

## Cruel traces: bone surface modifications and their relevance to forensic science

By: [Charles P. Egeland](#) and Travis Rayne Pickering

**This is the peer reviewed version of the following article:**

Egeland, C.P., Pickering, T.R. 2020. Cruel traces: bone surface modifications and their relevance to forensic science. WIREs Forensic Science, e1400. <https://doi.org/10.1002/wfs2.1400>

**which has been published in final form at <https://doi.org/10.1002/wfs2.1400>. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.**

**\*\*\*© 2020 Wiley Periodicals LLC. Reprinted with permission. No further reproduction is authorized without written permission from Wiley. This version of the document is not the version of record. \*\*\***

### **Abstract:**

The reconstruction of perimortem and postmortem events is of critical importance to criminal investigations. In many cases, the information required for these reconstructions can be accessed through the analysis of skeletal remains. One particular class of skeletal data—trauma to the surfaces of bones, or bone surface modifications (BSMs)—can reveal much about the perimortem and postmortem intervals. While the study of BSMs originated within the fields of paleontology and archeology and was only later integrated into forensic science, a fruitful interdisciplinary exchange of data and methods is now commonplace. BSMs from thermal alteration, sharp-force trauma, terrestrial and aquatic scavengers and predators, bacteria and fungi, insects, weathering, and sediment abrasion can supply investigators with valuable information about the agents and events of a corpse's deposition, including weapon type, local environmental conditions, the postmortem interval, and the presence, temperature(s), and/or length(s) of thermal exposure. Based on a review of this rich body of literature, we argue that (a) all associations between a BSM and its alleged source must rest on observational cause-and-effect studies; (b) secure identifications of BSMs should rely both on the intrinsic features of the modifications themselves and relevant contextual data; (c) the scientific validity of BSM research depends, ultimately, on rigorous blind-testing and the establishment of error rates; and (d) researchers need to make a concerted effort to enhance interanalyst correspondence through objective definitions, measurements, and/or codes of BSM features. The most promising path forward lies in the combination of digital image analysis and multivariate predictive modeling.

**Keywords:** archeology | bone surface modifications | forensic anthropology | paleontology | taphonomy

### **Article:**

## **1 INTRODUCTION**

Modern criminalistics is a complex, multidisciplinary endeavor that comprises a vast range of scientific theories, techniques, and applied technologies. Among the oldest and most fundamental branches of criminalistics is forensic osteology, which, in the broadest sense, is the “investigation and assessment of discovered [human, *Homo sapiens*] bones” (Dettmeyer, Verhoff, & Schütz, 2014, p. 377). Today, such investigations and assessments routinely include the analysis of perimortem and postmortem trauma to bone cortices, what we refer to here as bone surface modifications, or BSMs, which potentially provide critical information about the agents and events of body deposition. After sketching the thematic boundaries of our review, we trace the roots of BSM studies within the fields of paleontology, archeology, and forensic science. This historical backdrop reveals the critical influence of taphonomy and the core principle of uniformitarianism on the development of BSM studies. We then proceed to survey in detail several classes of BSMs, the criteria by which they might be identified, and their potential utility in forensic settings. Secure BSM identifications, we argue throughout, ultimately hinge on a hierarchical set of inferences that require direct observation of cause-and-effect relationships (actualism) and the integration of contextual information (a configurational approach). We close by considering the state of BSM studies as it relates to current evidentiary standards for scientific evidence. While more actualistic research, in addition to rigorous blind-testing and interanalyst correspondence, are required, we are hopeful that methodological advances can help fully establish the validity of BSM data—both scientifically and in a court of law.

## **2 SCOPE AND HISTORICAL BACKGROUND**

### **2.1 Scope**

We begin our review of the development and relevance of BSMs in forensic science by invoking the standard refrain of anyone reviewing a scholarly topic: it is impossible to cover the full breadth and depth of a vast and rapidly growing corpus of BSM research. As paleontologists and archeologists, we engage most frequently with, and derive much of our terminology from, the literature of those fields. However, this paper also draws heavily on forensic studies, and we use the corresponding terms from this field as appropriate. With some exceptions, we also limit our review to those BSMs that can be seen with the naked eye or with low-powered magnification ( $\times 10$  to  $\times 50$ ). We therefore discuss only in passing a wide variety of histological and crystalline changes that affect bone cortices. For our current purposes, we also do not consider the complex and voluminous subjects of bone breakage or blunt force and ballistic trauma to bone, which some researchers would group under the BSM rubric.

### **2.2 Paleontology, archeology, and uniformitarianism**

Because the study of BSMs was pioneered in the fields of paleontology and especially archeology in the 1800s, we continue our review with a consideration of these disciplines. As historical sciences, paleontology and archeology share the overarching goal of reconstructing the dynamics of past natural systems. The stores of data mined to meet this end—respectively, the fossil and archeological records—are, however, static entities of the present. As such, these records lack any inherent dynamism or behavior that can be observed or analyzed by the scientist in order to explain their coming into existence. In an attempt to bridge this considerable gap between their goal (past dynamics) and their sources of investigation (present statics),

paleontologists and archeologists typically take a uniformitarian approach (Hutton, 1794; Lyell, 1830–1833) to construct analogically based, cause-and-effect hypotheses.

Philosophers of science caution that this method is fraught, noting that its basic tenet—that is, natural laws are invariant across time and space—is obviously untestable. It is also evident that uniformitarian hypotheses are necessarily circumscribed by the current limitations of scientific knowledge and investigatory tools and techniques. For instance, we cannot appeal to unknown or speculated processes (e.g., supernatural intervention) in order to explain the origin of a pile of mammoth bones (paleontology) or a cache of ancient stone tools (archeology)—or, for that matter, the origin of the Rocky Mountains (geology) or the Milky Way (astronomy).

Nevertheless, we contend that uniformitarianism has yielded much progress in the historical sciences (see, e.g., Simpson, 1970). Indeed, we hazard that it remains the most productive of all approaches to shedding light on past events, which, by definition, are unobservable in the present. Uniformitarianism, quite simply, has utility. In its most straight-forward application, the scientist compares a past result (e.g., an ancient lithic artifact) to a present result (e.g., a stone implement created experimentally by himself or herself) and argues, by analogy, that the past result came into being through the same process that he or she was able to observe in the production of the present result. Forensic science itself is predicated in part on such uniformitarian principles: it is no accident that crime scene analysis is equated with archeology (Gardner & Bevel, 2009, p. 15), and not for naught are its practitioners labeled “reconstructionists” (Chisum & Turvey, 2007). One might also argue, as Beary and Lyman (2012, p. 504) do, that because of the relatively short postmortem intervals involved, forensic investigators are on firmer ground than their counterparts in the historical sciences, who deal with timescales of hundreds if not thousands, millions, or billions of years.

We must nevertheless acknowledge the pragmatic weakness of uniformitarianism—that is, the phenomenon of equifinality. Indeed, equifinality is a flaw that holds the potential to thwart the interpretation of any open system (e.g., von Bertalanffy, 1968, pp. 131–134), in which the end state can be attained by more than one process. The looming threat of equifinality confounds many a paleontological and archeological hypothesis about the formation of, respectively, fossil and archeological bone assemblages. The archeological literature, for example, is rife with dispute whether—based on such relevant variables as species composition and skeletal part representation—a bone assemblage was formed primarily through the action of ancient human hunters or that of apex predators, such as lions (*Panthera leo*) (e.g., Binford, 1981; contra Bunn & Kroll, 1986). The impasse has much to do with the generally accepted model of skeletal part survivorship in paleontological and archeological assemblages, which posits that bones with denser cortices and lesser amounts of associated edible tissues (e.g., skeletal muscle and marrow) better survive destructive processes—*no matter the process* (e.g., butchery by humans, feeding by large carnivores)—than do ones that are more thin-walled and have higher associated nutritional value (summarized by Cleghorn & Marean, 2007; see also, Brain, 1981; Bunn, 1991). In addition, other abiotic, “density-mediated” processes, such as subaerial weathering (G. J. Miller, 1975) and anadiagenesis (Rolfe & Brett, 1969), can act on differential bone and bone portion densities to produce skeletal part profiles that mimic those created by hungry humans and carnivores.

It is BSMs that hold the power to break such potential equifinal stalemates. This is because the placement, form, and/or frequency of many individual types of BSMs are diagnostic of the processes and/or actor that imparted them. We endeavor here to discuss the utility of BSMs in forensic science from this perspective. First, however, we close this introductory section with a consideration of the development of BSM studies within the historical science subfield of taphonomy and their eventual integration into modern criminalistics.

### 2.3 Taphonomy and the origins and development of modern bone surface modification studies

The term taphonomy was coined by I. A. Efremov (1940), who defined it as the study of the transition, in all details, of organics from the biosphere (the living world) into the lithosphere (the fossil record). As such, BSM studies are a subdiscipline of taphonomy.

The study of a mass of large vertebrate fossils found in Kirkdale Cave, England, stands as one of the most celebrated early taphonomic studies. It was the theologian and geologist William Buckland (1784–1856) who first asserted that this bone assemblage was created by hyenas (*Crocota crocota spelaea*), carnivores that were long extinct in England but whose ancient occupation of that country was verified by their fossilized remains. Employing analogical reasoning, Buckland (1823, 1836) went beyond the simple presence of hyena fossils at Kirkdale Cave to identify the “solid calcareous excrement,” also found in the cave, as the fossilized feces (coprolites) of hyenas. The diagnosis was based on straightforward observation and extrapolative logic: “[the coprolites were] at first sight recognised by the keeper of the Menagerie at Exeter Change, as resembling, both in form and appearance, the faeces of the spotted or Cape Hyaena, which he stated to be greedy of bones, beyond all other beasts under his care (Rudwick, 1992). To this deduction, Buckland transcended the initial disarray of the cave's jumbled teeth and bones to find other clues that revealed the origin of the assemblage. Specifically, he noticed that the fossils were broken in recurrent patterns and that their surfaces were scarred with gouges and scrapes—both of which he surmised were created by hyena chewing. Fortuitously, Buckland was able to test this hypothesis when a traveling show troupe, featuring a live hyena, passed through his area. Buckland persuaded the ensemble to feed its hyena the tibia of an ox (*Bos taurus*). It came as no surprise to Buckland that the hyena not only broke up the bone in a pattern matching the fractured fossils of Kirkdale Cave, but that it also imparted gnawing damage and other tooth marks that were dead ringers for the marks on the ancient bones.

By mid-century, influenced by Buckland and the uniformitarian principles propounded by Hutton and especially Lyell, pioneering taphonomists were applying analogical reasoning to explain ancient human behavior. In particular, Édouard Armand Isidore Hippolyte Lartet (1801–1871), discoverer of the original Cro-Magnon Man (France) skeletons, recognized what he deduced were slicing marks inflicted accidentally on animal bones as early humans defleshed their prey with stone knives. Lartet (1860) confirmed his hypothesis by conducting experiments using replicated stone artifacts to fillet the bones of modern animals, imparting marks identical to those on the bones from archeological sites. In the wake of Lartet's work, other researchers increasingly employed taphonomic reasoning, with a focus on BSMs, in order to unriddle archeological occurrences. These activities not only yielded additional hypotheses of butchery by prehistoric humans in various geographic and temporal contexts (Breuil, 1932, 1938, 1939; Lubbock, 1913; Peale, 1872; Pei, 1933, 1938), but also recognized the potential role of

carnivores as additional taphonomic agents involved in the formation of archeological palimpsests (e.g., Wyman, 1868).

However, it was only in the 1950s that assigning the relative taphonomic contributions of early human ancestors, carnivores, and porcupines (*Hystrix africae australis*) to the voluminous early Pleistocene fossil assemblages of South Africa became a major preoccupation of anthropologists. Debate engendered by this work (Dart, 1957; contra Washburn, 1957) resulted in rudimentary systemization of BSM identification (e.g., Binford, 1981; Brain, 1981). Emerging from these formative studies, it was naturalistic and experimental ethology and ethnoarcheology (e.g., Andrews, 1990; Binford, 1978, 1981; Blumenshine, 1986, 1988; Brain, 1967, 1981; Bunn, Bartram, & Kroll, 1988; Crader, 1983; Domínguez-Rodrigo, 1999; Haynes, 1980; Yellen, 1977), as well as laboratory-based microscopy (Guilday, Parmalee, & Tanner, 1962; Shipman, 1981; Shipman & Rose, 1983) that were essential to the quasi-codification of BSM diagnostics by the late 1990s. Various reviews of the field followed (Bonnichsen & Sorg, 1989; Egeland, 2012; Fernández-Jalvo & Andrews, 2016; Fisher, 1995; Lyman, 1994).

