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Investigating the potential of micro-focus computed tomography in the study of ancient bone tool function: results from actualistic experiments

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ABSTRACT

Many experiments have sought to recreate the types of damage that would be expected in ancient stone and bone weapon tips. This damage is usually presented as visible fractures or microscopic surface modification. Fatigue tests conducted on bovine bones, however, show the development of internal micro-cracks that result from stress, prior to actual breakage. In this paper I present the results of an experimental investigation of bone points subjected to a variety of activities. I assess the presence of microdamage using micro-focus computed tomography. The results show that two patterns of micro-cracks develop in bone and are best viewed in longitudinal section. Micro-cracks are a cumulative feature dependent on the amount of load applied and the duration of activity. When subjected to high enough loading rates, micro-cracks will merge together to eventually form a fracture. Although further tests are needed to confirm the exact point at which these fatigue fractures begin to form, micro-focus computed tomography has the potential to reveal whether an individual bone point underwent multiple or prolonged impacts and thus to elucidate the probable function/s of ancient pointed bone tools where no visible damage is apparent. Micro-focus computed tomography is a non-destructive and non-invasive procedure and therefore safe to use on archaeological artefacts.

1. Introduction

The aim of this paper is to explore whether internal micro-cracks develop in cylindrical bone tools created from bovine cortical bone and used in particular activities. Following Leng (2006), I use micro-focus computed tomographic scanning to reconstruct the 3D internal structure of the bovine bone. I present the results of an unused (control) bone point and contrast it to those of four experimentally treated bone points. Three of the experimental pieces were subject to various forms of dynamic loading, such as would result from hunting, trampling and hide piercing. The fourth was an unused point that had been allowed to undergo natural weathering for two years. The rationale for this study is that those bone points, used in the past for utilitarian activities such as hunting, that display no visible signs of fracturing, may show signs of internal micro-cracks that form from stress and develop prior to full-blown fracturing. Such a technique may allow us to identify past activities of bone tools that appear, from the surface, to be of uncertain function.

2. Background to past functional studies

The study of bone tools has concentrated primarily on the identification of use-traces to identify past function, using the principle of tribology (e.g., Chomko, 1975; LeMoine, 1994). This principle states that when two surfaces come into contact and friction is produced, similar materials and similar modes of use will result in similar types of wear, identifiable under a microscope. The underlying premise is that types of wear equate to specific functions and/or specific contact materials (Semenov, 1964; Chomko, 1975; Olsen, 1989; Griffitts, 2001). There have been a host of such studies, focused on the identification of archaeological bone tool functions, published under the auspices of the International Council of Archaeozoologists' Worked Bone Research Group (e.g., Choyke and Bartosiewicz, 2001; St-Pierre and Walker, 2007; Legrand-Pineau et al., 2010). Although use-wear can develop relatively quickly (Buc and Loponte, 2007; Van Gijn, 2007), most tools pass through a stage of indistinct polish before sufficient use-wear traces build up to allow for accurate identification of contact material or function (LeMoine, 1994; Griffitts, 1997). Tools used for different lengths of time in the same activity and on the same material may appear different (Buc and Loponte, 2007; Thompson et al., 2011). Many bone points for example, including awls and hunting points, may develop rounding along the tip and edges

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(Arndt and Newcomer, 1986; Buc, 2011) making identification of specific function difficult.

The challenge of identifying ancient stone and bone tools that have been subject to impact, such as would result from hunting-related activities has been, in part, resolved through the principles of fracture mechanics of brittle solids in a method known as macrofracture analysis (Odell, 1981; Fischer et al., 1984; Lombard, 2005, 2007; Villa and Lenoir, 2006; Lombard and Pargeter, 2008; Villa et al., 2009a, 2009b; Bradfield and Lombard, 2011). This method examines impact fracture terminations, certain of which are considered diagnostic of longitudinal impact, such as would occur as a result of hunting. Recently a number of experimental studies have been conducted to test the reliability of this method in distinguishing between hunting-related damage and damage resulting from other factors (Pargeter, 2011; submitted for publication; Pargeter and Bradfield, 2012; Bradfield and Brand, submitted for publication). One of the limitations of this method is that, in any given experimental hunting sample, macrofractures and diagnostic impact factures only occur in a minority of cases, making it difficult to interpret the possible hunting function of individual pieces. What is needed is a way to identify tools that have undergone impact, but which show no visible signs of damage on the surface.

