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The role of artificial contact materials in experimental use-wear studies: A controlled proxy to understand use-wear polish formation

Lisa Schunk [a,b,c,*], Walter Gneisinger [b], Ivan Calandra [b], João Marreiros [b,c,d]

[a] *Institute for Archaeology, Faculty of Historical and Pedagogical Sciences, University of Wroclaw, Poland*
[b] *TraCEr, Laboratory for Traceology and Controlled Experiments at MONREPOS Archaeological Research Centre and Museum for Human Behavioural Evolution, RGZM, Neuwied, Germany*
[c] *Institute for Prehistoric and Protohistoric Archaeology, Johannes Gutenberg University, Mainz, Germany*
[d] *ICArEHB, Interdisciplinary Center for Archaeology and Evolution of Human Behaviour, University of Algarve, Faro, Portugal*

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ABSTRACT

Traceological studies aim at the recognition and the identification of use-wear traces on artefacts to gain a functional interpretation of past human technologies. However, the development of use-wear traces is known to be dependent on different mechanics involved, such as those related to the contact materials, but also to the tool raw material and morphology, the use intensity and the performed task. Therefore, an understanding of the fundamental mechanics affecting wear formation is necessary to build reliable interpretations based on causation.

The cause-effect relationship between individual variables and the formation of use-wear can only be investigated by conducting controlled, second-generation experiments. To test individual variables, others have to be standardised. This applies, for instance, to the contact material.

The here presented sequential second-generation experiment tested for differences between soft and hard contact materials. Simultaneously, this experiment aimed to validate the comparability of artificial and natural contact material as a standardised substitute, but also as an ethically more acceptable choice. Combined with qualitative and quantitative use-wear analyses, the data generated throughout the experiment did not only provide insights into the development of use-wear, but also into abrasion processes within the experimental setup. Concerning these aspects, no significant difference between the natural and artificial contact materials could be observed. Consequently, while not used as direct proxies to interpret wear on archaeological artefacts, the use of standardised contact materials can be an advantageous choice in controlled experimental setups. Moreover, the experiment highlights the relevance of use intensity and duration in the context of wear formation.

1. Introduction

Traceological analyses try to answer questions about how past artefacts were produced, used and altered. When studying the use of stone tools, the goal is to identify the performed movement and the material the tool was in contact with through the traces of use. Such functional interpretations imply the reliable identification of the variables likely to be involved in the development of use-wear. Variables include the performed task and the properties of the contact material, as well as the raw material properties, tool morphology and use intensity and/or duration (Hayden, 1979; Keeley, 1980). During the last couple of decades, use-wear analysis as a sub-discipline of archaeology has undergone several changes, including methodological developments, theoretical and conceptual shifts (Grace, 1996; Evans et al., 2014; Stemp et al., 2015; Macdonald et al., 2018; Marreiros et al., 2020 for reviews). One of these developments is the integration of quantitative surface characterisation techniques such as focus variation microscopy (Macdonald, 2014; Pfleging et al., 2019; Stemp et al., 2019; Macdonald et al., 2020) and confocal microscopy (e.g. Evans and Donahue, 2008; Stemp and Chung, 2011; Giusca et al., 2012; Stemp et al., 2013; Evans et al. 2014; Macdonald et al. 2018; Stemp et al. 2019; Álvarez-Fernández et al., 2020; Bradfield, 2020; Martisius et al., 2020; Pedergnana et al., 2020a, b) coupled with surface metrology software (d'Errico and Backwell, 2009; Sahle et al., 2013; Ibáñez et al., 2019; Martisius et al., 2018; Calandra et al., 2019a,b,c). Based on this quantitative approach, standardised criteria for the variability within and between different

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* Corresponding author at: Institute for Archaeology, Faculty of Historical and Pedagogical Sciences, University of Wroclaw, Poland.
E-mail address: lisa.schunk@rgzm.de (L. Schunk).

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types of use-wear can be defined. This way, while the quantitative approach supports and complements a qualitative use-wear analysis, it also allows to explore in more detail aspects such as sub-types of traces within the so-called “families of wear traces” (e.g. Ibáñez et al., 2019; Marreiros et al., 2020).

Most quantitative use-wear studies have been applied on experimental replicas with the aim to improve the identification and discrimination of the contact material (Evans and Donahue, 2008; González-Urquijo and Ibáñez-Estévez, 2003; Evans and MacDonald, 2011; Pedergnana and Ollé, 2017; Martisius et al., 2018; Ibáñez et al., 2019; Álvarez-Fernández et al., 2020; Pedergnana et al., 2020a). While these studies have successfully shown that different worked materials correlate with distinct wear traces, how and when these traces form is still only vaguely understood. However, this information has crucial implications on the interpretation of aspects such as use duration and the performed movement. Thus, if the goal is to understand the role of the contact material in the formation process of use-wear, then experiments should be conducted under controlled conditions, as would be the case for highly controlled, second-generation experiments (sensus Marreiros et al., 2020). The “human factor” (i.e. variability), as well as subjectivity (e.g. applied force), is reduced to a minimum by the use of a mechanical device. The high level of control in a second-generation experiment allows for focussing on basic fundamental mechanics by testing and measuring the effect of individual variables. Additionally, aspects such as tool functionality, efficiency or tool use duration can be addressed, allowing to infer human behaviour. When performed sequentially (Stemp and Stemp, 2003; Ollé and Vergès, 2014; Pedergnana and Ollé, 2017; Ibáñez and Mazzucco, 2021), such second-generation experiments allow for investigating the mechanics of use-wear formation. This also means, highly controlled experiments do not function for reproducing archaeological findings. Instead, by conducting second-generation experiments, physical and mechanical causalities can be investigated. To test individual variables within an experimental setup, others have to be standardised (Eren et al., 2016; Lin et al., 2018; Marreiros et al., 2020).

The use of modern material substitutes is not uncommon in experimental design due to their inherent advantages (e.g. Dibble and Pelcin, 1995; Dibble and Rezek, 2009; Iovita et al., 2014, 2016; Key et al., 2018; Kranioti et al., 2019; Dogandžić et al., 2020; Eren et al., 2022). The artificial materials used in this study are modern substitutes, produced in bulk and therefore uniform and standardised to match given specifications. Thus, they improve data reproducibility and internal experimental validity (Eren et al., 2016, 2022). Furthermore, they are an ethically more acceptable choice as a substitute for materials derived from animals and/or endangered species. Artificial materials also alleviate any health and safety issues arising when experimenting with biological material, especially over extended periods of time. On the contrary, the high degree of standardisation and the uniformity of modern samples reduce the effects inferred by unknown variables encountered in natural samples, e.g., due to their structure or composition. Consequently, results need to be viewed with caution, making it initially necessary to detach results from the interpretation of the archaeological record.

The here presented sequential second-generation experiment tested for differences in wear formation between hard and soft contact materials as one independent variable. To do so, as many inhomogeneous variables as possible were standardised. Besides the sensor-monitored mechanical device, standardised, machine-cut samples made of two different raw materials were used. With the aim to understand the influence of hard and soft contact material on wear formation on the one hand, and to produce reliable and reproducible data on the other, commercially available, standardised, artificial contact materials were introduced into the experimental design. Thus, the experiment also aimed at validating the comparability of artificial and natural contact materials in studies that address the understanding of the mechanical processes involved in the formation of diagnostic wear traces.

2. Material and methods

The methods applied within the experiment are described and illustrated in detail in the protocol on protocol.io (https://doi.org/10.17504/protocols.io.eq2lyn91pvx9/v2). Thus, the methods and materials described here should be seen as a short summary.

2.1. Experimental design

The experiment was designed (Fig. 1) with the aim to identify patterns and processes by testing the influence of individual factors within a complex system. Thus, the experimental setup involved a modular mechanical device, the SMARTTESTER® (Calandra et al. 2020; Fig. 2). The use of a mechanical device minimised the “human factor” and allows for the reduction of subjectivity and human action bias. The SMARTTESTER® conducts precise, repeatable and sensor-monitored movements. The linear setup (see Calandra et al., 2020) was used to perform unidirectional cutting movements with defined cutting lengths. Three parameters were fixed and monitored during the experiment: peak

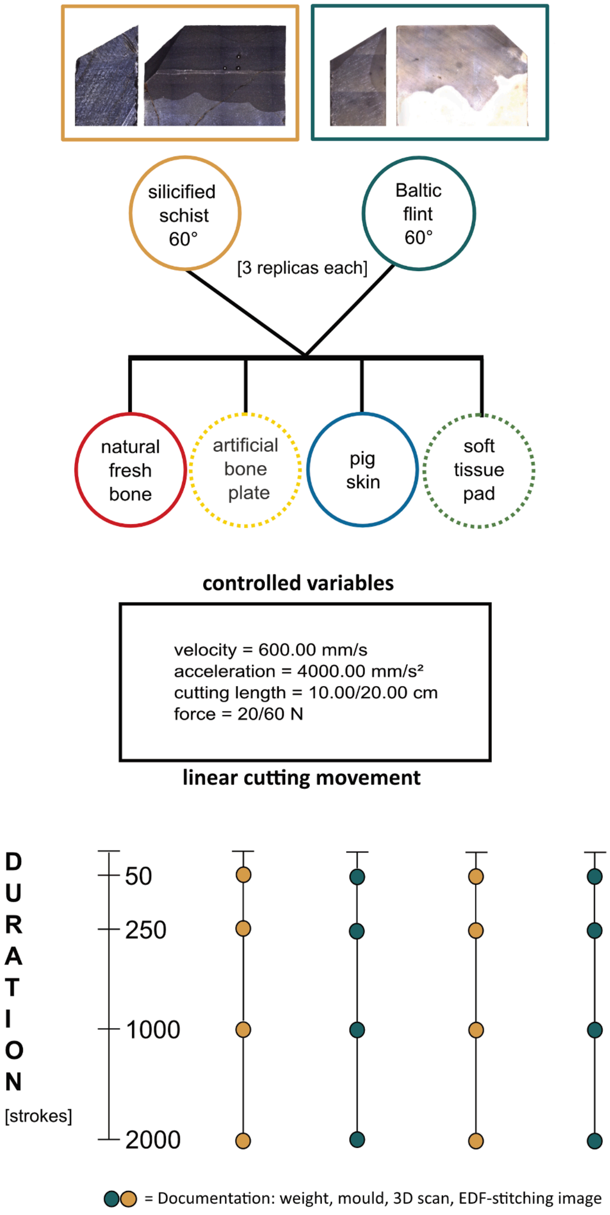

Fig. 1. Experimental design.