#### 2.4 Introduction of bone surface modification studies to criminalistics

The study of BSMs in criminalistics emerged from the more general study of “tool marks,” a term that forensic analysts typically apply to all human-directed marks that appear on bone or any other substrate (e.g., metal, clothing, wood, soft tissue). Tool mark analysis explicitly or implicitly drew its theoretical rationale from the work of French criminologist Alexandre Arnould Edmond Locard (1877–1966), whose oft-cited phrase “[i]l est impossible au malfaiteur d'agir avec l'intensité suppose l'action criminelle sans laisser des traces de son passage” (1923, p. 79)—criminal acts leave traces—was later canonized by Reginald Morrish in his 1940 treatise, *The Police and Crime-Detection To-Day*, as “Locard's Exchange Principle.” Pioneers like Kockel (1900), de Rechter and Mage (1927), May (1930), and Burd and Kirk (1942) established that a variety of implements did, in fact (as Locard might have predicted), leave distinctive traces on wood and metal. Other investigators realized that bone, too, preserved forensically informative marks, and case studies emerged in the German (Schulz, 1906; Ziemke, 1921), the French (Thomas & Cuelenaere, 1952), the Russian (Motovilin, 1965), and the English (Thomas & Gallent, 1947) literature. The most influential work during this early phase of forensic BSM research was probably that of Wolfgang Bonte (1939–2000). He was the first forensic investigator to systematically define criteria for the identification and analysis of cut and saw marks on bone (Bonte & Mayer, 1973; Bonte, 1974, 1975; see also Andahl, 1978).

This forensically focused research on BSMs developed in parallel with, but largely independent of, similar trends in paleontology and archeology. The absence of any significant cross-pollination at this time was due to distinctions in disciplinary background and research foci. Most BSM work in the forensic sciences was conducted by medical practitioners and criminologists whose primary concern was (and, in many cases, still is) the perimortem interval and cause-of-death, while that in the historical sciences focused on the postmortem interval and understanding the formation of ancient bone assemblages. Anthropologically trained osteologists (i.e., forensic anthropologists), whose expertise was increasingly being applied to forensic matters, devoted considerable effort to skeletal individualization and pathology and, thus, only rarely employed BSMs in their casework (Bass, 1969, 1979; Krogman, 1939, 1962;

Stewart, 1951). Although presaged in earlier work (e.g., Krogman, 1943a, 1943b; Snow & Luke, 1970), Snow's (1982, p. 97) call for the expansion of forensic anthropology “beyond its traditional and largely self-imposed boundaries of skeletal identification” was a formal and explicit promotion of more methodical attention to perimortem and postmortem trauma and, eventually, the incorporation of taphonomy into forensics (Dirkmaat, Cabo, Ousley, & Symes, 2008; Ubelaker, 2018). This was a shift in perspective that encouraged, if not required, the use of BSMs. It is now quite common for forensic studies to draw on paleontological and archeological literature and vice versa. As we will see, BSMs play a significant role in this conversation.

### 3 CLASSES OF BONE SURFACE MODIFICATIONS AND THEIR IDENTIFICATION

#### 3.1 Theoretical and terminological considerations

Given their potentially destructive effects on bone, it is tempting to consider BSMs and other classes of taphonomic data as nuisances for forensic investigators—a veil to be removed before anything of value can be said about a set of skeletal remains. To some extent, this is true. Thermally induced color changes can, for instance, obscure skeletal features that would otherwise be useful for victim identification. However, BSMs produce valuable forensic information as well. Those same thermally induced color changes can also reflect the temperature to which the victim's skeletal remains were at one time subjected (see Section 3.2.1). The dual nature—subtractive and additive—of taphonomy makes it both a challenging and indispensable aspect of forensic science (Dirkmaat et al., 2008; Pokines, 2013a).

To gauge the degree of information loss due to, or extract unique information from, BSMs, we must link them with as much precision as possible to specific causes. In our view, this “fidelity of inference” (Haglund & Sorg, 1997, p. 14) is most successfully attained through actualism—a tried and true uniformitarian procedure that uses cause-and-effect observations of present-day processes in order to assign meaning to past events. Gifford-Gonzalez (1991) offers a useful analytical framework for constructing and evaluating actualistic arguments with taphonomic data. In a forensic context, our ultimate goal may be to associate a linear striation on a bone, an example of what Gifford-Gonzalez calls a taphonomic *trace*, with a human suspect wielding a knife, which is referred to as a taphonomic *actor*. In order to satisfy evidentiary standards, this interpretive leap must be tempered by the possibility that similar traces can be produced by several actors—that is, traces are potentially susceptible to equifinality. In order to achieve a stronger causative connection between trace and actor, Gifford-Gonzalez argues that two additional, intermediate factors must be considered: taphonomic *causal agents* and taphonomic *effectors*. A causal agent is the immediate physical cause of a trace (this is roughly synonymous, at least for anthropogenic BSMs, with the Scientific Working Group for Forensic Anthropology's (2011, p. 4) “trauma mechanism”), while an effector is the object that brings the trace into being. In our example, the causal agent of a linear striation is simply a sharp edge. The need to distinguish between a causal agent and an effector is readily apparent when we consider the variety of objects that possess a sharp edge—a sand grain, the corner of a rock, and, yes, a knife. Even when we successfully identify an effector, the potential actor(s) are still myriad: the forensic (not to mention legal and, perhaps, mortal) implications of an accidental fall onto a knife's edge are quite different from those of an intentional stabbing. Careful actualistic studies

of known actors, effectors, causal agents, and traces help associate BSMs of known origin with unique taphonomic signatures that can, in turn, be applied in order to produce highly probable identifications of unknown BSMs.

We must stress, however, that the intrinsic features of a BSM, *when used in isolation*, are often insufficient for reliable identifications. As an illustration, consider that the deep incisions created on bone surfaces by shark teeth resemble those of human-directed sharp-force trauma (see Section 3.2.2). It is difficult, based on morphology alone, to distinguish these BSMs. Additional information—say, a far-inland terrestrial recovery scene—makes a shark origin for these types of marks highly unlikely. This issue is well known to archeological taphonomists. So much so, in fact, that a “configurational approach,” which, as Fisher (1995, p. 45) puts it, considers “factors in addition to mark morphology, including the location and orientation of the marks on bones, the sedimentary context of the site, and the depositional environment,” is now standard practice in the field (Binford & Stone, 1986; Bunn, 1991; Bunn & Kroll, 1986; Domínguez-Rodrigo, Pickering, & Bunn, 2010; Pickering & Wallis, 1997). The hope is that configurational evidence yields a unique taphonomic “signature” for each type of BSM (cf. Pokines, 2013a, p. 11).

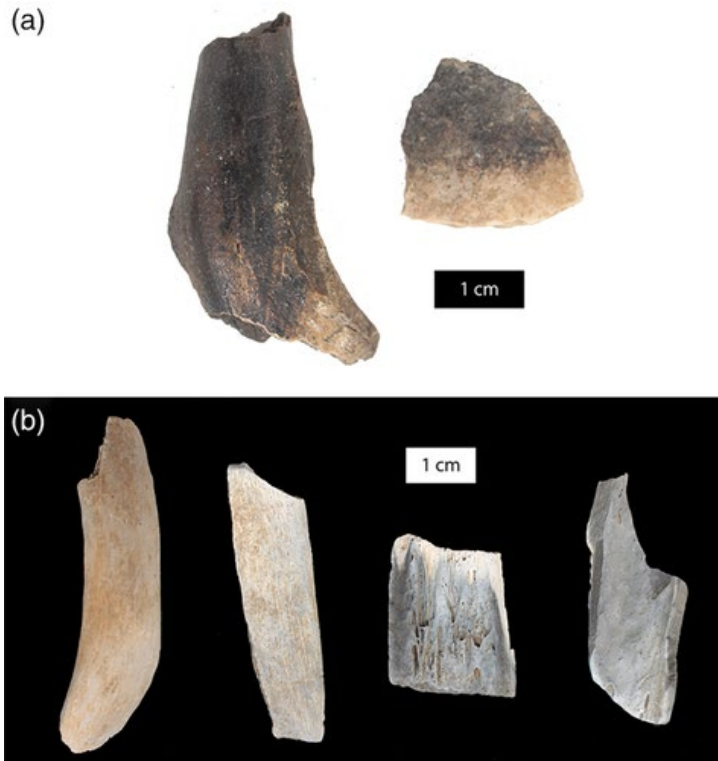
A final note on terminology. The term BSM as we apply it here circumscribes a wide variety of descriptive labels that appear in the forensic literature. Some are very precise, such as “crime mark” or “witness mark,” which investigators reserve for marks created during the perpetration of a crime, and “test mark,” which are those created experimentally for comparative purposes (Black & Thomson, 2017; Ross & Radisch, 2019; Thomson & Black, 2017). Other terms like “artifact,” “defect,” “lesion,” or “trauma” are more broadly applied to any perimortem or postmortem modification that includes, but is not limited to, BSMs (Symes, L'Abbé, Chapman, Wolff, & Dirkmaat, 2012).

### 3.2 Anthropogenic bone surface modifications

This section concentrates on BSMs created largely or exclusively by humans as taphonomic actors.

#### 3.2.1 Thermal alteration

Bone transforms in a variety of ways after exposure to heat (Buikstra & Swegle, 1989; Imaizumi, 2015; Mayne Correia, 1997; Symes et al., 2013; Thompson, 2004; Thompson & Ulguim, 2016; Ubelaker, 2009). The most common heat-induced BSM is a change in color, which results from thermally provoked chemical modifications to organic matter in bone (Mamede, Gonçalves, Marques, & Batista de Carvalho, 2018). At lower temperatures, such as those attained during boiling, macroscopic surficial color change is limited to the bleaching that occurs as soft tissues like marrow are leached from the bone matrix. However, as a bone is carbonized (i.e., the conversion of organic molecules into carbon) and calcined (i.e., the loss of all organic material) at successively higher temperatures and/or over prolonged periods of exposure, its cortical surface undergoes a predictable sequence of color changes from the pale yellow or creamy white of fresh bone to the reddish browns, browns, dark browns, and blacks associated with carbonization and, eventually, to the grays, bluish grays, and ivory whites of calcination (Nicholson, 1993; Shipman, Foster, & Schoeninger, 1984; Wahl, 1981) (Figure 1).



**FIGURE 1.** (a) Human rib and cranial fragments with brown and black cortical surfaces; (b) Human rib (left) and long bone (right) fragments with gray and bluish-gray cortical surfaces. These specimens were recovered from an archeological context and, thus, the production of the discoloration was not observed. They closely resemble the cortical surfaces indicative of carbonization (a) and calcination (b) in actualistically verified cases of thermal damage. Photos by C. P. Egeland

Thermally induced color changes to bone can be recorded in several ways. The most easily implemented approaches require little or no equipment and are based largely on intuitive—but often subjective and imprecise—categories like Baby's (1954, p. 2) now-classic tripartite (a) nonincinerated; (b) incompletely incinerated (“smoked” or blackened); and (c) completely incinerated (light- or blue-gray to buff) scheme (see also, e.g., Wahl, 1981; Bontrager & Nawrocki, 2015; Keough, L'Abbé, Steyn, & Pretorius, 2015; Carroll & Smith, 2018; Greiner et al., 2019). The use of formal color spaces can produce more precise and replicable scoring systems. Shipman et al.'s (1984) pioneering use of the Munsell Soil Color Chart, which employs comparative cards to organize bone cortex colors based on hue (color), value (lightness), and chroma (purity or saturation), is a notable example that is applied widely (Bennett, 1999; Gilchrist & Mytum, 1986; Nicholson, 1993; Ullinger & Sheridan, 2015; Wärmländer, Varul, Koskinen, Saage, & Schlager, 2019; Weitzel & McKenzie, 2015). The Commission Internationale de l'Eclairage's (CIELAB) system also expresses colors in three values:  $L^*$  (lightness),  $a^*$  (position between red and green), and  $b^*$  (position between yellow and blue). Unlike Munsell data, CIELAB values are device independent, amendable to ratio-scale statistics, and less susceptible to interanalyst variation (Devlin & Herrmann, 2015; Krap et al., 2019; Ullinger & Sheridan, 2015; Wärmländer et al., 2019). Other, less well-known color spaces are also available to taphonomists (Ellingham, Thompson, Islam, & Taylor, 2015).