3. The properties of bone

Bone is anisotropic and responds in predictable ways when stressed (Johnson, 1985; Knecht, 1997). For this reason it behaves much like inorganic brittle solids (Guthrie, 1983; Johnson, 1985; Kasiri and Taylor, 2008), more so when dry than when wet, making it suitable for macrofracture analysis (Bradfield and Lombard, 2011). There is a slight difference in fracture properties between dry and wet bone, as well as between different skeletal elements and bone of different species, depending on the specific microstructure (Taylor and Prendergast, 1997; Lucksanasombool et al., 2001; Adharapurapu et al., 2006; also see Karr and Outram, 2012). A property of brittle solids is their tendency to deformation wear, characterized by the formation of crack networks, caused by elastic deformation around impact points (Sklar and Dietrich, 2004; Thompson et al., 2011).

A long bone such as a humerus or femur consists of cortical and trabecular bone. Archaeological bone points were made from the denser and stronger cortical bone, which in turn consists of Haversian bone and plexiform bone. Viewed in cross section, Haversian bone consists of a number of osteons, made up of Haversian canals and concentric cement lines, surrounded by lamellar bone matrix (Fig. 1). Running perpendicular to the Haversian canals are Volkmann's canals. These canals serve to supply blood to the rest of the bone. Also present in the bone matrix are air spaces called voids or lacunae. On the other hand, plexiform bone has a brick-like structure and is found in large, rapidly growing animals such as bovids (Martin and Burr, 1989). It consists of alternating layers of parallel-fibred bone and lamellae (Fig. 1; Adharapurapu et al., 2006). The fatigue strength of plexiform bone is slightly greater than Haversian bone because the volume fraction of voids in Haversian bone, which are, together with canals and vascular spaces, the sites around which stress concentrates, is higher than that in plexiform bone (Lakes et al., 1990; Kim et al., 2005, 2006). Therefore more energy is required for crack propagation in plexiform bone (Kim et al., 2005).

Bone is known to develop micro-cracks as a result of fatigue and other accumulated mechanical stress factors, usually when subject to a dynamic load greater than its tensile strength (Johnson, 1985; Lakes et al., 1990; Kim et al., 2006; Leng, 2006). Such damage manifests as cracks and/or separations in the non-lamellar portion of plexiform bone and between cement lines in Haversian bone (Schaffler et al., 1989; Abdel-Wahab et al., 2012). Micro-cracks in Haversian bone are short and randomly oriented, whilst in plexiform bone micro-cracks are longer and parallel to the lamellar bone, albeit that they develop less frequently (Kim et al., 2005). Micro-crack deformation in cortical bone has been recorded to range from 1 μm to 3.5 μm in diameter and can easily reach 100 μm in length (Leng, 2006; Kasiri and Taylor, 2008; Abdel-Wahab et al., 2012). These measurements are taken from the transverse profiles. Cracks that are oriented longitudinally, however, are known to result in lower fracture toughness and lower work of fracture compared to cracks oriented transversely (Lucksanasombool et al., 2001) and are therefore likely to develop more rapidly and obtain greater dimensions than their transverse counterparts (O'Brian et al., 2003). This is due to the intrinsic nature of long bones which tend to experience failure parallel to the fiber structure

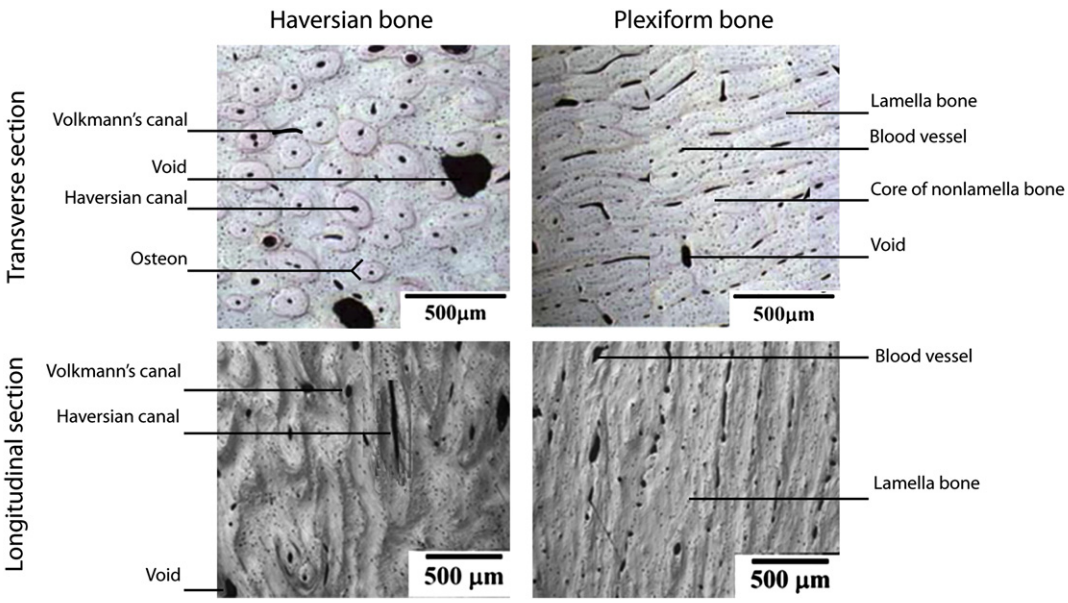

Fig. 1. Thin section comparison of Haversian and plexiform bone showing diagnostic structures. Figure is adapted from Kim et al. (2006).