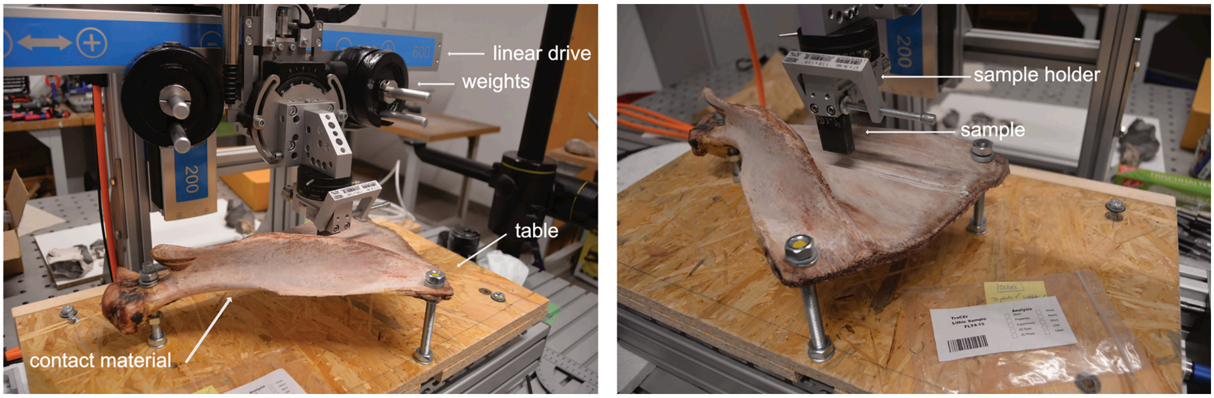

Fig. 2. Experimental setup. Linear drives of the Inotec SMARTTESTER®. Weights totalling 6 kg are attached to the sample holder. An experimental standard sample (here FLT4-15) is clamped into the sample holder. The cow scapula is horizontally fixed on the table as contact material.

velocity, acceleration and downward force applied by dead weights mounted on the sample holder. These factors were measured continuously during the experiment and two additional sensors recorded the penetration depth and friction; friction was approximated with a compression load cell fixed between the free running sample stage and a rigid support frame in direction of cutting movement.

A sample holder ensured the correct positioning of the experimental samples (described below) during the experiment: Samples were clamped perpendicular to the contact material and any deviating angle was corrected to ensure parallel alignment of the cutting edge with the surface of the contact material. Within the programming of the SMARTTESTER®, a 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.

The experiment was conducted sequentially with four cycles totalling 2000 cutting strokes. The first cycle consisted of stroke number 1–50, the second of stroke 51–250, the third of stroke 251–1000 and the final cycle ranged from stroke number 1001–2000.

2.2. Experimental sample preparation

Standardised samples were used in the experiment, which allowed for the exclusion of some confounding factors in the experimental design. Two materials were chosen: Baltic flint and silicified schist. The raw material was treated as an independent variable within the experimental setup. The samples were produced according to the following protocol (Fig. 3): Selected raw material nodules were cut into slices with a lapidary slab saw. Raw material intra-variability was reduced by limiting the number of nodules. Further, the slices were cut into size-defined blanks. Using a diamond band saw, a unifacial edge angle of 60° was produced along the width of the blank (= active edge). For a cutting movement, this presents a relatively high edge angle value but it was chosen to prevent rapid severe edge damage and material loss since more acute edge angles are more prone to this type of damage. In addition, the leading side of the active edge was modified again with the diamond band saw, creating a 45° chamfered edge, with a defined remaining edge length. The idea behind the chamfered edge was to minimise the risk of immediate fracturing by distributing the forces applied locally across a larger surface, as soon as contact between sample and contact material was initiated. In total, 24 experimental standard samples were prepared, 12 flint and 12 silicified schist samples. In an effort to economise on blank production and to reduce raw material intra-variability, cut blades were “recycled” after half of the samples (i.e., 12 blades) had been used experimentally: the first ~ 10 mm of the active edge were removed from each used sample as “slices” with the diamond band saw and 12 new samples could be produced this way, keeping the previously used active edge segment for subsequent analysis.

As part of the sample preparation protocol, a cleaning procedure was applied. A rinse in tap water was followed by cleaning in a preheated ultrasonic bath. The samples were packed in individual plastic bags filled with ~ 100 ml of demineralised water and non-ionic detergent. At 45 °C and 100 kHz, the samples were left in the ultrasonic bath for 10 min. In a next step, the detergent solution was exchanged with tap water to rinse off detergent residues in a first step. This was repeated two more times. The samples were finally rinsed with ~ 100 ml purified water and air dried.

To ensure the possibility of analysing the exact same area of the samples before, between and after the experiment, a coordinate system was applied directly on the samples’ surfaces (Calandra et al., 2019c).

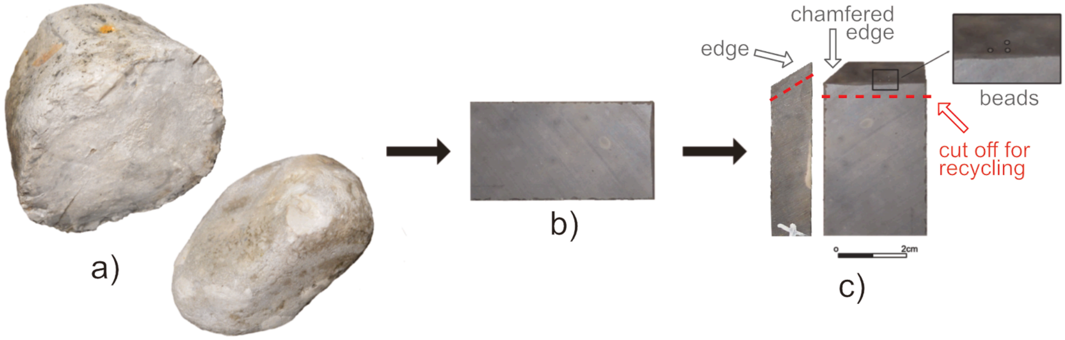

Fig. 3. Standard sample production. The raw pieces (a; here Baltic flint) are cut into blanks (b) with a lapidary slab saw. A diamond band saw was used to cut the blank in order to create a typical standard sample with a defined edge angle (c) and a 45° chamfered edge. Highlighted are the three beads used as coordinate system (see Calandra et al., 2019c). The red dotted line indicates where the samples are cut after they have been used in order to “recycle” the blank and to reveal a new surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Three 100–200 μm diameter ceramic beads were adhered with epoxy resin on the two main surfaces (dorsal and ventral side) of the tool.

2.3. Contact materials

To address the research question, in addition to the raw material, another independent variable was introduced – the contact material (Fig. 4). Both extremes were tested: hard and soft contact material, presented as natural and as soft artificial substitutes. Therefore, a fresh cow scapula (*Bos primigenius*) and fresh pig skin (*Sus scrofa domesticus*) were selected. The reasons for choosing a cow scapula can be explained by the size and shape. The morphology of the bone offers the possibility to perform long cutting strokes on a relatively straight surface, providing better conditions for a comparison of the results with the other tested contact materials. It was provided by a butcher in a fresh state. The periosteum and small pieces of flesh were still attached to the bone. The cutting experiment was carried out in a laboratory under ambient room temperature conditions. Two pieces of natural pig skin were also provided by a butcher by separating the skin from the flesh below. Experiments on the skin were conducted on the SMARTTESTER® at room temperature; overnight the mounted skin was kept cold in a fridge. Within this experiment, the cow scapula and the pig skin represent the natural contact material. As a second category, artificial contact materials were used and tested as an equivalent to the natural materials. Artificial generic bone plate made of modified bone-like polyurethane coated with a rubber skin imitating the periosteum was used (SYNBONE®). In the experimental application, this served as an artificial equivalent to a fresh, defleshed bone. As artificial skin, a SYNBONE® soft tissue pad with a matrix was used. This skin pad is made of “ecoflex” silicone.

2.4. Sample documentation

As a raw material property, the hardness of the two involved rock types – flint and silicified schist – was measured. Hardness was acquired on the experimental blanks with a Leeb rebound hardness tester (in HLC), allowing for a rapid and non-destructive test procedure (Rodríguez-Rellán, 2016; Corkum et al., 2018). The Leeb rebound hardness test requires certain sample properties (mass, size, surface roughness and slopes). While the experimental samples provide ideal flat and smooth surfaces, they do not fulfil the minimum size requirement. Therefore, an additional stable supporting base was used. The samples were placed on the base and connected with a layer of reversible coupling paste. To estimate intra-sample variability, each sample was measured ten times, each time at a different location.

The experimental standard samples were documented before and after each sequential cycle following an identical protocol. This protocol consists of four steps: weighing, 3D scanning, documentation with a digital microscope and preparation of silicone moulds of the active edges. The samples’ weight was measured with a weighing scale. With a structured-light scanner, the experimental samples were scanned using a S-150 field of view (FOV). Based on the 3D models, for instance changes in volume and in the edge angle can be calculated. The samples were visually documented with a digital microscope (ZEISS Smartzoom 5). Three of the four surfaces per samples (one lateral and the two main surfaces) were documented with a PlanApo D 1.6x/0.10 objective. In a final step, moulds of the edge of the two main surfaces were taken after cleaning the samples’ surfaces with 2-propanol 70 % v/v. The treatment with alcohol, however, was not sufficient for the samples used on the fresh cow scapula. Thus, these samples were cleaned following an additional cleaning protocol. The presence of mainly lipids and collagen in addition to abraded mineral particulates was considered to act as binder with adhesive properties. Therefore, a cleaning agent containing enzymes such as lipase and protease was used in preference to acids or alkalis requiring subsequent neutralisation. After cleaning, the respective samples were analysed with a SEM coupled with an EDX detector (ZEISS EVO 25 + Bruker Quantax XFlash 6|30 M) to verify the absence of residues **(see Supplementary data 1)**. As a moulding material,

