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Multi-stage experiments in Bronze Age spear combat: insights on wear formation, trauma, and combat contexts☆

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A B S T R A C T

This paper presents and discusses an experimental investigation of Bronze Age spear combat, with a focus on the impacts of bronze points against each other and other materials such as wooden shafts and shields, and animal tissues which act as a proxy for the human body.

A replicable methodology comprising of a series of interconnected experiments gradually shifting the ratio between control and actualism is presented. The results offer fresh insights into prehistoric combat dynamics and the relationship between combat style, contact material, and the formation of wear traces. A comprehensive account of the morphology and formation dynamics of the damage inflicted on weapons, skin, and bone is provided, supported by detailed photographic documentation.

The experimental design permitted to assess the frequency and type of collisions that would occur in actual spear combat. Furthermore, the development and modification of wear traces over time was also observed for the first time on spear points. The tests provided further insights into the level of training and skill required to execute specific movements with different combat objectives. Potential indicators for spear use in various combat contexts, such as fighting against multiple opponents versus more controlled encounters like duels, have been identified. The wear traces produced experimentally find convincing comparisons in the archaeological record.

In conclusion, the results contribute to a more detailed understanding of Bronze Age armed encounters and provide robust guidance for interpreting combat marks on archaeological copper alloy weapons and on bones.

1. Introduction

In Europe, the Bronze Age is arguably the period in which warfare becomes institutionalised and its practices and symbols penetrate several aspects of society including economics and worldview (Harding 2007; Horn and Kristiansen 2018; Molloy and Horn 2020; Vandkilde 2014). In order to properly understand European Bronze Age, one cannot leave aside the investigation of weapons, their use, and their users. By investigating the events weapons have been through before they entered the archaeological record, it is possible to gain insight on the reality of Bronze Age violent encounters or formulate hypotheses on what influenced their placement in specific contexts such as water depositions, hoards, or graves (e.g. Amkreutz et al., 2019; Dolfini 2011; Melheim and Horn 2014; Molloy 2011; Mörtz 2018; Mörtz et al., 2021; Tarbay et al., 2021).

An effective way to reconstruct an artefact's ways of use and infer its life-path is by implementing experimental archaeology and wear analysis. This methodology is well established in the study of artefacts made of materials such as stone or flint, but for metal implements this approach has only very recently left its infancy (see Dolfini and Crellin 2016 for a review). Recently, experimental investigation of wear on Bronze Age weapons has increased, but these studies focused mostly on swords leaving other weapon categories largely unexplored (cf. Gentile and van Gijn 2019; Hermann et al. 2020b; Knight 2019). Similarly, the experimental investigation of trauma inflicted with Bronze Age weapons primarily researched lesions from swords and daggers (cf. Downing and Fibiger 2017; Strong and Fibiger 2023; Molloy 2007). In contrast to earlier work, this paper focuses on the much-understudied bronze spears by presenting a methodologically refined experimental approach to the investigation of their use and of the development of wear traces on their surface.

The first attempt at experimental research on bronze spears is represented by the work published by Anderson in 2011. Bronze Age spear replicas were thrown and thrust at leather and bronze shields.

☆ The authors wish to dedicate this paper to the memory of Prof. David Fontijn.

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Additionally, a series of 'informal strikes' involving short-shaft spears, shields, and a sword were tested. Finally, the offensive potential of the spear points was tested against a 'fresh pig carcass', used as a substitute for the human body. Anderson concluded that the absence of tip damage on archaeological spears could not represent good evidence for lack of use in thrusting and throwing motions (2011, 608). Furthermore, she proposed that Bronze Age spears could have been effectively mounted on short shafts and used in a 'sword-like manner' while she deemed longer shafts to be quite unwieldy (Anderson 2011, 605, 607). On the other hand, she noted that the trace patterns obtained in her experiments did not achieve a sufficient degree of similarity with the patterns observed on original items, ascribing this discrepancy to inconsistencies in material properties between replicas and originals or to the methodology employed for the strikes (Anderson 2011, 606-10). More recently, further experiments with replicas of bronze spears were published by Hermann et al. within the larger framework of the Bronze Age Combat project, which mostly focused on swords (2020a). These experiments envisaged a series of 'controlled weapon tests' with bronze spears colliding against bronze swords and replicas of shields made of bronze, leather, or wood held statically against a solid frame. They identified 'tip pressure' wear traces as a proxy for impacts against shields and, like Anderson, they deemed the short-spear sword-like use as particularly serviceable (Hermann et al., 2020a, 94).

In summary, experimental knowledge on combat wear formation on bronze spears is relatively narrow in its scope and would benefit from further methodological refinement. Although throwing activities and impacts against static shields have been more extensively tested in previous research, several other scenarios, such as spear point-against-point impacts, arguably the main cause of wear development, are still mostly unexplored. Lastly, most of the spear combat situations recreated so far revolved around the use of short-shaft spears, held in one hand and used in a sword-like manner. Although this scenario may be plausible, there is currently no direct evidence which supports the short-spear hypothesis for the Bronze Age. On the other hand, there are several indicators for the use and circulation of longer spears coming from the archaeological record (e.g. Arnoldussen and Visser 2014, 100; Hooper and O'Connor, 1976) as well as from coeval iconography (cf. Horn 2019; Skoglund et al. 2022; Toreld 2015).

This paper aims at contributing to the study of Bronze Age combat and of the wear formation dynamics on bronze items by:

- Proposing an extensive, fine-tuned, and modular experimental framework with different degrees of variable control.
- Investigating different modes and contexts of use of the spears within a variety of close-combat situations, with a focus on longer shafts (both with one hand and two hands).
- Exploring for the first time the frequency and transformation of wear traces on bronze weapons over time.
- Presenting a detailed account of the wear marks produced on spear points in several different conditions, with the employment of stereomicroscopy (up to ×55 magnification). Additionally, a reference collection of pictures of all wear traces produced in the tests is made available(supplementary data: additional data).
- Expanding the knowledge on Bronze Age (spear) combat by assessing the suitability of these weapons for the execution of different combat styles or inflicting different types of wounds.
- Providing additional insights for the study and identification of osteological evidence for weapon trauma.

Finally, a small example of wear traces detected on archaeological Bronze Age spears is provided for comparison and to display the potential of the approach.

2. Materials and methods

An accurate control of the variables involved in an experiment is crucial for its scientific validity and its potential for replicability. On the other hand, strict control often limits the extent to which the process that takes place in the laboratory is analogous to the past action one is trying to emulate. Finding a good compromise between actualism and variable control is one of the main challenges of experimental archaeology, and it is particularly relevant in the design of experiments aimed at reconstructing combat action (Gentile 2022). The method here presented envisages a series of interconnected experiments in which control is gradually reduced in favour of analogy. In this workflow, the performance and results of one test are both informative for, and tested against, the performance and outcome of the following test. By doing so, it is possible to strengthen confidence in the results of each test and increase generalisation.

2.1. Users and materials

A series of experiments was performed in 2020 in Leiden (NL) and it focused on the testing of replicas of Bronze Age spears handled by expert users to study the outcome of collisions of the weapons against each other, wooden shields and an animal carcass used as a proxy for a human body (see also Gentile 2022).

2.1.1. Users

The weapons were handled by two of us (C.vD., engagement and wounding tests, and O.tM., engagement tests) each having more than a decade of experience in training and teaching historical martial arts, and a specialisation in medieval polearms and one-handed weapons. Both expert users are recognised trainers by the National Sport Federation of Historical European Martial Arts of the Netherlands (HEMA-bond).

2.1.2. Weapon replicas

Two replicas of Bronze Age spears (A and B) were commissioned to the archaeologist and bronze-smith Ørjan Engedal (Fig. 1, left). The replicas reproduced Late Bronze Age flame-shaped type spears and were based on one specimen found in the Netherlands (Butler 1987, Fig. 5 n.11). The points were 27 cm long, with a blade part 19 cm long and 4,5 cm wide, and a socket part 8 cm long with an internal diameter of 2 cm. Their weights were 260 and 266 g. The replicas were crafted with a composition of Cu 90%, Sn 9.2% and Pb 0.8% to imitate Late Bronze Age alloying traditions (cf. Molloy and Mödlinger 2020). After casting, they underwent two rounds of hammering separated by an annealing phase

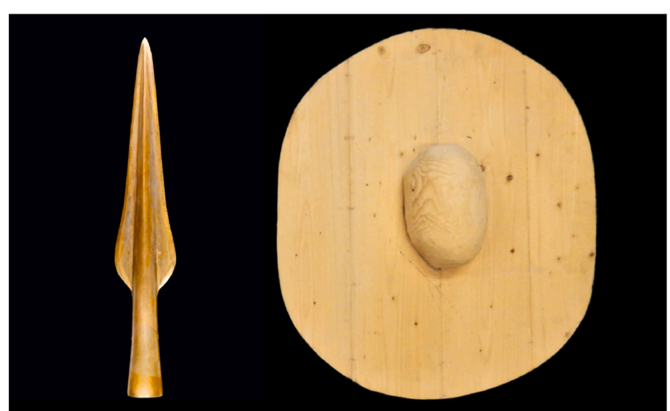

Fig. 1. one of the replica spear-points (left) and one of the replica shields (right) used in the experiments. Photos: Valerio Gentile.

at c. 500 °C. Hammering reduced the edges from 1.8 to 2 mm to below 0.3 mm thickness. The spears were mounted on shafts of dried European ash (*Fraxinus excelsior*) 170 cm long and with a diameter of 30 mm, which falls within the size range of the few surviving Bronze Age spear shafts known (cf. Hooper and O'Connor 1976; Arnoldussen and Visser 2014). The almost exclusive preference of ash to produce spear shafts is well-documented for the Bronze Age (Arnoldussen and Visser 2014). The spearheads were attached to the shaft using brass screws and bolts passing through the peg-holes to allow quick mounting and dismounting of the points for examination. The head of the screws and the bolts were wrapped in layers of duct tape prior to each experiment to prevent their direct contact against the opponent's spear. The total length of the spear replicas (point and shaft) measured c. 182 cm, with the shafts running inside the bronze points for c. 15 cm.

