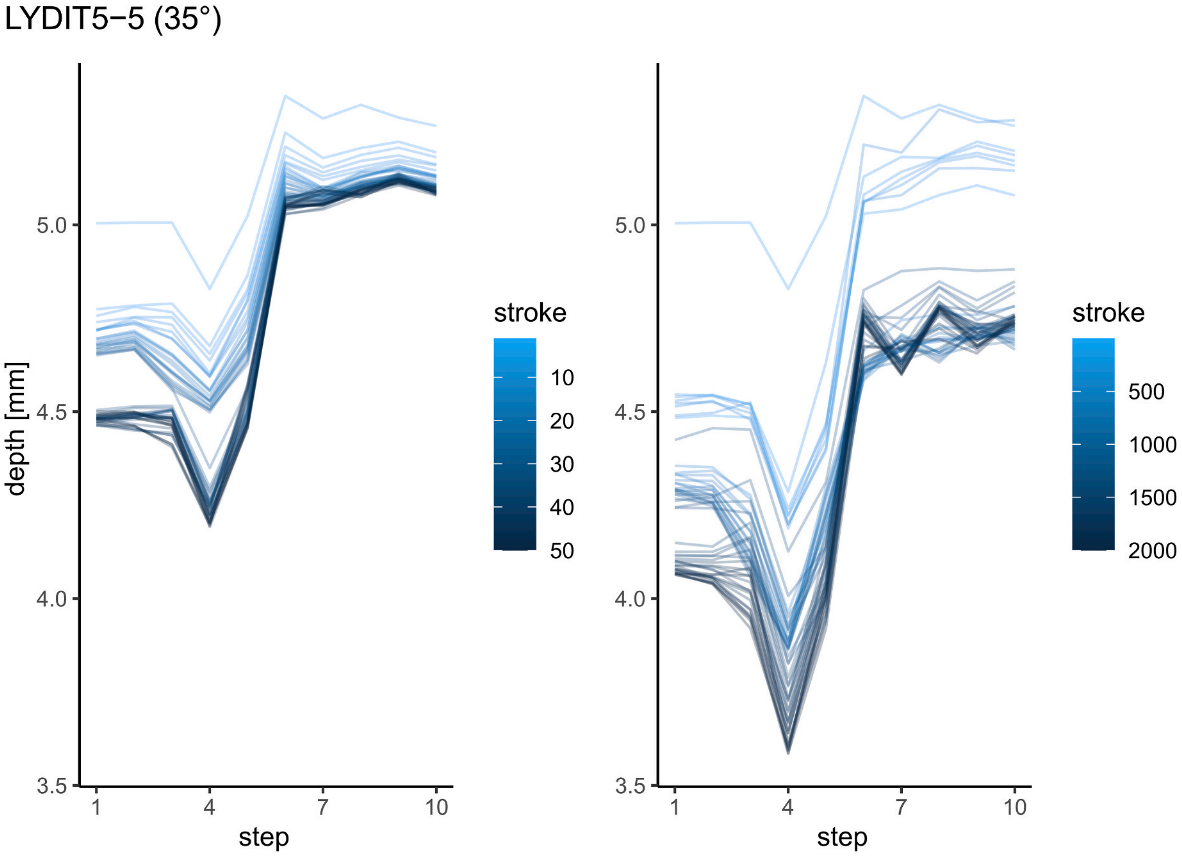

Fig. 11. Sensor-recorded penetration depth achieved with a cutting movement performed by the SMARTTESTER®. Exemplarily presented here are the recording of sample LYDIT5-5. The left graph shows each cutting stroke within the first cycle (1–50 strokes). The right graph shows each 40th cutting stoke across all cycles (1–2000 strokes). The darker the colour, the longer the use duration (number of strokes). Steps on the x-axis indicate the measuring frequency within the 17 cm long cutting movement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

Understanding lithic technology is key to gaining knowledge about early hominin behaviour because it allows insight into cultural and technological dynamics and the human decision-making processes behind these dynamics. Here, *Keilmesser* were chosen as a tool type defined by the interplay of their specific standardised technological and typological characteristics. Specimen in flint and silicified schist were selected to study tool design and its effect on their potential functionalities. To test selected design features against archaeological data, standard samples made of flint and silicified schist have been used in a highly controlled and mechanical experimental setup to perform unidirectional cutting and carving movements. By doing so, not only functionality could be tested, but also the effect of the edge angle and the raw material on tool performance could be investigated for each type of movement (see similar approaches by Key et al., 2020b; Key, 2016; Key and Lycett, 2014).

