

Chapter 3

Perimortem Lesions on Human Bones from the Bronze Age Battlefield in the Tollense Valley: An Interdisciplinary Approach



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Introduction

The recent discovery of the remains of an armed conflict dating to about 1300–1250 BC in the Tollense Valley in the federal state of Mecklenburg-Western Pomerania, Northeast Germany, has led to ongoing intensive investigations of this remarkable site. An interdisciplinary research project, financially supported by the Deutsche Forschungsgemeinschaft (German Research Foundation) since 2010, has engaged in the excavation and analysis of the human remains, focusing in particular on the main site being researched, Weltzin 20 (e.g. Jantzen et al. 2011, 2014a; Jantzen and Terberger 2011; Krüger et al. 2012; Terberger and Heinemeier 2014; Terberger et al. 2014; Lidke 2014a; Lidke et al. 2014b, *in press*; Brinker et al. 2014a, b). Until the end of 2014, a total of about 11,000 human skeletal remains were recovered from the valley, nearly 8500 of them being from Weltzin 20 alone. The minimum number of individuals (MNI) recognized for the whole valley has steadily increased over the

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years to at least 133 units (2014 record), 83 of which are from Weltzin 20 (MNI based on the number of left femora). Osteoarchaeological studies suggest a strong dominance of young adult male individuals within the bone assemblage (Brinker et al. 2015). Additional weapon finds, as well as numerous bones with lesions, hint at the occurrence of a violent event of unusual scale. Among the almost 100 perimortem injuries observed on the human remains, stabbing and projectile point traumas clearly dominate, while a few sharp blow injuries have also been identified. Whereas injuries caused by stabs and blows mainly affect the front side of the upper body, most of the arrowhead lesions were identified on the back of the trunk; blunt force trauma focusing on the skull is also attested.

This spectrum of injuries corresponds to a range of late Bronze Age weapons found in the valley including numerous flint and bronze socketed arrowheads, different types of spearheads, axes, wooden clubs, and a sword, the latter assigned to Period III of the Nordic Bronze Age (Dombrowsky 2014, *in press*; Lidke 2014b; Lidke et al. 2014b; Terberger 2014; Kloof and Lidke 2014). In general, the individuals showing perimortem injuries are spread over the entire excavated area. Injuries caused by close combat as well as by ranged weapons are found side by side. This suggests a conflict scenario in which both ranged and close-combat weapons were employed. It is currently presumed that a group of people would have been attacked by archers while trying to cross the river. The group would then have scattered around the valley, and the fighting would have shifted northwards, with combatants from both parties being killed by arrows as well as by blunt force and bladed weapons at several locations throughout the valley (Jantzen et al. 2014b; Lidke et al. 2015).

Current research on the Tollense Valley site is opening a new window into the complexity of Bronze Age warfare, which may have involved thousands of combatants wielding a variety of nonstandardized weapons. More extensive discussion about this subject, the battlefield site, and the reconstructed conflict scenario, as well as the previously conducted anthropological investigations of the skeletal remains, can be found in the literature (Jantzen et al. 2014b; Lidke et al. 2015, *Accepted*; Brinker et al. 2015, 2016).

With regard to perimortem injuries, recent research has focused on characterization and differentiation of the injury patterns including the identification of the possible weapons that caused them. An overview of the previous results is given in Brinker et al. (2015). In this study, certain specific injuries will be presented in more detail, focusing in particular on the penetrating injuries, which have yielded some of the most important information for reconstructing the Tollense Valley conflict scenario. This paper aims to demonstrate how specific questions regarding the characteristic features of the injuries, the possible type of weapon, and the direction of the attack can be answered by using non-destructive high-resolution imaging and 3D reconstruction combined with experimental weapon testing.

Materials and Methods

One skull and a left femur, both with embedded objects, and a left hipbone (os coxa) with a piercing wound from site Weltzin 20 were examined as part of this research. The skull (ALM 2008/0460-0254) was fragmented postmortem. The fragmented skull calotte consists of the nearly complete right parietal bone, the fragmented left parietal bone with remains of the frontal bone and the fragmented occipital bone. The hipbone (ALM 2008/0460-0036) and the femur (ALM 2013/0463-1959) are completely preserved. A range of established methods have been used to determine the sex and skeletal age of the human remains (e.g. Buikstra and Ubelaker 1994). A trauma was considered perimortem based on distinctive criteria for fresh bone fracture and absence of healing (e.g. Villa and Mahieu 1991; Sauer 1998; McKinley 2004; Boylston 2004; Buikstra and Ubelaker 1994: 160; Wedel and Galloway 2014). To identify projectile lesions, published experiments (e.g. Smith et al. 2007; Letourneux and Pétilion 2008) and forensic studies of high-velocity projectile trauma were taken into consideration (Wedel and Galloway 2014; Kneubuehl et al. 2008; Dodd and Byrne 2006; Coe 1982; Denton et al. 2006; Marchetti et al. 2003). These were integrated by the experiments with replicas of Bronze Age weaponry conducted by our project team (see below). We used a modified version of the Istanbul protocol (Appleby et al. 2015) to reach standard levels of precision in our observations.

In order to obtain information about the shape and size of the weapons and the direction of attack, a transdisciplinary suite of methods, including experiments on animal bones, 3D imaging, 3D reconstructions, and digital injury simulation, were deployed for the analysis of the lesions. The experiments were conducted on pig carcasses with replicas of Bronze Age arrowheads and stabbing weapons (cf. Lidke et al. 2014a). The various injuries created in our experiments were compared with the aforementioned hipbone lesion using macroscopic examination as well as microscopic analysis. In addition, cross-sections of different projectiles and stabbing weapons were created in floral foam and compared with the cross-section of the injury.

The injury patterns of the experimental bones as well as those of the Bronze Age bones were analysed using a Keyence Digital Microscope VHX-5000. The digital microscope offers high-depth field measurements and creates a deep composite image. 2D measurements such as radius, distance, angle, and area and 3D measurements such as volume, angle, distance, and profile were also obtained. The Stitch Image function can be used in both 2D and 3D and allows the capture of wide area images by using a pattern-matching algorithm.

As in many other bones from the Tollense Valley, clinical CT scanning was performed on the skull, femur, and hipbone discussed here by the Department of Diagnostic and Interventional Radiology, University Hospital Rostock, Germany, in order to obtain further information concerning the injuries. To better visualize the embedded objects and wound canals (i.e. the marks left by the perforating injuries),

and also possible signs of healing, additional micro-CT imaging was carried out. This technique provides a much higher resolution than clinical CT imaging, which can be crucial for a correct diagnosis of the changes seen in archaeological bone (see also Flohr et al. 2015). The human remains and different types of socketed bronze arrowheads found in the valley were scanned at the BAM Federal Institute for Materials Research and Testing, Berlin, Germany, using the BAM-225 kV device for microcomputed tomography (micro-CT). This consists of a micro-focus X-ray tube (X-RAY WorX XWT 225-SE) with 225 kV maximum acceleration voltage and a flat-panel detector (Perkin Elmer PE 1640) with 2048×2048 pixels at a pixel pitch of 0.2 mm. For the measurement, the acceleration voltage was set to 190 kV; the target current was 100 μ A. A pre-filter of 1 mm copper was used; 2400 projection images with 10 s exposure time each were taken for the full rotation. The volume data with voxel sizes from 26 to 55 μ m were obtained by a standard Feldkamp filtered back-projection algorithm.