Two wooden shields with central handle (Fig. 1, right) were modelled after the shape and size of the wooden Bronze Age shield excavated in Annandale (Molloy 2009). Taking the shrinkage of archaeological wood into account (Nguyen et al. 2018), the reproductions were made 75 cm long, 67 cm wide and 18 mm thick. The shields used during the experiments are not exact replicas of the Annandale shield (made from a single piece of alder), but rather functional reproductions made from four planks and a single beam of spruce (*Picea abies)*, which were glued together and strengthened with wooden dowels (Gentile 2022). These reproductions can be used in the same manner as the original shield, allowing the expert users to fight using analogous restrictions and protection.

2.1.3. Animal material

A roe deer (*Capreolus capreolus*) carcass was employed as an analogy for a human body under the expectation that lesions inflicted on it by the spear attacks would be sufficiently similar to lesions that would be inflicted on a human body (cf. Anderson 2011; Molloy 2007, 2008; Strong and Fibiger 2023). Likewise, the potential wear forming on bronze weapons impacting with animal (medium size mammal) tissues is assumed to be not significantly different from the one produced by human tissues for diagnostic purposes.

Importantly, no animal killing was commissioned nor rewarded: the carcass was obtained from a game butcher after muscle tissues and internal organs were removed and it would have been otherwise discarded (Gentile 2022). Although it is expected that such treatment reduced the analogy with the most robust areas of the human body, the removal of muscle made the target better imitate other areas often hit during combat, such as the head and forearms, where skin and bone are closer to each other (Hermann et al. 2020b, 1068-70; Horn 2023, 59–61; Kellett 2015; Molloy 2007; 2008). In the tests, the skin in the areas affected by the strikes was c. 1 mm thick. Human skin thickness differs substantially according to different parameters but is on average around 1.2 mm thick (cf. Lee and Hwang 2002): considering that one of the trials' aims was to recreate small bleeding wounds (see below), the degree of analogy was deemed acceptable. Furthermore, the skin was dehaired before the experiments to simulate contact with human skin and facilitate the documentation of the wounds.

2.2. Experiment layout

2.2.1. Choice of combat movements and approaches

Due to the lack of direct information on prehistoric ways of fighting, the basic bio-mechanical notions of historic manuals on combat with analogous pole weapons (Knight and Hunt 2008; Meyer and Forgeng 2015; Thalhoffer and Schulze 2010) were used to build an elementary scaffolding of combat movements which were plausible with the Bronze Age weapons tested (cf. Gentile and van Gijn 2019; Hermann et al. 2020a). Drawing upon this knowledge, the combat tests were divided into '*engagement*' and '*wounding*' phases. The first is the phase in which combatants attempt at gaining dominance over the adversary and break through each other's defences. The latter identifies the phase in which, after overcoming the rival's defence, a combatant delivers a blow to the opponent's body according to opportunity as well as intention (van Dijk and ter Mors 2021).

Fig. 2. Moments from Experiment 3 with expert users sparring freely according to different styles. From top to bottom: one-handed spear and shield, two-handed spear binding, two-handed spear striking. Photos: Valerio Gentile.

Two-handed spear and one-handed spear (and shield) techniques most likely to be performed with these kinds of weapons were selected to be tested (Fig. 2). The two-handed techniques were further split into two different skill and context dependent approaches. When facing a single opponent, for example during a duel, 'binding' can be successfully deployed. In this combat style combatants maintain contact between their weapons while fighting. This allows the moves of an opponent not only to be seen but also to be felt through the weapon, enabling a much faster and more accurate response. In this situation, one uses the binding to probe or create small openings in an opponent's defence to exploit. Resorting to binding when defending against multiple opponents would not be as effective, since leaving the bind - and thus control - over an opponent's weapon to attend an attack coming from another source would provide an opening for the first opponent to hit. In this situation, the deployment of a more 'striking'-oriented combat style would better defend against multiple directions: a firm counterstrike is used to

Table 1
Experiment 1 – description of combinations.

Combat combination	Attacker	Defender
One-handed spear (and shield)		
1	The spear was held in a couched position, to simulate a thrust to the defender's upper body	From a couched spear position, the spear of the attacker was pushed with the wings to the ground, to create an opening
2	The spear was held in a couched position, to simulate a thrust to the defender's upper body	From a couched spear position, the spear of the attacker was struck with a sweeping motion to the midrib, to push it to the side and create an opening
3	The spear was held in a couched position, to simulate a thrust to the defender's upper body	From a couched spear position, the shaft of the attacker was struck with a sweeping motion to the right side, to create an opening
Two-handed spear binding		
4	The spear was held horizontally at the right shoulder, to simulate a thrust to the defender's lower body	The spear was held horizontally at the right shoulder and then pushed the attackers spear on the wings to the right side, to create an opening
Two-handed spear striking		
5	The spear was held horizontally at the right hip, to simulate a thrust to the defender's upper body	The spear was held vertically above the left shoulder and then struck the attacker's spear with a sweeping motion on the midrib, to create an opening
6	The spear was held horizontally at the right hip, to simulate a thrust to the defender's lower body	The spear was held vertically above the right shoulder and then struck the shaft of the attacker, to create an opening
7	The spear was held horizontally at the right hip, to simulate a thrust to the defender's lower body	The spear was held vertically above the left shoulder and then struck the attacker's spear with a sweeping motion on the edge, to create an opening

quickly block or push away an incoming attack before striking or returning to guard position, without attempting to further control the opponent's weapon (cf. van Dijk 2020, 69–75). In terms of skill, binding techniques are to be considered more advanced while striking solutions are to be considered more basic and easier to learn as they are more in tune with instinctive behaviours (cf. Gentile and van Gijn 2019). Nevertheless, as explained above, regardless of skill, in certain contexts it is more serviceable to use one approach instead of the other. The differences between binding and striking approaches are less prominent in (one-hand) spear-and-shield combat since defence is entrusted mainly to the shield. Even when binding, the shield would compensate for the opening created while leaving a bind without having control over an opponent's weapon. In the wounding experiment, different attacks which could have been executed within these three approaches were tested. During all the experiments, spears were held both in an overhand and underhand position. In absence of external factors (e.g. specific combat formations like the phalanx), usually both combat positions are used interchangeably during combat according to the situation.

2.2.2. Experimental setup

The experimental programme envisaged three experiments with different but complementary designs (Gentile 2022). Two experiments were dedicated to the testing of the engagement phase (Experiment 1 - controlled collisions, and Experiment 3 – free sparring) and one to the wounding phase (Experiment 2). The numbering reflects the chronological order in which the experiments were carried out.

The experiments were performed in this particular sequence to better allow the expert users to gain insights into the capabilities and characteristics of the bronze spears necessary to optimally perform the succeeding experiment. Earlier experiments with bronze swords had demonstrated that bronze weapons can develop use wear as well as structural damage rather fast (Gentile and van Gijn 2019; Hermann et al. 2020b; Knight 2019). Therefore, the first experiment (engagement), besides answering the specific research questions on wear formation, also allowed to assess whether the bronze spears could withstand forces and techniques normally used with historic steel weapons. In the second experiment (wounding) the force levels used to execute the attacks were calibrated on the insight gained during the first experiment. Additionally, Experiment 2 provided insights on the type of attacks and necessary strength required to inflict the intended trauma during each combat style. The gained knowledge then was incorporated in the third experiment (engagement) recreating the most analogous situations to actual combat, in order to permit the emergence of unpredictable variables, and to assess to what extent results of more controlled experiments are confirmed when actualism increases.

The replicas and wear traces they developed were documented by the means of stereomicroscopy (Leica M80) before and after each experiment. Multiple sketches for each side of the weapons were produced with the purpose of mapping the occurrence of the traces during the tests. All the experiments were also recorded by means of regular and high-fps cameras.

2.2.2.1. Experiment 1 (engagement, controlled collisions). The first experiment was designed to induce specific collisions between weapons based on types of attacks and defences which are most expected to occur within the different types of combat approaches discussed above, with the aim to assess the material affordances of the weapons and explore a connection between combat movement and use-wear formation. A total of seven combat combinations of attacks and defences were put together (see Table 1).

On a rate of perceived exertion (RPE) from 1 to 10 (Borg 1982, 379–380) the movements were performed with RPE of 5–6) for one handed, a RPE of 5–6 for two handed binding, and a RPE of 7–8 for two handed striking combinations. These values matched the level of strength the expert practitioners would have used for each style with historic weapons of the same type. At the expense of actualism, in this experiment one of the weapons was not moved at normal speed but kept more static in a manner similar to previous experimental research (cf. Anderson 2011; Hermann et al., 2020a; Knight 2019). This choice was operated to ensure bronze-on-bronze collisions, which normally constitute a rarer occurrence in real combat (see Experiment 3). This degree of control also permitted to better monitor the angle at which the two spear points met.