A wide range of actualistic studies indicates that no or only slight bone cortex color change occurs up to ~150–200°C, while colors associated with carbonization predominate between ~200 and 400°C, and evidence of calcination begins to appear at ~400°C and becomes common at temperatures >700°C (Devlin & Herrmann, 2015; Ellingham et al., 2015; Nicholson, 1993; Shipman et al., 1984). While attempts to equate specific bone cortex colors with discrete and precise temperature ranges and/or durations of thermal exposure probably cannot satisfy *Frye* or *Daubert* criteria (Ellingham et al., 2015; Krap, van de Goot, Oostra, Duijst, & Waters-Rist, 2017; Thompson, 2004), CIELAB approaches that use image capture devices with standardized lighting may eventually offer a way to meet these evidentiary standards (Krap et al., 2019; see Section 4).

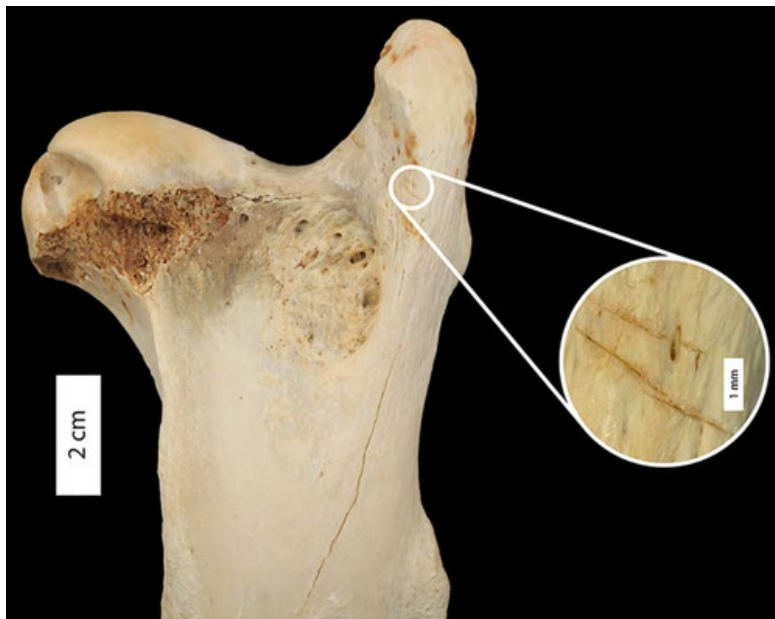
A host of factors influence the temperature(s) and length(s) of exposure experienced by a bone, including intrinsic features of the bone itself, the position of the bone surface relative to the heat source(s), oxygen availability, and insulation of the bone surface by soft tissue, clothing, and/or structures (Binford, 1963; Walker, Miller, & Richman, 2008). The complexities of a thermal event virtually ensure that color changes are not uniform across a skeleton or even across a single bone. Patterns of color gradients can in fact reveal a great deal about thermal events (Symes et al., 2013; Symes, Rainwater, Chapman, Gipson, & Piper, 2015). Carroll and Smith (2018, p. 961), for instance, find that bone surfaces in a simulated accidental house fire exhibit “the full spectrum of colour alteration,” while those in a simulated funeral pyre show “a predominately white colouration.” They attribute this to the “consistent burn caused by the continual management of the fire, supplementation of the fuel load and a sufficient oxygen supply” in the pyre scenario and the “inconsistent burning” of the house fire scenario. Keough et al. (2015) report that zones of off-white coloration adjacent to burned areas—so-called “heat borders” and “heat lines”—appear only on bones burned with adhering flesh, likely because heat exposure follows the progressive and uneven retreat of burning soft tissue. Color gradients also reflect burial environment. Due to the insulating effects, radiative potential, and organic content of sedimentary matrices, bones embedded in sediment usually do not achieve the same degree of cortex color change as do exposed bones when burned at the same temperature and/or for the same duration (Bennett, 1999; de Graaff, 1961; Stiner, Kuhn, Weiner, & Bar-Yosef, 1995). Organically rich topsoil in particular appears to minimize the rate and extent of cortex color change, which may be due, at least during the early stages of a thermal event, to the delayed pyrolysis of bone carbon in favor of soil carbon (Walker et al., 2008, p. 133). Bone surfaces take on atypical colors like pink, green, and yellow if heated in association with metals (Dunlop, 1978). Such staining often occurs in isolated patches, however, and can also appear in the absence of heat, which draws attention to the fact that a variety of taphonomic processes can mimic the full spectrum of thermally induced color changes (Bradfield, 2018; Dupras & Schultz, 2013). A configurational approach and, in some cases, histological and/or chemical methods, can help reliably identify thermally induced color change (Brain & Sillen, 1988; Mamede et al., 2018; Pijoan, Mansilla, Leboeiro, Lara, & Bosch, 2007; Stiner et al., 1995).

Trammell (2020) offers an interesting case study involving a partially dismembered corpse recovered near a river in Missouri. The skeletal remains preserve the entire range of thermal alteration, from unburned to carbonized to fully calcined. Closer examination revealed calcination on the heads of one humerus and one femur and only carbonization on their respective diaphyses. This pattern is inconsistent with the burning of an intact body, where the

thick soft tissue of the shoulder and hip joints is expected to insulate the proximal epiphyses of the arm and thigh, respectively (Symes et al., 2015, p. 36). This unusual pattern can be explained if the upper and lower limbs were detached from the body, such that the proximal ends of the humerus and femur were freed from the protective covering of their respective joints, before the corpse was burned. Cut marks (see Section 3.2.2) around both acetabula, on the proximal epiphyses of both femora, and on the proximal and distal ends of one humerus supports this hypothesis. The perpetrator later confessed to killing, dismembering, and subsequently burning parts of the victim in a steel barrel.

### 3.2.2 Sharp-force trauma

Sharp instruments (i.e., objects that are edged, pointed, and/or beveled) hold the potential to create many types of marks on bone surfaces in both the perimortem and postmortem intervals (Love, 2019; McCardle & Lyons, 2015; Reichs, 1998; Symes, Chapman, Rainwater, Cabo, & Myster, 2010). Here, we distinguish four types of sharp-force BSMs: cut marks, punctures, chop marks, and saw marks. A cut mark is the product of a single stabbing or slicing action that runs along the contour of a bone surface (Figure 2). A puncture forms from single or multiple stabbing motions that cause a sharp object to fully penetrate through a bone's cortex and into the medullary cavity or trabecular bone. A chop mark results from a single or multiple hacking motion(s) directed at an angle or perpendicularly to a bone surface. While punctures and especially chop marks are considered blunt-force trauma with a sharp object when they create conspicuous fractures and infractions (Symes et al., 2002, p. 407, 2012, p. 365; McCardle & Lyons, 2015, p. 1)—the Spanish and Portuguese forensic literature even uses the specific term *cortocontundente* for sharp-blunt hacking marks (Ross & Radisch, 2019, p. 170)—we consider them as sharp-force BSMs here. A saw mark forms by reciprocating or circular actions on a bone surface (Figure 3).



**FIGURE 2.** Posterior view of a donkey (*Equus asinus*) proximal femur showing incisions. The creation of these cut marks with a non-serrated metal knife was observed. Photos by C. P. Egeland



**FIGURE 3.** (a) Posterior and medial views of a proximal human femur showing a kerf; (b) profile view of kerf; (c) plan view of kerf. The creation of these marks with a wavy-set hacksaw was observed. Photos by C.P. Egeland

Nearly any sharp object wielded by a human can, at least potentially, create one or more of these BSMs. However, most of the implements encountered in forensic settings possess metal blades of some sort, and their designs suit them ergonomically to particular tasks. These design features influence the way in which a tool is used and, thus, the types of BSMs typically created by a tool class (saw, knife, hatchet, etc.), tool type (serrated or non-serrated knife, mechanically powered or non-mechanically powered saw), or individual tool. For instance, while most every type of knife can produce punctures and cut marks, chop marks usually result from the use of heavier knives, such as machetes, swords, or butcher's knives. Saw marks can similarly be created by a wide variety of sharp implements, but are most frequently associated with toothed blades, especially saws. Our descriptions of sharp-force BSMs rest largely on these general associations.

Many taphonomic analyses focus on the morphology of the linear indentations—deep marks like kerfs or more superficial ones like incisions, striations, and/or scratches—that sharp edges generate on bone surfaces. Archeological studies with stone and metal tools establish and define many of the relevant macro- and microscopic features that, in forensic settings, can help distinguish among classes and types of metal implements (Blumenschine, Marean, & Capaldo, 1996; Bunn, 1981; Domínguez-Rodrigo, de Juana, Galán López, & Rodríguez, 2009; Greenfield, 1999; Lewis, 2008; Potts & Shipman, 1981; Shipman & Rose, 1983). These attributes include the dimensions (i.e., length, width, depth), trajectory/orientation, plan view shape, and cross-section of the mark itself and the presence and/or extent of secondary striations or fracturing.

Distinguishing cut marks from chop marks and, therefore, slicing from hacking actions, is in most cases relatively straightforward. Both types of mark have V-shaped cross sections because

of their convergent blades, but the narrow, shallow incisions and symmetrical cross sections that are typical of cut marks are distinct from the comparatively wide, deep, and asymmetrical kerfs of chop marks (Lewis, 2008). What is more, cut marks tend to be sinuous in trajectory with only limited fracturing; chop marks are straight and commonly co-occur with flaking along the side of the kerf and, when created by especially heavy implements, show extensive fracturing (Alunni-Perret et al., 2005; Humphrey & Hutchinson, 2001; Wenham, 1989). Many saws possess teeth that are laterally offset, or bent, relative to the long axis of the blade. This “tooth set” opens up the kerf to ease the reentry of the blade during cutting and, thus, sets the functional width of a saw (Symes, Berryman, & Smith, 1998). Consequently, saws typically create kerfs with vertical walls and flat, rounded, or W-shaped floors (Symes et al., 2002, 2010).

Apart from these broad generalizations, actualistic studies demonstrate that the morphology of sharp-force BSMs can frequently provide more precise distinctions. Bartelink, Wiersema, and Demaree (2001), for instance, show that wider blades tend to produce wider cut marks. Importantly, they find that this relationship holds whether or not the force with which and the angle at which the blade incises the bone surface is tightly controlled (e.g., a mechanical device versus a free-hand implement). Nevertheless, cut mark widths do overlap to some extent across blade types, which complicates attempts to predict blade width (and, thus, blade type) solely from mark widths (see also Cerutti, Magli, Porta, Gibelli, & Cattaneo, 2014). Maples (1986, p. 224) also points out that living bone rebounds after it is temporarily compressed by a sharp instrument, a reaction that may result in a mark that is slightly *narrower* than the offending blade. It is possible in many cases to distinguish marks created by serrated blades from those of non-serrated blades. Serrated blades (e.g., bread and table knives) typically impart shallower cut marks, with asymmetrical profiles and flatter, wider floors along with regularly spaced striations along kerf walls, than do smooth blades (e.g., scalpels, pocket knives), which tend to produce deeper cut marks with symmetrical, V-shaped profiles and irregular, haphazard, or no striations (Crowder, Rainwater, & Fridie, 2011, 2013; Greenfield, 1999; Norman et al., 2018; Tegtmeier, 2012). Stabbing motions aimed perpendicularly to the bone surface also result in distinctive plan view morphologies between blade types (Thompson & Inglis, 2009). The cut marks and punctures of serrated blades often possess a Y-shape with a small “kink” at the intersection of the grooves. Nonserrated blades, on the other hand, tend to produce T-shaped marks. Thompson and Inglis (2009, p. 134) find that the puncture marks penetrating cancellous bone preserve these morphologies most clearly, but also question whether they “are present, or as clear, on the hard tissues when the knife must penetrate the soft tissues first.” This is an important consideration given that the bones of people who absorb sharp-force assaults are insulated by at least soft tissue. Feldman's (2015) extensive experiments do, in fact, show that flesh and fabric affect the transfer of energy from blade to bone and, thus, the appearance of the resulting cut marks. Other studies suggest that chop marks can be associated with classes or even types of sharp implements based on the degree of damage and the internal morphology of the kerf (Humphrey & Hutchinson, 2001; Tucker et al., 2001; de Gruchy & Rogers, 2002; Alunni-Perret et al., 2005; Lewis, 2008; but see Rometti, Nogueira, Quatrehomme, & Alunni, 2020).

