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TECHNICAL NOTE

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Microscopic Indicators of Axe and Hatchet Trauma in Fleshed and Defleshed Mammalian Long Bones*

ABSTRACT: The characterization of wounds in bone caused by chopping weapons has been based on either semi-fleshed or defleshed specimens. This approach has not been adequately justified as reflecting actual cases involving fleshed bone. Likewise, the histological appearance of features in chopping wounds also deserves further attention. We used 11 fresh pig (*Sus scrofa*) articulated hind limbs, including the femur, tibia, and fibula with contiguous surrounding flesh (including an intact epidermal layer), to receive wounds using two axes and two hatchets. Scanning electron microscopy analysis of these wounds exhibited osteon pullouts in the fracture surfaces of fleshed specimens, suggesting the attenuation of force by the surrounding flesh. Lamellar separation was also exhibited at the impact sites and fracture surfaces of both fleshed and defleshed specimens. A consistently rough morphology is characteristic of fracture surfaces while impact surfaces are smooth and yielded evidence of striations from each implement.

KEYWORDS: forensic science, forensic anthropology, trauma, axe wounds, hatchet wounds, microscopy, SEM analysis, chopping

The use of scanning electron microscopy (SEM) in forensic anthropology has been seen increasingly in recent publications on analyses of sharp force trauma to bone (1–7). The use of SEM analysis affords the advantage of improved resolution, three-dimensional (3D) information, and increased magnification, something that is not available with conventional stereo-microscopy (5,7). Alunni-Perret et al. (2) also explain that the increased depth of field involved in SEM also allowed these researchers to obtain information regarding knife and hatchet wounds that enabled their differentiation, something that would not have been possible by simple macroscopic examination. SEM is essential in order to maximize the quantity and quality of useful data in research and forensic casework.

When considering the mechanism of bone fracture at the histological level, it is important to understand the structure of bone at this level. In compact bone, osteons are arranged next to each other in layers of concentric lamellae, in a tubular fashion, and parallel to the long axis of the bone in the diaphysis. This orientation enables the long bone diaphysis to resist great compressive and tensile forces. Despite this, fracturing may occur if a force is directly applied to the lateral side of the diaphysis, exceeding the tensile strength of the bone. Interstitial lamellae are found in the areas between the osteons and are the remnants of older osteons whose matrix has been almost completely recycled. A third type of lamella found in compact bone is circumferential lamella which is found on the outer and inner surfaces of bone, adjacent to the bone's periosteum and endosteum, respectively.

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In his landmark paper, Piekarski (8) defined the phenomenon of an osteon "pullout" as occurring in lower energy or slower propagating fractures. Pullouts result when a low energy fracture follows the path of least resistance in bone and travels through the interstitial matrix. The propagating crack is then bridged by the osteons as their tensile strength exceeds the shear strength at each concentric interlamellar interface (9). The osteons eventually fail above or below the crack interface, producing an irregular pulled-out appearance as individual fibers are pulled out of the matrix. A rough fracture surface is the result of a fracture propagating around the osteons while in high energy situations, the fracture simply cuts across these structures, producing a much smoother surface (4).

Tucker et al. (1) examined characteristics of wounds caused by machetes, axes, and cleavers on the cut surfaces of bone using SEM. Trauma was inflicted on 28 semi-fleshed domestic pig long bones. SEM analysis failed to find striations imparted to the bone by the axes as these bones were shattered or otherwise broken by the wedge-action of the blade. Trauma inflicted by the machetes and cleavers was also described. The surfaces of each weapon were subsequently examined by SEM and although they did correspond with the characteristics seen in the bone trauma in the case of the cleavers and machetes, the axe edges did not correspond to the bone trauma. In this situation, it was the absence of features in the trauma that aided in the identification of the axe as the causative weapon.