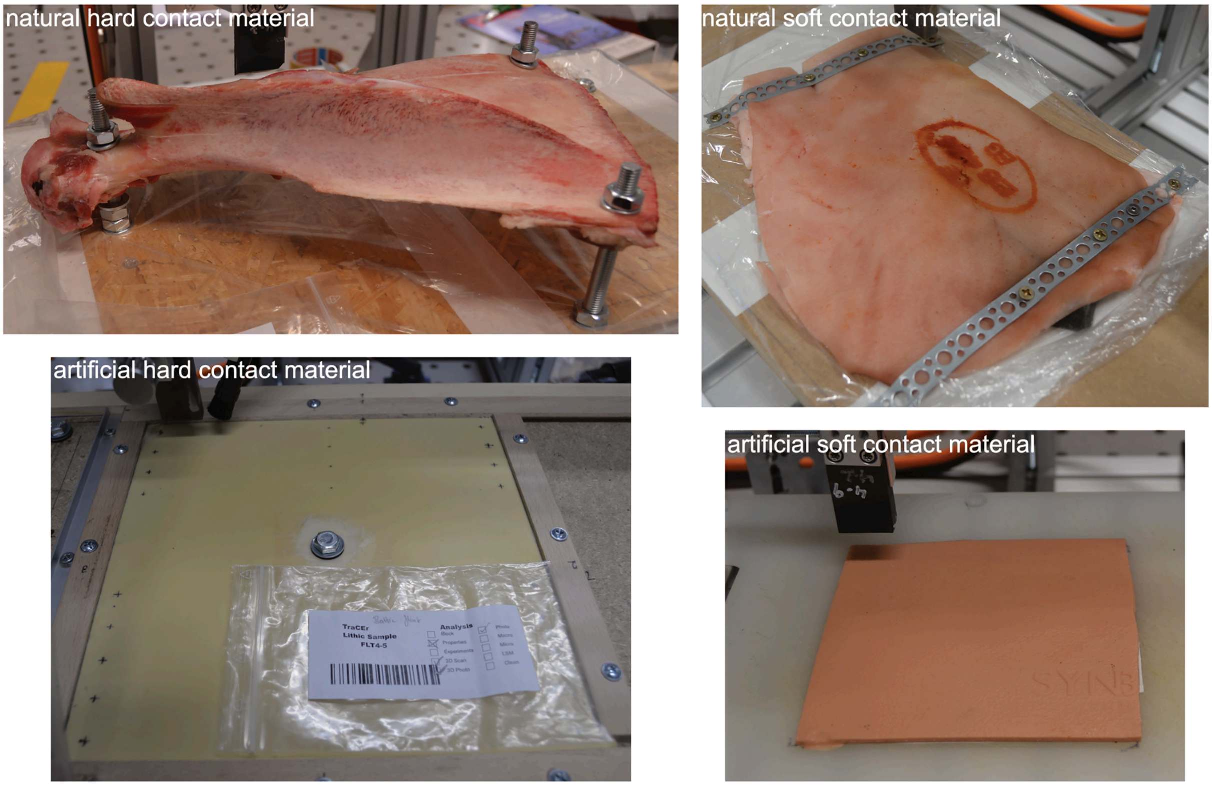

Fig. 4. Contact materials: natural cow scapula and artificial bone plate (left); natural pig skin and artificial soft tissue pad (right).

Provil® novo light regular was used. Subsequently, a second moulding material was used, AccuTrans AB. Qualitative and quantitative use-wear analysis was conducted on (mainly) the moulds of all 24 experimental samples. For reasons of consistency, use-wear analysis only refers to data from the side of the standard samples cut with the lapidary slab saw. Use-wear analysis was carried out on all samples before the first and after the last cycle of the experiment. An additional systematic sampling led to the selection of eight (i.e. four flint and four silicified schist samples) out of the total 24 experimental samples for a microscopic analysis of the cycles in between. Each of the four samples per raw material was tested on a different contact material: bone cow scapula, bone plate, pig skin and skin pad. The qualitative use-wear analysis was carried out in a high-power approach by means of an upright light microscope (ZEISS Axio Scope.A1 MAT). The samples were studied using EC-Epiplan 5x/0.13, 10x/0.25 and 20x/0.40 objectives. Traces were documented as an EDF black and white image. The acquisition for quantitative use-wear analysis was executed with a laser-scanning confocal microscope (ZEISS Axio Imager.Z2 Vario + ZEISS LSM 800 MAT). The objective C Epiplan-Apochromat 50x/0.95 was generally used. In a few cases, the C Epiplan-Apochromat 20x/0.70 was chosen, because the small working distance of the 50x objective (0.22 mm) made it virtually impossible to image the sample. The FOV was 255.56 × 255.56 µm or 638.9 × 638.9 µm, respectively. Each sample was measured three times at nearby, but non-identical spots. These scans are treated as replicas and verify the level of homogeneity within each trace. Additional wide field black and white EDF images were taken with the C Epiplan-Apochromat 10x/0.40 and 20x/0.70 objectives.

2.5. Data processing for quantitative use-wear analysis

The data acquired with the confocal microscope was processed in batch with different templates in ConfoMap (a derivative of MountainsMap Imaging Tophography developed by Digital Surf, Besançon, France; version ST 8.1.9286. Details about the templates can be found in the protocol (https://doi.org/10.17504/protocols.io.eq2lyn91pvx9/v2). The ConfoMap templates for each surface in MNT and PDF formats are available on Zenodo (https://doi.org/10.5281/zenodo.7229779). This also includes all original and processed surfaces, as well as the results.

All descriptive analyses (summary statistics, scatter plots and principal component analysis) were performed in the open-source software R version 4.0.2 through RStudio version 1.3.1073 (RStudio Inc., Boston, USA) for Microsoft Windows 10. Reports of the analysis in HTLM format, created with knitr v. 1.29 and rmarkdown v. 2.3 are available on Zenodo (https://doi.org/10.5281/zenodo.7229814). The raw data, the scripts and the RStudio project are also saved in the same repository.

3. Results

3.1. General results

All 24 experimental standard samples completed the four cycles with a total of 2000 cutting strokes each. The samples experienced minimal material loss. Thus, none of the samples lost their functionality over time.

3.2. Leeb rebound hardness data

Based on the tested samples, flint is harder than silicified schist (Fig. 5). The arithmetic mean for the flint is 960 HLC while the one from silicified schist is 903 HLC. The variability in HLC for silicified schist is considerably higher compared to flint: flint hardness ranges from 944

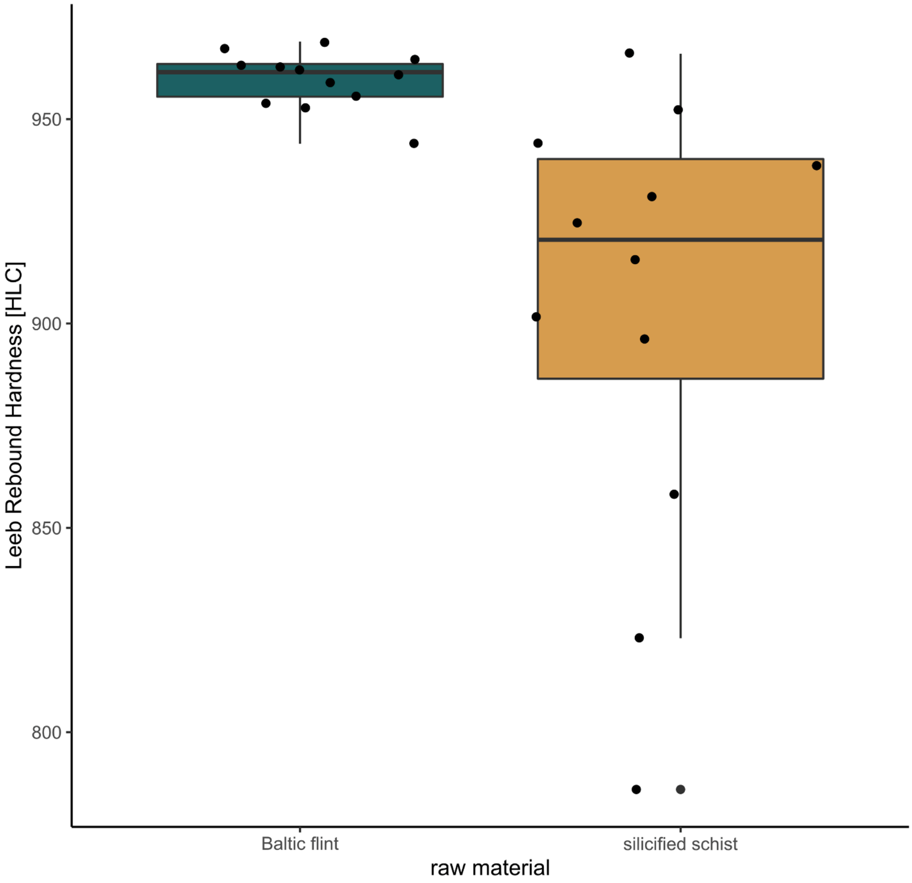

Fig. 5. Leeb Rebound Hardness in HLC measured for the two raw materials flint and lydite (n = 24 samples).

HLC to 969 HLC, while the range for the silicified schist is 786 – 966 HLC. Hardness is just one raw material property that makes silicified schist different from flint. Silicified schist is a raw material characterised by fine layers (schistosity) and small cracks. When the impact body of the Leeb rebound hardness tester hits a less compact area of the surface (e.g. a crack underneath the surface), rebound energy gets dissipated and the Leeb hardness value will be smaller. This will be more frequently the case for the silicified schist than for flint.

3.3. *Identification of the contact materials*

All 24 experimental samples developed use-wear within the course of the experiment (Fig. 6). The visual appearance of the use-wear traces is different for the soft and hard contact materials. The polish resulting from working the cow scapula appears bright, smooth and with a sharp contour, as typical for bone. The same applies to the traces from the artificial bone plate, although the polish is less extended. The soft contact materials caused in all cases dull use-wear with diffuse contours affecting only the highest peaks of the surfaces.

The results of the quantitative use-wear analysis underline the findings from the qualitative use-wear analysis: the use of the soft contact materials has less of an effect on the surface of the tool than the hard contact materials. This becomes evident when plotting the data analysed according to the ISO 25178–2 parameters (21 ISO + SSFA parameters; International Organization for Standardization, 2012; **see Supplementary data 2**). To explain the data in more detail, individual parameters serve as representatives in place of the others. One of them is Sq, an amplitude parameter belonging to the areal field parameters. Sq is a measure of surface roughness, expressing the root mean squared height. Simply said, the higher the Sq value, the higher the surface roughness. With the aim to understand whether there is a trend towards an increase or decrease in surface roughness on the experimental samples after use, the mean value of the three measurements per sample was calculated and the difference from 0 to after 2000 cutting strokes was computed (Fig. 7). For the samples used on the soft contact materials the amplitude of change is really small (Fig. 8). However, there is no clear trend visible. For instance, the silicified schist samples show in four cases a (minimal) decrease in surface roughness and in two a slight increase. The results for the flint samples are similar. Other parameters from different categories were considered too (**see Supplementary data 3**). Among them are Vmc as volume parameter, as well as Asfc, HAsfc9 and epLsar as three fractal analysis parameters. The results for these parameters do not differ considerably from Sq and thus no significant differences between the samples used on soft natural and artificial contact materials can be pointed out. This is slightly different for the hard contact material. Generally, the use of bone has more impact on the samples' surface than the other tested materials. While the use of bone increases the Sq value, the opposite is true for the bone plate.