(Behrensmeyer, 1978). Different parts of the bone and the skeletal element from which the bone derives is also important in determining fatigue strength (Reilly and Currey, 1999). Techniques commonly used to examine micro-crack propagation for medical purposes are thin-sectioning (Burr and Hooser, 1995), scanning electron microscopy (Schaffler et al., 1994) and confocal laser microscopy (O'Brien et al., 2000). All these methods make use of two-dimensional thin sections and are therefore destructive procedures, unsuited to the examination of archaeological tools. Recently, Leng (2006) used micro-focus computed tomography to view micro-damage in cortical bone and its effects on bone strength *in vivo*, and I follow her in my approach.

4. Experimental procedure

Image data from the bone points were acquired using an X-Tek microfocus X-ray computed tomography (Nikon Metrology XTH 225/320 LC dual source industrial system) machine, hereafter referred to as the micro-CT scanner. This permitted the non-destructive investigation of the experimental tools for the purposes of imaging internal structures and performing 3D analyses of objects. Basically, the machine works by sending X-rays from a target through a rotating specimen to a detector panel. The images picked up by the detector panel are sent to a computer and the images reconstructed using advanced imaging software. The micro-CT scanner is capable of scanning objects ranging from a block of breccia to a seed-pod, achieving maximum spatial resolution in the region of 5–10 μm, depending on object geometry and the parameters chosen for the task. Imaging analysis software such as VG Studio Max used with the micro-CT image data allows the viewer to move through the object on any plane, essentially viewing a series of hundreds or thousands of individual images (e.g., .tif or .bmp files).

In order to enhance the contrast between the bone in the specimen and the surrounding environment, radio-opaque substances such as lead sulphide (PbS) or barium sulfate ($BaSO_4$) precipitate can be used to treat the bone prior to micro-CT scanning (Leng, 2006). These substances are absorbed by the bone and show up on x-rays as artificially dense. Because of the absorption factor, this approach is inappropriate for archaeological specimens. Alternatively, I embedded the bone point in a substance (flour) that permitted higher scanning energies to be used, while also minimizing beam scattering caused by the sharp bone-air boundary. The flour facilitated achieving necessary material contrast in the images and allowed for easy cleaning of the bone points after scanning. It should be noted, however, that this method too would adversely affect archaeological residues, although it would not destroy them as would lead sulphide and barium sulfate. After the bone was embedded in the flour matrix contained in a small plastic vial, the assembly was mounted on the manipulator arm of the micro-CT scanner. I tried using two different targets during scans – a 225 kV static target and a 225 kV rotating target. The specific parameters used for the six scans are presented in Table 1. Each bone point was scanned using 3000 projections. On average, a spatial resolution of 6.2 μm was achieved for each specimen – far higher than similar scans of *in vivo* bone in the study by Leng (2006). Due to the proximity of the specimens to the target needed to achieve the high resolution, only the first 10 mm from the tip were scanned. This was deemed acceptable since it encompasses the functional end where micro-structural damage ought to occur.

5. The experimental tools

Four experimental bone points were used in this series of scans. The first three scans were bone points made from the diaphyses of *Aepyceros melampus* (impala) metatarsals and subjected to dynamic loading whereby the point was affixed to a 125 g weight at the proximal portion and dropped from a height of 70 cm onto a hard linoleum surface, making the impact velocity 3.7 m/s. Impact force was calculated at 42.8 N and was generally parallel to the longitudinal axis of the point. Prior to loading, the first point was scanned as a control specimen. Subsequently, the point was loaded as described above until it fractured on the 42nd impact. Pre- and post-treatment scans were compared to assess the effect of loading. A second point was subjected to only 20 impacts, and did not fracture. This permitted comparison of bone points loaded until fracture and loaded, but without fracturing. Following recent experimental protocols, I opted for an actualistic approach to these impact experiments rather than the more formal four-point bending test, which is ill suited to recreate impact loading at the tip as would be expected from hunting damage. Although the option was available to use bone points from an actual hunting experiment (e.g., Bradfield and Lombard, 2011) I chose not to use these because I wanted to compare the before-and-after scans from the same bone.

Table 1
CT scan parameters for the experimental bone points. kV = kilovolts; μA = microamps; res. = spatial resolution and Mag. = magnification.