Subsequent to this, Alunni-Perret et al. (2) attempted to characterize the bone lesions made by a single blade knife and a hatchet (15 repeats each) from their class characteristics by the use of SEM. Defleshed sections of human femora were used and a device to regulate force was constructed to inflict the trauma. While they determined that wounds inflicted by the knife blade and hatchet were almost identical in macroscopic examination, it was found that SEM aided in visualizing 3D characteristics not visible to the naked eye or in light microscopy. SEM detected that hatchet wounds had a width that was relatively consistent for its entire length, with kerf walls and floors being quite smooth, edges that were uneven with significant flaking, and unilateral or bilateral cortical bone fractures. Hatchet wounds were also distinguished from knife strokes by the absence of unilateral elevation of the cortex. This study would also be helpful in that it would allow comparison of characteristics indicative of hatchet trauma.

The goal of this research is to inflict chopping trauma using axe and hatchet on fully fleshed hind limbs of domestic pigs. The resulting bone trauma would then be subjected to SEM analysis and compared with the results reported by Tucker et al. (1).

Materials and Methods

Eleven fully fleshed juvenile domestic pig (*Sus scrofa*) hind limbs and nine defleshed domestic pig bones were utilized in this study. Each fleshed hind limb contained a fully intact epidermal layer in addition to a femur, tibia, and fibula in articulation. The defleshed domestic pig long bones consisted of six defleshed humeri in addition to three defleshed femora with contiguous periosteum and minimal residual flesh.

Implements

The implements used to inflict wounds included two used axes, one used hatchet, and one newly purchased unused hatchet. Axe 1 was much sharper than Axe 2, slightly rusted, with visible striations on its blade. Axe 2 has a history of use for wood chopping and has a very dull and rusted blade with no visible striations. The blade on Hatchet 1 was also sharp yet not as sharp as Hatchet 2, slightly rusted, with clearly visible striations. Finally, Hatchet 2 was newly purchased for this study and has a very sharp blade, lacking rust. None of the blades were sharpened for our study. Note that sharpness scoring was based on the degree to which the implement blade caught on the dermal ridges of the thumb when carefully running it across the blade.

A trauma infliction station was set up using a section of drywall and placed flat on the floor in our laboratory. This was primarily done to provide an aid in preventing the implements used from damaging the underlying floor when inflicting trauma.

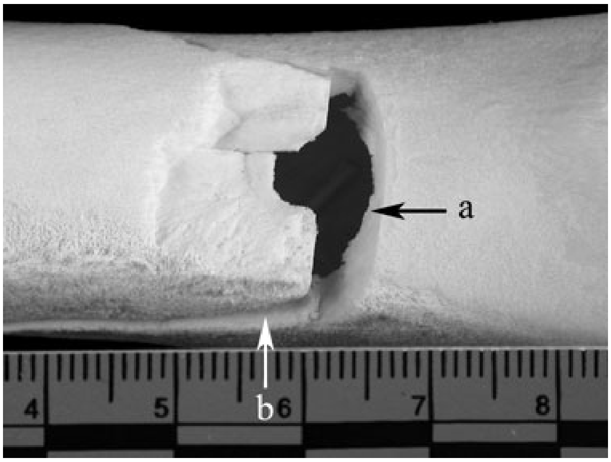

FIG. 1—*Lateral femur wound on a previously defleshed bone demonstrating an impact site (a) and fracture surface (b). (Photo by K. Lynn)*

Trauma Infliction

Trauma was inflicted as described by Lynn and Fairgrieve (10). This involved measuring the soft tissue thickness overlying the bone using a fine needle probe prior to inflicting trauma. Tissue thickness was also assessed by direct measurement within the inflicted wound.

Although the force used to inflict trauma with the implements varied, the amount of force was sufficient to penetrate the soft tissue and directly affect the underlying bone while not penetrating the substrate supporting the specimen. Fleshed and defleshed specimens were treated in an identical manner (10).