A good deal of actualistic work focuses on saw marks, especially those generated by the toothed blades of saws, in order to aid tool identification in cases of postmortem dismemberment (Bailey, Wang, van de Goot, & Gerretsen, 2011; Berger, Pokines, & Moore, 2018; Cerutti et al., 2016; Greer, 2018; Love, Derrick, & Wiersema, 2013; Love, Derrick, Wiersema, & Peters, 2015;

Nogueira, Alunni, Bernardi, & Quatrehomme, 2018; Nogueira, Quatrehomme, Rallon, Adalian, & Alunni, 2016; Norman et al., 2018; Pelletti et al., 2017; Saville, Hainsworth, & Ruddy, 2007; Symes et al., 2010; Williams & Davis, 2017). As with cut marks, the widths of saw mark kerfs correlate positively with the functional width of saw blades and are, thus, indicative of saw types (although we note that overlap in kerf width exists across these implements as well). Though analyses of a variety of other features assist in the identification of saw type (Symes et al., 2010), many are (a) difficult to validate across studies and between observers; (b) do not appear consistently enough to be widely applicable; or (c) permit only low precision distinctions between saw types (Love et al., 2013; Ross & Radisch, 2019). Saws with closely spaced teeth, for example, tend to produce fine and closely spaced striations, while those with distantly spaced teeth create coarser and more distantly spaced striations. Unfortunately, these patterns are not specific enough to consistently and quantitatively predict the actual tooth spacing of a saw from a mark. On the other hand, the distance between the successive waves or troughs of individual striations, or “tooth-hop,” can be a reliable indicator of tooth spacing. The measurement of this variable, however, while highly consistent across analysts, can only be taken when the striations appear clearly and in high frequency on the cut surface. At least one morphological feature, kerf profile, does nevertheless appear to be of broad discriminatory value. The profile of a kerf's wall and floor reflects the size, shape, spacing, and set of the saw teeth that created it. Distinctive, W-shaped profiles result when the acute bevels on the alternating faces of consecutive teeth excavate grooves that flank a raised island of bone on the kerf floor. These cross sections, which fall into the “Class C” category of Symes's (1992, p. 56) well-known taxonomy, typically, though not exclusively (see Berger et al., 2018), result from the use of crosscut saws. The chiseled teeth of rip saws, on the other hand, produce squared, rounded, or V-shaped profiles of Symes's “Class A” and “Class B” categories. Other modifications, including exit chipping, entrance shaving, and breakaway spurs, are indicative of the direction of saw progress through a bone rather than saw type. These BSMs, save perhaps kerf width, are much more reliably observed and/or measured on cortical bone than they are on trabecular bone.

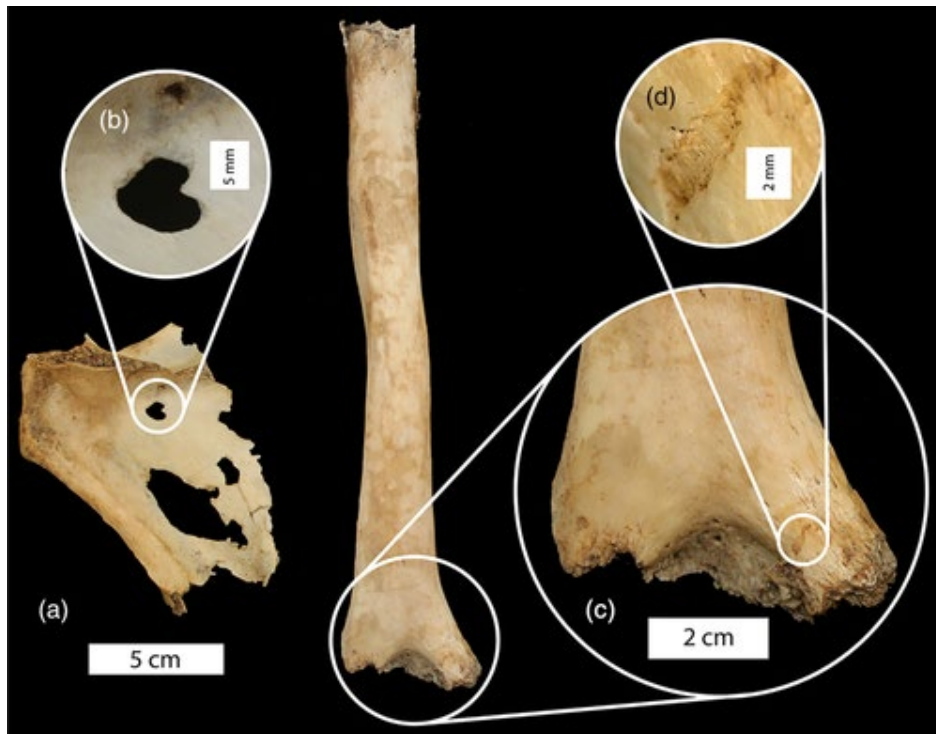
The complexities of sharp-force BSM identification and interpretation are nicely illustrated by Smith, Pope, and Symes (2009) in a case study involving multiple sharp-force BSMs. They describe three types of marks on the bones of a victim involved in a multiple stabbing incident: a narrow, rectangular puncture mark directed at the posterior surface of the scapula, a set of cut marks on the posteroinferior surface of the second rib, and several marks with a shaved or polished appearance on the posterosuperior surface of the third rib. A broken knife with a serrated blade was recovered at the crime scene. Given our discussion above, only the incisions on the second rib appear at first glance to be consistent with the recovered weapon. Smith et al. explain this apparent discrepancy by pointing out that the knife is beveled on one edge only and, in fact, squares off on both edges near the handle. Thus, it appears that the blade penetrated the scapula up to the handle, producing the rectangular puncture mark, and, as it passed between the second and third ribs, incised the former with its beveled edge and shaved the latter with its unbeveled spine. Further evidence linking the suspected weapon to the BSMs comes from microscopic identification, both within the cut marks and on the victim's soft tissue, of the regularly spaced striations characteristic of serrated knives.

### 3.3 Nonanthropogenic bone surface modifications

This section concentrates on BSMs created by non-human taphonomic actors and processes.

### 3.3.1 Terrestrial carnivores and other nonhuman mammals

Terrestrial carnivores treat human corpses in much the same way they do other potential resources, and their feeding behavior can leave distinctive modifications on bone surfaces (Horwitz & Smith, 1988; Haglund, 1997; Pokines, 2013b; Errickson & Thompson, 2016; Fernández-Jalvo & Andrews, 2016, p. 32; Sincerbox & DiGangi, 2018, pp. 63–74, 105–112, 134–141). The main source of these modifications is the dentition of the taphonomic actor, which produces four categories of tooth marks that we illustrate in Figure 4 (see also Binford, 1981, p. 44). When carnivores chew on soft cancellous bone, they often create wide, deep, and long tooth marks referred to as *furrows*. Sustained gnawing eventually results in the destruction of less dense bones or bone portions, especially, respectively, axial bones and long bone epiphyses. As carnivores chew down the length of a long bone from the softer epiphysis to the denser diaphysis, they tend to chip away, gnaw, and/or lick exposed surfaces to create crenulated and rounded/polished edges. A *puncture* occurs when a tooth or set of teeth penetrates the through-and-through thickness of a flat bone or into the medullary cavity of a long bone. When teeth contact a bone surface but fail to penetrate fully into the underlying cavity, they create circular or semi-circular depressions, *pits*, and/or elongated channels, *scores*, both of which show crushing of the outermost lamellae.



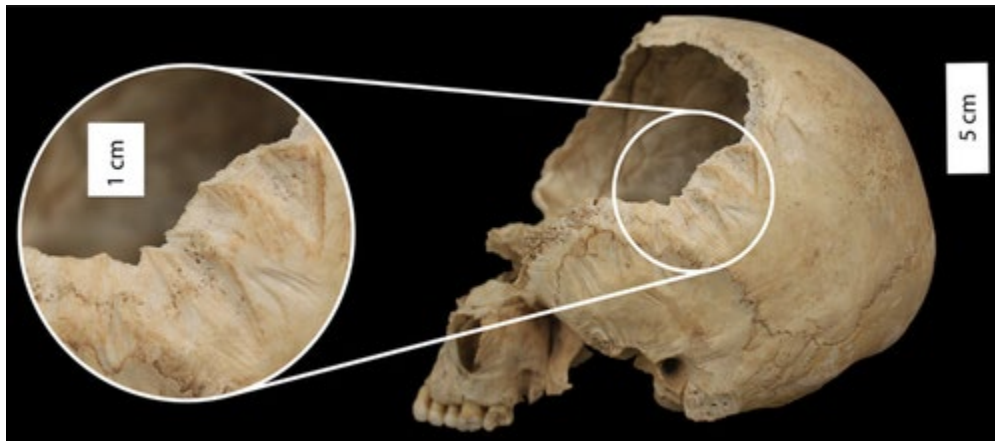
**FIGURE 4.** (a) Posterior views of a human scapula and humerus showing various types of damage; (b) puncture mark; (c) furrowing of the distal humeral epiphysis; (d) score. These specimens were recovered from a forensic context and, thus, the production of the marks was not observed. They closely resemble the tooth puncture marks (b), furrowing (c), and tooth scores (d) produced in actualistically verified cases of terrestrial carnivore feeding. Photos by C. P. Egeland

Attempts to identify specific carnivore taxa as taphonomic actors based on tooth mark dimensions generate mixed results (Domínguez-Rodrigo & Piqueras, 2003; Pickering, Domínguez-Rodrigo, Egeland, & Brain, 2004; Delaney-Rivera et al., 2009; Andrés, Gidna, Yravedra, & Domínguez-Rodrigo, 2012; Young, Stillman, Smith, & Korstjens, 2015; Fernández-Jalvo & Andrews, 2016, pp. 102–108; Sincerbox & DiGangi, 2018, pp. 52–54). On the one hand, overlap in tooth size and shape across carnivore taxa (not to mention the nearly infinite angles at which these teeth can attack and, thus, mark a bone surface) makes it difficult to tie specific marks to specific taxa. On the other hand, it is possible to discriminate large animals (e.g., wolves, *Canis lupus*) from small animals (e.g., foxes, *Vulpes* spp.) based on tooth mark dimensions, which, when the inventory of local carnivore species is known, may help identify the source of tooth marks. What is more, although most carnivores follow a similar sequence when they consume complete, fully fleshed corpses of humans and other large primates (Brain, 1981; Haglund, 1997; Pickering, 2001; Pickering & Carlson, 2004), they do differ in their predatory tactics and bone destruction capabilities, which can result in taxon-specific patterns of BSMs. Big cats, for example, typically stalk human prey from behind, issue a killing bite to the neck, and then shake the victim vigorously from side to side (Turner & Antón, 2000). The resulting hard tissue trauma, including tooth marks, thus clusters almost entirely on crania and cervical vertebrae, a configuration that differs from that of wolves, large domestic dogs (*Canis lupus familiaris*), and bears (*Ursus* spp.) (Camarós, Cueto, Lorenzo, Villaverde, & Rivals, 2016). Carnivores with robust jaws and dentitions, such as large canids and, especially, hyenids, tend to create very intensive furrowing and/or obliterate large portions of bones of human-sized animals. In contrast, smaller carnivores and/or those with gracile teeth specialized for flesh removal, such as felids, impart comparatively lighter damage to human-sized bones (Haynes, 1983; Keyes, Myburgh, & Brits, 2019; Pobiner, 2008; Pobiner & Blumenschine, 2003). The distribution of tooth-marking and bone destruction on such carcasses also differs among species of felids (Domínguez-Rodrigo et al., 2015; Domínguez-Rodrigo & Pickering, 2010) and between captive and wild felids and canids (Gidna, Yravedra, & Domínguez-Rodrigo, 2013; Sala, Arsuaga, & Haynes, 2014). For instance, captive animals almost always produce more tooth marks and higher levels of bone destruction than do their wild counterparts, a finding that Gidna et al. (2015, p. 1; see also Binford, 1978) attribute to “the tedium of confinement—a condition that prompt[s] repeated and prolonged bouts of chewing beyond what [is] required to simply extract nutrients from bones.” This, in addition to pending starvation, probably explains the unusually intense modification of human corpses by carnivores (usually pet dogs) that are trapped indoors with the remains for extended periods of time (Galtés et al., 2014; Steadman & Worne, 2007).

Bones or bone fragments that pass through the digestive tract of carnivores often emerge from this highly acidic environment with etched surfaces, polished edges, and, in some cases, extensive pock-marking (Schmitt & Juell, 1994; Fernández-Jalvo & Andrews, 2016, pp. 238–239; Hockett, 2018). While soil acids produce similar damage, bone specimens corroded by gastric juices can often be distinguished based on their size (they are small—indeed, small enough to be digested) and color (they are bleached white due to the action of digestive enzymes) in addition to the presence within their cavities of hair or fur. Most digested bones emerge from carnivore digestive tracts as taxonomically unidentifiable fragments. However, taphonomic analyses of the remains of wild baboons (*Papio ursinus*) and gorillas (*Gorilla*

*gorilla*)—both useful models for human corpses—show that ray elements regularly survive felid voiding, often as units in complete, articulated, and skin-covered digits (Fay, Carroll, Kerbis Peterhans, & Harris, 1995; Pickering, 2001; Pickering & Carlson, 2004; see also Murad, 1997).