To test the data further, a PCA was performed as descriptive statistics. The PCA was applied on seven selected parameters. These parameters are Sq, Ssk, Vmc, Mean density of furrows, Isotropy, Asfc and HAsfc9, spanning the different categories of field, SSFA and texture direction parameters. The PCA (Fig. 9) reflects the variance between the samples used on the four contact materials separated into flint and silicified schist samples. For the flint, Principal component 1 (PC1) reflects 48.08 % of the variance and is correlated with Sq, Vmc, and Asfc. The variance in Ssk, Mean density of furrows, Isotropy and HAsfc9 is represented by Principal Component 2 (PC2), which accounts for 16.98 %. PC1 and PC2 values differ slightly for silicified schist with 48.05 % and 21.03 %, respectively. The data does not cluster in groups; instead, the data points from the four contact materials overlap, especially concerning the silicified schist samples. The data points from the flint samples seem to cluster slightly with the tendency of a separation between bone plate and the other contact materials.

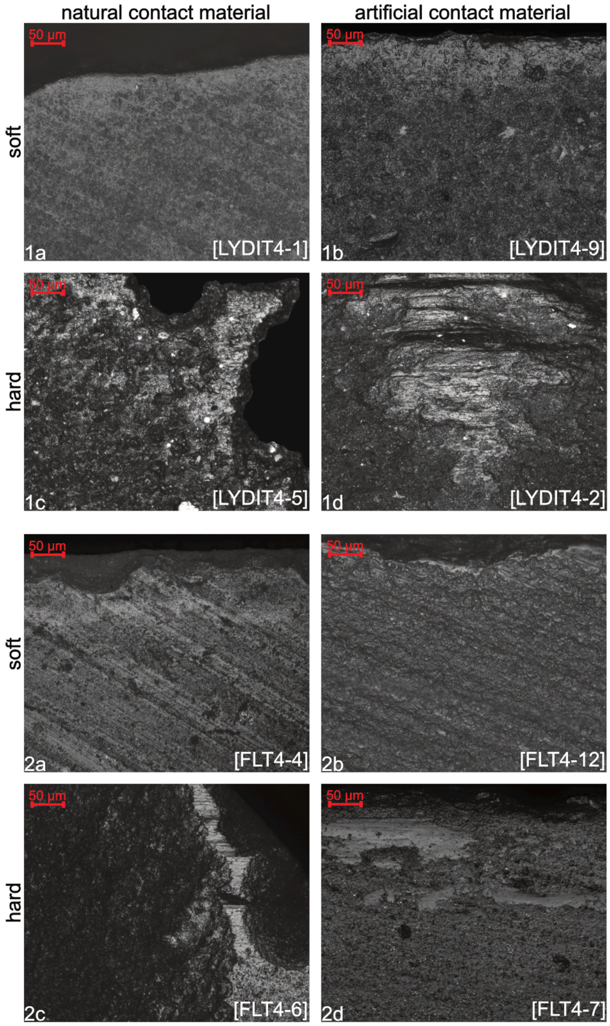

Fig. 6. Examples of use-wear after 2000 unidirectional cutting strokes. The images are taken with a ZEISS Axio Scope.A1 MAT with a 20x objective. The images 1a-d show silicified schist samples, images 2a-d flint samples. The samples were used a) on pig skin, b) on the skin pad, c) on cow scapula and d) on bone plate.

3.4. *Use-wear formation*

The eight microscopically analysed samples studied after each cycle, provide information about the timing of the wear formation (Figs. 10, 11). The soft contact material led to a slower formation compared to the hard material. However, the marginally developed traces can be correlated with the limited penetration depth into the contact materials. Both samples (FLT4-4 and LYDIT4-1) used on the fresh pig skin developed microscopically visible use-wear during the last cycle between 1000 and 2000 cutting strokes. By contrast, the samples tested on the fresh cow scapula developed use-wear earlier. In the case of the flint sample (FLT4-15), use-wear appeared after the second cycle (250 strokes), whereas traces of use-wear on the lydite sample (LYDIT 4–5) were already visible after the first cycle (50 strokes). An identical temporal development of the use-wear traces can be noted for the samples used on the artificial contact material (FLT4-7 and LYDIT4-2). Thus, the samples used on the hard natural contact material developed use-wear traces earlier than the ones used on the hard artificial contact material. Concerning the soft contact material, this difference is qualitatively not noticeable. Moreover, the use of both hard contact materials has more impact on silicified schist samples than on flint samples.

The quantitative use-wear analysis conducted after each cycle on the selected eight samples shows that the development of use-wear on the

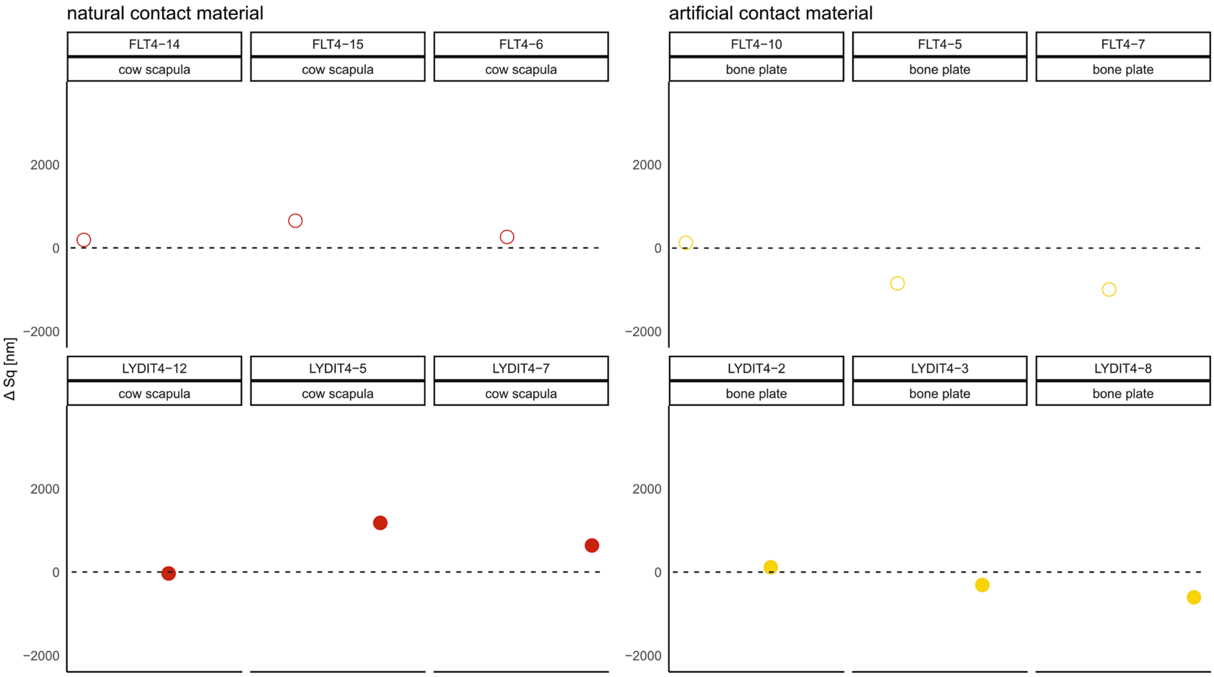

Fig. 7. Mean Sq value of the three taken measurements per sample calculated according to the ISO 25178-2. The plot shows the difference from 0 to 2000 cutting strokes on the hard contact materials.

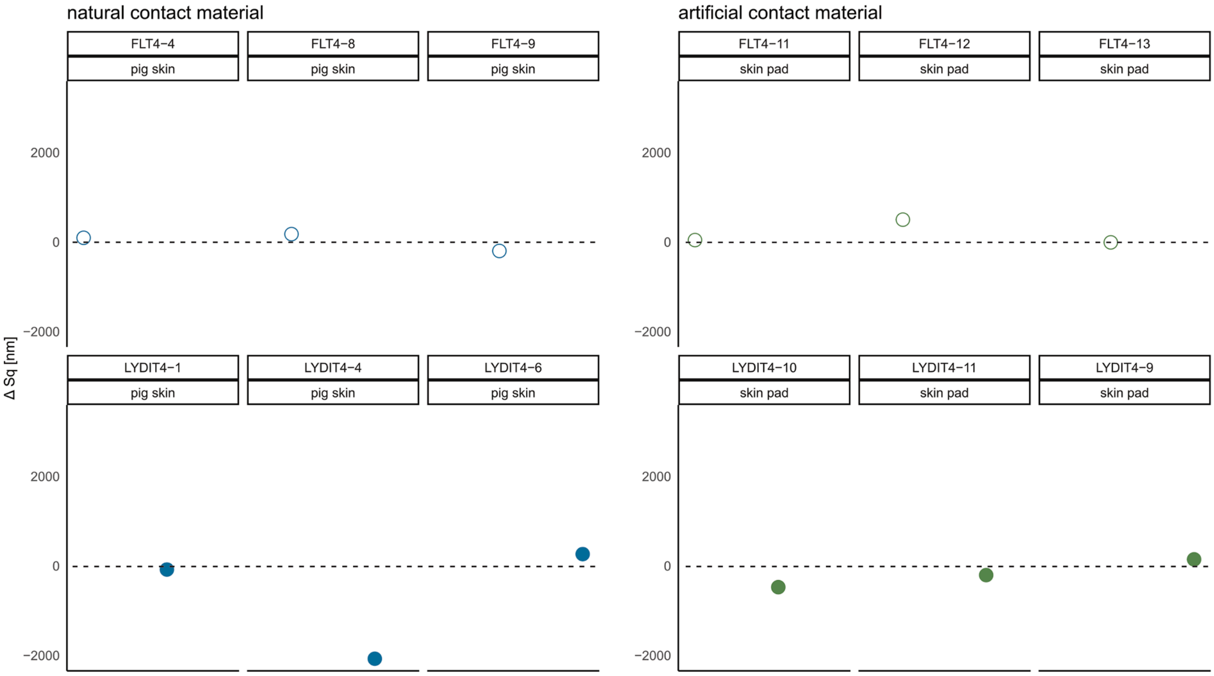

Fig. 8. Mean Sq value of the three measurements taken per sample calculated according to the ISO 25178-2. The plot shows the difference from 0 to 2000 cutting strokes on the soft contact materials.

experimental samples is a dynamic process, evolving throughout the course of the experiment. However, measured on the calculated parameters, the surface is not changing continuously into one direction. The use of the soft contact material for instance has less impact on the surface than the hard material, as mentioned earlier. Nevertheless, in contact with the pig skin, the surface of the flint and silicified schist sample seems to alter. Taking Sq as an example (Fig. 12), surface roughness increases in case of the silicified schist sample after 50 strokes to decrease within the following cycles again. The flint shows the same pattern, but a significant decrease does not occur before 1000 strokes. Similar surface effects can be noticed with the samples used on hard contact materials. This pattern is particularly visible on the samples tested on the cow scapula. Taking Sq as an example again, surface roughness increases significantly during the experiment on both flint and silicified schist and decreases in the case of silicified schist sample after 250 strokes. Interestingly, and corresponding to the qualitative use-wear analysis, surface texture modification seems to take place earlier on silicified schist than on flint.