3D CT imaging allows the exact measurement of the lesions, the visualization of the internal and external bone structures, and the quantification of very fine injury patterns. Volume rendering techniques (VRT) provide a 3D model that can be viewed from every perspective and also trimmed and sectioned virtually. By means of a segmentation process using volume segmentation and processing software (Seg3D by NIH Center for Integrative Biomedical Computing/VGStudio Max 2.2 by Volume Graphics GmbH), 3D volume and surface models of the injured bones and weapon finds were generated by threshold-based segmentation from clinical and micro-CTs. Based on these models, fragmented bones and fracture distributions could be digitally reconstructed. Furthermore, virtual cross-sections of the lesions were performed on the volume model in order to analyse and measure the perforation and to identify embedded objects. These objects were isolated for further analyses using segmentation techniques. In addition to the microscopic imaging, the 3D analyses allowed us to determine detailed characteristics of the specific injury patterns in relation to the weapons that caused them as well as possible trajectories and entry angles. The exported surface models of the injured bones and weapons were processed and cleaned (MeshLab by Visual Computing Lab – ISTI – CNR) and deployed for the digital simulation of the injury process and weapon matching, which was carried out using CAD and 3D modelling and animation software (AutoCAD by Autodesk, Cinema4D by MAXON).

Results

Hipbone Lesion

The left hipbone (os coxae) belongs to a juvenile individual. The age was determined from the auricular surface of the ilium (Lovejoy et al. 1985; Meindl and Lovejoy 1989), the os pubis (Brooks and Suchey 1990), and the fusion of the iliac crest (Buikstra and Ubelaker 1994), suggesting that the individual was probably

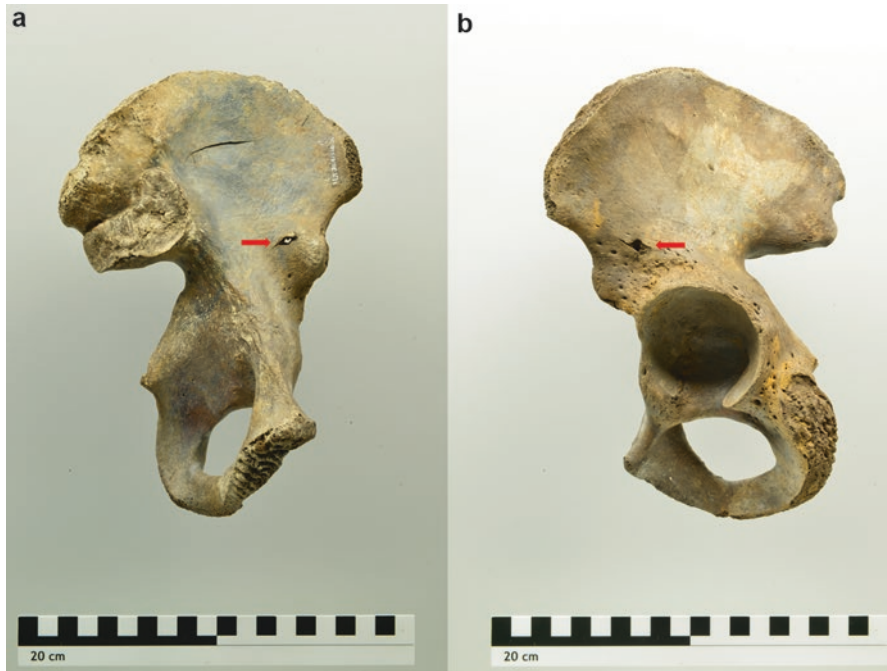


Fig. 3.1 (a) Outer and (b) inner face of a hipbone with a rhombic penetration injury caused by a pointed object (Images: S. Suhr © LAKD M-V)

18–20 years of age. Sex estimation is based on the morphological pubis features (e.g. subpubic region, greater sciatic notch, and absence of preauricular sulcus), which clearly indicate male characteristics.

The hipbone shows a rhombic full-thickness puncture at the ilium next to the inferior iliac spine (Fig. 3.1). The lesion measures about 15 mm anterior-posterior and 6 mm superior-inferior on the lateral side and about 11 mm anterior-posterior and 4 mm superior-inferior on the medial side of the hipbone. The penetration depth is about 19 mm. To identify the weapon that would have inflicted this wound, injury patterns created by experimental weapon testing with socketed bronze arrowheads (cf. Lidke et al. 2014a; Brinker et al. 2016) and spearheads on modern pig bones were compared with the hipbone lesion; the cross-sections of the weapons were also considered. Although useful, such macroscopic analyses were unable to determine which weapon might have caused the wound, as the lesions created by arrow and spearheads on modern pig bones were very similar to each other, both showing funnel-shaped penetrations with rhombic or triangular cross-sections (Fig. 3.2). Therefore, the analysis only led to determining that the lesion was caused by the ingress and perforation of a sharp metal point belonging to either weapon.

In order to resolve this issue, the hipbone injury was further analysed by micro-CTs and microscopic imaging, trying to narrow down weapon size and proportions. Furthermore, this aimed to investigate the point's trajectory and angle of entry and



Fig. 3.2 (a, b) Rhombic penetration injury caused by a bronze spearhead on a modern pig tibia. (c, d) Triangular penetration injury caused by a bronze spearhead on a modern pig fibula. (e, f) Rhombic penetration injury caused by socketed bronze arrowhead on a modern pig scapula, showing hinge fractures on the anterior side (e: exit side of the projectile) and on the posterior side (f: entry side of the projectile). (g, h) Rhombic penetration injury caused by a socketed bronze arrowhead on a modern pig vertebra (Images: S. Suhr © LAKD M-V)

therefore the direction of the attack. Several indicators of a sharp weapon point, which entered the bone at a downward-inclined angle, can be observed on both sides. The fracture is wider on the lateral side (about 13–15 mm) than on the medial side (about 7–8 mm) (Fig. 3.1). A further feature observed was an impression on the cortical bone on the superior-anterior margin of the wound (Fig. 3.3a), indicating that the point entered the bone on the lateral side (Langley 2007, 533). Hinged-out bone fragments (flakes still connected to the margin of the lesion), bevelling and external chipping on the lateral and medial side (Fig. 3.3a–f), lying opposite but asymmetric from each other, indicate an angle of entry other than 90° (Dodd and Byrne 2006, 104; Langley 2007, 536). In addition, there are longer and deeper fissures on the lateral side, extending from the anterior corner (about 7 mm) and posterior corner (about 15 mm) of the perforation (Fig. 3.3a). On the medial side of the bone, a much smaller fissure extends (about 2–3 mm) from the posterior corner of the perforation (Fig. 3.3b). The lengths of these fissures indicate that the initial energy of the shot or stab decreased as the weapon penetrated the bone, thus causing a smaller fissure on the exit side. Taking all fissures into account, the weapon probably struck with high kinetic energy, which perhaps indicates an arrowhead rather than a handheld weapon. Wastage and bevelling can be observed on both sides of the bone. The bevelling on the lateral side (Fig. 3.3e) indicates an acute angle and oblique penetration on entry (Kneubuehl et al. 2008, 290–291). The external bevelling on the medial side (Fig. 3.3f) indicates the exit of the point. Ballistic and forensic studies (Dodd and Byrne 2006; Denton et al. 2006; Scott and Buckley 2010) have documented that fractures of flat bones, like pelvis and cranium, may show external bevelling at the exit with a conical shape facing outwards (Fig. 3.3e).