Rodents and lagomorphs also produce tooth marks on human skeletal remains (Haglund, 1992; Pokines, 2013b). These animals gnaw and, at times, consume, bone for a variety of reasons. Herbivorous species, such as porcupines, tend to focus on dry bones in order to offset dietary mineral deficiencies. Omnivores, like rats (Muridae), gnaw bone for the same reason, although they can also leave marks incidentally on fresh bone when eating adhering soft tissue. In contrast to carnivores, who gnaw and puncture bone with all tooth types (Burke, 2013), rodents and lagomorphs nearly exclusively use their incisors (Shipman & Rose, 1983). These animals thus create straight, parallel, and flat-bottomed scores that are quite distinct from those of terrestrial carnivores and other mammals (Figure 5) (Fernández-Jalvo & Andrews, 2016, pp. 31–32). Pokines et al. (2017) document a positive relationship between incisor width and score width across several species of rodents, although this pattern, like that for carnivores, likely reflects general size of the bone-chewer rather than its specific identity.



**FIGURE 5.** Lateral view of a human cranium showing scores. This specimen was recovered from a forensic context and, thus, the production of the marks was not observed. They closely resemble the tooth scores produced in actualistically verified cases of rodent gnawing. Photos by C. P. Egeland

Several other mammal species are also known to gnaw, and thus potentially impart tooth marks on, bone, including omnivorous raccoons (Procyonidae) and opossums (Didelphidae) and even herbivorous artiodactyls, such as pigs (Suidae), deer (Cervidae), antelopes, cattle, sheep and goats (Bovidae), camels (Camelidae), and giraffes (Giraffidae) (Sutcliffe, 1973; Brothwell, 1976; Kierdorf, 1994; Hutson, Burke, & Haynes, 2013; Pokines, 2013b; Fernández-Jalvo & Andrews, 2016, p. 32; Sincerbox & DiGangi, 2018, pp. 82–89, 101–105, 112–116, 130–134). Very little systematic research exists on the range of variation in or distinctive features of the BSMs created by these animals. Cervid osteophagia can result in a forked end to chewed long bones, a feature that in some archeological contexts has been confused with humanly produced artifacts (Kierdorf, 1994; Sutcliffe, 1973). A handful of experiments reveal that wide, parallel scoring and L-shaped punctures on bones may be pig-diagnostic features, likely because suids use, respectively, their broad, flat, and closely spaced incisors to strip soft tissue from bone surfaces and their bunodont premolars to crush through bone (Domínguez-Solera & Domínguez-



Rodrigo, 2009; Greenfield, 1988). In a forensic context, Berryman (2002, p. 494) cites “areas of parallel scores that appeared to have been produced by a single action with multiple teeth contacting the bone surface as opposed to redundant or repetitive scoring from a single tooth” as strong evidence for pig scavenging of a partially skeletonized human corpse recovered in rural Tennessee.

### 3.3.2 *Birds*

Raptors are well-documented predators of small- to medium-sized primates (Hart, 2007), and avian scavenging, especially by vultures, plays a critical role in terrestrial ecosystems (DeVault, Rhodes, & Shivik, 2003; Whelan, Şekercioğlu, & Wenny, 2015). Vultures are known to produce punctures, pits, and scores during feeding episodes as their beaks and, probably less commonly, their talons, contact bone surfaces (Reeves, 2009; Pokines & Baker, 2013; Sincerbox & DiGangi, 2018, pp. 74–82). During the consumption of medium-sized mammals, griffon vultures (*Gyps fluvus*) create punctures that usually occur on thin bones like the scapula and those of the cranium. Pits and especially scores tend to be extremely shallow and at times co-occur with microstriations that run within the main groove and/or parallel or at an angle to it (Domínguez-Solera & Domínguez-Rodrigo, 2011). The scores created by American black vultures (*Coragyps atratus*) and turkey vultures (*Cathartes aura*) on pig carcasses are so superficial that Reeves (2009, p. 526) questions whether they can be reliably observed or identified even after short postmortem intervals (see also Fernández-Jalvo & Andrews, 2016, p. 33). Domínguez-Solera and Domínguez-Rodrigo (2011) caution as well that vulture punctures and pits resemble in many ways those created by terrestrial carnivores (see Section 3.3.1), and some vulture scores share attributes with sediment abrasion (see Section 3.3.6). Nonetheless, two characteristics appear to differentiate vulture BSMs from those of at least terrestrial carnivores: an absence of marks on epiphyseal portions of long bones (since vultures rarely remove or feed on tendons or ligaments), and V-shaped “tick” or “check” marks formed by the intersection of two scores. Eagles also create, albeit rarely, distinctive V-shaped, or “can-opener,” punctures on the bones of their prey (Bochenski, Tomek, Tornberg, & Wertz, 2009; Lloveras, Cosso, Solé, Claramunt-López, & Nadal, 2018; McGraw, Cooke, & Shultz, 2006). Komar and Beattie (1998) report that corvids produce conical punctures, presumably as they peck maggots from bone surfaces.

### 3.3.3 *Aquatic predators, scavengers, and grazers*

A variety of freshwater and marine organisms are known to create BSMs as predators, scavengers, or grazers, including crocodylians, sharks (Selachii), and a host of invertebrates (Sorg et al., 1997; Haglund & Sorg, 2002; Higgs & Pokines, 2013; Drumheller & Brochu, 2016; Sincerbox & DiGangi, 2018, pp. 94–101, 124–129). Crocodylians possess a homeodontic dentition that comprises ridged, conical teeth. These ridges, or carinae, run the superoinferior length of the mesial and distal faces of each tooth, which means that if and when that tooth contacts a bone, it has the potential to produce a deep groove through the center of the resulting tooth pit. Such bisected pits are extremely rare on bones consumed by terrestrial carnivores but make up between 10–40% of crocodylian tooth pits. The inertial feeding of crocodylians can also produce “hook scores”—L- or J-shaped marks that result from abrupt changes to the direction of teeth during biting events (Baquedano, Domínguez-Rodrigo, & Musiba, 2012; Drumheller & Brochu, 2014; Schneider, 2019). Njau and Blumenschine (2006, pp. 151, 153) argue, too, that

“[s]erial pitting, puncturing, or scoring, that is, multiple marks inflicted by adjacent teeth in one bite, provide a trace of crocodilian feeding almost as distinct as bisected marks and hook scores.” Because they do not gnaw on long bone epiphyses, crocodilians also do not produce the furrows and crenulated edges that often result from the feeding activities of terrestrial carnivores.

Apart from a handful of cases involving eye witness accounts (Ihama, Ninomiya, Noguchi, Fuke, & Miyazaki, 2009) or skeletal material in stomach contents (Işcan & McCabe, 1995; Rathbun & Rathbun, 1984), most descriptions of shark BSMs are based on post-hoc analyses of human remains that, based on soft tissue damage and/or the presence of embedded tooth enamel fragments, are presumed to have been consumed by sharks (Stock, Winburn, & Burgess, 2017). In one such study, Allaire et al. (2012, p. 1676) associate five types of BSMs with shark feeding: punctures with or without compression fractures, incised bone gouges, striations with lamellar shaving, and overlapping striations (see also Ames & Morejohn, 1980). Shark punctures are similar to those of crocodilians and terrestrial carnivores. Shark gouges, on the other hand, because they lack the crushing associated with the tooth scores of crocodilians and terrestrial carnivores (Işcan & McCabe, 1995, p. 20; see Section 3.3.1), are more likely to be mistaken for human-directed perimortem and postmortem sharp-force trauma (see Section 3.2.2). These mark types, then, at least based on morphology alone, probably cannot be considered diagnostic of shark feeding. The marks with striations, however, which likely result from the serrated teeth that characterize many, though not all, shark dentitions (Clua & Reid, 2018), may indeed be unique to these marine predators. B. E. Anderson, Manoukian, Holland, and Grant (2002) apply this criterion to a series of deep scores on the femora of a partial human corpse recovered in 1994 off the Hamakua Coast of Hawai'i. They identify a shark as the most likely source based on the serrated morphology of the marks and presence of an embedded enamel fragment, the chemical composition of which is consistent with that of a cartilaginous fish.

Some aquatic invertebrates (e.g., barnacles, mussels, and limpets) release biocements, byssal threads, or mucus in order to adhere to hard, stable substrates such as the surfaces of submerged bones (Bromley & Heinberg, 2006). This activity appears to leave distinctive BSMs, either in the form of discolored circular patches or raised areas surrounded by oval, sub-circular, or polygonal trenches. Although we await confirmation through controlled actualistic studies, paleontological and forensic observations of modified bones show that these “attachment scars” or “homing pits” lie underneath, and mimic the shape of, detached barnacle carapaces and mussel/limpet shells (Boessenecker, 2013; Higgs & Pokines, 2013; Pokines & Higgs, 2015).

Another taphonomic trace in aquatic, especially marine, environments is bioerosion, which results from the boring, grazing, or shelter-seeking behavior of small organisms into, upon, or within hard substrates (Bromley, 1994, 2004; de Gibert, Domènech, & Martinell, 2004; Höpner & Bertling, 2017). Annelid worms of the genus *Osedax* are well known (and, in fact, named for) their bone-eating behavior. These worms colonize and bore into the surfaces of decaying vertebrate skeletons not only to feed on bone with the aid of bacterial symbionts, but also in order to create cavities into which distressed individuals can withdraw (Glover, Källström, Smith, & Dahlgren, 2005; Rouse, Goffredi, & Vrijenhoek, 2004). The apertures of *Osedax* borings appear on bone surfaces as small (between 0.3 and 1.9 mm in diameter), pinprick-like openings with sharp, well-defined borders (Higgs et al., 2014). While each boring represents the activity of a separate individual, on densely colonized bones the subsurface

chambers can merge together and collapse to form larger, rounded pockmarks or even extensive areas of erosion (Danise & Higgs, 2015; Higgs et al., 2012). Clionid sponges are also known to bore into hard substrates, and the perforations that they create, while at times slightly larger (up to 5 mm), otherwise resemble those of *Osedax* (Bromley & D'Alessandro, 1984; Bromley, Hanken, & Asgaard, 1990; Higgs et al., 2012). Endolithic sponges focus mainly on calcareous substrates, however (Schönberg, 2008), and the sole claim for damage to bone by this type of sponge—a brief account of a submerged human cranium that offers no morphological description or photographic detail (Wood & Hodgson, 1996, p. 305; see also Steptoe & Wood, 2002)—is difficult to evaluate. Some modern species of bivalve mollusk apparently bore into nonfossilized bone (Savazzi, 1994, p. 66, 1999, p. 210), but taphonomic evidence for the circular or hourglass-shaped apertures they are known to produce on other substrates like fossilized bone, shell, coral, limestone, and wood (Kelly & Bromley, 1984) is currently limited to paleontological contexts (Belaústegui, de Gibert, Domènech, Muñiz, & Martinell, 2012). Surfaces colonized by microorganisms like algae also attract mollusk, echinoderm, and fish grazers. Many mollusks, especially gastropods and chitons, use a chitinous ribbon bristled with denticles—the radula—to scrape food from surfaces. This rasping action creates patches of closely spaced, elongated channels or striae that, because of their small size (<1 mm in all dimensions), are “hardly visible to the naked eye” (Voigt, 1977, p. 335; see also Akpan, Farrow, & Morris, 1982; Donn & Boardman, 1988). It appears that the spacing, orientation, and shape of these radulation traces can distinguish between gastropods and chitons, at least on coral and rock substrates (Bromley, 2004; Lopes & Pereira, 2019). There is little actualistic work with mollusk grazing on bone, although Dirks et al.'s (2015) preliminary experiments with terrestrial snails document BSMs very similar to the traces left on rock and shell substrates by marine mollusks. The grazing behavior of echinoderms also produces stellate patterns of shallow grooves on rock substrates (Bromley, 1975), but we are unaware of any description of such damage on non-fossilized bone. Wood and Hodgson (1996, p. 305) attribute a series of scores on a human femur from a late 18th century ship wreck to the opposable jaws of parrot fish, but this identification awaits actualistic verification.