Sample	Raw material	kV	μA	Res.	Mag.	f/s	Target
Pre-treatment	*A. melampus*	55	450	5.6	35.7	2	Static
Post-treatment	*A. melampus*	60	470	6.2	32.2	2	Static
Unbroken	*A. melampus*	50	500	6.2	32.2	1	Rotating
Hide piercing	*Bos primigenius*	50	500	6.2	32.2	1	Rotating
Trampling	*A. melampus*	50	500	6.2	32.2	1	Rotating
Weathering	*A. melampus*	55	400	6.2	32.2	1	Rotating

The next two points that were scanned came from previously published actualistic experiments that have recreated macro-damage from various activities. These bone points were fractured specimens subjected to goat trampling (Pargeter and Bradfield, 2012) and hide piercing (Bradfield & Brand, submitted). The former experiment used goats to replicate the damage to bone and stone tools that would be expected to accrue through trampling by small to medium sized bovids. Tools were placed on the surface and 5 cm below ground and trampled for fifty passes by thirty goats. Macrofracture damage to the bone tools was minimal and confined to the tips where the bone was thinnest and weakest (Pargeter and Bradfield, 2012). The latter experiment used bone points to pierce dry and fresh animal hide in order to simulate awl use. Each bone point was used for eighty penetrations or until in broke. Macro-fracture damage occurred at the tip and mid-point of the tool shafts (Bradfield & Brand, submitted).

The final bone point was made from a left-over bone shaft from the original Bradfield and Lombard (2011) experiment. This piece had been exposed to natural weathering conditions such as rain and direct sunlight for a period of two years prior to being fashioned into a bone point, after which time it was left exposed for a further month. At the time of scanning this piece had a roughened surface, typical of weathered bone. This piece was not used in any activity but was scanned in order to test the effect that time and weathering conditions have on the formation of micro-cracks and the potential for these to obscure results and affect interpretations on archaeological specimens.

6. Results

Fig. 2 presents images from four experimental bone points showing micro-cracks and certain identifiable natural features. Impact, hide piercing and trampling all produce micro-cracks in the