Sample Preparation

Soft tissue removal from fleshed specimens and the treatment of all bones prior to excision of bone fragments followed the procedures set out by the authors in a related study (10). Impact sites and radiating fractures (in the case of bisected bones) were then excised using a hand-held rotary saw under a fume hood, cutting larger fragments into smaller sections to facilitate SEM examination. The excised sections of bone were then degreased using a citrus-based degreaser for *c.* 12 h when necessary, after which the osteological elements were rinsed using clean water and allowed to dry. In order to provide a flat surface to ease in mounting on SEM studs, the specimens were ground using a rotary tool sanding cone.

After all specimens were processed in the aforementioned manner, suitable specimens were selected for mounting for analysis in the SEM (Table 1). Suitable specimens included sections of originally fleshed bones with a clear impact site or fracture surface and minimal damage due to desiccation (e.g., crumbling of bone). Sections of each defleshed specimens were also analyzed. A 12-mm carbon adhesive disk was used to attach each specimen to an aluminum stud. Some larger specimens required use of colloidal silver paint to secure a bond to the stud. Each specimen was then coated in *c.* 8–10 nm of gold using a Cressington Sputter Coater (Ted Pella, Inc., Redding, CA) to produce a conductive surface.

Microscopic Analysis

After mounting and sputter coating, specimens were examined using a Cambridge Stereoscan 120 scanning electron microscope. Impact sites and surrounding fracture surfaces were examined, noting general characteristics such as the overall appearance of kerf floors (if present) and walls, and edges and extremities of the wound, as per Alunni-Perret et al. (2). The presence and appearance of striations were also noted as per Tucker et al. (1), and the presence of a smooth or rough surface morphology was also noted.

TABLE 1—*Distribution of fleshed and defleshed specimens analyzed by SEM according to implement type.*

Elements	Axe 1	Axe 2	Hatchet 1	Hatchet 2	Total
Fleshed					
Femora	2	5	0	3	10
Tibiae	0	1	1	1	3
Fibulae	0	1	2	0	3
Total	2	7	3	4	16
Defleshed					
Humeri	2	2	2	1	7
Femora	0	0	1	1	2
Total	2	2	3	2	9

SEM, scanning electron microscopy.

Additional features that were evaluated included the presence of osteon pullouts and lamellar separation (separation of circumferential lamellae in a step-wise fashion), noting the differences observed between impact site/fracture surface interfaces. Lamellar separation was not indicated in the literature but came to our attention during analysis.

The presence of each of the aforementioned features was scored and the prevalence was calculated. As sample sizes here are small this necessitated expressing our results as simple fractions and percentages. The presence of each feature noted above was indicated and the mean entry site widths and lengths were calculated in addition to their standard deviations.

Results

Results were grouped according to the surface analyzed (the impact site or a fracture surface). The impact site is the location on the bone which was physically in contact with the implement when the wound was inflicted. A fracture surface, however, is the surface of an ensuing fracture emanating from the impact site which, in many cases, caused bisection of the bone (Fig. 1). For the fleshed specimens, fracture surfaces were found to have a rough surface morphology, having the appearance of rolling hills (Fig. 2). These surfaces were also found to exhibit osteon pullouts in seven of 10 specimens analyzed in addition to exhibiting lamellar separation on six of 10 occasions (Fig. 3; Table 2). Striations were only visible in one specimen inflicted with trauma by Axe 2. For the defleshed specimens, only one osteon pullout was seen on one fracture surface. While lamellar separation was seen in half of the fracture surfaces examined, this feature was apparent in eight of 10 impact sites. No striations were observed on the fracture surfaces of the defleshed specimens (Table 3).

The impact sites of the fleshed specimens were distinguished from the fracture surfaces based on their smooth surface morphology. Osteon pullouts were not seen on any impact sites whereas lamellar separation was seen in all seven cases (Fig. 3, bottom). Striations were also apparent in 48% of the specimens, contradicting the findings of Tucker et al. (1) while corroborating the discussion carried out by Reichs (11) (Table 2; Fig. 4). On the impact sites of the defleshed specimens, lamellar separation was apparent in eight of 10 impact sites. Striations were also observed here, contradicting the findings of Tucker et al. (1) (Table 3).