### 3.3.4 *Bacteria and fungi*

Microbes, especially bacteria and fungi, secrete acidic metabolites as they decompose organic matter (Child, 1995), and their colonization of bone produces distinctive damage at the microscopic histological level (Booth, 2017; Damann & Jans, 2017; Jans, 2008; Turner-Walker, 2012, 2019). At the macroscopic level, microbial attack creates small patches of discoloration—typically reds, blacks, and purples (Piepenbrink, 1986)—on bone surfaces, and, eventually, bioerosion in the form of cortical exfoliation (Domínguez-Rodrigo & Barba, 2006, 2007a, 2007b). This exfoliation, which Nicholson (1996) and others (Domínguez-Rodrigo & Barba, 2007a) attribute to the hyphae of fungi, results in pit- and score-like features that can be confused with the tooth marks of terrestrial carnivores (see Section 3.3.1). However, whereas tooth scores are symmetrical along their longitudinal axes, occur perpendicular or at oblique angles to the long axis of the bone, and penetrate through several layers of cortex, microbial bioerosion is, in contrast, asymmetrical along its longitudinal axis, often meanders randomly across the bone surface, and, in the early stages, excavates only the first few layers of lamellae. The taxonomic identity of the microbe(s) responsible for specific BSMs is difficult to establish, but such information can potentially reveal key parameters of the environment

immediately surrounding a bone, including temperature, pH, and oxygen availability (Damann, 2017).

### 3.3.5 Insects

Damage to modern (Behrensmeyer, 1978; Tappen, 1994), archeological (Derry, 1911; Huchet, Deverly, Gutierrez, & Chauchat, 2011; Pittoni, 2009; Thompson et al., 2018; Watson & Abbey, 1986; Wylie, Walsh, & Yule, 1987), and paleontological (Britt, Scheetz, & Dangerfield, 2008; Hill, 1987; Kaiser, 2000; Roberts, Rogers, & Foreman, 2007) bones is commonly attributed to the activities of terrestrial insects, especially termites (Termitoidae). These associations are reasonably, but indirectly, inferred based on contextual information (e.g., the presence of pupae, colonies, subterranean galleries, nests, exoskeletal remains, or BSMs, themselves), whereas experiments that systematically and unambiguously link specific insect taxa to specific BSMs are comparatively rare (Brothwell, 1992). Backwell, Parkinson, Roberts, d'Errico, and Huchet (2012), in the most comprehensive actualistic study of insect damage to date, describe the modification of bone by southern African harvester termites (*Trinervitermes trinervoides*). These termites attack fleshed, dry, and slightly weathered bone, which suggests that it is not only trace minerals, but also proteins and lipids, that are attractants for them. Termites can be surprisingly destructive as they tunnel through and consume bone. Wylie et al. (1987, p. 341) even provide archeological evidence for the destruction by termites of an entire juvenile human skeleton. Apart from bone destruction, termites produce six major classes of BSM (Backwell et al., 2012, p. 79; see also Watson & Abbey, 1986): bore holes, pits, star-shaped marks, patches of striations, surface etching, and discoloration. Bore holes appear as semi-circular perforations ~3 mm in diameter, while pits and star-shaped marks are semi-circular depressions between 1 and 3 mm in diameter that, when viewed under low- to mid-level magnification ( $\times 25$ – $50$ ), possess grooves either within or emanating radially from them. Striations are parallel or sub-parallel grooves <1 mm in length that appear in patches across the bone surface. Each of these marks is morphologically distinct, but they probably represent different stages of bioerosion produced by the actions of termite mandibles. Boreholes, for example, likely begin as star-shaped marks and pits. Harvester termites also deposit a residue that is often associated with dark staining and acid-like scouring of the outer lamellae.

The mandibles of cockroaches (Blattoidea), ants (Formicidae), and hide beetles of the genera *Dermestes* and *Omorgus* produce perforations and striations similar in size to those of termites (Dirks et al., 2015; Dirrigl & Perrotti, 2014; Go, 2018; Parkinson, 2012; Zanetti, Visciarelli, & Centeno, 2014). Cockroach marks do not, however, appear in the tightly clustered patches characteristic of termites, and insect striations in general are wider and less evenly spaced than the radulation traces of gastropods (see Section 3.3.3). The larvae of *Dermestes* are also known to excavate into hard substances like bone to create pupation chambers, which tend to be flask- or bulb-shaped (i.e., a narrow entrance that opens into a wider cavity) in cross section and are several millimeters in maximum width (Martin & West, 1995; West & Martin, 2002). Insect BSMs are identified on human remains in forensic contexts (Queiroz et al., 2017), and Viero et al. (2019, p. 313) caution that bore holes in particular can be mistaken for gunshot entry wounds. Backwell et al. (2012, p. 84) also note that termite-stained bone surfaces resemble those discolored by thermal damage (see Section 3.2.1). Because the ecological requirements of insects, like those of microbes, can be highly specialized, evidence for their activity reveals

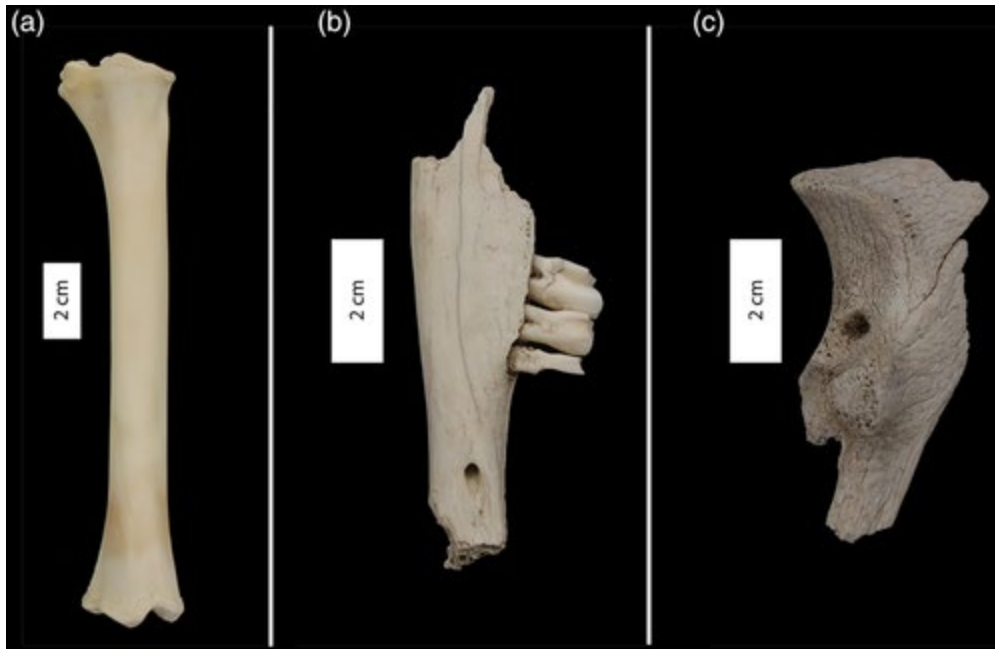
much about the circumstances surrounding the decomposition of a body. Termites, for instance, are active in both subterranean and subaerial conditions, while hide beetles operate solely in subaerial settings (Martin & West, 1995). Beetle damage, then, can only occur when bones are exposed on the surface. The activities of both termites and beetles are also regulated by temperature and humidity (Backwell et al., 2012; West & Martin, 2002).

### *3.3.6 Sediment abrasion*

Scratches or striae often appear on bone surfaces as the result of incidental kinetic contact with sedimentary particles (Behrensmeyer, Gordon, & Yanagi, 1986; Fiorillo, 1989; Olsen & Shipman, 1988). Such sediment abrasion is thus most likely to occur after advanced decomposition, when disarticulated bones no longer encased in soft tissue or protected by clothing are tumbled, rolled, or otherwise perturbed by fluvial processes, various types of soil mass wasting (e.g., creep, slide, flow, topple), or even the trampling of feet. Particularly important in forensic circumstances, though, is the risk of mistaking sediment abrasion for anthropogenic cut marks (see Section 3.2.2). While this potential equifinality is not surprising given the similarities in the underlying taphonomic effector (i.e., a sharp object, whether a tool or sedimentary particle), experiments do reveal a handful of features that distinguish the two mark types (Domínguez-Rodrigo et al., 2009). Under low magnification, sediment abrasion appears as series of shallow, even superficial, striae that commonly intersect with each other. This morphology contrasts with the deep and often non-overlapping incisions that characterize cut marks created by human-wielded metal tools. Moreover, the main groove of an abrasion mark typically contains discontinuous and unevenly spaced microstriations due to microscopic imperfections along the edges of sedimentary particles. Such features are either absent among the internally “clean” incisions of non-serrated metal blades or contrast markedly with the continuous and regularly spaced internal striations of serrated metal blades (Greenfield, 1999).

### *3.3.7 Weathering*

Bones exposed on terrestrial landscapes deteriorate chemically and mechanically over time and, in doing so, progress through a series of BSM stages (i.e., “weathering stages”) from bleaching and shallow, longitudinal cracking and flaking of the outermost lamellae to splintering and exfoliation of the original cortical surface and, eventually, complete disintegration (G. J. Miller, 1975; Behrensmeyer, 1978; Johnson, 1985; Junod & Pokines, 2013; Blau, 2017) (Figure 6). Because this sequence is predictable and correlates with time, weathering is commonly used in forensic contexts to estimate the postmortem interval (PMI), especially when corpses are fully skeletonized and do not occur with temporally informative cultural material. However, the rate at which bones reach, and the length of time they remain within, each stage varies considerably due to macro- and microenvironmental factors that affect levels of solar radiation, rates of moisture loss and gain, fluctuations in temperature, and the crystallization and recrystallization of minerals within pore spaces. Intrinsic properties of bones like microstructure, size, shape, and density also affect the rate of surficial weathering (Lyman & Fox, 1989). What is more, most actualistic research on weathering and PMI uses nonhuman mammal bones, which are distinct microstructurally from adult human bones. Many of these studies, then, may not be directly applicable to forensic contexts (Junod & Pokines, 2013, p. 292).



**FIGURE 6.** (a) Anterior view of a white-tailed deer (*Odocoileus virginianus*) radius showing an unweathered cortical surface; (b) lateral view of a goat (*Capra hircus*) mandible showing longitudinal cracking; (c) anterolateral view of a medium-sized bovid ulna showing extensive flaking, deep cracking, and deterioration of the cortical surface. Specimens (b) and (c) were recovered from a modern surface context and, thus, the production of the marks was not observed. They closely resemble modifications associated with actualistically verified early stage subaerial weathering (b) and late-stage subaerial weathering (c). Photos by C. P. Egeland

J. H. Miller's (2009, pp. 60–66) work in Yellowstone National Park illustrates the effect of macro-environmental variables on weathering. He finds that bones of large ungulates in Yellowstone's temperate ecosystem persist in all weathering stages for longer periods of time relative to those in tropical, semi-arid African savannas. Higher latitude and denser vegetation (both of which reduce levels of ultraviolet [UV] radiation) and persistent snowpack (which stabilizes bone temperatures at or below freezing) appear to be largely responsible for slower weathering rates. This highlights a general trend: bones deposited in cooler environments with less UV radiation tend to exhibit slower weathering rates, while those deposited in warm, arid environments with more intense UV radiation exhibit faster weathering rates. Bones deposited in similar macroenvironments can nevertheless experience different weathering processes due to unique microenvironments. Pig bones exposed to the humid, subtropical environment of central Florida, for instance, achieve complete surface bleaching nearly 100 days earlier, and surface flaking nearly 20 days earlier, in the open than they do in shaded areas (Schultz, Hawkins, & Mitchell, 2018). Even bones from the same skeleton can exhibit different weathering stages.

Mann and Owsley (1992) encounter just such a situation with a set of human remains recovered from an agricultural field in rural Ohio. They report three separate grades of weathering damage on the skeleton: little or no weathering on the thorax and arm bones, bleaching and slight cracking on the legs, and more extensive cracking on the pelvis. They attribute this complex pattern of subaerial exposure to the slow deterioration of clothing over two or more years. The skeleton also preserves evidence of at least two episodes of gunshot trauma. While damage to the

cranium is indicative of a perimortem incident, the interruption of weathering cracks by perforations on the pelvis provides surprising evidence for a postmortem gunshot event as well. As Mann and Owsley (1992, p. 1386) note wryly, “[a]lthough it is not uncommon for a human skeleton to be altered postmortem (for example, carnivore chewing and breakage), it *is* uncommon to encounter one that is shot” (emphasis in the original).