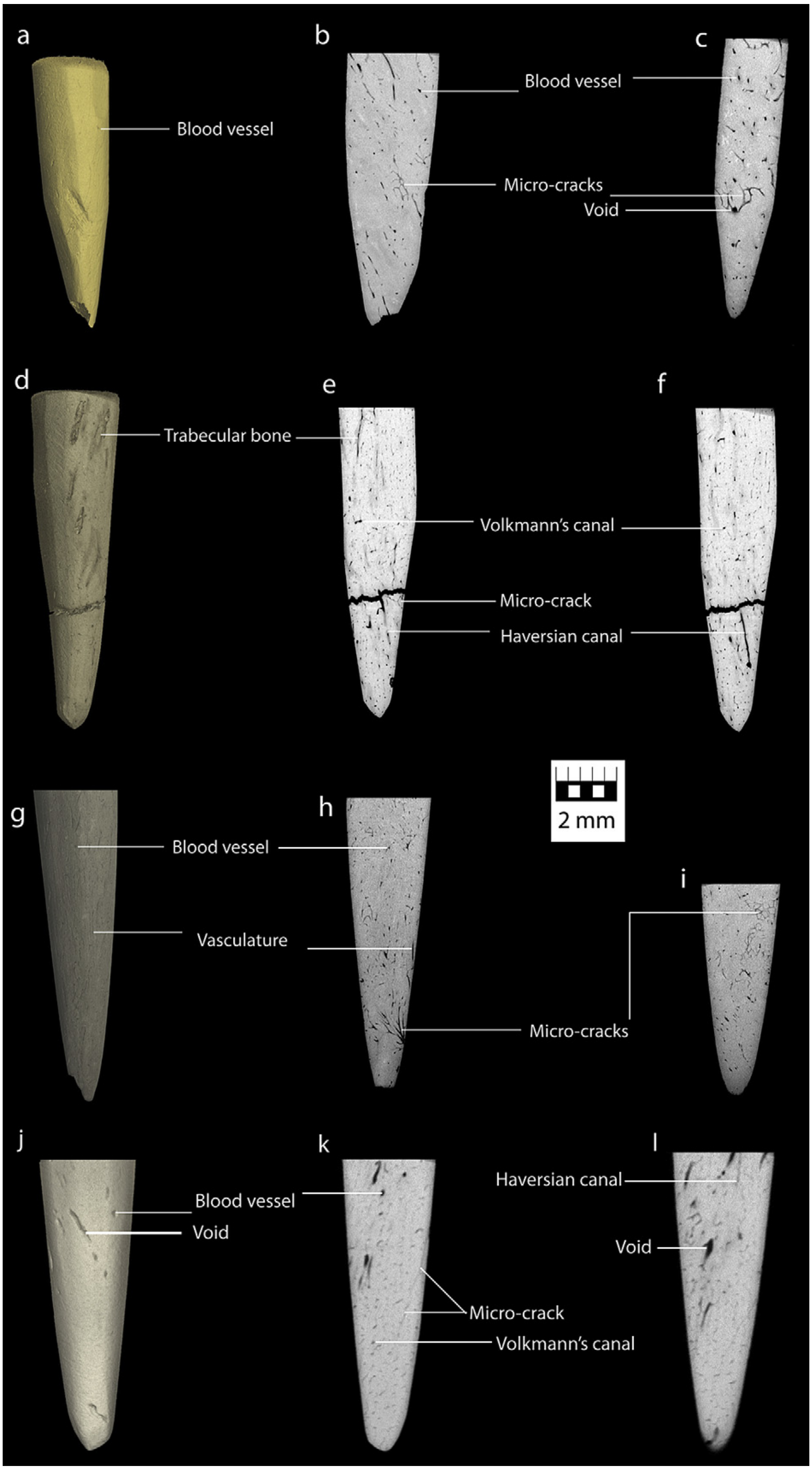

Fig. 2. Selected 3D renderings (left side) and 2D greyscale representations (middle and right side) of the experimental bone points in longitudinal section showing micro-cracks and natural features. Top row (a–c): three views of micro-crack propagation due to loading for 20 impacts; Second row (d–f): three views of micro-crack propagation from hide piercing; Third row (g–i): three views of micro-crack propagation caused by post-depositional trampling Bottom row (j–l): three views of micro-crack propagation due to weathering.

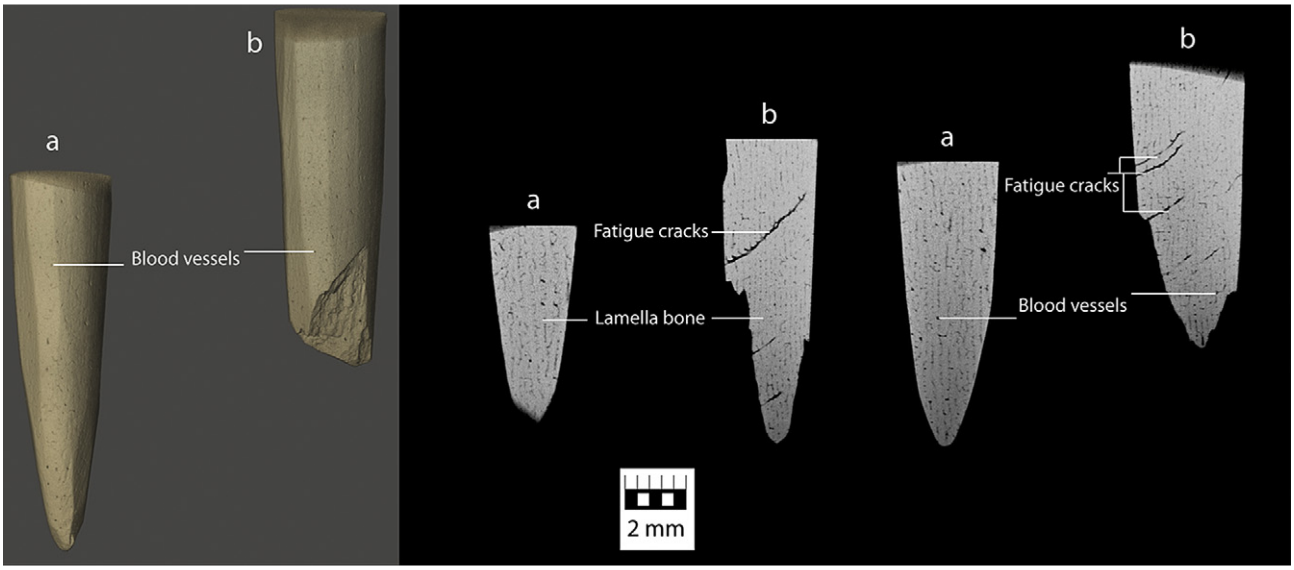

Fig. 3. Comparison of bone point showing pre- (a) and post-treatment (b) CT scans, where treatment involved loading until failure. Notice the wide fatigue cracks in the region of 53 μm.