For documentation, each weapon was ideally broken down into two sides (A and B) and two edges, S for striking and D for defending and used accordingly. This division was operated to maximise the chance of distinguishing the damages produced by attacking movements from those derived by defences. Each combination was performed a minimum of two times with combatants exchanging roles, to further assess the consistency of the results. At the end of two repetitions, the replicas were inspected for traces and photographed with macro lenses. This was done to ensure the immediate documentation of any mark in case further collisions modified or replaced the original trace. To further minimise such risk, the trials were subdivided into three sessions: at the end of each session, the spears were also documented by means of stereomicroscopy.

2.2.2.2. Experiment 2 (wounding). This experiment aimed at gaining insights into the wounding potential of the Bronze Age spears, namely assessing their suitability for inflicting lethal as well as deliberately non-lethal trauma, and at exploring the role that cutting and stabbing through flesh and bone could play in the formation of wear traces on bronze spear-points. The secondary aim of the tests was to contribute to the understanding of the traumas inflicted on bones (and flesh) by Bronze Age weapons.

In order to achieve these goals, fourteen attacks were performed on a roe deer carcass torso and two attacks on roe deer long bones (tibia). During the attacks both the carcass and long bones were hung from a suspension system inspired by the one used by B. Molloy in his tests (2007; 2008, 125; see also Strong and Fibiger 2023). The targets were attached to this system from the top by means of a wooden peg attached to a split chain hanging from the horizontal beam of a wooden structure and were held firm at the bottom by two ropes attached to sandbags (supplementary data: Fig. 1). The distance between the attacker and the targets was c. 120 cm, with the targets hanging roughly at shoulder height. The suspension system allowed the targets to move slightly when hit while offering some resistance. This configuration better simulates the behaviour of a combatant when struck and thus is preferable to hitting static, fixed targets.

The attacks consisted of three distinct types and were based on techniques from late medieval combat manuals which explain the use of weapons for a host of various martial contexts, ranging from duels to fight-for-life situations (van Dijk 2020; Kellett 2015). The three types of attacks traditionally mentioned in fights books are cuts (*Schnitt*), strikes (*Haw*) and thrusts (*Stich*), based on the wound they intend to inflict (e.g. Hagedorn 2017; Meyer and Forgeng 2015). Accordingly, three types of attacks were tested in this experiment:

1. Cutting attacks, consisting of pulling or pushing a part of the edge or point along the skin. The cutting attack resembles the 'whipping' attack mentioned by Anderson in her cutting trials, which resulted in deep cut wounds into a pig leg (Anderson 2011, 602–3).
2. Striking attacks, in which the weapon's edge slams against the target in a continuous motion.
3. Thrusting attacks, in which the point is pushed into the target in a continuous motion

These types of attack were performed both with full force power (RPE 7–8), called strong attacks, and less-force (RPE 4–5), named soft attacks. Strong attacks were performed with the expert user's intention to create deep and large wounds, while soft attacks were meant to create smaller and more superficial wounds. Each attack movement performed is compatible with the openings created by the engagement styles selected for the other experiments.

Finally, a combination of attacks was performed in a more actualist manner. The attacks were performed in succession in one single flow, with each attack using the momentum generated by the previous. This sequence was not predetermined, but the expert user spontaneously picked and performed the next attack while completing the former, similarly to what would happen in a real combat situation.

2.2.2.3. Experiment 3 (engagement, free sparring). The third experiment was designed to push to the extreme the level of actualism in recreating combat situations while retaining a sufficient amount of control and safety. This approach was intended to test the preliminary observations of Experiment 1 and to explore aspects which could not be investigated in controlled collisions, such as the degree of combat wear-trace formation over time or the occurrence of combat-related marks not yet discovered.

Contrary to what was performed in Experiment 1, the expert users were not tasked with reproducing specific movements but with sparring freely according to the three approaches established (Fig. 2): one-handed spear and shield, two-handed binding, and two-handed striking. In this experiment wooden shields were actively used for the required style, representing the first time spear points are not tested against static targets but in a dynamic way which mimics how shields were used in the Bronze Age (cf. Molloy 2009).

Due to safety reasons the testing only focused on the engagement phase without stepping into the wounding phase. Each combat was not fought for a predetermined time but continued until the combatants separated. These breaks or disengagements occur naturally during combat, for instance, when an attack is defended adequately and a new line of attack is needed to break an opponent's defence. The action which took place between the start of an engagement and a disengagement was referred to as an 'exchange' and constituted the unit of analysis of the experiment. Four exchanges per combat style were intended to be performed. The spear-points were photographed after each exchange and, at the end of the experiment, they have been analysed under the microscope. The video footage was used to keep track of the number and type of impacts (e.g. point-against-shaft or point-against-point) occurred during the exchanges.

3. Results

At the end of the experiments, a total of 46 wear traces were documented (supplementary data: Table 1). Below the results of each experiment are discussed in detail.

3.1. Experiment 1 (engagement, controlled collisions)

At the end of Experiment 1, a total of 16 collisions took place (seven combinations repeated two times and two additional collisions, see Table 2), which produced 17 wear traces. Similarly to sword-combat experiments (Gentile and van Gijn 2019), some collisions produced more than one trace on the weapons. On the other hand, contrary to previous experiments, some other impacts did not produce any visible mark on the spears.

The vast majority of the wear traces recorded in the test fit well within the categorisation already provided for combat marks on swords (Gentile and van Gijn 2019). Therefore, the same jargon will be used here for the sake of consistency and comparability. Features such as *dents*, *notches, bowing*, and *flattening*, and others have all been identified on the spears, as well as secondary features such as instances of *fissuring, thickening*, *burrs*, and *trails* (supplementary data: Table 1; Figs. 3 and 4). In some instances, it was also possible to observe grooves inside the combat marks produced, as it was for sword combat features (cf. Gentile and van Gijn 2019, 137-9.), which constitutes a proxy for the orientation of the blades on impact.

Although the previously established nomenclature accurately described most of the traces recorded, small additions have been necessary to describe novel types of marks generated during the experiments. One of these features consists of a plastic deformation of the edge, similar to the dents described in Gentile and van Gijn (2019), but with the metal not entirely deforming downwards (from the edge towards the core of the object) but also sideways, displacing the edge from its original outline rather than completely cutting through. The resulting mark appears as an indentation that only partially cuts in the metal and folds protruding on one side of the edge, similarly to how *bowing* was described on swords: consequently, it will be referred as '*bowing dent*' (Fig. 3C and D and 4E-H).

Thanks to the experiment's setup, it was possible to conclude that such features originate when, in an edge-against-edge collision, the angle formed between one weapon's edge and the flat of the other weapon is rather small: this results in one weapon's edge discharging kinetic energy sideways on the edge as well as on the flat of the opponent weapon. These conclusions are corroborated by the recurrent presence of trails on the opposite side of where the dented edge folds towards, indicating the area and the angle of the initial hit. In one case, this kind of collision also produced blow marks on the midrib which were aligned with the trail connected tothe bowing dent, providing additional evidence of a very narrow angle of impact, close to an edge-against-flat

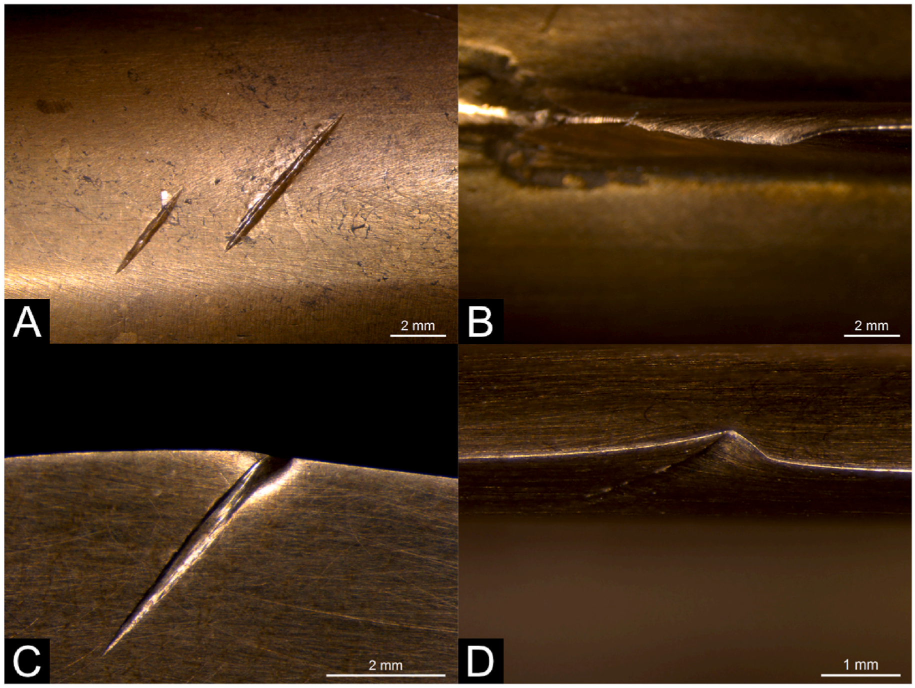

Fig. 3. Some of the combat wear produced on bronze spear-point replicas during the controlled collisions experiment (sessions 1 and 2). (A) Blow marks, (B) bowing, top view (C–D) bowing dent with trail, side and top view. Photos: Valerio Gentile.

situation (Table 2 and cf. Gentile and van Gijn 2019).