Based on the conducted measurements, flint is harder than silicified schist. Silicified schist appears as the more brittle and fragile raw material, most likely a result of schistosity planes, banding and natural fault lines or cracks. In comparison to flint, it is also characterised by lower hardness readings on the Leeb C scale. Not only due to the lower hardness, but also due to the schistosity planes, the banding or the natural cracks, silicified schist appears as the more brittle and fragile raw material. However, in the studied archaeological assemblages, silicified schist represents the majority of the stone tools. One reason for that is unequivocally the local occurrence of the raw material near the sites (Andree, 1928; Günther, 1988; Jöris, 2001). The conducted experiment hints at another potential reason that might have played a role in human decision-making. The raw material properties, as studies on Pleistocene stone tools have long argued, not only influence tool morphology but also crucially impact tool performance during use (Delgado-Raack et al., 2009; Eren et al., 2014; Key et al., 2020b; Marreiros et al., 2020; Nonaka et al., 2010; Odell, 1981; Schunk, 2022). While experimental studies concerning for instance knapping choices address raw material properties (e.g. Dogandžić et al., 2020), studies focusing on tool design (edge morphology, edge angle etc.) or tool use often neglected this topic (Evans et al., 2014). Effects of use on the analysed standard samples demonstrate a dependency on the raw material. Concerning the more acute edge angle (35°), the damage on flint samples is less noticeable compared to that on the silicified schist samples and the breaking pattern is visually often similar to retouch. Thus, the edge angle of the flint samples was less frequently affected. By contrast, the silicified schist samples experienced alteration. Especially during cutting, samples with acute edge angles were more often affected by microfracturing and small breakages. These alterations do affect the tool performance to some extent, but rarely tool function (all 24 samples completed the 2000 strokes). In general, the 10° difference between the two sets of standard samples (35° and 45°) seems to affect durability when used to perform cutting actions. Although none of the samples were altered or damaged in a way that it could not function anymore (all 24 samples completed the 2000 strokes), the 35° samples exhibit more damage in the form of small fractures and material loss. On the other hand, in the carving experiment, more alteration could be documented on the 45° samples, irrespectively of the raw material.

Despite the measured lower hardness and the documented alteration of the silicified schist samples, these samples did perform better in most cases, as measured by the achieved penetration depth per tool (material