Discussion

As a chopping weapon enters the bone, its smooth surface is expected to leave an equally smooth appearance on the impact site while ensuing fractures propagate through the bone, following the path of least resistance. The present research suggests that while chopping weapons tend to impact bone with a high amount of energy because of the swinging action used and the mass and dimension of the blade, the resulting secondary fractures would involve a lower amount of energy. In addition, as flesh is known to act as a shock absorber, it is suggested that the defleshed bones

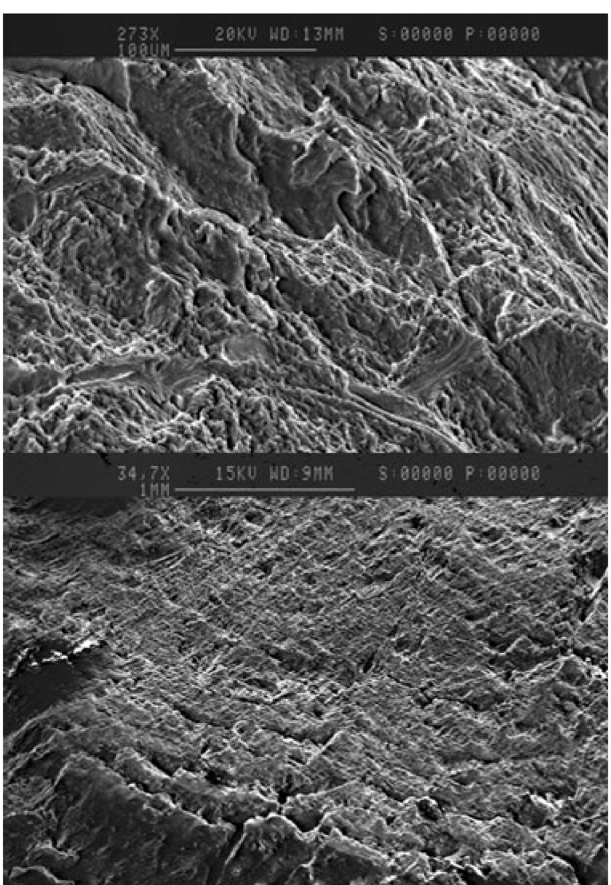

FIG. 2—*SEM images demonstrating a rough fracture surface (top) and smooth impact site (bottom). (Photo by K. Lynn)*