The importance of the angle of impact was further highlighted when replicating a striking-style edge-against-edge collision (Table 1, combat combination 7). The first iteration of the combination produced notches on both the spears (Fig. 4A–D). The second iteration did not produce any visible damage: the expert user in charge of the active movement acknowledged to not have been able to hit the other spear on the edge but on the shaft, circumstance corroborated also by the video footage. Therefore, the second combination was repeated. However, also on this occasion the expert user expressed dissatisfaction with the angle of impact achieved. This impression found confirmation in the blow mark developed on the midrib of the moving spear and the blunting of the edge of the spear held still: clear proxies of edge-against-flat collisions (see also Gentile and van Gijn 2019). The third attempt produced bowing dents on both the blades (Fig. 4E–H), indicating that edge collision was indeed achieved, but edge alignment was still less perpendicular than in the first attempt, which produced notches instead.

Drawing upon these findings one can infer that, within the brackets of a given combat combination, a variety of different wear traces (e.g. (bowing) dents or notches) could be produced, and that the angle of impact plays a decisive role in which mark (from said gamut) ultimately forms. There seems to be no strong correlation between trace produced and the offensive or defensive nature of combat gesture, as observed also in previous experiments with swords (cf. Gentile and van Gijn 2019). The combinations in session three demonstrated how the same type of combat damage can occur on both the attacking and defending spears involved in the combination (Table 2). For what concerns blade-against-shaft impacts, in one episode blunting (with fissuring) wear occurred on one of the edges. In all the other contacts no wear was recorded on the points. On the other hand, the shafts developed cuts each time they collided against the blades and in one case it was splintered to the extent of rendering the weapon unusable.

When comparing the type and severity of the damage produced across the combat styles tested, one-handed combat and two-handed binding were significantly less detrimental to the spears than two-handed striking (cf. the only shallow bowing dent in session 1–2 to the deeper bowing dents and notches of session 3: Fig. 3C and D and Fig. 4). Overall, the weapons proved to be perfectly suitable for the combat movements chosen and were able to withstand the amount of force that would have been required for the use for their later, medieval homologues.

3.2. Experiment 2 (wounding)

The experiment produced a vast array of traumas (Table 3; Figs. 5 and 6). In order to describe the types of trauma, in particular the wounds inflicted on the skin, a terminology based on the nomenclature used in forensic pathology was implemented (cf. Dolinak et al. 2005; Payne-James, 2016). A first categorisation was made between *stab* and *cut* wounds: the first is as wide as it is long, whereas the second is longer than it is wide. Wounds on the skin were further classified on the basis of their depth:

- *Impressions*, which did not cut the skin and were only shortly visible.
- *Shallow wounds*, which only cut the top layers (epidermis) and into the lower layer (dermis) of the skin but did not completely penetrate it. These wounds, nevertheless, commonly cut deep enough to inflict bleeding.
- *Deep wounds*, which completely penetrated the skin and thus could damage muscles and tendons up to bones and internal organs.

Some general remarks can be made concerning the correlation between the type of wounds and the attacks. As expected, strong attacks inflicted more severe damage than soft attacks. On the other hand, using one or two hands appears to be a much less relevant variable. Strong strikes and thrusts created large and penetrating wounds, and broken bones, while soft attacks inflicted smaller and shallower wounds. Similarly, soft thrusts could be used to inflict smaller wounds, while forceful thrusts completely transfixed the carcass. It was possible to inflict long cuts while pushing or pulling the blade across the skin, and the force used with these attacks mattered less, in terms of the size of the wounds, than with thrusts and strikes.

The soft two-handed pull and push attacks (attacks 1 and 2, Table 3) were performed with the edge, while the other one-handed pull attacks

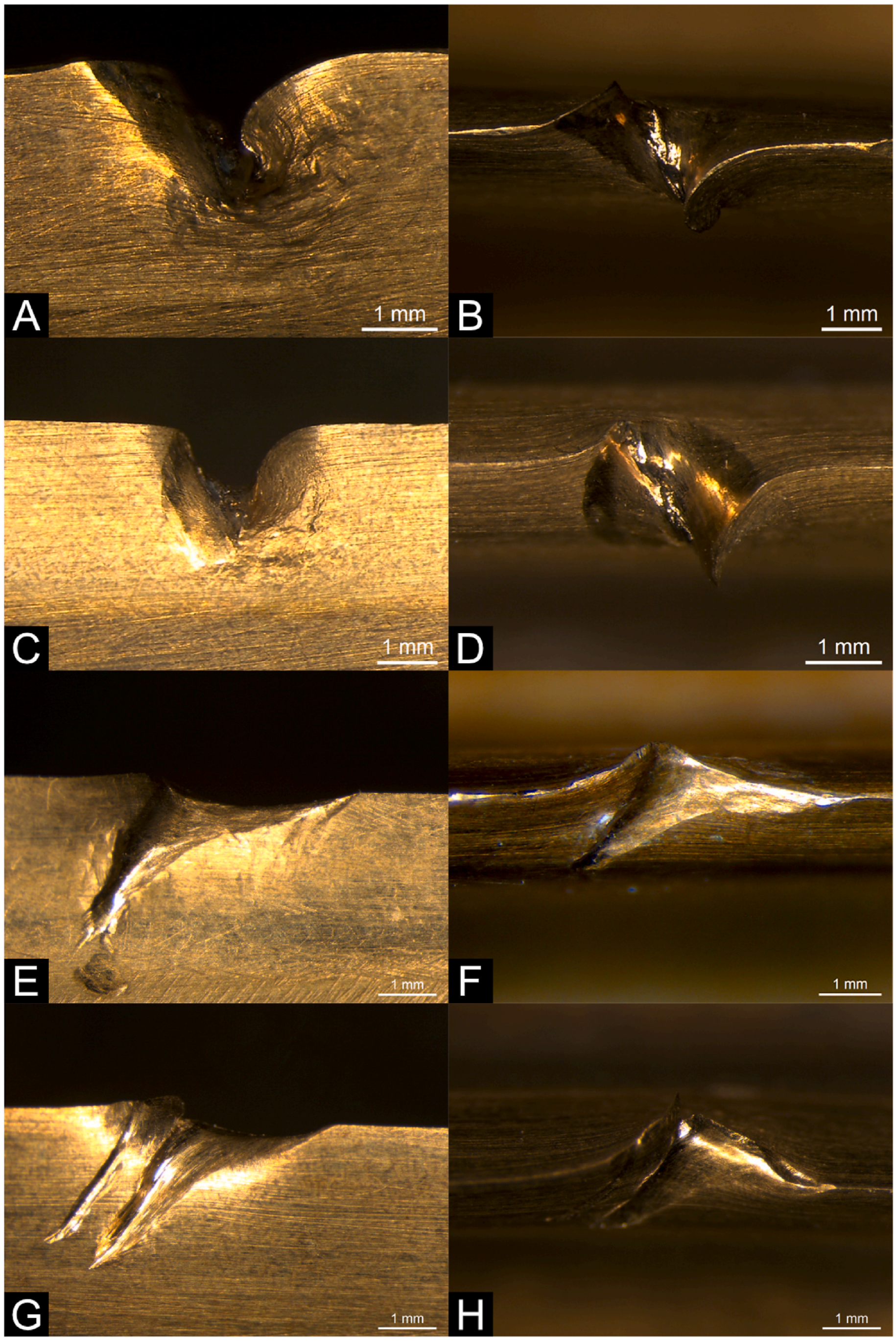

Fig. 4. Some of the combat wear produced on bronze spear-point replicas during the controlled collisions experiment (session 3). (A–B) Notch with burr, side and top view. (C–D) Notch with burr, side and top view. (E–F) Bowing dent with trail, side and top view. (G–H) Bowing dent with trails, side and top view. Photos: Valerio Gentile.

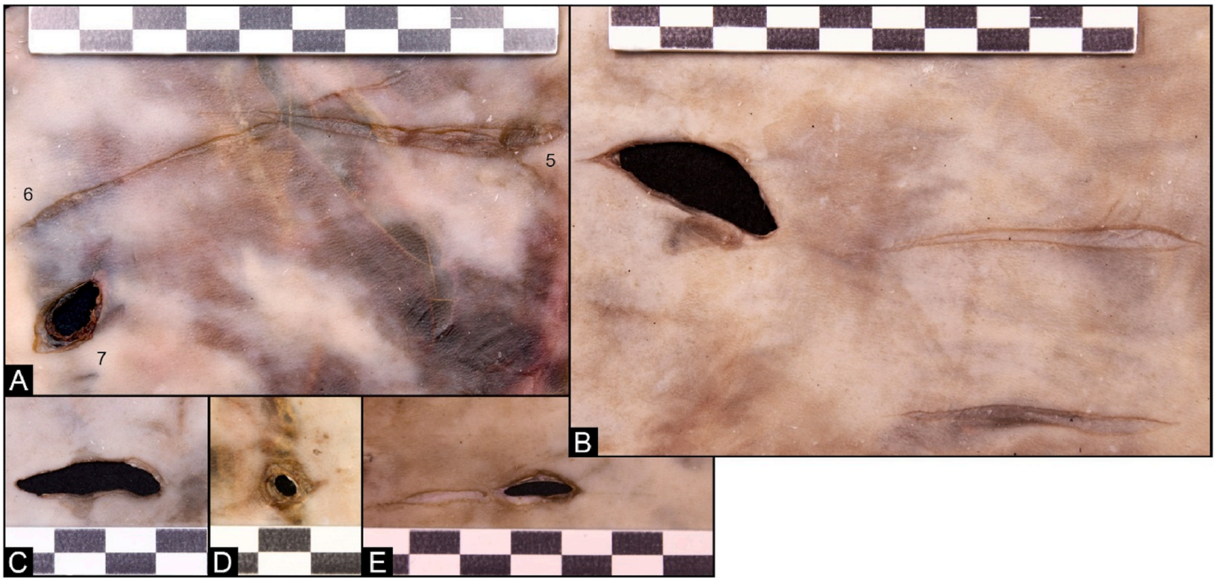

Fig. 5. Skin trauma produced during the wounding experiment. (A) shallow cut (attack 5); shallow cut (attack 6), deep stab (attack 7). (B) deep cut and shallow cuts (attack 9). (C) deep cut (attack 11). (D) deep stab (attack 8). (E) shallow cut and deep cut (attack 10). Photos: Casper van Dijk.

were performed with the tip and the push attacks again with edge (attack 5 and 6, Table 3). Both types of attacks created similar shallow cuts; however, a difference in control was expressed by the expert user, with pulling being more reliable in inflicting shallow cuts than pushing. This aspect was further confirmed during the actualistic combination, consisting of two soft pull and one soft push cuts. The pull cuts, executed with the tip, created two long shallow cuts. However, while performing the push cut with the edge, the tip was caught in the skin and transformed into a thrust which inflicted a large stab wound and a broken rib.