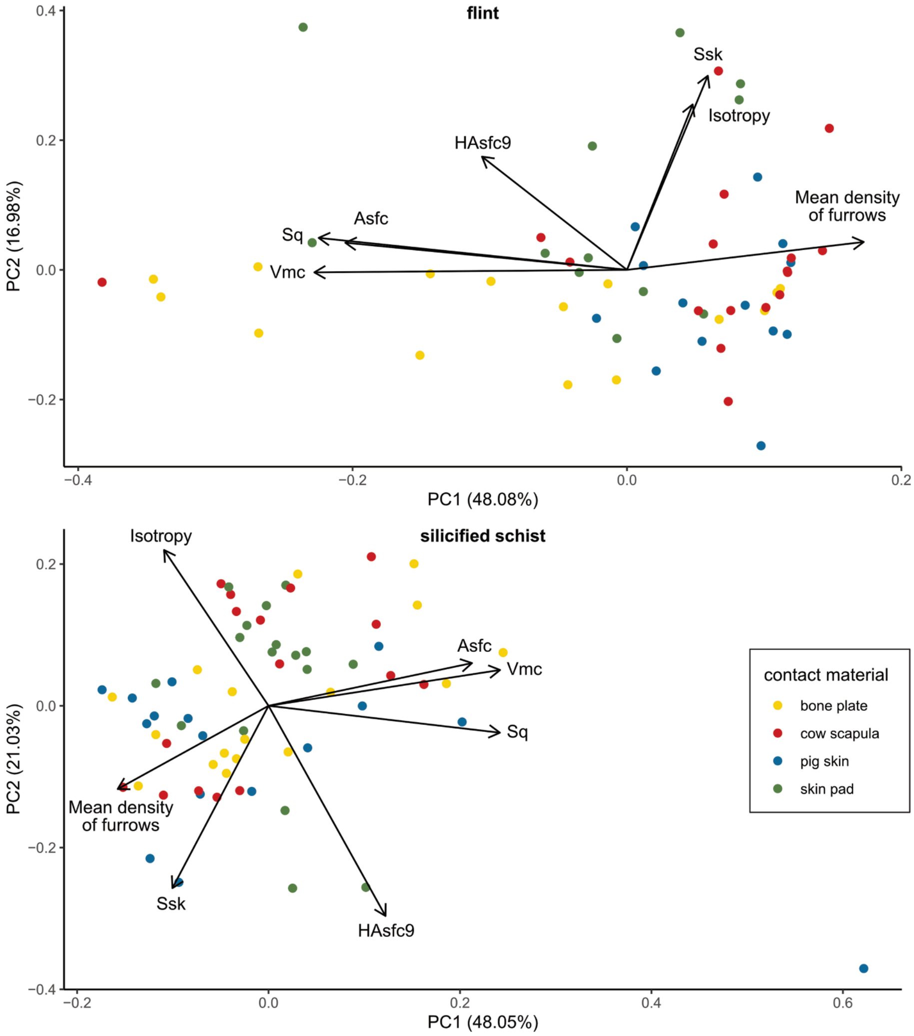

Fig. 9. Principal component analysis applied to the measurements taken on flint (top) and silicified schist (bottom) standard samples after 2000 cutting strokes, reflecting variation regarding the contact material.

4. Discussion

The identification of use-wear traces is known to be dependent on different mechanics involved, such as those related to the contact material, but also the tool raw material and morphology, the use intensity and the performed task (e.g. Lerner, et al., 2007; Giusca et al., 2012; Pedergnana and Ollé, 2017; Martisius et al., 2018; Ibáñez et al., 2019; Álvarez-Fernández et al., 2020; Ibáñez and Mazzucco, 2021). This multitude of possible influencing variables renders a functional interpretation of past human technologies complicated, but not impossible. Prerequisite for a reliable interpretation is a clear understanding of the cause-effect relationships between individual variables. No less important is the understanding of use duration in these relationships. The presented sequential second-generation experiment tested for the effect of hard and soft contact material on wear formation. For this reason, a natural cow scapula and pig skin have been tested in comparison to artificial equivalents – a bone plate and a soft tissue pad.

The cutting movement performed on natural as well as on artificial contact material led to the development of use-wear over time. The amplitude of change is smaller for the soft contact materials. This means, hard contact material has a greater capacity to lead to surface texture modifications. At the same time, the use of natural contact materials seemed to favour wear formation in comparison to the tested artificial contact materials when considering the quantitative data only. While some contact materials as for instance antler, bone and ivory as one category, or especially cereals as another, leave distinguishable and identifiable use-wear traces (Stemp, 2014; Ibáñez et al., 2014; Ibáñez et al., 2016; Pedergnana et al., 2020a; Ibáñez and Mazzucco, 2021; Rodriguez et al., 2021), others such as meat and hide do not. Correspondingly, the study shows that the visual appearance of the use-wear traces on experimental samples differs for the soft and hard contact materials (Fig. 6). Based on the qualitative assessment, the use-wear traces of natural as well as artificial contact materials appear to be comparable. However, the natural cow scapula led more intense surface abrasions than the artificial equivalent. The results suggest that not only the hardness of the contact material is of relevance, but also structural properties such as the heterogeneity and its condition (e.g. fresh vs. dry), which is where natural and artificial equivalents may differ significantly (e.g. the presence of lubricants in natural fresh materials). While structural homogeneity in natural contact materials can likely not be reached, varying conditions are known to affect use-wear formation (e.g. Buc, 2011; Zhilin, 2017; Thun Hohenstein et al., 2020; Martisius, 2022). Further experimental studies focusing on the variation in contact materials, including their conditions, are inevitable to address use-wear in that concern.

The results of the quantitative use-wear analysis confirm the textural changes of the micro-surface after 2000 cutting strokes, associated with visual polish formation and underlining the benefits of a combined qualitative and quantitative use-wear analysis. Interestingly, the analysis of the samples after each sequential cycle highlights the dynamic

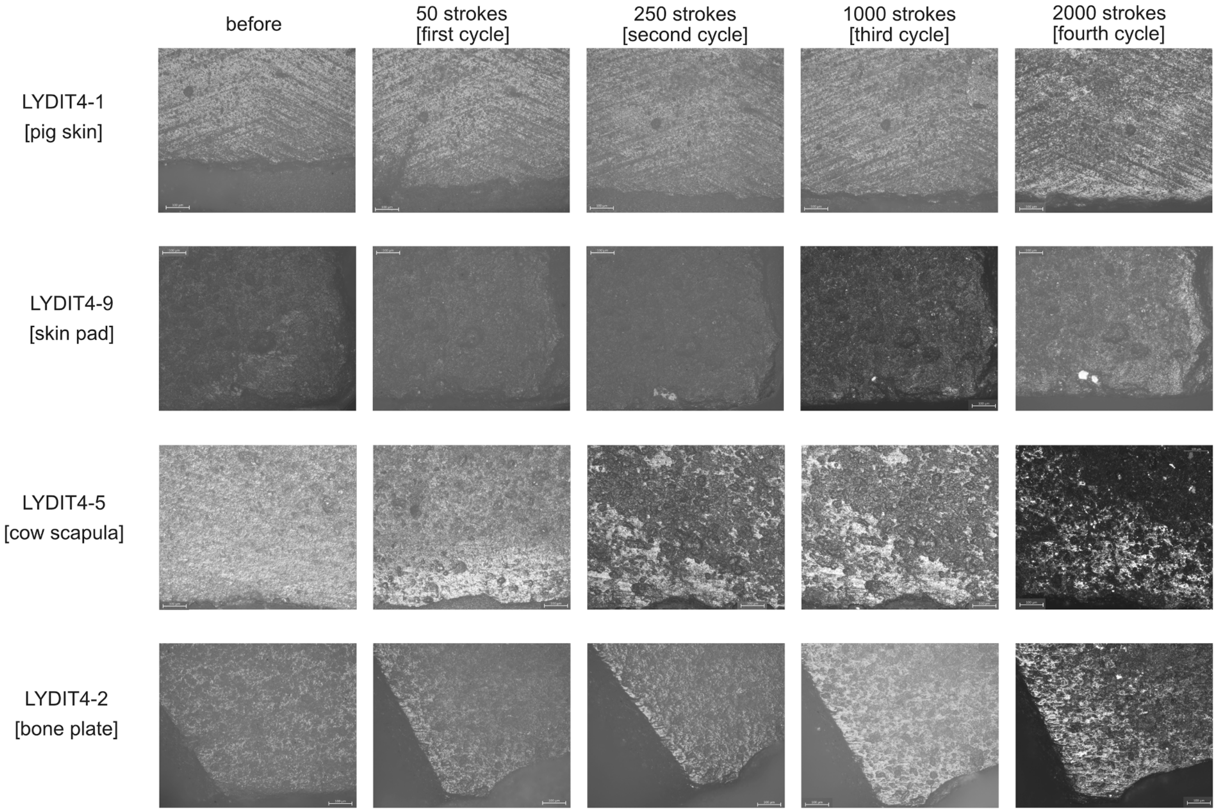

Fig. 10. Use-wear development on silicified schist samples throughout the experiment. The images are taken with a ZEISS Axio Scope.A1 MAT using a 10x objective.