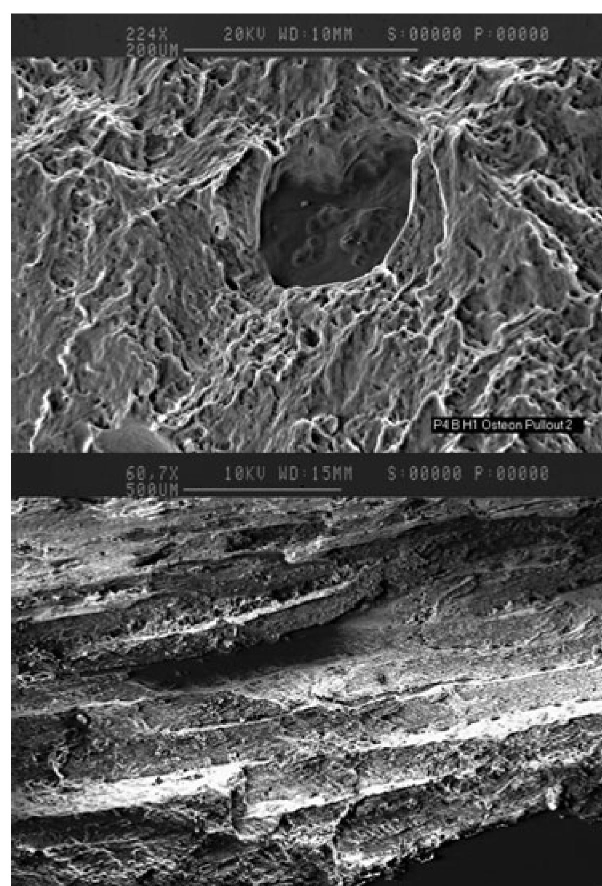

FIG. 3—*Osteon pullout (top) on the fracture surface of a fibula and lamellar separation in a step-wise fashion (bottom) on the fracture surface of a previously fleshed femur. (Photo by K. Lynn)*

TABLE 2—*Presence of osteon pullouts, lamellar separation, and striations and topography of fracture surfaces and impact sites of fleshed specimens examined by SEM.*

			Features			
Specimen Number	Bone	Implement	Osteon Pullouts	Lamellar Separation	Topography	Striations
Fracture Surface						
P3	Fibula	H1			Rough	
P4	Fibula	H1	✔		Rough	
P5	Femur	H2	✔		Rough	
P8	Femur	A2	✔	✔	Rough	
P8	Fibula	A2		✔	Rough	
P9	Femur	A2	✔	✔	Rough	
P9	Femur	A2		✔	Rough	
P10	Femur	A1	✔	✔	Rough	
P11	Femur	A2	✔	✔	Rough	✔
P12	Femur	H2	✔		Rough	
Impact Site						
P5	Femur	H2		✔	Smooth	
P5	Tibia	H2		✔	Smooth	✔
P6	Femur	H2		✔	Smooth	
P7	Femur	A1		✔	Smooth	
P9	Tibia	A2		✔	Smooth	✔
P11	Tibia	H1		✔	Smooth	
P12	Femur	H2		✔	Smooth	✔

SEM, scanning electron microscopy.
A positive indication is scored as present (✔).

TABLE 3—*Presence of osteon pullouts, lamellar separation, and striations and topography of fracture surfaces and impact sites of defleshed specimens examined by SEM.*

			Features			
Specimen Number	Bone	Implement	Osteon Pullouts	Lamellar Separation	Topography	Striations
Fracture Surface						
P15	Humerus	H1			Rough	
P17	Humerus	A1		✔	Rough	
P17	Humerus	A1			Rough	
P18	Humerus	A2			Rough	
P20	Femur	H2		✔	Rough	
P20	Femur	H2	✔	✔	Rough	
P13	Humerus	A1		✔	Rough	
Impact Site						
P13	Humerus	A1		✔	Rough	
P14	Humerus	A2		✔	Smooth	✔
P15	Humerus	H1		✔	Smooth	✔
P16	Humerus	H2		✔	Smooth	✔
P17	Humerus	A1		✔	Smooth	
P18	Humerus	A2		✔	Smooth	✔
P19	Femur	H1			Rough	
P20	Femur	H2			Smooth	✔
P20	Femur	H2		✔	Smooth	

SEM, scanning electron microscopy.
A positive indication is scored as present (✔).

will exhibit characteristics more indicative of a higher energy impact because of the absence of this feature. Further, it is also suggested that fleshed bones will depict the opposite, exhibiting characteristics more indicative of a lower energy impact.

When examining the fracture surfaces of the fleshed specimens, it was found that each surface had a rough surface morphology while only one surface depicted striations. As the ensuing fracture would not be expected to demonstrate the striations imparted by the axe onto the bone, it is possible that one portion of this specimen included the impact site. In addition, these fracture surfaces