During a strong one-handed strike (attack 12, Table 3), due to the violence of the impact, the carcass was dragged along the movement and after the initial contact both the edge and the tip were drawn over the skin, creating a secondary cut. This explains the difference in trauma compared with the wounds of other strike attacks. The damage inflicted on bone was heavily dependent on the force and type of attack used: a strong strike on the tibia completely shattered the bone, while a softer pull cut with the point produced a small cut (Fig. 6B–E).

Little wear was recorded on the spear performing the attacks. One strike caused a bowing on the edge of the spear (Fig. 7). Such an attack (14, Table 3) was particularly violent: it impacted the carcass in the region of the spine, and then hit the suspension system, completely tearing the carcass from the support. Although the video footage indicates that the spear point impacted the carcass first, the possibility that the feature was altered by the following impact against the suspension system cannot be excluded. During the experiment, also the chipping feature developed earlier in Experiment 1 was slightly altered by the loss of its burr (see below).

Overall, the tests demonstrated that this type of weapon could inflict a large variety of traumas, from shattered bones to shallow bleeding cuts, depending on the attack type and force used. Furthermore, the tests demonstrated how most wounding tends to leave little to no trace identifiable on bones. Expectedly, among the visible traces, those resulting from soft/non-lethal attacks appear less conspicuous.

3.3. Experiment 3 (engagement, free sparring)

At the end of Experiment 3, in which the two expert practitioners sparred freely, 22 new wear traces were observed (supplementary data: Table 1). Among these, four had superimposed or modified marks produced in previous experiments. At the same time, similarly to the other experiments performed, Experiment 3 confirmed that not every collision produces wear traces on the blades (cf. Table 4 and supplementary data: Table 1).

The expert users set to perform combat movements with the same force across the experiments but in Experiment 3, unlike previously, both weapons were used actively. Therefore, the force of the collisions between weapons might have been higher in certain conditions. Furthermore, the distance between the users was not fixed but constantly changing. The less controlled nature of the setup enabled the production and identification of features previously not documented. One novel feature is the bending of the tip of one of the spears as a result of the collision against the wooden shield (Fig. 8A). It is important to note that such a feature presents an evident curvature and differs from the 'tip pressure' recorded in other experiments testing Bronze Age weapons against shields (Hermann et al. 2020a). This discrepancy could be attributed to the dynamic use of the shield as opposed to hitting shields statically anchored to a barrier as it was for other tests. Other new features detected during the free sparring consisted of wear close to or directly on the socket rim, in the form of either blow marks or plastic deformations (Fig. 8B and C). This wear was likely the product of spears sliding past each other and cutting/denting the rim of the socket of the opponent's spear when sliding back. Finally, large *round depressions* on the sockets were produced by violent collisions against the opponent's socket or shaft (Fig. 8D).

Shield fighting in Experiment 3 produced traces which are highly compatible with the ones obtained in Experiment 1. The marks produced consisted mostly of edge blunting and marks on the flat of the weapon, which are an indication of the wide angle at which collisions seem to take place in this kind of combat. This is further confirmed by the shallowness of the bowing dent created during this combat (Fig. 9A and B), which barely cut into the spear edge, similarly to the bowing dent produced in Experiment 1 using the same combat style (Fig. 3C and D). However, in addition to the types of traces already recorded in the corresponding style in Experiment 1, one instance of a particularly small dent (less than 0,5 mm deep) was also recorded.

The binding approach, which hardly produced any wear in Experiment 1, caused more traces in Experiment 3. For example, one asymmetrical dent was produced on each spear-point, likely the result of the same collision (Fig. 9C and D). The discrepancy between experimental results might be ascribed to two factors. On the one hand, the potentially different force of impact in Experiment 3 might have fostered the creation of additional wear traces (see above). On the other hand, the

Table 2
Experiment 1 – combinations tested and outcome.

Session	Combat style	Combat combination	wear on Spear A	wear on Spear B	Notes
1	one-handed spear	1 (two times)	no visible wear	no visible wear	
1	one-handed spear	2 (two times)	**Attack:** blow marks on the midrib (trace ID: 3,4); **Defence (active):** blunting of the edge (trace ID: 1,2)	**Attack:** blow marks, bowing dent (trace ID: 5,6); **Defence:** blunting of the edge (trace ID: 7)	
1	one-handed spear	3 (two times)	**Attack:** cut marks on the shaft	**Attack:** cut marks on the shaft	
2	two-handed spear binding	4 (two times)	no visible wear	**Attack:** blunting of the edge (trace ID: 8)	
2	two-handed spear striking	5 (two times)	no visible wear	no visible wear	
2	two-handed spear striking	6 (one time)	no visible wear	**Attack:** shaft splintered	
2	two-handed spear striking	6 (one time)	**Defence:** blunting of the edge (trace ID: 9)	**Attack:** cut marks on the shaft	Repetition of one combination after shaft breaking of Spear B. This time with the blade of Spear A against a spare shaft
3	two-handed spear striking	7 (two times)	**Defence:** notch, chipping (trace ID: 10, 11); **Attack:** cut marks on the shaft	**Attack:** notch, grazing (trace ID: 16,17)	Defence of Spear B against Spear A hit the shaft
3	two-handed spear striking	7 (one time)	**Attack:** blunting of the edge (trace ID: 13)	**Defence:** blowmark (trace ID: 15)	Repetition of one combination since previous defence of Spear B against Spear A did not hit at the intended angle.
3	two-handed spear striking	7 (one time)	**Attack:** bowing dent (trace ID: 12)	**Defence**: bowing dent (trace ID: 14)	Repetition of one combination since previous defence of Spear B against Spear A did not hit at the intended angle

Table 3
Experiment 2 – description of movements and trauma inflicted.

Attack	Starting position spear	Intention	Attack type	Target	Outcome
1	Vertically above the right shoulder	Two-handed soft attack	Pull cut	Carcass	20 mm wide shallow cut
2	Horizontally at the left hip	Two-handed soft attack	Push cut	Carcass	20 mm wide shallow cut
3	Horizontally at the right hip	Two-handed soft attack	Thrust	Carcass	6 mm wide deep stab
4	Vertically above the right shoulder	Two-handed soft attack	Strike	Carcass	32 mm wide impression
5	Couched spear at the right side	One-handed soft attack	Pull cut	Carcass	57 mm wide shallow cut
6	Horizontally at the left hip	One-handed soft attack	Push cut	Carcass	60 mm wide shallow cut
7	Horizontally at the right hip	One-handed soft attack	Thrust	Carcass	16 mm wide deep stab; cut rib
8	Vertically above the right shoulder	One-handed soft strike	Strike	Carcass	6 mm wide deep stab
9	Couched spear at the right side	One-handed soft attack (actualistic sequence)	2 pull cuts, 2 push cuts	Carcass	34 mm wide deep cut; 69 mm wide shallow cut; 56 mm wide shallow cut; broken rib
10	Couched spear at the right side	One-handed strong attack	Pull cut	Carcass	17 mm wide shallow cut; 14 mm wide deep cut
11	Horizontally at the right hip	One-handed strong attack	Thrust	Carcass	22 mm wide deep cut; cracked rib
12	Vertically above the right shoulder	One-handed strong attack	Strike	Carcass	20 mm wide deep cut; 28 mm wide shallow cut; 6 mm wide deep cut
13	Horizontally at the left hip	Two-handed strong attack	Push cut	Carcass	12 mm wide shallow cut
14	Vertically above the right shoulder	Two-handed strong attack	Strike	Carcass	12 mm wide deep cut
15	Couched spear at the right side	One-handed soft attack	Pull cut	Tibia	3,5 mm wide cut (bone)
16	Vertically above the right shoulder	Two-handed strong attack	Strike	Tibia	shattered tibia

higher number of traces produced by the binding style could also be the product of the relatively smaller number of collisions of this kind performed in Experiment 1 compared to the extensive combat exchanges that took place in Experiment 3 (Table 4).

Similarly to what was noticed for one-handed spear combat, free sparring with the two-handed striking approach yielded results very consistent with the ones obtained in Experiment 1. Despite the relative brevity of the engagements compared to the other styles, the points developed signs of edge-against-flat collisions as well as violent edge-against-edge impacts which produced a conspicuous notch (Fig. 9E and F) with considerable similarities to those produced in Experiment 1 (Fig. 4A and B). The violence of the impacts is also exemplified by the newly recorded features labelled round depressions. As in Experiment 1, shafts accumulated several more cuts during the striking encounters and after three engagements one spear-point was completely snapped off its shaft right below the socket by a defensive counter strike, determining the premature conclusion of the tests.