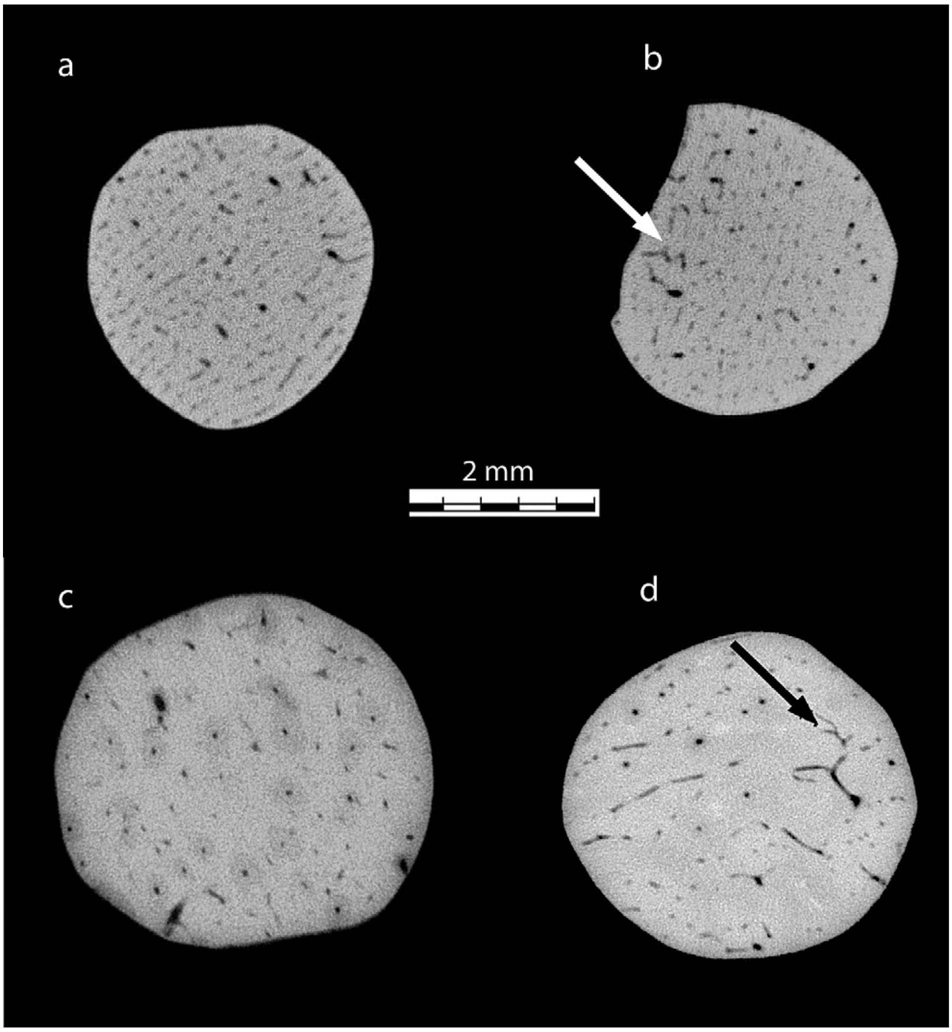

Fig. 4. Comparison of four transverse sections. a: Pre-treatment scan showing no micro-cracks; b: post-treatment scan showing two micro-cracks just to the right of the fracture line; c: Awl used to pierce animal hide. Note the clear Haversian system; d: bone point loaded for 20 impacts showing micro-cracks to the top left of the image.