After identifying the likely entry and exit point of the weapon, a vector-based 3D reconstruction was carried out to reconstruct the possible proportions of the weapon and its entry trajectory (see Ryan and Milner 2006 for a similar procedure). First, we measured the distance of the horizontal middle line between the margins of both sides of the fracture and the length of the perforation. The tolerance of the measurements lies at 0.5–1 mm. Three vectors were then plotted according to the surface model of the lesion (Fig. 3.4a). One vector was placed at the rims of the entry and another at the exit. The distance of the vectors correlates to the length of the penetrating injury. A third vector was plotted running between the midpoints of the first and second vectors. This vector represents the central axis of the weapon point and therefore the direction of its entry trajectory. Six surface models of bronze arrowheads (Fig. 3.5) and a bronze spearhead from the Tollense Valley finds were positioned on the vectors. The keyframe function in Cinema4D was used to move them along the central axis, simulating the path followed by the point as it penetrated the bone. Only one arrowhead (ALM 2007/655) did not extend or fall below the maximal width at the entry vector while following the path down to the minimal width of the exit vector (Fig. 3.4a). Subsequently, the vectors and arrowhead were positioned on the surface model of the lesion (Fig. 3.4b), and the arrowhead was again moved along the path (central axis) (Fig. 3.4c–e). It became clear that an arrowhead, or some other point with similar proportions, was very likely to have caused the wastage and hinging fractures on the entry side as well as the rhombic margins at the

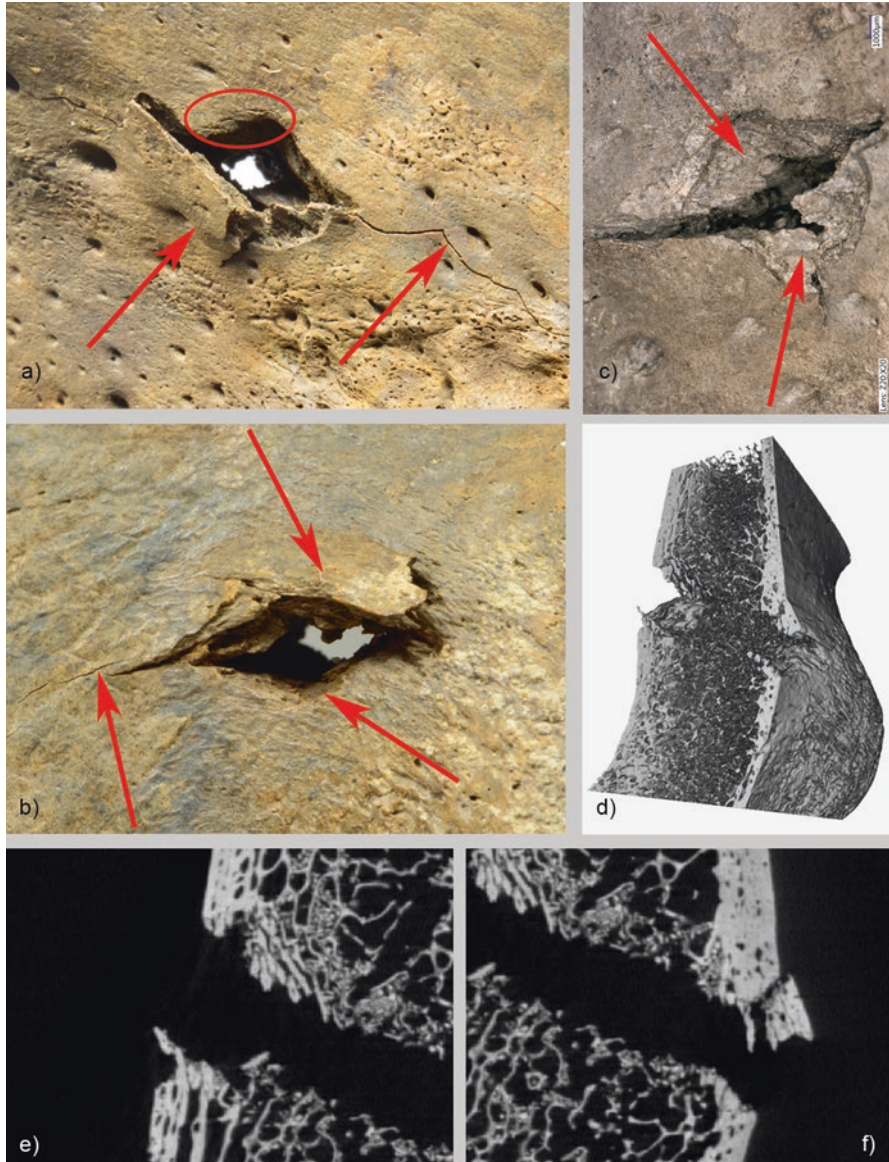


Fig. 3.3 Characteristic features of the hipbone injury: (a) the circle shows an impression, while the arrows point to hinge fractures, external chipping, and long fissure on the lateral side; (b) the arrows show hinge fractures, external chipping, and a small fissure on the medial side; (c) beveling on the lateral side; (d) micro-CT volume clipping – section through the injury canal; micro-CT cross-sections sagittal, entry side (e) and exit side (f) (Microscopic and micro-CT analyses a–f H. Harten-Buga © Univ. Hamburg; Images a–d S. Suhr © LAKD M-V; micro-CT data acquisition d–f A. Staude © BAM)