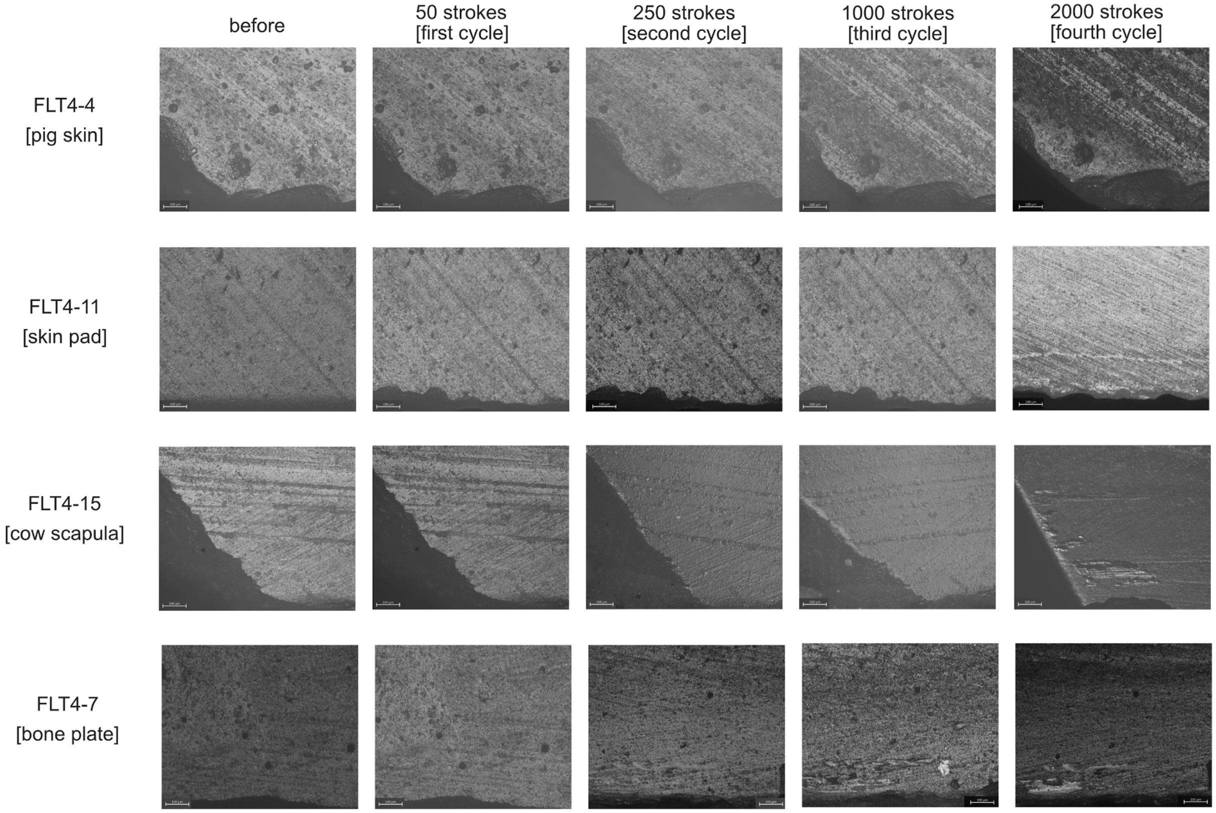

Fig. 11. Use-wear development on flint samples throughout the experiment. The images are taken with a ZEISS Axio Scope.A1 MAT using a 10x objective.

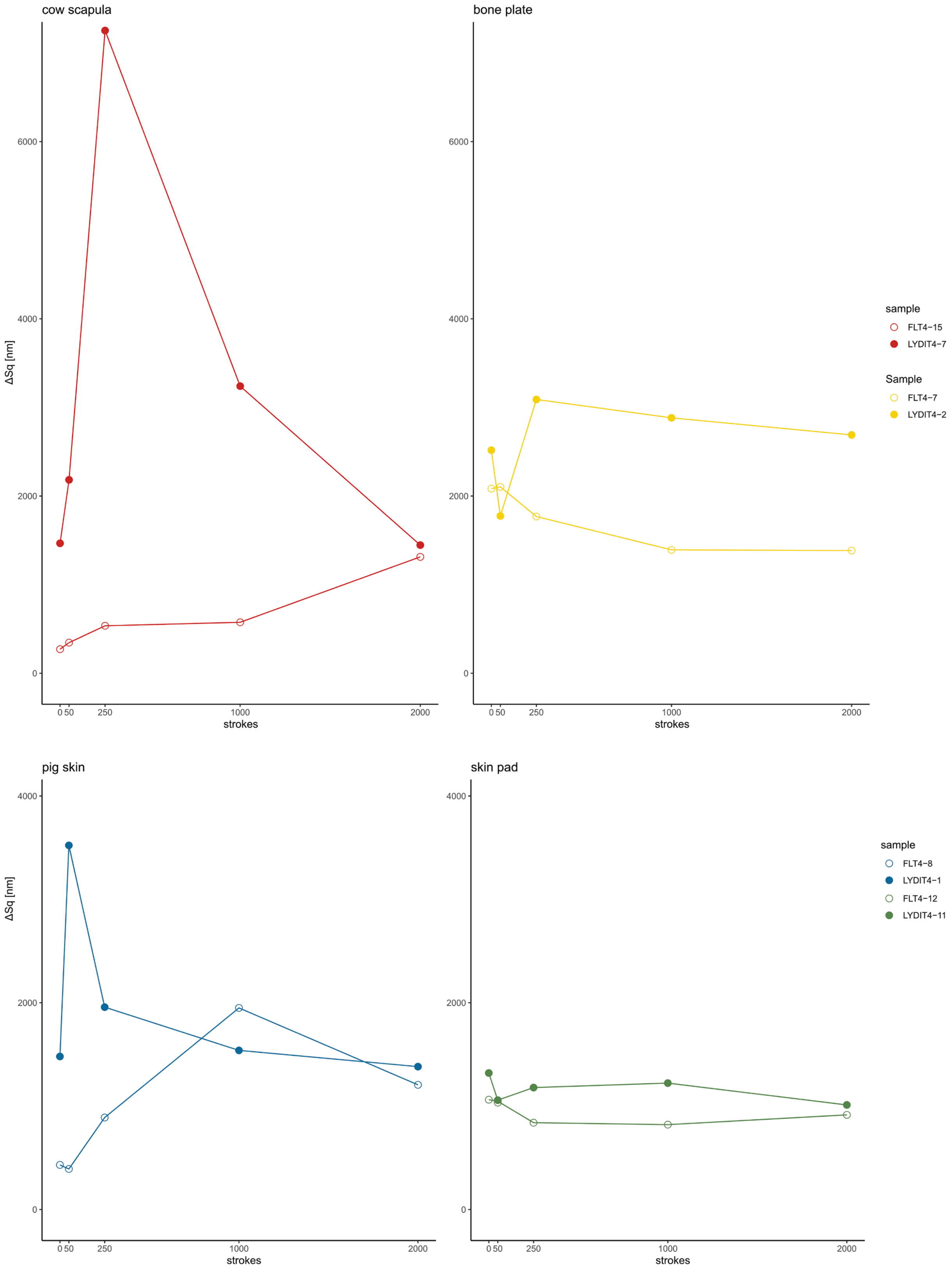

Fig. 12. Quantitative use-wear development on samples used on hard (top) and soft (bottom) contact materials. Sq as a parameter was calculated according to ISO 25178-2.

nature of the use-wear formation process. The surface changes are not reflected in a continuous increase or decrease of the calculated parameters, instead, these processes alternate over time. In their experimental study Ibáñez and Mazzucco (2021) documented a continuous wear development based on qualitative and quantitative data towards a decrease in surface roughness. However, the experimental samples constitute one crucial difference between both experiments. While Ibáñez and Mazzucco used knapped samples, due to the defined research questions and goals, the presented study is based on machine-cut experimental standard samples. It should be noted that the experimental standard samples are not to be compared to knapped samples or intended to replicate a natural surface. Instead, the use of these samples creates a comparable framework by reducing variability and thus, eliminating an influencing factor. Hence, the machine-cut surface appears rather polished due to the use of a lapidary slab saw and a fine-grained diamond band saw and differs from natural (knapped) surfaces. This means, relating to the results from Ibáñez and Mazzucco, the initial surface of the experimental samples likely influences the outcome.

With the exception of sample LYDIT4-2 and LYDIT4-11, the resulting surface texture modification is at first equal to an increase in surface roughness, as expressed by the Sq parameter. In the following cycle, this trend was reversed and the surface roughness decreased. Again, these observations are assumed to be correlated with the initial surface texture of the experimental samples. The first rapid increase in surface roughness documented on most samples could be explained with initial abrasion processes (Schmidt et al., 2020) removing the surface created by the saws and leading to a temporary state of a more "natural" surface. The subsequent decrease in surface roughness is in accordance with the data from other similar studies (Ibáñez and Mazzucco, 2021; see also Rodriguez et al., 2021).

Furthermore, the assumption that the initial surface roughness plays an important role becomes evident when comparing the results of the two sample raw materials involved. In comparison to silicified schist, flint is the harder raw material, as shown (Fig. 12). At the same time, flint has a lower surface roughness. Based on the measurements taken of the standard samples before the experiment was conducted, the mean Sq value for flint is 918.5 nm, while the value for silicified schist is 1786.6 nm. Data shows that the formation of use-wear did not progress at the same rate for both raw materials (Stemp and Stemp, 2003). Polish as surface texture modification developed more rapidly on silicified schist. Flint needed to be used more intensively for the surface to be affected. The data indicates that the two aspects, raw material hardness and surface roughness, likely play a significant role concerning surface texture modification. A surface with a higher surface roughness seems more prone to abrasion processes than an equivalent one with a lower surface roughness. The same can be said for raw materials with a lower hardness compared to harder raw materials. Nevertheless, it remains unclear whether use-wear formation on silicified schist and flint progresses through the same stages. The data suggests that this could be the case (Fig. 13), especially when considering the before mentioned decrease in surface roughness after an initial increase. These observations emphasise the need of raw material characterisation in functional analyses as one variable involved (e.g. Lerner, 2007; Lerner et al., 2007; Lerner, 2014; Pedergnana and Ollé, 2017; Marreiros et al., 2020). Otherwise, questions related to tribological aspects including fracture mechanics and abrasion processes (Schmidt et al., 2020) will not be answered.