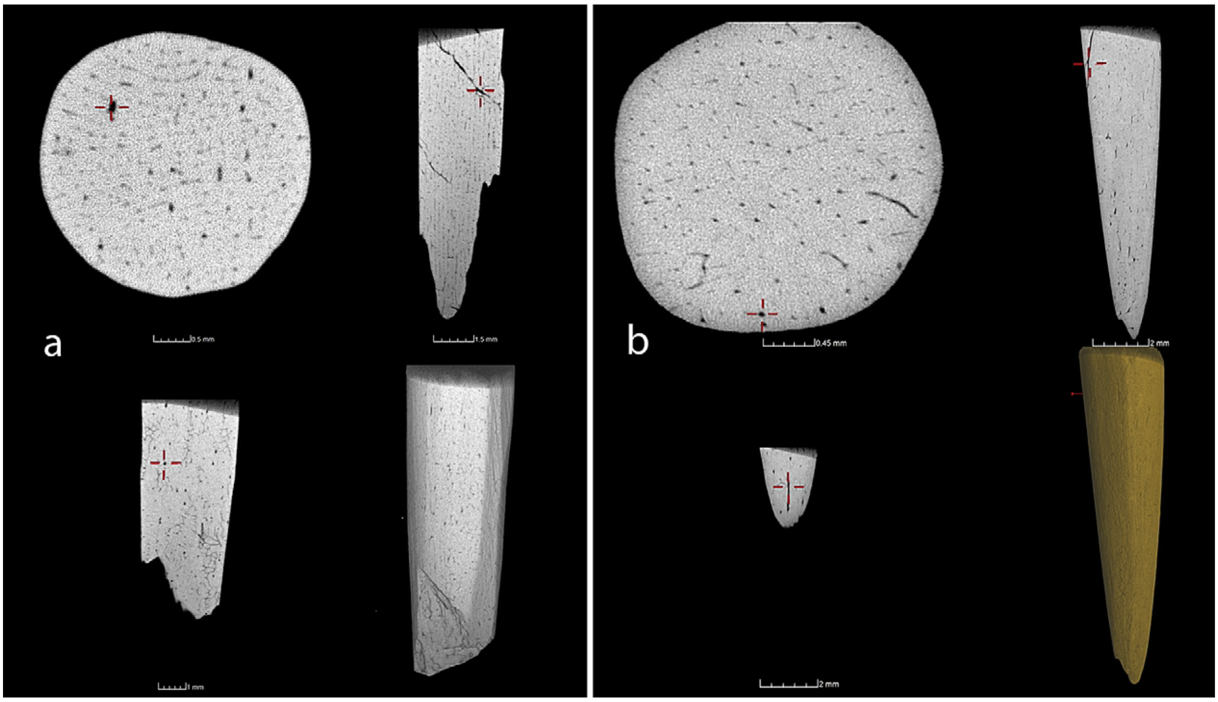

Fig. 5. Four-perspective views where a) shows a fatigue crack and b) shows a blood vessel. Note the similarity of the two features in cross-section.

bone and all are connected to one of the natural spaces in the bone, i.e. canals, blood vessels or voids. The weathered bone point developed a micro-crack very different to the other specimens. Here the micro-crack (Fig. 2k) presents as a jagged-edged line that extends about a quarter ways around the circumference of the bone. It can be likened to the circular flaking of dry weathered whole long bones when the outer layers detach from the lower ones in a concentric manner akin to the microscopic version of Stage 2 of Behrensmeyer's (1978) classification.

My scans showed that micro-cracks are most easily seen in longitudinal section. Two video files, of the pre- and post-treatment bone points shown in longitudinal section, are included in the Supplementary material to this article by way of illustration. In general, micro-cracks as seen in longitudinal section, present as a net of fine lines similar in appearance to shattered glass. The point loaded for 20 impacts, top row, developed micro-cracks originating from a void (Fig. 2c). The bone awl used for hide piercing, middle row, did not develop the same fracture mesh or net pattern as the first specimen. Instead the micro-cracks present as single fine lines originating from the macrofracture. This piece of cortical bone, while still retaining traces of the trabecular bone at its surface (Fig. 2d), displayed a clear Haversian system – the only bone point in this paper to do so. As mentioned above, the different micro-structure of the bone needs to be taken into account during analysis as it affects the way in which micro-cracks will look. In Haversian bone micro-cracks will be short and randomly oriented between cement lines; whilst in Plexiform bone cracks usually will be longer and parallel to the lamellar structure (Kim et al., 2005; Abdel-Wahab et al., 2012). The trampled bone point, bottom row, developed both patterns also originating from natural lacunae in the bone.

Supplementary video data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2013.02.007.

Fig. 3 presents a comparative image of the pre- and post-treatment scans of the bone point loaded until fracture. Immediately noticeable are the fatigue cracks that cut through the natural bone structure. These cracks are five times wider than the micro-cracks and form when bone is loaded to the point of failure. Had the bone point continued to undergo impact, it is clear that it would have eventually fractured along one or more of these lines. The different fracture patterns evident in the four bone points that I scanned are consistent with Shipman's (1981) observation that different breakage conditions will produce different micro-structural responses. As mentioned, micro-cracks form along or around existing lacunae in the bone. The more the bone is loaded or the more impacts it experiences, the greater the number of micro-cracks that will develop. Eventually, these micro-cracks will group together and merge to create the large fatigue cracks that we see in Fig. 3b. Continued loading or impact will result in bone failure and the development of a macrofracture, such as is visible in the 3D image in Fig. 3.

Fig. 4 presents four transverse images, two of which show micro-cracks (Fig. 4b and d). In this perspective, these cracks can sometimes be difficult to distinguish from Volkmann's canals and blood vessels. This problem is highlighted in Fig. 5, where a fatigue crack (Fig. 5a) is indistinguishable from a blood vessel (Fig. 5b) when viewed from a different plane perspective. This is particularly apparent in the transverse sections. The problem of accurately identifying features emphasizes the important role micro-CT scanning and image analysis software can play in this respect. Being able to view an object in three-dimensions and through any plane has clear advantages over standard microscopic thin-sectioning.