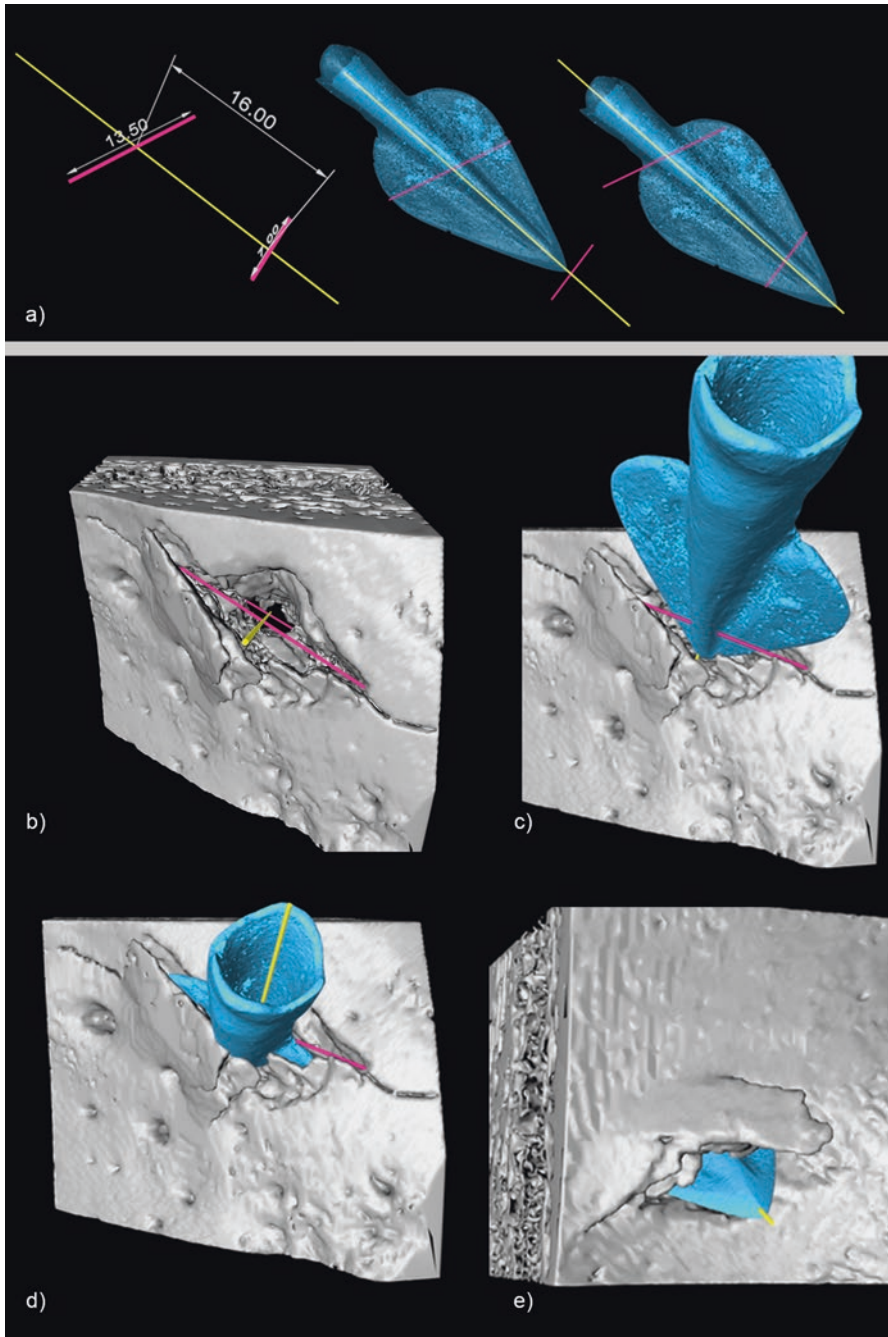


Fig. 3.4 Vector-based 3D reconstruction and simulation of weapon matching: (a) 3D models of bronze arrowheads positioned at the vectors; (b) vectors positioned at the micro-CT volume model of the lesion; (c–e) simulation of the path followed by the point through the bone (Images: H. Harten-Buga © Univ. Hamburg)

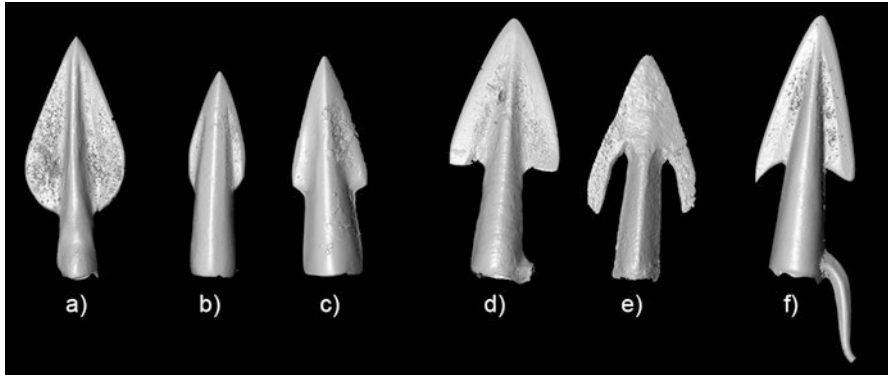


Fig. 3.5 3D models of six bronze arrowheads from the Tollense Valley finds: (a) ALM 2007/655, type 5 variant A, leaf-shaped. (b) ALM 2012/954, 15, type 5 variant B, slim shape. (c) ALM 2010/1860, 7, type 4 variant B2, slightly rhombic. (d) ALM 2008/458, 89, type 4 variant B1, triangular head with straight base. (e) ALM 2012/988, 1, type 4 variant A1, triangular blade with long wingtips. (f) ALM 2010/1860, 16: type 4 variant C, extra barb (Typology by Eckhardt (1996), integrated with Dombrowsky (2014)). Rendering: H. Harten-Buga © Univ. Hamburg; micro-CT-based 3D models: A. Staude © BAM

entry and exit. The tip of the point would have protruded approximately 8–10 mm from the surface of the bone on the exit side (Fig. 3.4e).

Furthermore, the 3D models of the bone and arrow enabled us to reconstruct the presumed angle of the projectile's trajectory. Although this ran at approximately a 90° angle based on the longitudinal axis (vertical middle axis) of the human body (Fig. 3.6a, c), it is most likely that the arrowhead would have penetrated the bone at a sharper angle of approximate 60° due to the morphology and anatomical position of the hipbone in the human body (Fig. 3.6a). If a shooting or stabbing perforation occurs at an angle other than 90°, the shape of the external margins of the fracture alone is no accurate indicator of the shape and size of the weapon's point. An acute or obtuse angle and/or oblique orientation of the projectile's cutting edges most likely produce a unique entry shape while following the path through the bone before the point comes to a halt. The entry angle and orientation of the weapon were identified based on wastage, hinging of bone, fissures, bevelling, and the examination of the injury canal. Taking into account the geometric relations of the lengths of the canal and the width of the entry and exit margins, it was possible to reconstruct the profile and size of the point and therefore to narrow down the type of weapon that must have caused the injury. Based on our analysis, we are now confident that the punctured fracture of the hipbone must have been caused by a small projectile point similar in shape and size to one of the bronze arrowheads recovered from the Tollense Valley, or to some other point of very similar proportions and shape.