Based on the data from this experiment, the crucial impact of use intensity or duration on wear formation becomes evident. Measurements taken before and after each cycle highlight the complementary nature of qualitative and quantitative data. Initial surface modifications are barely or not at all visible, but quantifiable. Results indicate that changes on the samples' micro surface texture are more visible during

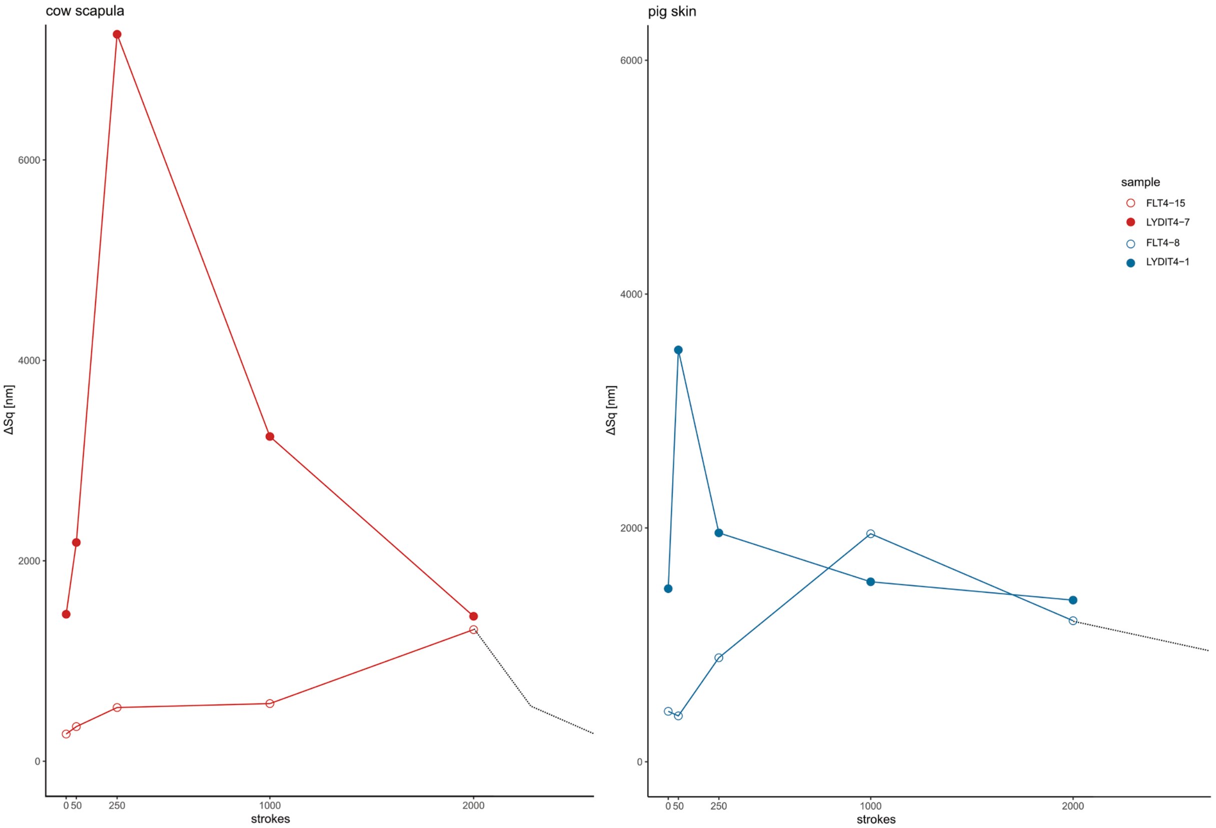

Fig. 13. Quantitative use-wear development on samples used on pig skin and cow scapula. Sq as a parameter was calculated according to ISO 25178-2. The black dotted lines indicate a hypothetical trend how Sq could develop on a flint in case the samples would be used further.

the first cycles (Ibáñez and Mazzucco, 2021) according to the quantitative measurements. Perhaps due to the machine-cut surfaces of the experimental standard samples, the processes and resulting patterns of surface texture modifications are complex, making it nearly impossible to determine the cycle based on the quantitative data. Especially for samples used on soft contact material, this problem is also known for samples with a natural, knapped surface (Ibáñez and Mazzucco, 2021; Rodriguez et al., 2021). Depending on the stage of development, worked material can only be identified with a low degree of confidence due to the problem of similar surface characteristics and thus an overlap of unused and used areas. At the same time, use-wear can also appear as quantitatively identical after the use of different contact materials at different stages (see LYDIT4-1 (50 strokes) and LYDIT4-7 (1000 strokes) as an example; Fig. 12). These aspects make it difficult to discriminate functional traces and simultaneously hard to identify the use duration based on either qualitative or quantitative data solely.

With the aim to address use-wear formation processes of different types of traces as well as the mechanical fracture principles behind the processes, variable control needs to be considered in experimental design, at least in a first step (Fig. 14). The mechanical understanding of

Fig. 14. Application of an archaeological-like experimental approach compared to a supplementary standardised experimental approach. Illustration by Nicole Viehöver.

wear formation processes will build the basis for archaeological applications and interpretations of the various types of evidence observed on artefacts. Artificial contact material can function as a standardised, controlled proxy for a specific material property. Even though the surface texture modification seems slightly weaker when hard artificial instead of natural contact material is used, the cause-effect relationship is still comparable. Thus, artificial contact material leads to reproducible results and allows for pattern recognition in use-wear formation.

5. Conclusions

Reconstructing past stone tool use aims at understanding early hominin behavioural dynamics. While the study of traces left on the artefacts' surface after use can provide evidence for the contact material and the performed movement, the understanding of the formation processes of the different types of use-wear traces holds further potential. These data can contribute to the reconstruction of other crucial aspects such as the intensity of use, the condition of the contact material, and ultimately improve the recognition of diagnostic wear patterns. The sequential experiment presented in this paper aimed at investigating use-wear formation on two different raw materials when unidirectional cutting movements were performed on hard as well as on soft contact materials. Simultaneously, artificial contact materials were tested as a controlled proxy within the experimental design. It could be demonstrated that the use of the different contact materials involved led to the development of wear traces over time. Hard contact material causes surface texture modifications more intensively compared to soft contact material. Based on the quantitative data, the use of the natural hard contact material seemed to favour wear formation in comparison to the artificial equivalent. Additionally, the following observation could be made: use-wear formation is highly dependent on the initial surface texture of the samples itself as well as on use intensity or duration. To better understand the implications of the observations mentioned, additional sequential studies are needed in the future. With the aim to discriminate the character of the different types and sub-types of use-wear and to create a framework for reliable functional interpretations, it is indispensable to scrutinise the abrasive processes, including fracture mechanics, responsible for the formation of use-wear. Thus, controlled experiments are unavoidable to prove the causality of relationships. To implement variable control, standardised, artificial contact material can be used, allowing for reproducible results, as well as more ethical experimentations. This study highlights the complementary character of qualitative and quantitative use-war analyses.

CRediT authorship contribution statement

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

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.

Data availability

Data is available on online repositories

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2022.103737.

References

Álvarez-Fernández, A., García-González, R., Márquez, B., Carretero, J.M., Arsuaga, J.L., 2020. Butchering or wood? A LSCM analysis to distinguish use-wear on stone tools. J. Archaeolog. Sci.: Rep. 31 https://doi.org/10.1016/j.jasrep.2020.102377.

Bradfield, J., 2020. The perception of gloss: A comparison of three methods for studying intentionally polished bone tools. J. Archaeolog. Sci.: Rep. 32 https://doi.org/10.1016/j.jasrep.2020.102425.

Buc, N., 2011. Experimental series and use-wear in bone tools. J. Archaeol. Sci. 38, 546–557. https://doi.org/10.1016/j.jas.2010.10.009.

Calandra, I., Gneisinger, W., Marreiros, J., 2020. A versatile mechanized setup for controlled experiments in archeology. Sci. Technol. Archaeolog. Res. 6 https://doi.org/10.1080/20548923.2020.1757899.

Calandra, I., Pedergnana, A., Gneisinger, W., Marreiros, J., 2019a. Why should traceology learn from dental microwear, and vice-versa? J. Archaeol. Sci. 110, 105012 https://doi.org/10.1016/j.jas.2019.105012.

Calandra, I., Schunk, L., Bob, K., Gneisinger, W., Pedergnana, A., Paixao, E., Hildebrandt, A., Marreiros, J., 2019b. The effect of numerical aperture on quantitative use-wear studies and its implication on reproducibility. Sci. Rep. 9 https://doi.org/10.1038/s41598-019-42713-w.

Calandra, I., Schunk, L., Rodriguez, A., Gneisinger, W., Pedergnana, A., Paixao, E., Pereira, T., Iovita, R., Marreiros, J., 2019c. Back to the edge: relative coordinate system for use-wear analysis. Archaeol. Anthropol. Sci. 11, 5937–5948. https://doi.org/10.1007/s12520-019-00801-y.

Corkum, A.G., Asiri, Y., El Naggar, H., Kinakin, D., 2018. The Leeb Hardness Test for Rock: An Updated Methodology and UCS Correlation. Rock Mech. Rock Eng. 51, 665–675. https://doi.org/10.1007/s00603-017-1372-2.

d'Errico, F., Backwell, L., 2009. Assessing the function of early hominin bone tools. J. Archaeol. Sci. 36 https://doi.org/10.1016/j.jas.2009.04.005.

Dibble, H.L., Pelcin, A., 1995. The Effect of Hammer Mass and Velocity on Flake Mass. J. Archaeol. Sci. 22, 429–439. https://doi.org/10.1006/jasc.1995.0042.

Dibble, H.L., Rezek, Z., 2009. Introducing a new experimental design for controlled studies of flake formation: results for exterior platform angle, platform depth, angle of blow, velocity, and force. J. Archaeol. Sci. 36, 1945–1954. https://doi.org/10.1016/j.jas.2009.05.004.

Dogandžić, T., Abdolazadeh, A., Leader, G., Li, L., McPherron, S.P., Tennie, C., Dibble, H. L., 2020. The results of lithic experiments performed on glass cores are applicable to other raw materials. Archaeol. Anthropol. Sci. 12 https://doi.org/10.1007/s12520-019-00963-9.

Eren, M.I., Lycett, S.J., Patten, R.J., Buchanan, B., Pargeter, J., O'Brien, M.J., 2016. Test, model, and method validation: the role of experimental stone artifact replication in hypothesis-driven. Archaeology null 8, 103–136. https://doi.org/10.1080/19442890.2016.1213972.

Eren, M.I., Mukusha, L., Lierenz, J., Wilson, M., Bebber, M.R., Fisch, M., True, T., Kavaulic, M., Walker, R.S., Buchanan, B., Key, A., 2022. Another tool in the experimental toolbox: On the use of aluminum as a substitute for chert in North American prehistoric ballistics research and beyond. North American Archaeologist 43, 151–176. https://doi.org/10.1177/01976931221074386.

Evans, A.A., Donahue, R.E., 2008. Laser scanning confocal microscopy: a potential technique for the study of lithic microwear. J. Archaeol. Sci. 35, 2223–2230. https://doi.org/10.1016/j.jas.2008.02.006.

Evans, A.A., Lerner, H., Macdonald, D.A., Stemp, W.J., Anderson, P.C., 2014. Standardization, calibration and innovation: a special issue on lithic microwear method. J. Archaeol. Sci. 48, 1–4. https://doi.org/10.1016/j.jas.2014.03.002.

Evans, A.A., MacDonald, D., 2011. Using metrology in early prehistoric stone tool research: Further work and a brief instrument comparison. Scanning 33, 294–303. https://doi.org/10.1002/sca.20272.