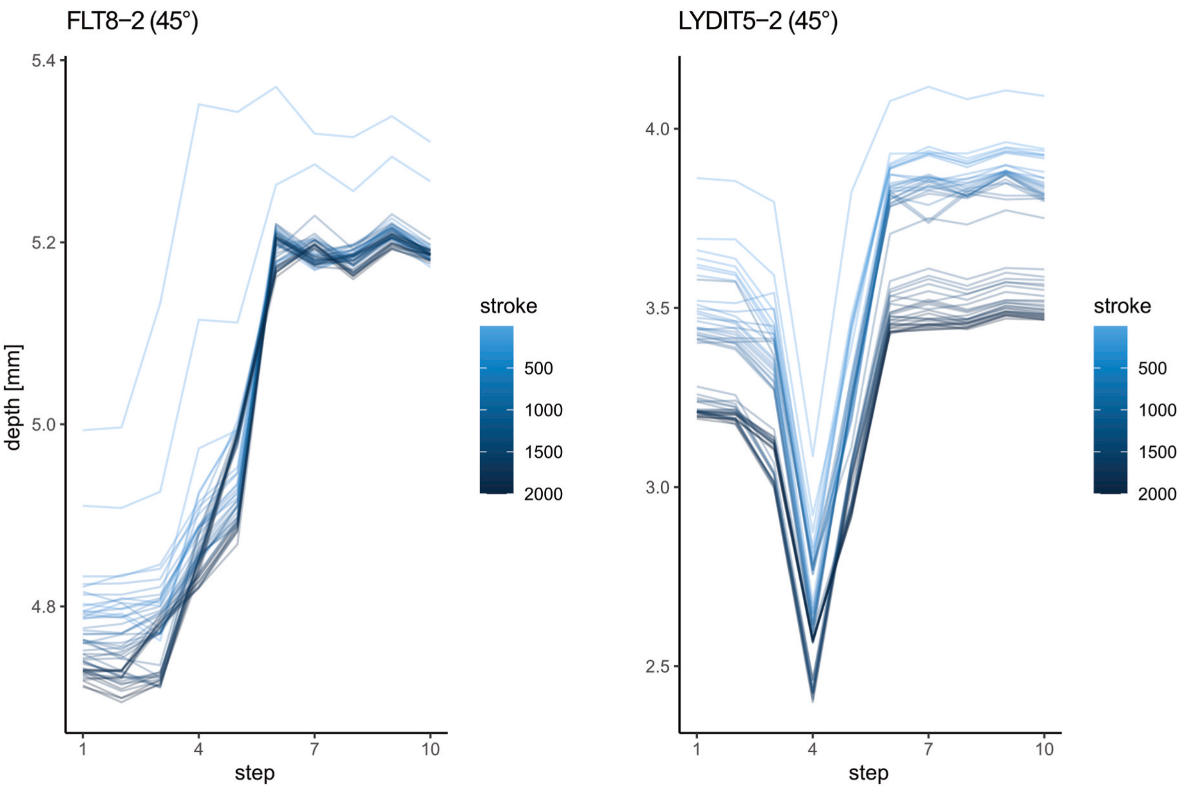

Fig. 12. Sensor-recorded penetration depth achieved harnessing the cutting movement of the SMARTTESTER®. On the left is the recording of the sample FLT8-2 and on the right the recording of the sample LYDIT5-2. For details about the graph see Fig. 13.

displacement). Interestingly, the data suggests that the raw material affects tool performance and possibly human tool recycling processes, too. An important criteria thereby is the tool sharpness. Sharpness has rarely been addressed on Palaeolithic studies (but see Key et al., 2022, 2018; Macdonald et al., 2022, 2020; Stemp et al., 2019), even though being a key geometric feature on stone tool performance. One reason for that is likely to be found in the difficulty to measure sharpness. Although sharpness might correlate with the edge angle, sharpness cannot be directly evaluated based on the edge angle only. Sharpness seems to be more relevant for initiating a movement (i.e. a cut), while the edge angle is more important for the overall performance (Key et al., 2022). Studies focusing on the sharpness of metal knives point out the influence that sharpness has on grip force, durability (McGorry et al., 2003), the contact material and the force needed to perform a task (Schuldt et al., 2013, 2016). According to Key, Fish and Eren (Key et al., 2018), sharpness can be tested by the measurement of force, material displacement and work (energy required to perform a task) combined with the tool performance. Two measures might be relevant to address sharpness: tool edge angle as well as tip radius/curvature (Atkins, 2009; Key et al., 2022; McCarthy et al., 2010; Schuldt et al., 2013; Stemp et al., 2019). These thoughts are important when considering the results of the experiment. An observation made during the experiment is that the silicified schist samples experienced more microfracturing, which occurred when the contact material and the samples were in contact. Thus, in turn, is likely to have caused constant ‘self-resharpening’. The flint samples, however, were not altered significantly. It is assumed that the flint samples become blunt through abrasion during use. This would explain why the silicified schist samples were more efficient in the sense of material removal from the bone plate, as they were continually ‘resharpened’ rather than worn down. The reduced efficiency due to early stage blunting can be counteracted by increasing force. While force is clearly a parameter influencing tool performance, for the conducted experiment, force could be excluded as an influencing factor, because it was constantly applied by the 5 kg dead weight throughout the experiment. To achieve the same penetration depth with flint as with silicified schist, the application of more force (i.e. an increase in dead weight) would have been needed. Due to its more pronounced fragility, silicified schist seems to overcome the effect of early blunting by the loss of small fragments, which keeps the edge sharp to a certain degree. Experiments on edge blunting with a variety of chert samples demonstrated that already one abrasive cutting stroke (indentation cutting on industrially produced flexible plastic) has to be compensated by a 38% increase in force and 70% increase in work to achieve identical performance results (Key et al., 2018; Key, 2016). These observations are supported in this study by the analysis of the sensor-recorded penetration depth. Here, details reveal differences between the data obtained with the silicified schist and the flint samples. The samples FLT8-2 and LYDIT5-2 can be compared as representative examples (Fig. 12). Both have 45° edge angles and were used for cutting. The flint sample shows a continuous increase of the penetration depth during the first 100, maximum 150 strokes. After that, the increase appears only minimal. The silicified schist sample, however, also displays a rapid increase in penetration depth from the first stroke onwards, but the increase seems to occur stepwise. Whenever the material displacement (contact material) during the cutting seems only negligible, a few strokes later, the sample penetrated deeper again. This observation points to a likely correlation between the documented microfracturing of the silicified schist samples and the inherent ‘self-resharpening’ properties of the raw material through microfracturing.