#### **4 THE PRESENT AND FUTURE OF BONE SURFACE MODIFICATIONS IN THE FORENSIC SCIENCES**

We conclude our review with an assessment of the present and future of BSM research in the forensic science of the 21st century. Perhaps the most important issue stems from the US Supreme Court's decision in *Daubert v. Merrell Dow Pharmaceuticals, Inc.* (1993), which, along with later rulings in *General Electric Co. v. Joiner* (1997) and *Kumho Tire Co. v. Carmichael* (1999), define the admissibility criteria for expert testimony in all federal cases and, for those that adopt them, state cases. These so-called “Daubert” standards include “whether the theory or technique in question can be (and has been) tested, whether it has been subjected to peer review and publication, its known or potential error rate and the existence and maintenance of standards controlling its operation, and whether it has attracted widespread acceptance within a relevant scientific community” (1993, p. 580). A close reading implies that admissibility rulings should focus as much, if not more, on the validity of the methodology as they do on the expertise and prior experience of the expert practitioner.

Methodological rigor is, of course, part and parcel of standard scientific practice. A 2016 report by the President's Council of Advisors on Science and Technology (PCAST) nevertheless questions the validity of many forensic techniques. While the report makes no mention of BSMs, its focus on “feature-comparison” methods, which “attempt to determine whether an evidentiary sample (e.g., from a crime scene) is or is not associated with a potential ‘source’ sample (e.g., from a suspect), based on the presence of similar patterns, impressions, or other features in the sample and the source” (2016, p. 1), is certainly relevant here. The PCAST report goes on to argue that feature-comparison methods must demonstrate *foundational validity*, a designation that, at minimum, requires (a) empirical testing by several research groups under appropriate conditions; (b) clear evidence for repeatability and reproducibility; and (c) assessment of error rates. We think it is telling that the two methods in the report that most closely resemble BSM analysis—human bite mark analysis and firearm tool mark analysis—are described, respectively, to be “far from meeting the scientific standards for foundational validity” and “short of the scientific criteria for foundational validity” (PCAST, 2016, pp. 9, 11).

Before we can assess the validity of BSM research in light of the PCAST report, recall that the morphological features of several classes of BSM have yet to be securely established through actualistic observations. While additional research is obviously required to meet this need, we also acknowledge the considerable logistical hurdles that accompany some types of actualistic BSM research, especially in deep aquatic contexts where direct observations of taphonomic actors and their resulting traces are, to put it mildly, difficult to make. Potential solutions include controlled experiments in aquaria and/or the use of video monitoring in natural settings. In a series of experiments off the coast of British Columbia (Canada), Anderson and colleagues (G. S. Anderson, 2009; G. S. Anderson & Bell, 2014, 2017; G. S. Anderson & Hobischak, 2004)

show through video monitoring that pig carcasses deposited in marine environments attract a host of scavengers, from whelks and sea stars to crustaceans and fish. If BSMs are present on the pig bones, it might be possible to link them to a taphonomic actor through reference to the video footage. This brings us to our first conclusion: regardless of the mechanism, BSM studies must rest on a solid actualistic foundation in order to fully establish their scientific and forensic validity.

Where, then, do we stand on the validity of BSM methods? Our response rests largely on the results of blind-test studies, which should first involve an actualistic study to produce a sample of BSMs with a known taphonomic history. Several analysts—human and/or computer, all of which are naïve as to the origin of the BSMs—then use a set of criteria in order to render decisions on the taphonomic actor, causal agent, and/or effector responsible for each individual mark. The correspondence of these classifications to the known mark identities in turn determines the repeatability, reproducibility, and error rate of the methodology. The PCAST report specifies two approaches to blind testing, subjective and objective, and we also discuss a third, hybrid, approach. Formal blind tests are still relatively rare in BSM research, but some examples are provided below.

Traditionally, most analyses of BSMs are based on subjective feature-comparison methods; that is, procedures that rely heavily on human judgment about what features are considered meaningful and how similar those features must be to indicate a probable match between an unknown mark and a known mark type. Here, we provide an example from the archeological literature. Blumenschine et al. (1996) report error rates for the identification of three types of BSMs: metal knife cut/scrape marks, carnivore tooth pits/scores, and percussion marks. (The latter type of mark—small pits and/or microstriations created by the impact and scraping of stone cobbles against bone cortices when breaching the marrow cavities of long bones—is not of much forensic significance but is an important class of BSM for archeologists who study Paleolithic peoples; Blumenschine & Selvaggio, 1988.) When asked to assign 20 unknown (to the analysts) marks from actualistic assemblages to one of these three categories with the aid of  $\times 16$  magnification and a published list of qualitative identification criteria, three experienced analysts did so with misidentification rates between 0 and 5%. Blumenschine et al. (1996, p. 505) thus conclude that these BSMs can be distinguished from each other with a high degree of accuracy and reproducibility as long as (a) analysts develop a reliable search image for each type of mark based on experience with actualistic collections; (b) identification criteria are consistently applied; and (c) bone surfaces are scanned under a strong, obliquely oriented light source with at least  $\times 10$ – $16$  magnification.

Objective approaches to BSM method validation involve features and procedures that are highly standardized, quantifiable, and can, respectively, be identified or performed by automated systems and/or with little or no human judgment. We turn to a forensic study of thermally altered bone for an example of this approach. Krap et al. (2019) use flatbed scanners and digital cameras to record CIELAB colorimetric data from samples of human and pig bones heated to temperatures ranging from room temperature to 900°C. Bivariate scatterplots of  $L^*$  and  $b^*$  values reveal well-defined clusters of specimens that share narrow ranges of exposure temperatures (e.g., 250–350°C). These clusters, and the  $L^*$  and  $b^*$  thresholds that inform the decision rules to distinguish them, are determined visually rather than with a statistical algorithm. For that reason,



the study falls short of full objectivity. Nevertheless, assignment of a subset of burned specimens (not included in the original clustering procedure) to these defined temperature ranges results in misclassification rates between 0 and 14%.

In hybrid models of BSM method validation, human analysts identify and define mark features, measure (for quantitative features) and/or score (for qualitative features) them, and then input the resulting data into a statistical algorithm for classification. We return to the forensic literature for an example. Using a sample of 58 saw marks produced by four different saw types (a crosscut saw, two types of hacksaw, and an electrical reciprocating saw), Love et al. (2013) document two qualitative features, kerf floor shape and kerf wall shape, and two quantitative features, minimum kerf width and average tooth hop, that, when viewed under indirect lighting at  $\times 5\text{--}50$  magnification, appear sufficiently frequently and show high measurement/scoring correspondence between analysts. Based on these variables, random forest algorithms presented with unknown (to the algorithm) experimental marks produce saw type misclassification rates between 9 and 17%, although the authors caution that these results “are specific to the four saw types used and variables observed” and that “[s]everal of the variables often observed on crime marks were absent from the experimental marks” (Love et al., 2013, p. 42).

BSMs studies are thus making important strides toward methodological validation, which takes us to our next conclusion: because most validation studies are limited to a narrow range of taphonomic actors, causal agents, and/or effectors, the resulting error rates do not necessarily reflect directly our ability to identify or interpret crime/witness marks. The scope of a validation study is dictated by logistical and fiscal limitations and, of course, the research problem(s) at hand. If a need to distinguish cut marks from chop marks arises, the resulting study is likely to focus (and understandably so) on taphonomic causal agents and effectors that typically produce those types of marks rather than, say, sand particles, the sharp edges of which may produce sediment abrasion. That said, the limited universe of potential categories to which an unknown mark could be assigned in the resulting blind tests may not be comparable to that of a forensic case, where many other taphonomic processes are likely operant. In other words, not every mark from the forensic case is necessarily *either* a cut mark *or* a chop mark, so the validity of distinguishing those two types of mark, while relevant, cannot fully evaluate the validity of identifications of unknown crime/witness marks, which, after all, may be *neither* a cut mark nor a chop mark. So, in addition to expanding blind tests to encompass a greater variety of BSMs, we must also associate BSM identifications with an estimate of certainty, which in any case more closely corresponds with scientific notions of error, where some level of uncertainty due to instrumentation function and inherent variation in the object(s) of interest is always present (Christensen, Crowder, Ousley, & Houck, 2014). These estimates can take the form of a subjective assessment of “high” or “low” confidence identifications, as is done in some archeological studies of fossil assemblages (Marean, Abe, Frey, & Randall, 2000, p. 14), or, more preferably, quantitative statements of probability as in some hybrid validation studies of actualistic collections (Harris, Marean, Ogle, & Thompson, 2017).

We therefore believe that BSM studies, in forensic science or otherwise, can achieve the foundational validity called for in the PCAST report, but significant hurdles remain. Perhaps of greatest importance is poor inter-analyst correspondence in the initial definition, measurement, and/or coding of BSM features. Inconsistent results can arise across research groups because

BSMs are measured or coded in slightly different ways, even when common criteria and powerful microscopic techniques are applied. This is less of an issue when dissimilar taphonomic effectors (e.g., metal blades versus carnivore teeth) are at play because they typically result in BSMs with widely divergent features (e.g., metal cut marks versus carnivore tooth marks; Blumenschine et al., 1996), but it becomes more significant for similar taphonomic effectors (e.g., sharp blade versus sharp sedimentary particle) that create BSMs with considerable overlap in feature expression (e.g., cut marks versus sediment abrasion; Domínguez-Rodrigo et al., 2017, 2019; Harris et al., 2017; Merritt, Pante, Keevil, Njau, & Blumenschine, 2019). Domínguez-Rodrigo (2019, p. 2722) recognizes the problem when he states that “[h]igh accuracy [i.e., low misclassification rates] could be reliable if the basic (and crucial) initial analytical step in identifying the corresponding category of each variable (i.e., shape or trajectory of microstriations or groove section shape, etc.) could be objectively derived.”

We think the fusion of image capture and analysis technology with multivariate predictive modeling offers an attractive path forward. Photogrammetry, 3D scanning, and 3D digital microscopy produce remarkably detailed models of individual marks on bones (Bello & Galway-Witham, 2019; Courtenay et al., 2019; Courtenay, Huguet, & Yravedra, 2020; Linares-Matás et al., 2019; Maté-González et al., 2019; Maté-González, Yravedra, González-Aguilera, Palomeque-González, & Domínguez-Rodrigo, 2015; Merritt et al., 2019; Otárola-Castillo et al., 2018; Pante et al., 2017), and digital photography, 2D scanning, and spectrophotometers are able to collect precise colorimetric data from bone surfaces (Krap et al., 2019; Wärmländer et al., 2019).

There are a variety of proprietary and open-source software packages that are able to characterize the resulting images and 3D models through algorithms rather than qualitative criteria. We note, however, that while potentially less subjective than qualitative descriptions of mark morphology or bone surface color, not all of these methods are fully automated, nor are they immune to inter-analyst error (e.g., some 3D digital microscopy techniques require human users to manually trace mark profiles with a stylus, and photogrammetry involves the manual manipulation of the bone surface and/or camera). While a wide range of statistical approaches are available to aid BSM classifications, the complex, multivariate and multidimensional datasets now being produced are particularly amenable to a family of predictive modeling techniques referred to collectively as “machine learning” methods. The power of these approaches lies in their use of iterative processes to learn, or “tune,” the value(s) of parameters that best differentiate among classes of phenomena (BSMs, in this case) in order to classify, often with an estimate of probability, unknown samples (Domínguez-Rodrigo, 2019; Ousley, 2016). What is more, machine learning readily accommodates any data type, from nominal to ratio scale.

A study by Byeon et al. (2019) illustrates the power of this type of integrated approach to BSM classification. They first use computerized pattern recognition on a sample of 59 grayscale images of bone surfaces with either stone tool cut marks or sediment abrasion taken under a x30 binocular microscope. These images are then used to train Convolutional Neural Network (CNN) and Support Vector Machine (SVM) learning algorithms to recognize the two types of BSM. When the trained algorithms are asked to classify a testing set of 20 unknown (to the algorithms) images, they do so with error rates between ~10% (CNN) and ~20% (SVM). Human experts with 7–20 years of experience misclassify the same images at rates of ~37%. These results, while

certainly impressive, probably represent only the lower bounds of the algorithms' discriminatory power—the authors point out that a larger sample of training images and more intensive image pre-processing will likely improve performance. A similar methodology yields comparable error rates for algorithms trained to distinguish stone tool cut marks created on the surfaces of fleshed versus defleshed long bones (Cifuentes-Alcobendas & Domínguez-Rodrigo, 2019). As we continue to refine these types of validation studies, one major task is to broaden their scope to encompass more than two classes of BSM.

We close by stressing again the importance of a configurational approach to BSM identification. It is hazardous to base our identifications exclusively on intrinsic features—regardless of how those features are obtained or described. The location of a BSM on a bone's surface, the presence of other BSMs, the nature of the recovery scene, and other contextual factors can and must play a key role in BSM identification and interpretation. The versatility of machine learning makes it likely that these additional data can be readily incorporated into any analysis. When we consider that many criminal investigations rely on skeletal evidence to reconstruct the perimortem and postmortem intervals, it is clear that BSMs are, and will continue to be, a key component of the forensic sciences.