During the striking style exchanges, modifications of previously recorded traces also occurred. Impacts on one point modified a notch produced in Experiment 1 by altering its profile and bending its burr inwards. Nevertheless, the feature is still recognisable as a notch (Fig. 10). Close to this trace, a more radical change affected the bowing produced in Experiment 2. The impacts deepened the feature to the extent of rendering it similar to a dent (Fig. 10B–C, H-I). Remarkably, the presence of a trail on the same side of where the metal folded, which could unlikely be the result of a single collision, suggests that the

Fig. 6. Bone trauma produced during the wounding experiment. (A) cut on a rib (attack 7). (B) cut on tibia (attack 15). (C) Broken rib (attack 9). (D) cracked rib (attack 11). (E) shattered tibia (attack 16). Photos: (A–B) Valerio Gentile, (C–E) Casper van Dijk.

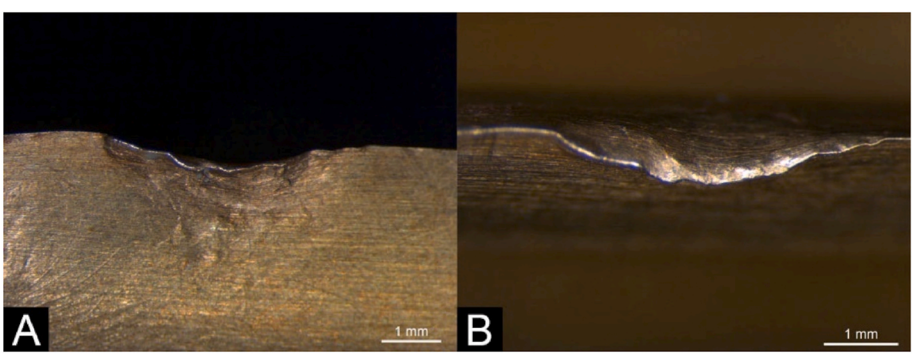

Fig. 7. Bowing wear trace produced on bronze spear-point replica during the wounding experiment. (A–B) side and top view. Photos: Valerio Gentile.

observed morphology was the product of at least two impacts over the same area. In addition to that, a second small bowing trace was observed over the profile of the original trace produced in the wounding experiments. Finally, the fissuring produced during the binding tests of Experiment 1 was modified by further collisions, which narrowed the fracture opening towards the edge but also deepened the fissures originated earlier.

4. Discussion

The experimental trials provided several insights on combat with bronze spears and on the dynamics of wear formation. The multi-stage framework of the tests permitted to gain new knowledge while at the same time increasing confidence in the interpretation (see also Gentile 2022), and the traces produced show close similarities to traces found on archaeological bronze spears.

4.1. Combat wear traces formation and change

For what concerns the formation of use-wear, several considerations can be drawn. First of all, the nomenclature created to classify the combat wear produced on swords (Gentile and van Gijn 2019) has proven to be effective in describing most of the wear identified on spears as well. On the other hand, the novel experimental setup enabled the observation of the emergence of traces previously undocumented, which required a new nomenclature. The accurate reconstruction of the circumstances in which marks develop permitted to draw conclusions on the formation dynamics of most combat traces. Overall, force and angle of impact over the two planes (parallel and perpendicular to the edge) emerged as fundamental variables in shaping the morphology of the combat marks. This finding is at odds with what previous studies concluded (cf. Anderson 2011, 605).

Although the tests demonstrated the development of a range of different wear traces in presence of similar conditions, combining the

Table 4
Experiment 3 – Type of impacts and length of the exchanges.

Combat style: one-handed spear and shield					
	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Total
Point-against-point impacts	2	1	2	2	7
Point-against-shaft impacts	4	4	4	3	15
Shaft-against-shaft impacts	3	1	1	4	9
Point-against-shield impacts	8	7	10	14	39
Exchange time (seconds)	17	15	21	19	72
Combat style: two-handed spear binding					
	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Total
Point-against-point impacts	2	2	1	1	6
Point-against-shaft impacts	7	15	11	3	36
Shaft-against-shaft impacts	5	13	10	6	34
Exchange time (seconds)	22	40	32	13	135
Combat style: two-handed spear striking					
	Exchange 1	Exchange 2	Exchange 3	Total	
Point-against-point impacts	0	1	1	2	
Point-against-shaft impacts	2	4	1	7	
Shaft-against-shaft impacts	5	8	1	14	
Exchange time (seconds)	7	15	3	25	

results of the experiments allows to draw some connections between styles used and wear traces produced. This might likely be a product of the influence that each combat style has on force and angle of the impacts. Overall, one-handed (implying the use of a shield) and two-handed binding styles produced mostly blunting traces or small (bowing) dents, whereas two-handed striking combat seems the only context in which also conspicuous notches can develop. Round depressions formed only in violent two-handed striking clashes, whereas tip-bending occurred only in one-handed spear and shield combat. Even in the case of the same categories of damage produced by different styles (e.g. bowing dents), the ones resulting from two-handed striking were more pronounced (cf. Fig. 3C–D, Fig. 9A–B, and Fig. 4E–H).

In general, the influence that organic contact material has on the development of wear traces on bronze implements is limited but present. Contact with wood has only rarely left traces on the spears in the form of blunting traces and a bent tip. Similarly, the impact with skin and bone produced visible (blunting) marks on the bronze blades only in the case of exceptionally violent collisions.

Another achievement of the experimental setup was the observation and investigation - for the first time - of the formation and modification of combat wear traces over time. The layout of Experiment 3 allowed to examine how frequently bronze-on-bronze type of collisions – which have been shown to be responsible for the formation of most wear traces - occur in actual spear combat (Table 4), and have a glimpse at the pace at which combat traces develop. Results validated the assumptions that this type of contact represents only a small component of a combat encounter. Several of these findings have important consequences for the reconstruction of the life-path of archaeological objects. The

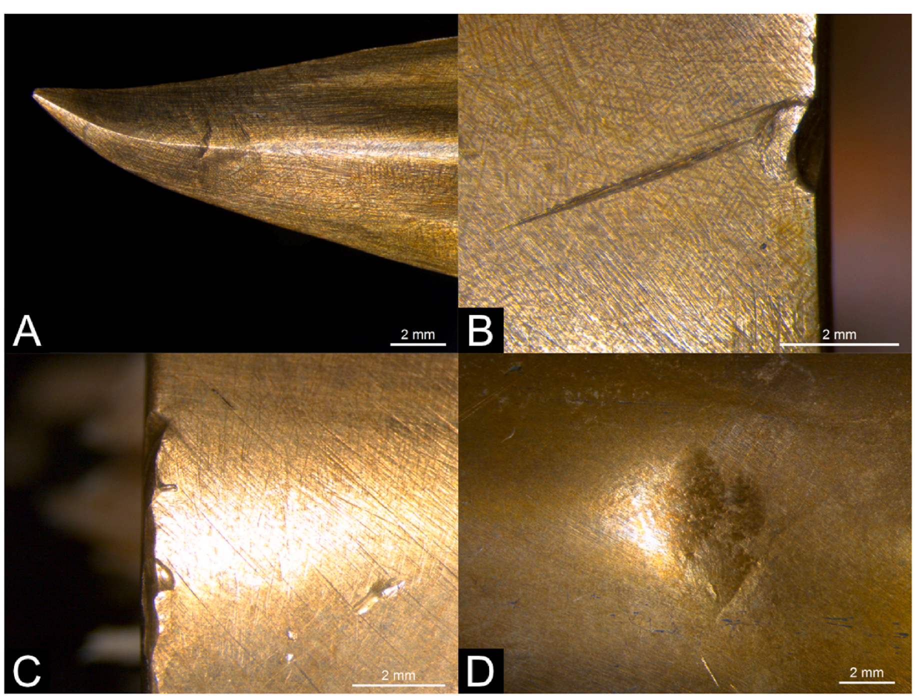

Fig. 8. Combat wear produced on bronze spear-point replicas during the free sparring experiment. (A) Bent tip. (B–C) socket rim damage. (D) round depression. Photos: Valerio Gentile.