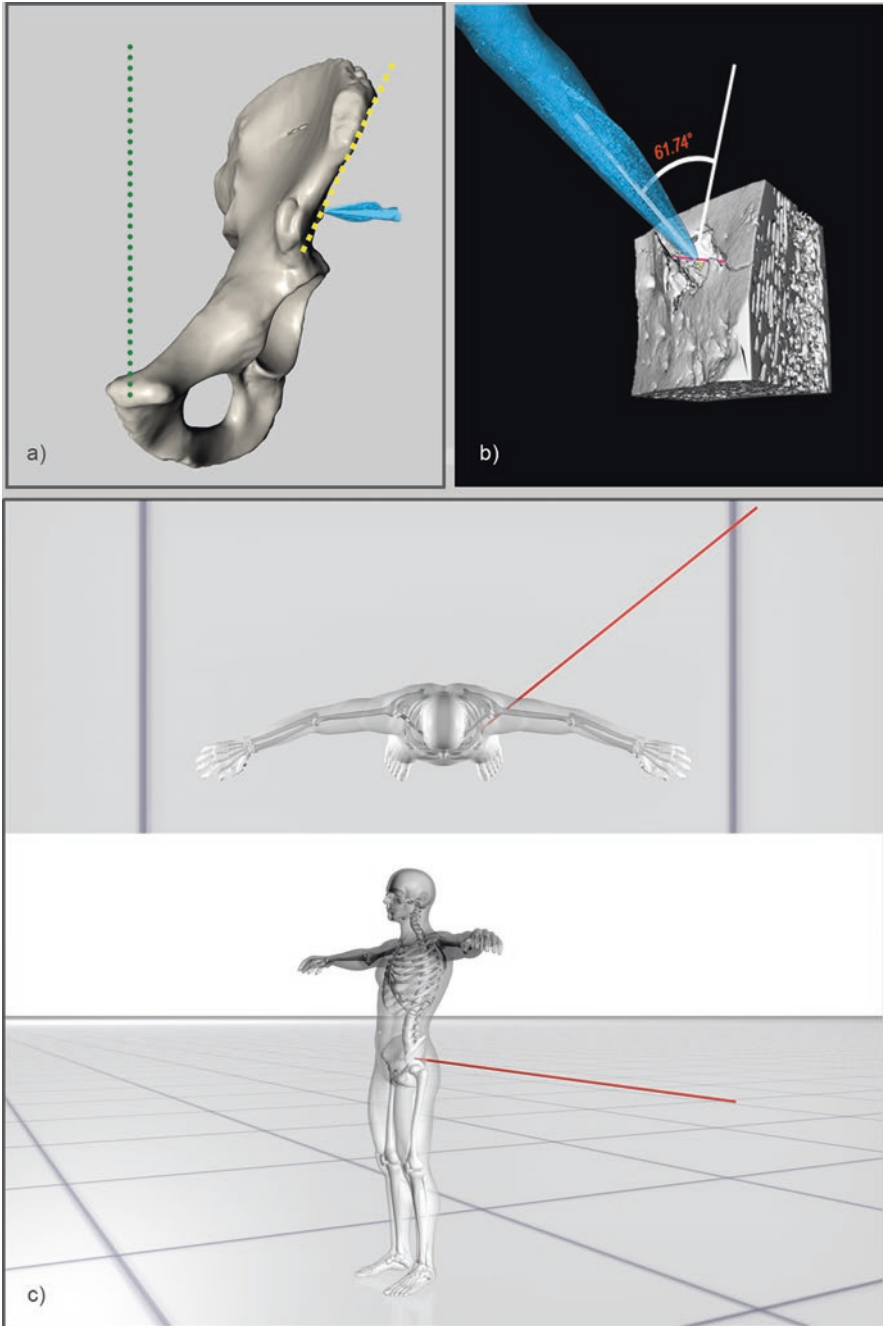
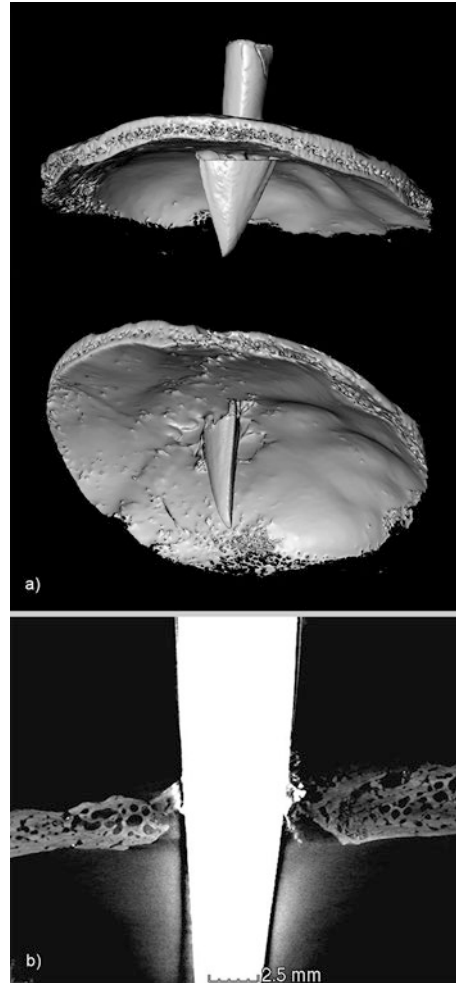


Fig. 3.6 Reconstruction of the weapon's trajectory and entry angle: **a** Concept anatomical position – longitudinal axis of the human body (*green dotted line*) and vertical axis of the bone in the penetration area (*yellow dotted line*); **b** 3D representation of the entry angle; **c** 3D visualization of the direction of attack (Images: H. Harten-Buga © Univ. Hamburg; micro-CT data acquisition: A. Staude © BAM)

Fig. 3.7 (a) 3D models of the cranial bone with embedded arrowhead showing the injury features on the entry (above) and exit side (below); (b) micro-CT frontal section image of the bone with embedded bronze arrowhead (Micro-CT-based 3D models **a** H. Harten-Buga © Univ. Hamburg; micro-CT images **b** A. Staude © BAM)



Cranial Calotte with Embedded Arrowhead

Most remarkable among the skeletal remains showing violent lesions is a cranial calotte with a socketed arrowhead embedded in the occipital bone (Jantzen et al. 2014b, 239; Terberger et al. 2014, 98). According to the available diagnostic features, namely, the analysis of cranial suture closures (Szilvássy 1988), the skull fragment belongs to an adult individual of undetermined sex. The arrowhead is embedded in the upper left area of the occipital planum (Fig. 3.7a). The projectile penetrated the bone adjacent to the lambdoidal suture between the left parietal and the occipital for approximately half its length (Brinker et al. 2015, 348: Fig. 3.1). The fracture shows a rhomboid shape corresponding to that of the arrowhead on the entry site at the ectocranial surface as well as typical features of a high-velocity projectile trauma. External bevelling is visible at the endocranial surface (exit site)

(e.g. Galloway et al. 2014, 55f). Micro-CT imaging revealed that the bone surface around the projectile shows no signs of bone remodelling. However, the arrowhead is partially surrounded by small particles of the same density as the bronze, which presumably result from the corrosion of the arrowhead (Fig. 3.7b).