7. Discussion and conclusions

The experimental bone points were subjected to similar activities and conditions to those that their archaeological counterparts may have experienced, namely, hide piercing, post-depositional trampling, weathering and longitudinal impact consistent with use as a hunting weapon. The impact velocity of this latter group, however, was markedly less than that recorded for arrows shot from traditional Bushman bows, at roughly 33 m/s (Hitchcock and Bleed, 1997), but did allow for multiple controlled impacts. The minimum force needed for micro-crack propagation is between 7.3 and 10.1 N (Abdel-Wahab et al., 2012), far less than is generated through the impact velocity of an arrow. During high speed impact, bone fracture toughness reduces greatly with increased loading rates resulting in fracture surfaces similar to brittle solid fracture in inorganic solids (Arndt and Newcomer, 1986; Adharapurapu et al., 2006; Griffitts, 2006; Bradfield and Lombard, 2011). However, as Shipman (1981) demonstrated, different breakage conditions produce different micro-structural responses in bone. It is these micro-structural responses that I am concerned with in this paper, and whether it is possible, based on micro-crack formations, to discern the past function of a bone tool.

The results obtained from the Micro-CT scans are consistent with findings from thin-section microscopic analyses of bone and provide some interesting new insights. Micro-cracks form around areas of stress concentration. These are usually the weak areas in the cortical bone, namely, the voids and canals (Leng, 2006). There are seven categories of micro-cracks based on their location in relation to these features (Norman and Wang, 1997). The specific categories are not important here; what is important is the size of the micro-cracks in order to differentiate them from naturally occurring features, such as canals; and the dimensions of the micro-cracks to differentiate them from weathering features. Micro-CT scanning allows for micro-cracks, and other naturally occurring features, to be viewed in three-dimensions and thus obtain a more detailed understanding of micro-crack and fracture propagation. This ability, as has been shown, is vitally important in distinguishing between utilitarian and natural fractures as well as natural features such as canal spaces. However, as with most methods, the benefits are partly off-set by certain limitations.

Micro-CT analysis is an extremely time-consuming and potentially costly exercise. The small sample size presented in this paper is a consequence. While science strives for reproducibility of results, the degree to which this can be achieved in micro-CT scanning is, to a large extent, dependent on the skill and experience of the technician. Regular filament changes of the x-ray generator require a reconfiguration of the machine so that scans run several months apart, using the same parameters, may not yield results of identical quality. Although only five bone points were scanned during this experiment, the results show that specific activities and ambient conditions result in specific micro-crack formations; a study of which may inform on the past activities of archaeological bone tools. The difference in results between the two targets (static and rotating) used in these experiments was negligible. The rotating target does provide a slightly crisper image although the necessary detail is visible on both. In order to achieve the necessary magnification and resolution only the tip of the bone points could be accommodated in the field of view. Larger specimens are possible but not to the level of detail needed to view internal micro-structure. On archaeological specimens, where the working end is ambiguous or where the research question is to investigate hafting arrangement, multiple scans can be performed along the length of the specimen and then digitally stitched together using a software program. Here too, one would run into problems with the fragmented nature of most archaeological assemblages and the uncertainty of how much of the original specimen remains. This is particularly apparent in older assemblages.

One of the questions at the forefront of archaeological research in recent years has been the antiquity of the bow-and-arrow technological system (e.g., Shea, 2006; Lombard and Parsons, 2008; Lombard and Phillipson, 2010; Lombard, 2011; Parsons and Lombard, 2011). The idea that bone points were only used as arrow components after ~12 ka ago now seems untenable in light of recent archaeological finds that suggest a date of between 35 and 44 ka ago for material culture akin to that of the more recent Holocene assemblages (Robbins et al., 2012; d'Errico et al., 2012). More enigmatic are the morphologically similar bone points from securely dated Middle Stone Age deposits at Blombos Cave and Sibudu Cave in South Africa (Henshilwood et al., 2001; d'Errico and Henshilwood, 2007; Backwell et al., 2008). These tools, which date between 77 and 64 ka ago, have been interpreted as projectile points, based on comparative morphology and use-wear (Henshilwood et al., 2001; Backwell et al., 2008). Macrofractures, however, can develop through a number of reasons and use-wear traces can sometimes be obliterated through post-depositional taphanomic processes. In the absence of unambiguous surface indicators, micro-CT scans might provide one avenue of further functional exploration, helping to resolve the question of whether these bone points functioned as weapon tips.

The potential application of micro-CT scanning to archaeological problems is evident. Whether it be to view the internal structure of an object (Jacobson et al., 2011), or to discern the intentionality of engraved lines (Jacobson et al., 2012), micro-CT scanning has the ability to bring new information to old archaeological problems, making it yet another tool in the archaeologist's repertoire for understanding the past. Micro-CT scanning is a non-destructive and non-invasive procedure making it ideally suited to the study of scarce or unique archaeological artefacts.

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