Although second-generation experiments reveal fundamental mechanics by testing the effect of individual variables, they also have their limitations. They contribute with crucial insights on understanding major aspects of past lithic technologies, however, second-generation experiments do not seek to resolve overarching archaeological research questions per se; instead, they are focused on fundamental, mechanistic aspects. This often concerns uniform principles, for instance physical principles, operating uniformly across space and time (Eren et al., 2016; Lin et al., 2018). The identification of patterns, processes

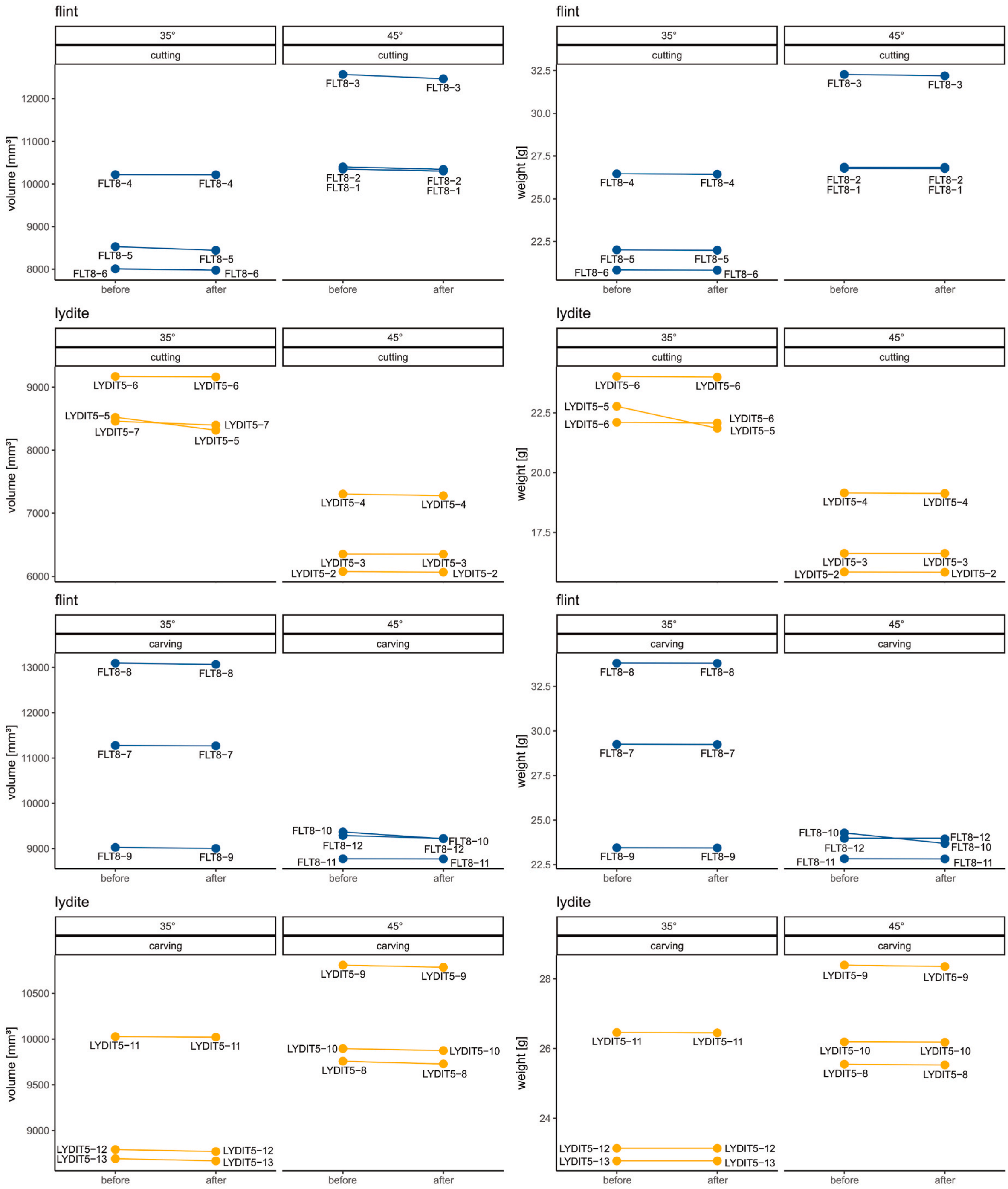

Fig. 13. Volume and weight changes of all 24 samples involved in the experiment from their unused state (before) to after 2000 strokes. Note that the initial volume and weight values deviate due to the non-standardised sample length.

and the test of key properties should be the aim of these experiments. A fundamental factor of the mechanical and tribological processes involved in tool use is the contact material (Marreiros et al., 2023). It is known that different contact materials correlate with diagnostic use damage on the artefacts' edge and surface. Therefore, in this approach, the use of contact materials with defined and standardised physical properties is crucial.