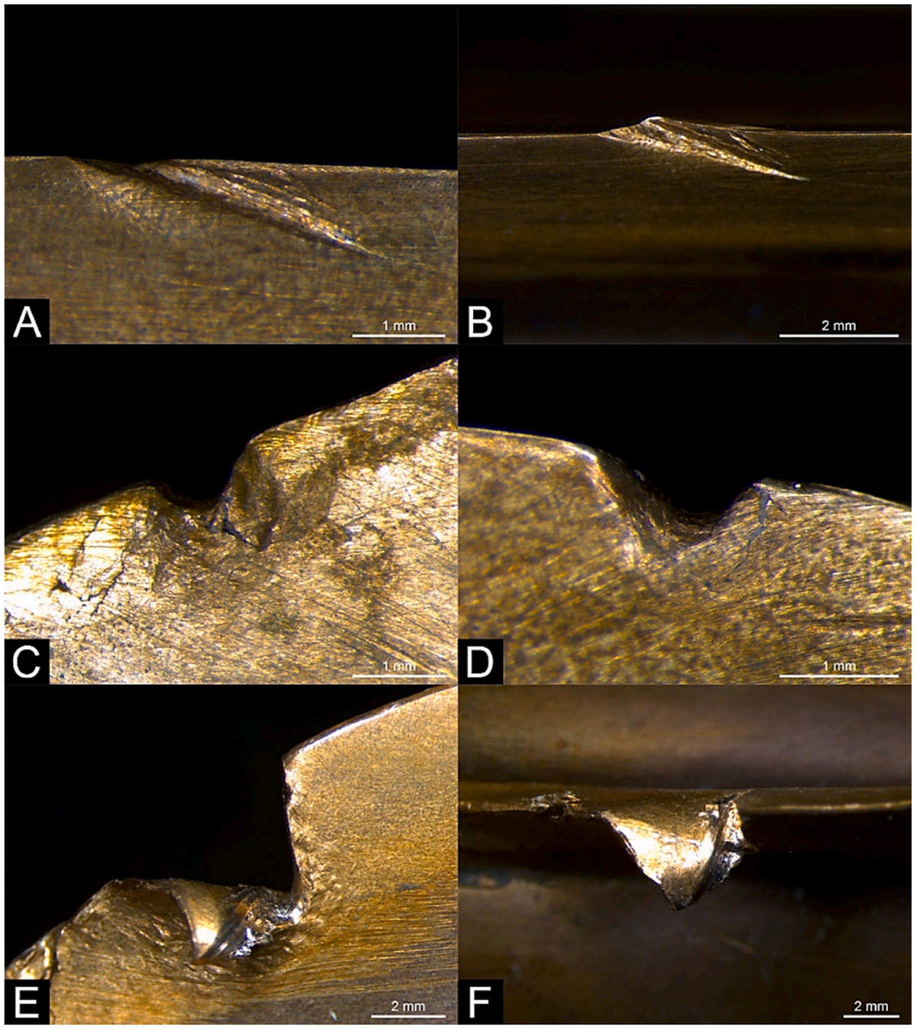

Fig. 9. Combat wear produced on bronze spear-point replicas during the free sparring experiment. (A–B) Bowing dent with trail, side and top view. (C–D) two different asymmetrical dents with visible fissures. (E–F) Notch with burr, side and top view. Photos: Valerio Gentile.

empirical evidence gathered points towards the possibility that spear-points could have gone through more than a few rounds of combat without receiving particularly visible damage. Similarly, the tests demonstrated that, in some cases, further blows can overwrite or alter previous traces causing the loss of information. While the resulting feature could still be recognisable as a combat trace, it could be challenging to infer the original shape or reconstruct the sequence of events that resulted in the trace observed on an archaeological item.

The experiments also highlighted how combat action frequently produces blunting wear such as bowing or flattening which could be easily repaired through the hammering of the area of interest. Also bowing dents would be relatively straightforward to restore through hammering, as most of the material is rather displaced than lost. Finally, besides the loss of information caused by ancient repairs, diagnostic wear traces could also be lost to post-depositional events. The experiments have provided empirical evidence for fissuring originating from and worsening as a consequence of use of the spears in combat (see Fig. 4C and D). It is plausible that such features would expand and break down the surrounding areas as corrosion and patination make their way into the cracks (Horn and von Holstein 2017).

4.2. Combat wear traces on archaeological items

Several factors make the study of wear traces on metalwork particularly challenging (Dolfini and Crellin 2016). As discussed above, corrosion could alter or destroy traces of use (Horn and von Holstein 2017), but also restoration practices can, at times, cause a loss of information (Sych et al. 2020). Furthermore, for what concerns spears in particular, the dearth of experimental references significantly hampered the application of this type of analysis (see introduction). Despite these limitations, researchers have effectively detected and described traces on Bronze Age spears which suggest their use in combat (e.g. Horn 2015; Horn and Karck 2019; Melheim and Horn 2014; Tarbay et al. 2021; 2024).

The experiments discussed in this paper produced several marks which can be compared with the traces documented on archaeological items in previous studies and could thus be used to further advance and expand earlier interpretations. Likewise, the results are expected to provide a substantial contribution to future investigations of wear traces on archaeological items. Nevertheless, it has to be considered that the degree of similarity between experimental and archaeological traces is often relying on a visual assessment by the analyst (van Gijn 2014). For this reason, even though a long and detailed discussion of the traces of

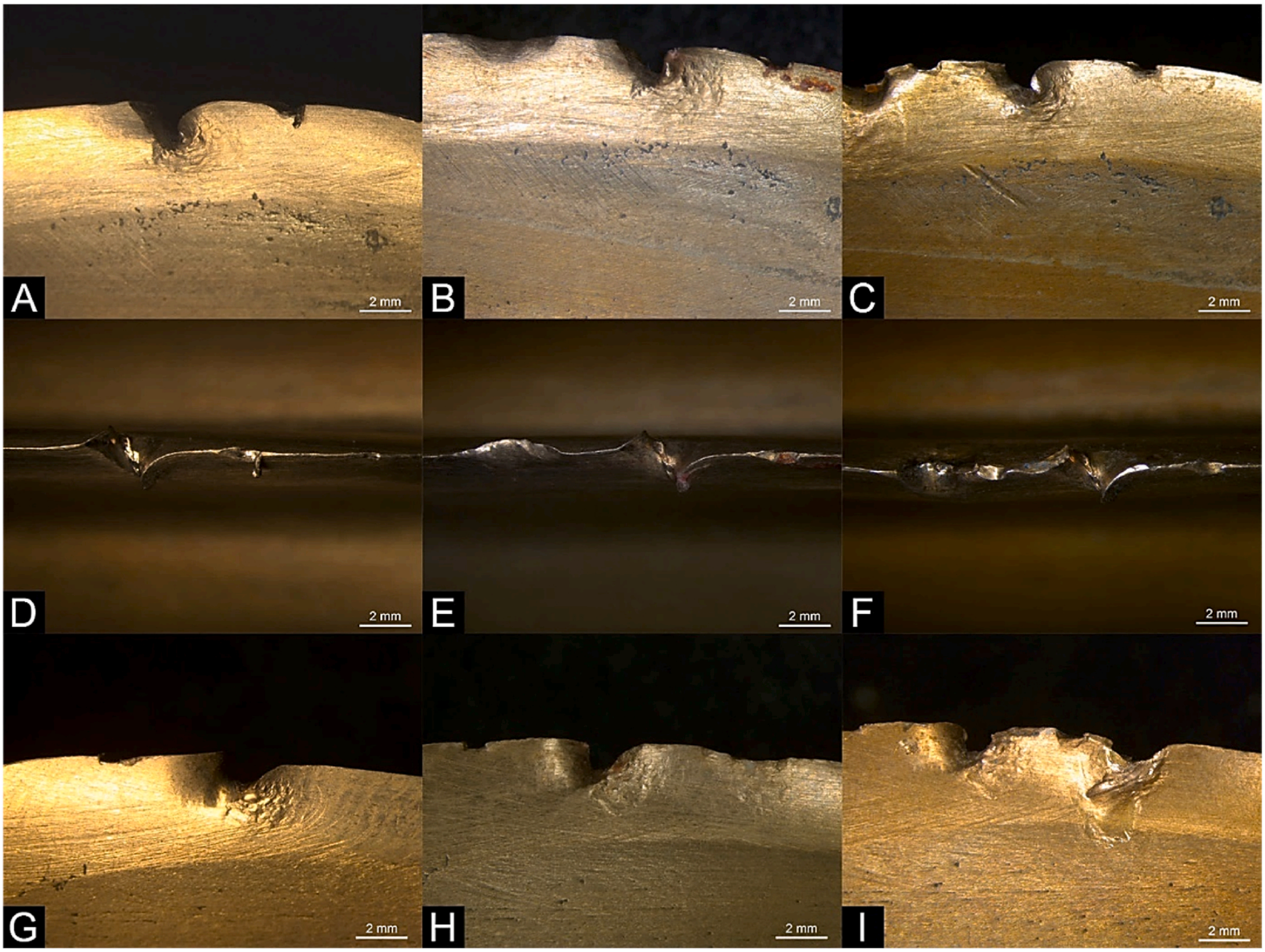

Fig. 10. Wear development on the same portion of spear edge at the end of each experiment. (A–C) view from one side at the end of Experiment 1, Experiment 2, and Experiment 3. (D–F) top view at the end of Experiment 1, Experiment 2, and Experiment 3. (G–I) view from the other side at the end of Experiment 1, Experiment 2, and Experiment 3. Notice the loss of burr on the chipping feature from A,D to B,E. Notice the overwriting of the bowing feature and the folding of edges and burr from B,E to C,F. Photos: Valerio Gentile.

use found on Bronze Age spears goes beyond the scope of this paper, a small sample of archaeological comparisons is presented below to enable the reader to independently evaluate the effectiveness and applicability of the methodology.

Three Late Bronze Age spear-points from the Drents Museum (Assen, NL – specimens: 1905.II.6, 1922.VIII.1, 2014.X.1021) have been selected to showcase the application of this approach. The points have been analysed with the same microscope and camera used to document the wear traces on the experimental replicas. The items show different level of corrosion or conservation treatments, but they all present features analogous to the traces reproduced experimentally. Marks compatible with the 'typical' combat traces, such as dents and notches, already documented on archaeological swords (Gentile and van Gijn 2019; Hermann et al., 2020b), have also been identified in the sample (Fig. 11A,C,D). Interestingly, the archaeological spear-points have also been found bearing marks with significant compatibility with newly discovered combat traces such as bowing dents, socket rim damage, or round depressions (Fig. 11B,E,F). The presence of features such as round depressions or notches would argue for the use of two-handed striking approaches and/or fighting with rather basic movements. On the other hand, socket damage and small dents are more likely to be the product of a more skilful use and are compatible with two-handed binding. Bowing dents have been recorded forming during two-handed striking and one-handed spear and shield combat. In the light of this information, assuming that the traces found are unambiguously combat related (but see Gentile 2022), a reconstruction of the use of these items can be attempted: specimen 1905.II.6. appears likely to have been used with a binding approach. The juxtaposition of a small dent and a deep notch on the edge of 2014.X.1021 speaks against unskilled use and might rather be the product of use in different combat contexts. Both types of traces found on 1922.VIII.1. can be produced by two-handed striking combat, however the bowing dent could have had also another origin (e.g. one-handed spear and shield combat). These finds highlight the methodology's potential for further application and development. Furthermore, the results indicate that, at least in some cases, it might be possible not only to assess the use in combat of archaeological spear points but, to some degree, also link some traces to specific skill levels and contexts of use.