Giusca C, E.A., Macdonald D, Leach R., 2012. The effect of use duration on surface roughness measurements of stone tools. NPL Report ENG. National Physical Laboratories, Teddington.

González-Urquijo, J.E., Ibáñez-Estévez, J.J., 2003. The Quantification of Use-Wear Polish Using Image Analysis. First Results. J. Archaeol. Sci. 30, 481–489. https://doi.org/10.1006/jasc.2002.0855.

Grace, R., 1996. Review article use-wear analysis: The state of the art. Archaeometry 38, 209–229. https://doi.org/10.1111/j.1475-4754.1996.tb00771.x.

Hayden, B., 1979. Lithic use-wear analysis. Academic Press (New York, NY).

Ibáñez, J.J., Anderson, P.C., González-Urquijo, J., Gibaja, J., 2016. Cereal cultivation and domestication as shown by microtexture analysis of sickle gloss through confocal microscopy. J. Archaeol. Sci. 73, 62–81. https://doi.org/10.1016/j.jas.2016.07.011.

Ibáñez, J.J., González-Urquijo, J.E., Gibaja, J., 2014. Discriminating wild vs domestic cereal harvesting micropolish through laser confocal microscopy. J. Archaeol. Sci. 48, 96–103. https://doi.org/10.1016/j.jas.2013.10.012.

Ibáñez, J.J., Lazuen, T., González-Urquijo, J., 2019. Identifying experimental tool use through confocal microscopy. J. Archaeol. Method Theory 26, 1176–1215. https://doi.org/10.1007/s10816-018-9408-9.

Ibáñez, J.J., Mazzucco, N., 2021. Quantitative use-wear analysis of stone tools: Measuring how the intensity of use affects the identification of the worked material. PLoS ONE 16, e0257266.

Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., Jäger, F., 2016. Identifying Weapon Delivery Systems Using Macrofracture Analysis and Fracture Propagation Velocity: A Controlled Experiment. In: Iovita, R., Sano, K. (Eds.), Multidisciplinary Approaches to the Study of Stone Age Weaponry. Springer, Netherlands, Dordrecht, pp. 13–27. https://doi.org/10.1007/978-94-017-7602-8_2.

Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., Jäger, F., 2014. Projectile impact fractures and launching mechanisms: results of a controlled ballistic experiment using replica Levallois points. J. Archaeol. Sci. 48, 73–83. https://doi.org/10.1016/j.jas.2013.01.031.

International Organization for Standardization, 2012. ISO 25178-2 – Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters.

Keeley, L.H., 1980. Experimental determination of stone tool uses : a microwear analysis. University of Chicago Press.

Key, A., Fisch, M.R., Eren, M.I., 2018. Early stage blunting causes rapid reductions in stone tool performance. J. Archaeol. Sci. 91 https://doi.org/10.1016/j.jas.2018.01.003.

Kranioti, E.F., Grigorescu, D., Harvati, K., 2019. State of the art forensic techniques reveal evidence of interpersonal violence ca. 30,000 years ago. PLoS ONE 14, e0216718.

Lerner, H., Du, X., Costopoulos, A., Ostoja-Starzewski, M., 2007. Lithic raw material physical properties and use-wear accrual. J. Archaeol. Sci. 34, 711–722. https://doi.org/10.1016/j.jas.2006.07.009.

Lerner, H.J., 2014. Intra-raw material variability and use-wear formation: an experimental examination of a Fossiliferous chert (SJF) and a Silicified Wood (YSW) from NW New Mexico using the Clemex Vision processing frame. J. Archaeol. Sci. 48, 34–45. https://doi.org/10.1016/j.jas.2013.10.030.

Lerner, H.J., 2007. Digital Image Analysis and Use-Wear Accrual as a Function of Raw Material: An Example from Northwestern New Mexico. Lithic Technology 32, 51–67. https://doi.org/10.1080/01977261.2007.11721043.

Lin, S.C., Rezek, Z., Dibble, H.L., 2018. Experimental Design and Experimental Inference in Stone Artifact Archaeology. J. Archaeol. Method Theory 25, 663–688. https://doi.org/10.1007/s10816-017-9351-1.

Macdonald, D., Stemp, W., Evans, A., 2018. Exploring the microscale: Advances and novel applications of microscopy for archaeological materials. J. Archaeolog. Sci.: Rep. 18 https://doi.org/10.1016/j.jasrep.2018.02.036.

Macdonald, D.A., 2014. The application of focus variation microscopy for lithic use-wear quantification. J. Archaeol. Sci. Lithic Microwear Method: Standardisation, Calibration Innovation 48, 26–33. https://doi.org/10.1016/j.jas.2013.10.003.

Macdonald, D.A., Bartkowiak, T., Stemp, W.J., 2020. 3D multiscale curvature analysis of tool edges as an indicator of cereal harvesting intensity. J. Archaeolog. Sci.: Rep. 33, 102523 https://doi.org/10.1016/j.jasrep.2020.102523.

Marreiros, J., Calandra, I., Gneisinger, W., Paixão, E., Pedergnana, A., Schunk, L., 2020. Rethinking Use-Wear Analysis and Experimentation as Applied to the Study of Past Hominin Tool Use. Journal of Paleolithic Archaeology 3. https://doi.org/10.1007/s41982-020-00058-1.

Martisius, N.L., 2022. Accessing the ephemeral using multiscale 3D microscopy of bone microwear. J. Archaeolog. Sci.: Rep. 45, 103634 https://doi.org/10.1016/j.jasrep.2022.103634.

Martisius, N.L., McPherron, S.P., Schulz-Kornas, E., Soressi, M., Steele, T.E., 2020. A method for the taphonomic assessment of bone tools using 3D surface texture analysis of bone microtopography. Archaeological and Anthropological Sciences 12. https://doi.org/10.1007/s12520-020-01195-y.

Martisius, N.L., Sidéra, I., Grote, M.N., Steele, T.E., McPherron, S.P., Schulz-Kornas, E., 2018. Time wears on: Assessing how bone wears using 3D surface texture analysis. PLoS ONE 13, e0206078.

Ollé, A., Vergès, J.M., 2014. The use of sequential experiments and SEM in documenting stone tool microwear. J. Archaeol. Sci. 48 https://doi.org/10.1016/j.jas.2013.10.028.

Pedergnana, A., Calandra, I., Evans, A.A., Bob, K., Hildebrandt, A., Ollé, A., 2020a. Polish is quantitatively different on quartzite flakes used on different worked materials. PLoS ONE 15. https://doi.org/10.1371/journal.pone.0243295.

Pedergnana, A., Ollé, A., 2017. Monitoring and interpreting the use-wear formation processes on quartzite flakes through sequential experiments. Quat. Int. 427 https://doi.org/10.1016/j.quaint.2016.01.053.

Pedergnana, A., Ollé, A., Evans, A.A., 2020b. A new combined approach using confocal and scanning electron microscopy to image surface modifications on quartzite. J. Archaeolog. Sci.: Rep. 30 https://doi.org/10.1016/j.jasrep.2020.102237.

Pfleging, J., Iovita, R., Buchli, J., 2019. Influence of force and duration on stone tool wear: results from experiments with a force-controlled robot. Archaeol Anthropol Sci 11, 5921–5935. https://doi.org/10.1007/s12520-018-0729-0.

Rodriguez, A., Yanamandra, K., Witek, L., Wang, Z., Behera, R.K., Iovita, R., 2021. The effect of worked material hardness on stone tool wear. https://doi.org/10.31219/osf.io/uhkbr.

Rodríguez-Rellán, C., 2016. Variability of the rebound hardness as a proxy for detecting the levels of continuity and isotropy in archaeological quartz. Quat. Int. 424, 191–211. https://doi.org/10.1016/j.quaint.2015.12.085.

Sahle, Y., Hutchings, W.K., Braun, D.R., Sealy, J.C., Morgan, L.E., Negash, A., Atnafu, B., 2013. Earliest stone-tipped projectiles from the Ethiopian rift date to >279,000 years ago. PLoS ONE 8. https://doi.org/10.1371/journal.pone.0078092.

Schmidt, P., Rodriguez, A., Yanamandra, K., Behera, R.K., Iovita, R., 2020. The mineralogy and structure of use-wear polish on chert. Sci. Rep. 10, 21512. https://doi.org/10.1038/s41598-020-78490-0.

Stemp, W.J., 2014. A review of quantification of lithic use-wear using laser profilometry: a method based on metrology and fractal analysis. J. Archaeol. Sci. 48, 15–25. https://doi.org/10.1016/j.jas.2013.04.027.

Stemp, W.J., Chung, S., 2011. Discrimination of surface wear on obsidian tools using LSCM and RelA: Pilot study results (area-scale analysis of obsidian tool surfaces). Scanning 33. https://doi.org/10.1002/sca.20250.

Stemp, W.J., Lerner, H.J., Kristant, E.H., 2013. Quantifying microwear on experimental mistassini quartzite scrapers: Preliminary results of exploratory research using LSCM and scale-sensitive fractal analysis. Scanning 35. https://doi.org/10.1002/sca.21032.

Stemp, W.J., Macdonald, D.A., Gleason, M.A., 2019. Testing imaging confocal microscopy, laser scanning confocal microscopy, and focus variation microscopy for microscale measurement of edge cross-sections and calculation of edge curvature on stone tools: Preliminary results. J. Archaeolog. Sci.: Rep. 24, 513–525. https://doi.org/10.1016/j.jasrep.2019.02.010.

Stemp, W.J., Stemp, M., 2003. Documenting Stages of Polish Development on Experimental Stone Tools: Surface Characterization by Fractal Geometry Using UBM Laser Profilometry. J. Archaeol. Sci. 30, 287–296. https://doi.org/10.1006/jasc.2002.0837.

Stemp, W.J., Watson, A.S., Evans, A.A., 2015. Surface analysis of stone and bone tools. Surf. Topogr. Metrol. Prop. 4, 013001 https://doi.org/10.1088/2051-672x/4/1/013001.

Thun Hohenstein, U., Gargani, E., Bertolini, M., 2020. Use-wear analysis of bone and antler tools from Farneto (Bologna, Italy) and Sa Osa (Oristano, Italy) archaeological sites. J. Archaeolog. Sci.: Rep. 32, 102386 https://doi.org/10.1016/j.jasrep.2020.102386.

Zhilin, M., 2017. Mesolithic bone arrowheads from Ivanovskoye 7 (central Russia): Technology of the manufacture and use-wear traces. Quat. Int. 427, 230–244. https://doi.org/10.1016/j.quaint.2015.09.095.