Instead of centring on the impact of various contact materials on tool performance and design, which would involve the use of diverse materials such as wood or bone, our study delves into the relationship between artefact edge design and tool performance and use. Consequently, the experimental design employed a standard contact material to ensure no influence by inhomogeneities or compositional variability on the ultimate results.

Performing a second-generation experiment means testing the influence of individual factors within a complex system to test their effect-causation with the measured variables within the experiment. The obtained results are thus only valid within the same experimental framework. This means, the results cannot be directly transferred on a one-to-one basis to the archaeological record (Marreiros et al., 2020). By conducting a third-generation experiment, a degree of variability is introduced into the experimental system (Marreiros et al., 2020), incorporating human variance and testing the physical relationships detected and the models proposed during the previous generation of

Table 1
Standard sample volume loss, weight loss, edge angle increase and relative penetration depth after 2000 strokes relative to the state before the experiment. The data represents the mean values of the 3 flint/silicified schist samples per edge angle (35°/45°) and movement (cutting/carving), respectively.

		volume loss [mm^3]	volume loss [%]	weight loss [g]	weight loss [%]	angle increase [°]	angle increase [%]	hardness [HLC]	relative pen. depth [mm]
cutting	**flint 35°**	40.6	0.46	0.02	0.09	−0.25	−0.62	961.2	1.331
	flint 45°	69.3	0.62	0.03	0.10	0.09	8.92	961.8	0.935
	silicified schist 35°	91.4	1.05	0.33	1.44	28.6	71.50	916.9	2.143
	silicified schist 45°	12.9	0.20	0.01	0.06	3.08	6.33	901.8	1.673
carving	**flint 35°**	19.1	0.17	0.01	0.03	−0.19	−0.48	952.1	0.578
	flint 45°	72.5	0.79	0.01	0.04	2.7	5.53	960.5	4.809
	silicified schist 35°	17.1	0.19	0.00	0.00	1.37	3.49	890.6	0.802
	silicified schist 45°	25.1	0.25	0.02	0.07	1.36	2.82	930.3	1.066