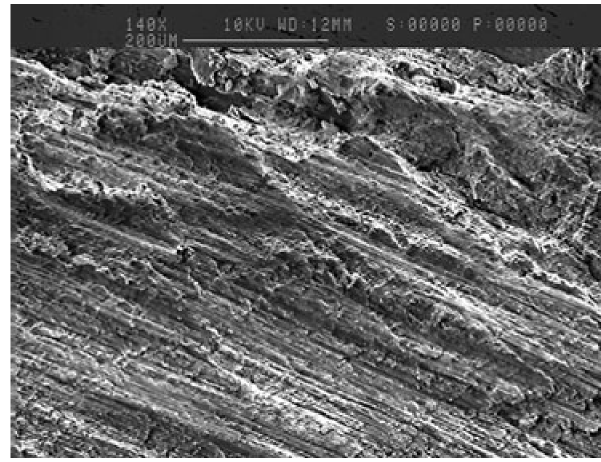

FIG. 4—*Striations on the impact site of a previously fleshed femur. (Photo by K. Lynn)*

exhibited at least one osteon pullout in seven of 10 specimens, indicating a slower propagating crack as first described by Piekarski (8). In those instances where no osteon pullouts were observed, it is possible that they were not visible because of the angle of the fracture surface or that these fractures were created with a greater amount of energy.

Lamellar separation in the fleshed specimens was observed on the periphery of six of 10 fracture surfaces where the circumferential lamellae are located. Although this phenomenon has not yet been described in the literature to our knowledge, it appears to have a similar mechanism to osteon pullouts, as indicated by a step-like pattern. This suggests that these layers may also act to bridge a propagating crack until the periphery is reached and the bone is completely bisected. As lamellar separation was seen in all seven impact sites of the fleshed specimens analyzed, this phenomenon may also occur as the implement enters the bone and pulls the circumferential lamellae along with it as it continues on that vector. This would cause the lamellae to separate as seen on each of these impact sites.

As we anticipated, there was a lack of osteon pullouts in all seven impact sites of the defleshed specimens. This supports the impact of the axe on the bone as having greater kinetic energy, cutting across the osteons as opposed to using them as bridges (8). This is corroborated further by the presence of a smooth morphology on all surfaces analyzed. Although striations were not observed on each specimen, they were seen on three of the impact sites, contradicting the findings of Tucker et al. (1), yet corroborating those of Alunni-Perret et al. (2), Reichs (11), and Wenham (12). As the study conducted by Tucker et al. (1), they found a lack of striations as being diagnostic of an axe wound, and as it has been cited in recent literature (2), our findings indicate that this is not always the case.

The fracture surfaces of the defleshed specimens exhibited osteon pullouts in one of six specimens. Once again, this emphasizes the observation that the overlying flesh acts to attenuate the force while in defleshed specimens, the lack of this shock absorber causes more rapidly propagating fractures. These fractures would then cut across these Haversian systems and all other structures. Despite this, a rough surface morphology still resulted. In addition, lamellar separation was observed in only half of the six specimens, suggesting once again that the fracture was propagating more rapidly than in the fleshed specimens, bridging the crack until the bone bisected or the energy was otherwise dissipated.

The impact sites of the defleshed specimens did not exhibit osteon pullouts because of the lack of attenuation of the force from flesh. In addition, lamellar separation was seen in eight of 10 specimens, reinforcing the theory that the weapon acts to pull these layers toward the lumen of the bone, causing them to separate and indicate directionality. Finally, although striations were seen in only five cases, these results demonstrate once again that the findings of Tucker et al. (1) cannot be extrapolated to all axes as this was the distinguishing feature in their study.

A logical extension of this study will be to determine if certain sections of fractures and impact sites exhibit variation in osteon pullout occurrence. An important consideration in this study is that the age of our specimens may affect the occurrence of this feature. As mammals grow and mature, the number of osteons increases. This would lead to an increased chance for pullouts to occur. Hence, an older victim may be more prone to have osteon pullouts than a juvenile victim. The question would now pertain to the relevance of osteon pullouts in studies if they are indeed dependent upon the age of the victim. As our study utilized immature domestic pig hind limbs, we need to expand this work to include specimens of varying age at death.

It is important to note that the angles of impact varied in our study. Although this reflects the reality of chopping wounds in a forensic context, such variation may account for the differences in our results and those in the current literature. This leads to the justification of a simple "present/absent" scoring system for the time being.