The arrowhead has a maximum length of 22.9 mm and maximum blade width of 12 mm. It is a willow leaf-shaped arrowhead type 5 variant A according to Eckhardt (1996; see also Dombrowsky 2014, 139ff.), a type commonly found in central Europe in the late Bronze Age (A. Dombrowsky, pers. Comm.). The arrowhead solely displays minor damage to the top of the socket and the wing ends. However, the tip of the point was also slightly bent following impact on the bone, as visible in the 3D image of the arrowhead (Fig. 3.8). This is probably due to the fact that the projectile had penetrated the bone at high velocity (Galloway et al. 2014, 55).

The skull was penetrated at an angle of approximately 88° relative to the central axis of the arrowhead and the tangential axis of the ectocranial surface (Fig. 3.9a). This explains the typical injury pattern associated with a perpendicular shot: sharp margins (no hinge fractures) on the entry side and external bevelling on the exit side (endocranial surface) (Langley 2007, 533–535; Kneubuehl et al. 2008, 290–291). The angle was taken from a surface model based on micro-CTs, which only covered a small region around the lesion in order to limit the size of the files. A volume model based on clinical CTs of the complete preserved fragment and the micro-CT model were superimposed onto a surface model of an intact, modified example skull for better visualization of the lesion's position (Fig. 3.9b).

Femur with Embedded Object

The femur belongs to a young adult. The epiphyseal closure of the femoral head suggests that this individual of undetermined sex was probably in their early 20s; the sex could not be determined. An embedded object, hardly visible from the outside, was observed in the distal femur. Based on clinical CTs, the clipping of the volume model (Fig. 3.10e, f) revealed a small pointed object of about 1 cm in length, which shows no apparent consistency with an arrow or spearhead from the Tollense Valley finds. In order to clarify the precise shape of the fragment and to obtain detailed information about the surrounding bone structure, a volume model based on micro-CTs was generated. This showed that the pointed object has a pyramidal shape with a slightly rhombic cross-section (Fig. 3.10a–d). The section images also indicate that the object is solid and its surface is heavily corroded. The penetrating wound canal shows a rhomboid shape and tapers toward its end following the shape of the object. The canal is surrounded by a formation of compacted trabecular debris. This is probably due to the fact that trabecular bone tissue was crushed as the object penetrated the bone, and the debris was displaced laterally; this clearly indicates a perimortem injury. Corrosion particles are also visible along the wound canal (Fig. 3.11). The object seems to be a broken tip of a sharp bronze weapon yet to be identified. Further typological and metallurgical studies are planned to try to identify the weapon type and to provenance the metal.

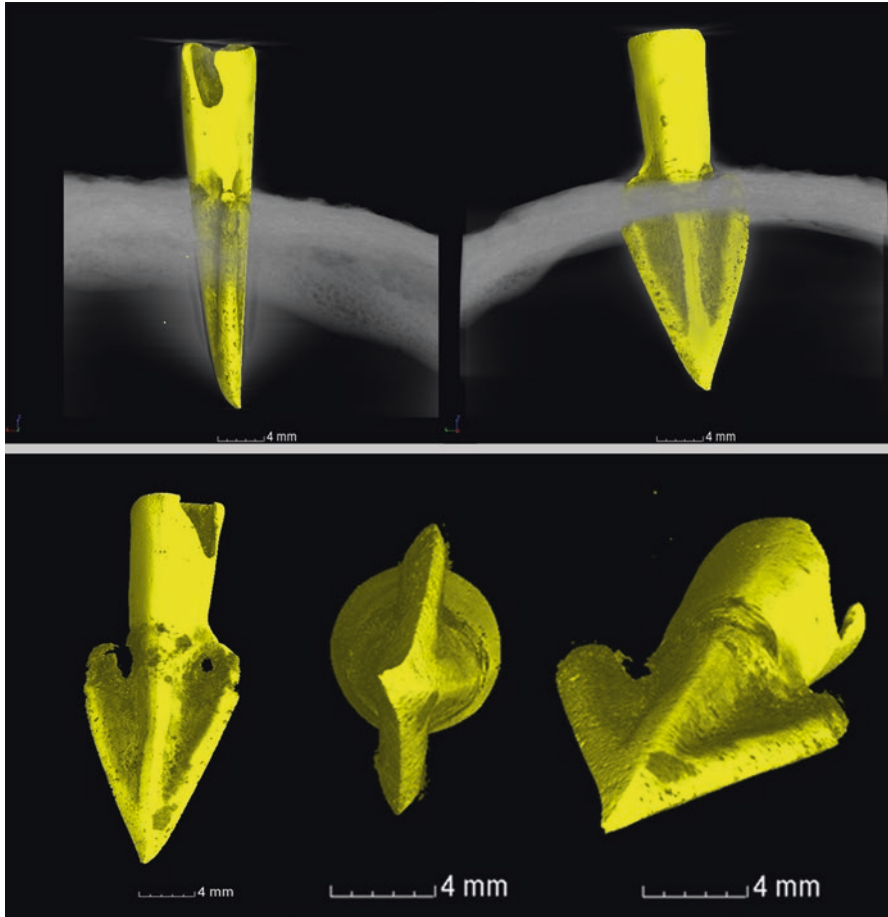


Fig. 3.8 Above: 3D reconstruction of the diploe and arrowhead, lateral (left) and anterior (right) view. Below: 3D micro-CT reconstructions of the socketed bronze arrowhead, general view (left), view from the tip (middle), obliquely from above (right). Scale bar: 4 mm (Micro-CT images: A. Staude © BAM)

Discussion and Concluding Remarks

A number of osteological studies and weapon tests have documented features, which are characteristic of traumas caused by lithic and osseous projectile points (e.g. Smith et al. 2007; Letourneux and Petillon 2008; Petillon et al. 2011; O’Driscoll and Thompson 2014; Yeshurun and Yaroshevich 2014, Duches et al. 2016). Patterns consistent with penetrating injuries were also observed in the weapon experiments carried out by our team using replicas of the bronze weapons from the Tollense Valley site (cf. Lidke et al. 2014a; Brinker et al. 2016). Our tests have further confirmed previous observations that the injury patterns created by bronze arrow and spearheads can be very similar to one another (e.g. Letourneux and Petillon 2008,