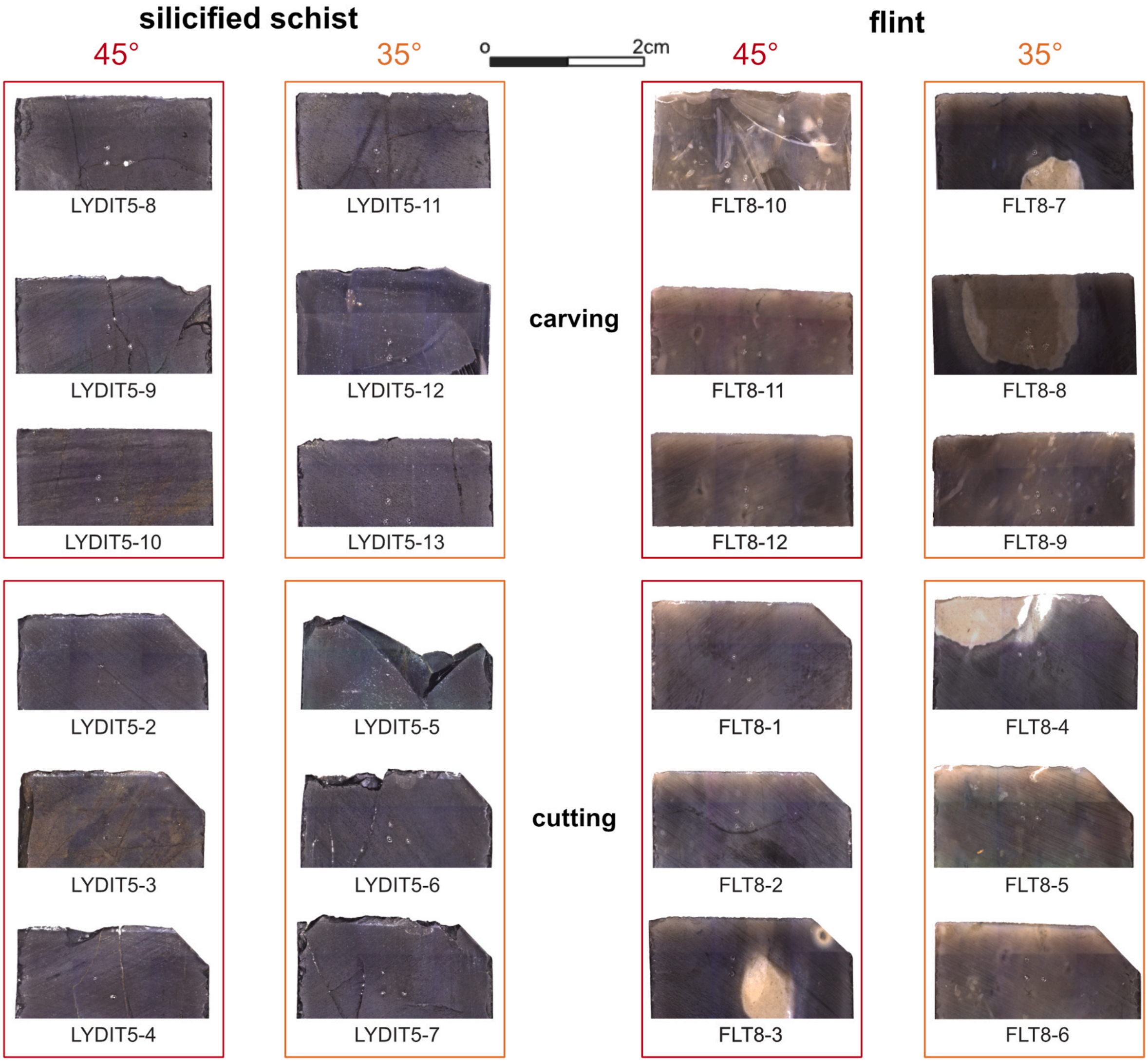

Fig. 14. Surfaces of all 24 samples involved in the experiment after 2000 strokes illustrating tool alteration.

experiments and, in this way, adding data sets for the interpretation of archaeological variability.

Despite an inherent potential for further analysis and expanded experimentation, the results of the experiment discussed here have implications for the interpretation of the archaeological record. The detected mechanical uniformitarian processes caused by the performed tasks combined with the samples' raw material properties and edge angles are as valid today as they were when Neanderthals used their tools (see also Lin et al., 2018). Additionally, the experiment was based on archaeological data as well tested edge angles were calculated from the 3D models of the analysed *Keilmesser*. Therefore, the results concerning functionality also provide information about the possible