4.3. Insights into bronze Age spear combat and combatants

In Bronze Age studies, much debate surrounds the practical and social aspects of warfare and of being a warrior (e.g. Brück and Fontijn, 2013; Frieman et al., 2017; Harding 2007; Horn 2023; Horn and Kristiansen 2018; Kristiansen 2002; Molloy 2017; Molloy and Horn 2020; Treherne 1995; Vandkilde 2018). Besides contributing to widening the

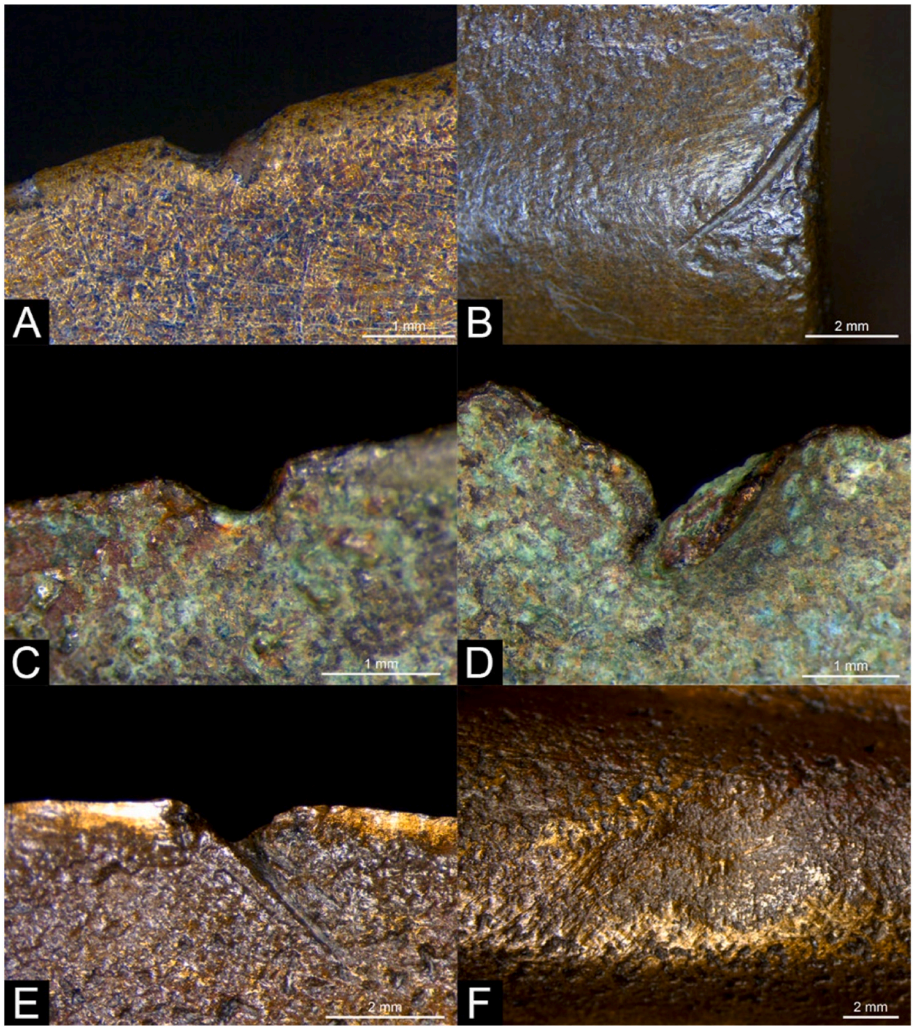

Fig. 11. Wear on archaeological specimens. (A–B) potential asymmetrical dent and socket rim damage on 1905.II.6. (C–D) potential asymmetrical dent and notch with burr on 2014.X.1021. (E–F) potential bowing dent with trail and round depression on 1922.VIII.1. Photos: Valerio Gentile.

knowledge on combat trace formation and enabling the interpretation of wear on ancient bronze spear-points, the results of the experiments provide new elements to draw general considerations on the contexts and ways of use of Bronze Age spears and on their users.

First of all, the tests demonstrated the remarkable combat suitability of long(er) shaft spears, contrary to what was postulated in previous literature. Wounding experiments showed the offensive potential of these weapons which were apt to inflict lethal wounds, commonly associated with 'warfare' or 'fight for life' situations. Nevertheless, it has also been demonstrated how a sufficiently skilled individual could manoeuvre the weapon in such a way as to inflict deliberately non-lethal bleeding wounds, a circumstance typically linked with formalised or codified combat, such as duelling. Furthermore, the same test showcased the elusiveness of non-lethal attacks traces on bones, compared to the more archeologically visible damage produced by attacks intended to be lethal. On the other hand, lethal attacks might escape detection as well: in our experiment, the strong attack on the tibia completely shattered the bone rather than slicing it (Table 3 movement 16; Fig. 6E). One wonders, thus, to what extent, instances of this type of damage in the archaeological record could have been mistakenly attributed to blunt force trauma instead.

Another aspect of combat with Bronze Age spears that emerged from our tests is the limited durability of the shafts, especially in certain combat contexts. Breakage of the shaft represents an obvious liability in combat and, therefore, it is plausible that Bronze Age fighters adopted countermeasures in order to mitigate such risk. An expedient could have been to reinforce the distal part of the wooden shaft with materials such as leather stripes or hide. Regardless, it is plausible that Bronze Age warriors preferred approaches that preserved the integrity of the weapons and/or featured more than one hafted spear in their panoply. Therefore, caution should be observed when using the number of spear points in contexts such as hoards or (multiple) burials as a direct proxy of the number of individuals who owned the weapons.

Even though the distinction between the traces produced by each combat style is not entirely clear cut, it has been shown above how the presence and size of certain features could assist in the estimation of the fighting style used with a certain spearpoint. Advanced combat approaches more likely implemented in one-on-one combat – i.e. binding – were perfectly executable with the spears tested and only took a minor toll on the integrity of the weapons. Therefore, duelling events and/or a more skilled use would be harder to detect on archaeological items due to the limited chance they have of creating conspicuous wear traces on the spear points. This aspect should be taken into account when drawing conclusions about Bronze Age (spear) combat and combatants.

Presumably, most spears were used according to different styles and in different contexts during their life-path, and thus could bear traces formed (and modified) in different circumstances. In fact, the small archaeological sample presented above shows the occurrence on the same point of traces that could be ascribed to different styles (see above and Fig. 11). Interestingly, potential indicators of 'change' in Bronze Age combat techniques have been already observed in the archaeological record (Hermann et al. 2020b; Horn 2014; 2015; Molloy 2017). Therefore, if the insights generated by this study would be applied to a large sample of spear-points, some trends surrounding the context and ways of use of spears across time and space could emerge. For example, a large(er) number of proxies for binding approaches could be taken as an indication of frequent participation in duels or one-on-one combat. Similarly, the dearth of two-handed striking traces might constitute an additional clue for the presence of skilled practitioners. However, it is important to bear in mind that these differences are not set in stone: group battles in pre-modern conflicts can break up into small combats against single opponents, on the other hand group battles involving spears could also see the use of approaches different from striking, for example, in the case of close combat formations. Additionally, it is important to remark how sub-optimal movements are likely to be performed in frantic combat: striking techniques in particular could have been deployed also by less skilled individuals regardless the context, or as a last resort.

5. Conclusion

The aim of this paper is to contribute to the study of Bronze Age combat and wear formation on ancient weaponry. The methods and the results of a wide-ranging but modular experimental framework based on different degrees of actualism and variable control have been presented, together with a reference collection of combat traces. Gradually shifting from more controlled to less controlled setups allowed to build on, and at the same time assess the results of the previous tests. This methodology permitted to observe the formation of several wear traces - some previously undocumented - and assess their origin. The experimental approach also allowed to study, for the first time, the development and modifications of combat wear over time. According to the tests, angle of impact and force emerged as important variables in trace formation. In turn, such variables are - to an extent - influenced by the combat situation. The findings showed how weapon proficiency and fighting styles could affect the type, severity, and frequency of trace formation. At the same time, the tests demonstrated the versatility of Bronze Age spears with long(er) shafts in different combat contexts. Similarly, strikes against animal tissues highlighted the potential of inflicting a range of different traumas with Bronze Age spears, provided a sufficient proficiency with the weapons. The same tests results provided also additional insights on the - limited - visibility of combat trauma on ancient bones.

Experimental archaeology and wear analysis of metal weaponry is a recent but fast-growing field of study (Dolfini and Crellin 2016). Several aspects still need much attention: ambiguity in interpretation must be reduced and already investigated research questions could benefit from replicative studies (Gentile 2022). With this paper, we hope to have provided the scientific community with useful tools for carrying out further combat experiments, as well as a guide for the interpretation of combat wear traces on archaeological specimens (see also the complete reference availableat supplementary data: additional data). Finally, we hope to contribute to a more in-depth understanding of Bronze Age martial practices and practitioners.

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CRediT authorship contribution statement

V. Gentile: Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **C.J. van Dijk:** Writing – original draft, Resources, Methodology, Investigation. **O. Ter Mors:** Resources, Investigation.

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

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