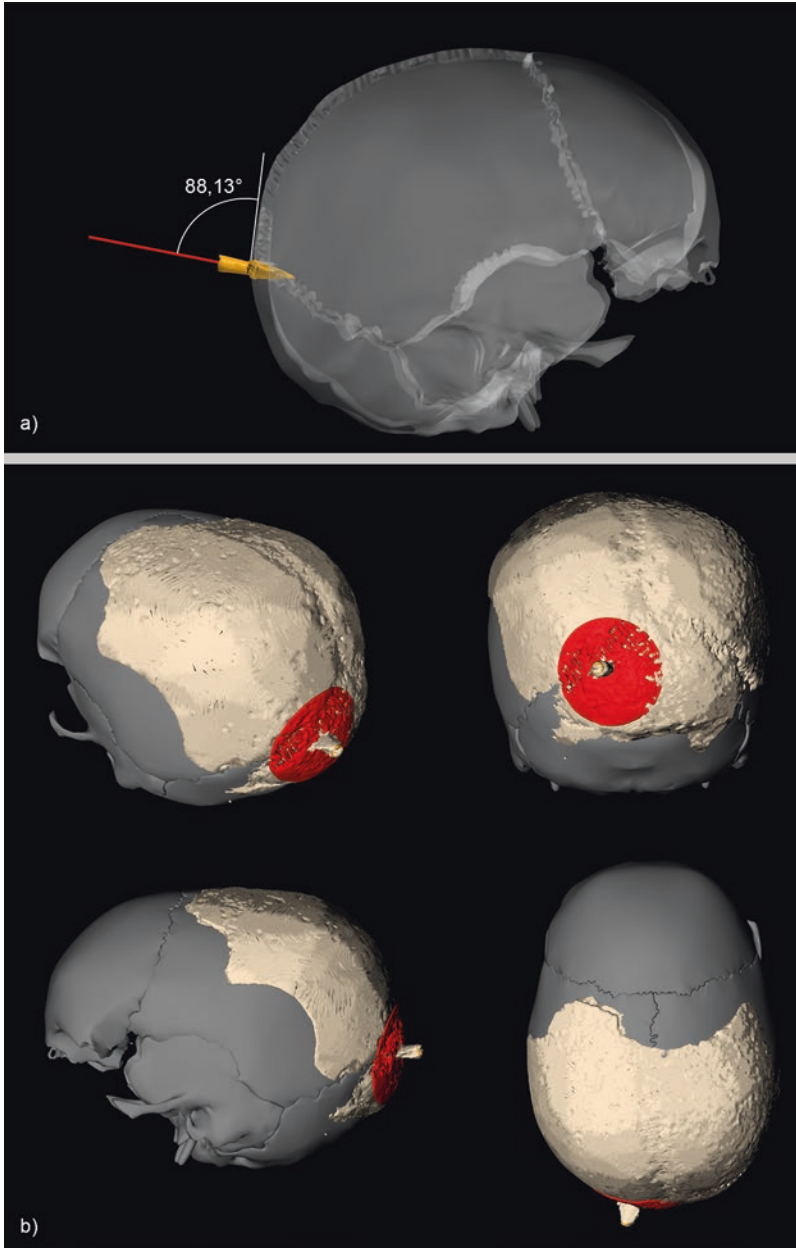


Fig. 3.9 Reconstructed skull and entry angle of the projectile point: (a) The point penetrated the bone at an angle of approximately 88° relative to the central axis of the arrowhead and the tangential axis of the ectocranial surface. (b) Views of the 3D reconstruction of the skull with the injury – micro-CT volume (red), clinical CT volume of the calotte (grey), skull reconstruction (opaque) (Analysis and reconstruction: H. Harten-Buga © Univ. Hamburg; micro-CT data acquisition: A. Staude © BAM; clinical CT data acquisition: K. Hauenstein, Department of Diagnostic and Interventional Radiology © Univ. Hospital Rostock)

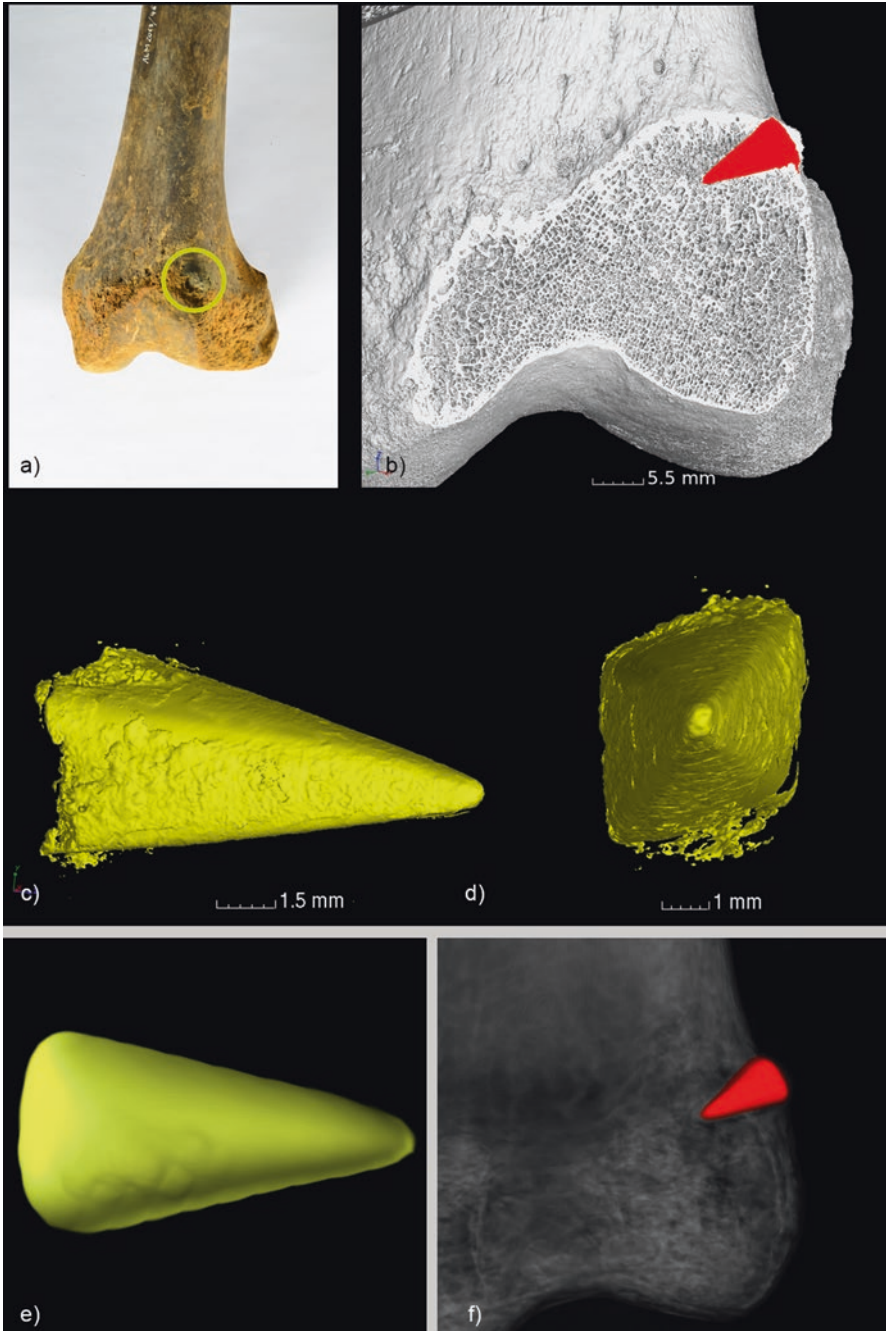


Fig. 3.10 (a) Distal femur with embedded object, anterior view. (b) 3D reconstruction of the distal femur with the object (red), scale bar 5.5 mm. (c, d) 3D reconstructions of the pointed object: view from above (c), scale bar 1.5 mm; view from the tip (d), scale bar 1 mm. (e, f) 3D reconstructions of the object and distal femur based on clinical CTs (Image a S. Suhr © LAKD M-V; micro-CT images b–d A. Staude © BAM; clinical CT analyses e–f H. Harten-Buga © Univ. Hamburg; clinical CT images, K. Hauenstein, Department of Diagnostic and Interventional Radiology © University Hospital Rostock)