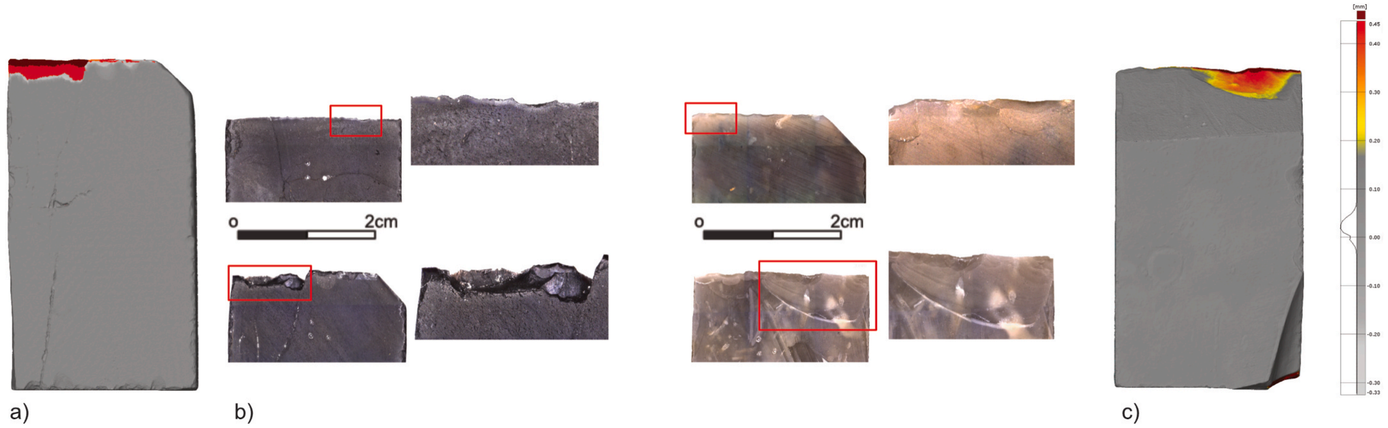

Fig. 15. Breakage pattern and tool alteration of silicified schist (left) and flint (right) samples after 2000 strokes in comparison. a) and c) displaying images of 3D models in which the models from before and after the experiment have been compared. The colourful areas highlight the differences between before and after (the darker the colour the larger the difference). b) illustrates images of the samples' active edges in original size (width) and close-ups emphasising the material loss. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