The question of whether or not a specimen was fleshed or defleshed at the time of the perimortem trauma or postmortem dismemberment is an issue in casework that has been recently noted (13). To that end, this study is a contribution to such a question.

Summary and Conclusions

A greater prevalence of osteon pullouts was found on the fracture surfaces of fleshed specimens while only one was found in all of the defleshed specimens examined. Lamellar separation was seen at the periphery of impact sites, suggesting that the blade forced these layers apart as it was drawn through the bone. Lamellar separation was also seen at the periphery of fracture surfaces, suggesting a similar mechanism to osteon pullout formation. We also found that striations were present on the smooth impact sites of fleshed and defleshed bones, contradicting the findings of Tucker et al. (1). Finally, the consistently smooth impact sites and rough fracture surfaces are useful features in the characterization and reconstruction of axe and hatchet wounds.

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References

1. Tucker BK, Hutchinson DL, Gilliland MFG, Charles TM, Daniel HJ, Wolfe LD. Microscopic characteristics of hacking trauma. J Forensic Sci 2001;46(2):234–40.
2. Alunni-Perret V, Muller-Bolla M, Laugier JP, Lupi-Pégurier L, Bertrand MF, Staccini P, et al. Scanning electron microscopy analysis of experimental bone hacking trauma. J Forensic Sci 2005;50(4):796–801.
3. Bromage TG, Boyde A. Microscopic criteria for the determination of directionality of cutmarks in bone. Am J of Phys Anthropol 1984;65(4):359–66.
4. Herrmann NP, Bennett JL. The differentiation of traumatic and heat-related fractures in burned bone. J Forensic Sci 1999;44(3):461–9.
5. Houck MM. Skeletal trauma and the individualization of knife marks in bones. In: Reichs KJ, editor. Forensic osteology: advances in the identification of human remains, 2nd ed. Springfield, IL: Charles C. Thomas, 1998;410–24.
6. Melbye J, Fairgrieve SI. A massacre and possible cannibalism in the Canadian Arctic: new evidence from the Saunaktuk site (NgTn-1). Arctic Anthropol 1994;31(2):57–77.
7. Wakely J. The uses of scanning electron microscopy in the interpretation of some examples of trauma in human skeletal remains. In: Grupe G, Garland AN, editors. The histology of ancient human bone: methods and diagnosis. Berlin: Springer-Verlag, 1990;205–18.
8. Piekarski K. Fracture of bone. J Appl Phys 1970;41(1):215–23.
9. Hiller LP, Stover SM, Gibson VA, Gibeling JC, Prater CS, Hazelwood SJ, et al. Osteon pullout in the equine third metacarpal bone: effects of ex vivo fatigue. J Orthop Res 2003;21(3):481–8.
10. Lynn KS, Fairgrieve SI. Macroscopic analysis of axe and hatchet trauma in fleshed and defleshed mammalian long bones. J Forensic Sci doi: 10.1111/j.1556-4029.2009.01061.x.
11. Reichs KJ. Postmortem dismemberment: recovery, analysis and interpretation. In: Reichs KJ, editor. Forensic osteology: advances in the identification of human remains, 2nd ed. Springfield, IL: Charles C. Thomas, 1998;353–88.
12. Wenham SJ. Anatomical interpretations of Anglo-Saxon weapon injuries. In: Hawkes SC, editor. Weapons and warfare in Anglo-Saxon England. Oxford Committee for Archaeology Monograph No. 21. Oxford, UK: Oxford University Press, 1989;21:123–39.
13. Symes SA. Suitcase man: the investigation, forensic analysis, and prosecution of a homicide with postmortem dismemberment. Proceedings of 60th Annual Meeting of the American Academy of Forensic Sciences, 2008 Feb. 18–23, Washington, DC. Colorado Springs, CO: American Academy of Forensic Sciences, 2008;14:22.

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