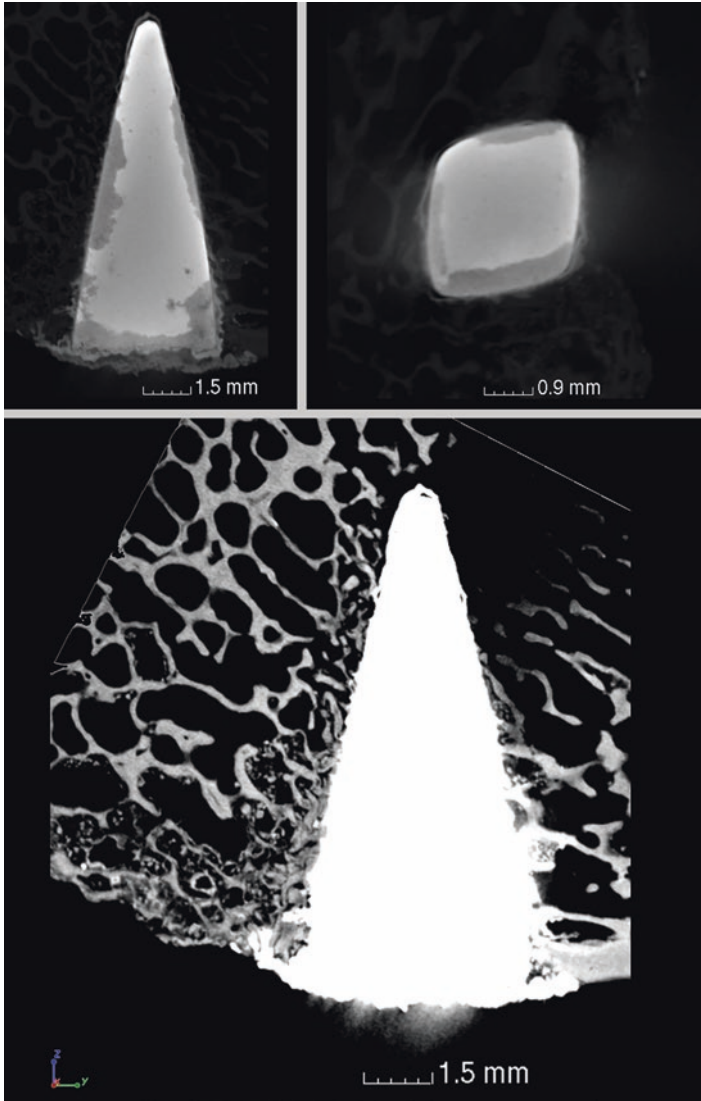


Fig. 3.11 Micro-CT cross-sections of the distal femur showing the longitudinal section (above, left) and cross-section (above, right) of the object as well as the wound canal (below) (Micro-CT images: A. Staude © BAM)

O’Driscoll and Thompson 2014). Therefore, while experimental weapon testing is crucial for providing information concerning the injury patterns and weapon types, it may not offer any clues as to whether the injury originates from a stab or a shot. This is the case with the hipbone lesion presented here, for which macroscopic and microscopic analyses alone do not allow us to discriminate between a handheld weapon and a projectile point (section “[Hipbone lesion](#)”).

In order to address this problem, we have presented in this chapter a method that enables the secure identification of the weapon used in such ambiguous cases, based on the hipbone lesion discussed above. 3D imaging and 3D reconstruction methods have shown that, in this particular case, distinctive injury patterns including the rhombic shape of the penetration wound are consistent with a specific type of socketed bronze arrowhead. Being able to discriminate between arrow and spearheads, and thus between ranged and handheld weapons, is especially important for the interpretation of the Tollense Valley conflict scenario, for which our study confirms that nonstandardized weapons were utilized on the battlefield. In the case of the injured hipbone discussed above, it was also possible to define the features created by an arrowhead striking a flat bone at an acute angle. Furthermore, the effect of a bronze arrowhead perforating a flat bone at an angle close to 90° and the deformation of the point associated with high-velocity impact were discussed with regard to a skull example (section “[Cranial calotte with embedded arrowhead](#)”). Since embedded points are very rare in the archaeological record (Smith et al. 2007, 541–542), the results of our study are extremely valuable for understanding the numerous penetrating injuries documented in the Tollense Valley skeletal material.

The potential of non-destructive, high-resolution 3D imaging is also evident in the case of the femur discussed above (section “[Femur with embedded object](#)”). Here, macroscopic examination was insufficient to determine the size, shape, and position of the embedded object. Our micro-CT-based sections and segmentations not only allowed us to address these problems but also revealed information about the deformation sustained by the trabecular structure upon impact. In the future, the results presented here will be integrated with ongoing palaeomechanical analyses. Palaeomechanics is a new transdisciplinary research method which investigates the relationship between the external mechanical forces affecting the bone vis-à-vis specific injury patterns. This will allow us to verify or falsify our current hypotheses concerning injury processes and weapon efficiency.

Acknowledgements The research discussed in this paper was carried out within the framework of the interdisciplinary Tollense Valley research project led by the State Authority for Culture and Protection of Monuments, Mecklenburg-Vorpommern (LAKD M-V), the University of Greifswald, the Lower Saxony State Office for the Preservation of Monuments (NLD), and the University of Hamburg. We thank the Ministry for Culture and Education Mecklenburg-Vorpommern and the German Research Foundation (DFG) for financially supporting the investigations. We also thank Sabine Suhr (LAKD M-V) for the photographs, B. Illerhaus (BAM, 8.5) for generating the micro-CT images, K. Hauenstein (Department of Diagnostic and Interventional Radiology, University Hospital Rostock) and J. Piek (Department of Neurosurgery, Surgical Clinic, University Hospital Rostock) for generating the clinical CT images, A. Dombrowsky (University of Greifswald, NLD) for the classification of bronze objects, H. Paulsen for the experimental weapon testing, and A. Schramm (LAKD M-V) for supporting the anthropological studies. This project was supported by the National Institute of General Medical Sciences of the National Institutes of Health under grant number P41 GM103545-18. Finally, the authors are grateful to Gundula Lidke (University of Greifswald, NLD) for her proofreading and generous help with the translation.

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