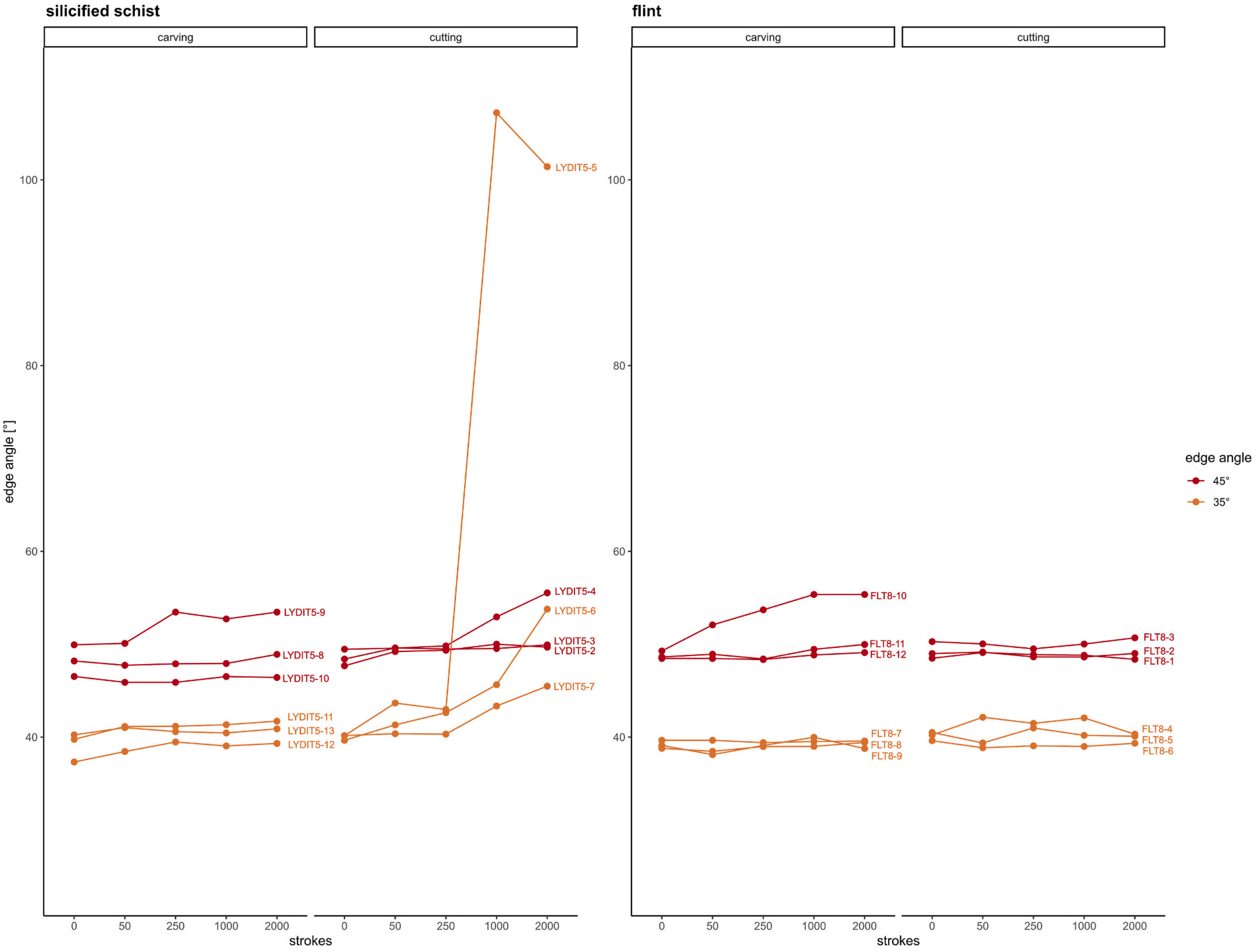

Fig. 16. Edge angle values calculated per sample used during the experiment (calculated with 3D-EdgeAngle '3-points' procedure; mean value of section 2 to 8 and distance 3 to 6; following Schunk et al., 2023). Note that the standard deviation when applying the '3-points' procedure is +5°, which is the reason why all data points are plotted higher than the actually are (i.e. 40° instead of 35°). The data points per sample represent the values after the performance of each cycle (0, 50, 250, 1000 and 2000 cutting/carving strokes).

utilisation of the *Keilmesser*. Moreover, the results are not only applicable to *Keilmesser* but to any other archaeological artefact made of the same raw material and edge angle. Although differences in tool performance due to the varying edge angle and raw material are noticeable, both movements - cutting and carving - could be performed without the standard samples losing function, meaning, the design of the average *Keilmesser* active edge should allow in theory for movements such as cutting and carving in contact with a yielding material. Based on common interpretations, scraping is also considered as a possible function of *Keilmesser* (Frick et al., 2017; Jöris and Uomini, 2019) and should be tested in future experiments. It is interesting in this context to note that tools with edge angles above 60° are often associated with tasks such as carving and scraping, while lower edge angles (<60°) are assigned to cutting tasks (Veil et al., 1994; Weiss, 2020). Nevertheless, the tested samples performed the carving movement without significantly compromising durability or efficiency and the edge angle solely does not indicate how suitable a tool is to perform a certain movement; the raw material and its properties seems to be as important. Taking these observations as a basis, maintenance, such as tool resharpening as a necessary counteraction to tool blunting, can be addressed.

The presented results indicate that the raw material properties of silicified schist, which on first appearance only seem to have negative consequences for the tool's use, might actually be beneficial during use. To perform a task with a tool made of silicified schist, less force and thus less work needs to be applied compared to performance with a flint tool. Of course, there might be a threshold of how much force silicified schist can tolerate before breaking. This threshold is likely higher for flint due to its elevated hardness values and the inherent fault lines and schistosity planes within the silicified schist. However, there is a limit of how much force can be applied by a human hand. While hardness was the main raw material property focused on during this study, others as for instance elasticity, mechanical strength or brittleness might also be relevant. These properties are beyond the scope of the present study and discussion, and therefore should be investigated further in future experiments.

5. Conclusion

The study aimed to investigate tool performance of Late Middle Palaeolithic *Keilmesser* by examining two relevant design features: raw material and edge angle. This was tested in a highly controlled, mechanical experiment. The second-generation experiment allowed for focusing on fundamental mechanics by testing the effect of individual variables. The tested standard samples with 35° and 45° edge angles performed cutting and carving as tasks while maintaining function. Unexpectedly, silicified schist samples outperformed flint samples. Although silicified schist samples experienced more material abrasion leading to a more pronounced edge angle change, a comparatively greater penetration depth could be achieved. However, the gain in cutting depth was accompanied by an increase in width and irregularity. Compared to flint, the raw material properties of silicified schist seem to cause a ‘self-resharpening’ of the active edge due to constant micro-fracturing. Thus, tools made of silicified schist might have been more efficient than flint tools when moderate force during cutting or carving was applied.

The experiment illustrates a bridge between standardised, controlled experiments and the archaeological evidence determining the experimental design, highlighting the time independent validity of the detected mechanical processes now as well as at the time of Neanderthals. Furthermore, the results emphasise the importance of raw material analyses and their correlation to aspects such as tool production, curation, and performance as well as material abrasion.

These results have implications for interpretations related to maintenance activities of past humans such as retouching and resharpening. It can be suggested that the choice of silicified schist by Neanderthals was not only dictated by the local availability of the raw material, but also by the performance of this raw material. This study provides additional significant insight into the potential character of past human behavioural repertoire as well as its variability in the archaeological record. It suggests a technological rational to reconstruct decision-making processes in the evolution of early human behaviour.

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CRediT authorship contribution statement

Lisa Schunk: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ivan Calandra:** Writing – review & editing, Formal analysis. **Anja Cramer:** Writing – review & editing, Methodology, Data curation. **Walter Gneisinger:** Writing – review & editing, Methodology. **João Marreiros:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2024.106003.

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