## **5 CONCLUSIONS**

Forensic investigations that rely on any form of skeletal evidence should consider BSM data carefully. However, the veracity of those data must be scrutinized closely. Observational cause-and-effect studies must be the bedrock of any attempt to associate a taphonomic actor with a specific type of BSM. What is more, a configurational approach that considers not only the intrinsic features of BSMs, but of all associated contextual information, must always inform BSM identifications. Only rigorous blind testing can establish the validity of BSM methodologies, and a key component of this is a concerted effort on the part of researchers to enhance inter-analyst correspondence through objective definitions, measurements, and/or codes of BSM features. In our view, these issues can best be tackled through the use of digital image analysis in combination with multivariate predictive modeling.

## **ACKNOWLEDGMENTS**

We offer our sincere thanks to our colleague and friend, Manuel Domínguez-Rodrigo, who has taught us much about the subject of bone surface modifications, and to the ever stalwart A.J. Heile for her diligent assistance in the early stages of manuscript preparation. Dallas Burkhardt, Anne Symonds, and the entire Interlibrary Loan staff at the UNCG Libraries assiduously tracked down many difficult-to-find references. Noell Egeland read through several drafts of this manuscript and offered incisive comments that improved its readability. The example set by R. Balzac continues to inspire our personal and scientific endeavors. We are particularly grateful to the Editor, Leslie Eisenberg, for inviting us to write this review, and to two anonymous reviewers, both of whom took time out of what are no doubt very busy schedules to carefully and critically examine our work. Any and all errors are the responsibility of the authors.

## **AUTHOR CONTRIBUTIONS**

**Charles Egeland:** Conceptualization; formal analysis; writing-original draft; writing-review and editing. **Travis Pickering:** Conceptualization; formal analysis; writing-original draft; writing-review and editing.

## REFERENCES

- Akpan, E. B., Farrow, G. E., & Morris, N. (1982). Limpet grazing on Cretaceous algal-bored ammonites. *Palaeontology*, **25**(2), 361– 376.
- Allaire, M. T., Manhein, M. H., & Burgess, G. H. (2012). Shark-inflicted trauma: A case study of unidentified remains recovered from the Gulf of Mexico. *Journal of Forensic Sciences*, **57**(6), 1675– 1678.
- Alunni-Perret, V., Muller-Bolla, M., Laugier, J.-P., Lupi-Pégurier, L., Bertrand, M.-F., Staccini, P., ... Quatrehomme, G. (2005). Scanning electron microscopy analysis of experimental bone hacking trauma. *Journal of Forensic Sciences*, **50**(4), 796– 801.
- Ames, J. A., & Morejohn, G. V. (1980). Evidence of white shark, *Carcharodon carcharias*, attacks on sea otters, *Enhydra lutris*. *California Fish and Game*, **66**(4), 196– 209.
- Andahl, R. O. (1978). The examination of saw marks. *Journal of the Forensic Science Society*, **18**(1–2), 31– 46.
- Anderson, B. E., Manoukian, A., Holland, T. D., & Grant, W. E. (2002). A death in paradise: Human remains scavenged by a shark. In D. W. Steadman (Ed.), *Hard evidence: Case studies in forensic anthropology* (pp. 189– 196). Upper Saddle River, NJ: Prentice-Hall.
- Anderson, G. S. (2009). Decomposition and invertebrate colonization of cadavers in coastal marine environments. In J. Amendt, M. L. Goff, C. P. Campobasso, & M. Grassberger (Eds.), *Current concepts in forensic entomology* (pp. 223– 272). Dordrecht: Springer.
- Anderson, G. S., & Bell, L. S. (2014). Deep coastal marine taphonomy: Investigation into carcass decomposition in the Saanich inlet, British Columbia using a baited camera. *PLoS One*, **9**(10), e110710.
- Anderson, G. S., & Bell, L. S. (2017). Comparison of faunal scavenging of submerged carrion in two seasons at a depth of 170 m, in the Strait of Georgia, British Columbia. *Insects*, **8**(1), 1– 15.
- Anderson, G. S., & Hobischak, N. R. (2004). Decomposition of carrion in the marine environment in British Columbia, Canada. *International Journal of Legal Medicine*, **118**(4), 206– 209.
- Andrés, M., Gidna, A. O., Yravedra, J., & Domínguez-Rodrigo, M. (2012). A study of dimensional differences of tooth marks (pits and scores) on bones modified by small and large carnivores. *Archaeological and Anthropological Sciences*, **4**(3), 209– 219.
- Andrews, P. (1990). *Owls, caves and fossils*, Chicago, IL: University of Chicago Press.
- Baby, R. S. (1954). Hopewell cremation practices. *The Ohio Historical Society Papers in Archaeology*, **1**, 1– 7.

- Backwell, L. R., Parkinson, A. H., Roberts, E. M., d'Errico, F., & Huchet, J.-B. (2012). Criteria for identifying bone modification by termites in the fossil record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **337–338**, 72– 87.
- Bailey, J. A., Wang, Y., van de Goot, F. R. W., & Gerretsen, R. R. R. (2011). Statistical analysis of kerf mark measurements in bone. *Forensic Science, Medicine, and Pathology*, **7**(1), 53– 62.
- Baquedano, E., Domínguez-Rodrigo, M., & Musiba, C. (2012). An experimental study of large mammal bone modification by crocodiles and its bearing on the interpretation of crocodile predation at FLK Zinj and FLK NN3. *Journal of Archaeological Science*, **39**(6), 1728– 1737.
- Bartelink, E. J., Wiersema, J. M., & Demaree, R. S. (2001). Quantitative analysis of sharp-force trauma: An application of scanning electron microscopy in forensic anthropology. *Journal of Forensic Sciences*, **46**(6), 1288– 1293.
- Bass, W. M. (1969). Recent developments in the identification of human skeletal material. *American Journal of Physical Anthropology*, **30**(3), 459– 461.
- Bass, W. M. (1979). Developments in the identification of human skeletal material (1968– 1978). *American Journal of Physical Anthropology*, **51**(4), 555– 562.
- Beary, M. O., & Lyman, R. L. (2012). The use of taphonomy in forensic anthropology: Past trends and future prospects. In D. C. Dirkmaat (Ed.), *A companion to forensic anthropology* (pp. 499– 527). Chichester, England: Wiley-Blackwell.
- Behrensmeyer, A. K., Gordon, K. D., & Yanagi, G. T. (1986). Trampling as a cause of bone surface damage and pseudo-cutmarks. *Nature*, **319**(6056), 768– 771.
- Behrensmeyer, A. K. (1978). Taphonomic and ecologic information from bone weathering. *Paleobiology*, **4**(02), 150– 162.
- Belaústegui, Z., de Gibert, J. M., Domènech, R., Muñiz, F., & Martinell, J. (2012). Clavate borings in a Miocene cetacean skeleton from Tarragona (NE Spain) and the fossil record of marine bone bioerosion. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **323–325**, 68– 74.
- Bello, S. M., & Galway-Witham, J. (2019). Bone taphonomy inside and out: Application of 3-dimensional microscopy, scanning electron microscopy and micro-computed tomography to the study of humanly modified faunal assemblages. *Quaternary International*, **517**, 16– 32.
- Bennett, J. L. (1999). Thermal alteration of buried bone. *Journal of Archaeological Science*, **26**(1), 1– 8.
- Berger, J. M., Pokines, J. T., & Moore, T. L. (2018). Analysis of class characteristics of reciprocating saws. *Journal of Forensic Sciences*, **63**(6), 1661– 1672.
- Berryman, H. E. (2002). Disarticulation pattern and tooth mark artifacts associated with pig scavenging of human remains: A case study. In W. D. Haglund & M. H.

- Sorg (Eds.), *Advances in forensic taphonomy: Method, theory, and archaeological perspectives* (pp. 487– 495). Boca Raton, FL: CRC Press.
- Binford, L. R. (1963). An analysis of cremations from three Michigan sites. *Wisconsin Archaeologist*, **44**, 98– 110.
- Binford, L. R. (1978). *Nunamiut ethnoarchaeology*, New York, NY: Academic Press.
- Binford, L. R. (1981). *Bones: Ancient men and modern myths*, New York, NY: Academic Press.
- Binford, L. R., & Stone, N. M. (1986). Zhoukoudian: A closer look. *Current Anthropology*, **27**(5), 453– 475.
- Black, S., & Thomson, G. (2017). Terminology. In S. Black, G. Ruttly, S. V. Hainsworth, & G. Thomson (Eds.), *Criminal dismemberment: Forensic and investigative analysis* (pp. 69– 77). Boca Raton, FL: CRC Press.
- Blau, S. (2017). The effects of weathering on bone preservation. In E. M. J. Schotsmans, N. Márquez-Grant, & S. L. Forbes (Eds.), *Taphonomy of human remains: Forensic analysis of the dead and the depositional environment* (pp. 201– 211). Chichester, England: John Wiley & Sons.
- Blumenschine, R. J. (1986). Carcass consumption sequences and the archaeological distinction of scavenging and hunting. *Journal of Human Evolution*, **15**, 639– 659.
- Blumenschine, R. J. (1988). An experimental model of the timing of hominid and carnivore influence on archaeological bone assemblages. *Journal of Archaeological Science*, **15**(5), 483– 502.
- Blumenschine, R. J., Marean, C. W., & Capaldo, S. D. (1996). Blind tests of inter-analyst correspondence and accuracy in the identification of cut marks, percussion marks, and carnivore tooth marks on bone surfaces. *Journal of Archaeological Science*, **23**(4), 493– 507.
- Blumenschine, R. J., & Selvaggio, M. M. (1988). Percussion marks on bone surfaces as a new diagnostic of hominid behaviour. *Nature*, **333**, 763– 765.
- Bochenski, Z. M., Tomek, T., Tornberg, R., & Wertz, K. (2009). Distinguishing nonhuman predation on birds: Pattern of damage done by the white-tailed eagle *Haliaeetus albicilla*, with comments on the punctures made by the golden eagle *Aquila chrysaetos*. *Journal of Archaeological Science*, **36**(1), 122– 129.
- Boessenecker, R. W. (2013). Taphonomic implications of barnacle encrusted sea lion bones from the middle Pleistocene Port Orford Formation, coastal Oregon. *Journal of Paleontology*, **87**(4), 657– 663.
- R. Bonnicksen, & M. H. Sorg (Eds.). (1989). *Bone modification*, Orono, Maine: Center for the Study of the First Americans.
- Bonte, W. (1974). Experimentelle Aufklärung individuell geprägter Sägespuren in einem weiteren Leichenzerstückelungsfall. *Zeitschrift für Rechtsmedizin*, **74**(2), 145– 154.

- Bonte, W. (1975). Tool marks in bones and cartilage. *Journal of Forensic Sciences*, **20**(2), 315– 325.
- Bonte, W., & Mayer, R. (1973). Analyse von Sägespuren bei krimineller Leichenzerstückelung. *Zeitschrift für Rechtsmedizin*, **72**(3), 180– 193.
- Bontrager, A. B., & Nawrocki, S. P. (2015). A taphonomic analysis of human cremains from the Fox Hollow Farm serial homicide site. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains* (pp. 229– 245). Amsterdam, Netherlands: Elsevier.
- Booth, T. (2017). The rot sets in: Low-powered microscopic investigation of taphonomic changes to bone microstructure and its application to funerary contexts. In D. Errickson & T. J. U. Thompson (Eds.), *Human remains: Another dimension. The application of imaging to the study of human remains* (pp. 7– 28). London, England: Academic Press.
- Bradfield, J. (2018). Some thoughts on bone artefact discolouration at archaeological sites. *Journal of Archaeological Science*, **17**, 500– 509.
- Brain, C. K., & Sillen, A. (1988). Evidence from the Swartkrans cave for the earliest use of fire. *Nature*, **336**(6198), 464– 466.
- Brain, C. K. (1967). Bone weathering and the problem of bone pseudo-tools. *South African Journal of Science*, **63**(3), 97– 99.
- Brain, C. K. (1981). *The hunters or the hunted: An introduction to African cave taphonomy*, Chicago, IL: University of Chicago Press.
- Breuil, H. (1932). Le feu et l'industrie de pierre et d'os dans le gisement du "Sinanthropus" a Chou Kou Tien. *L'Anthropologie*, **42**, 1– 17.
- Breuil, H. (1938). The use of bone implements in the Old Palaeolithic Period. *Antiquity*, **12**(45), 56– 67.
- Breuil, H. (1939). Bone and antler industry from the Choukoutien *Sinanthropus* site. *Palaeontologica Sinica*, **117**, 1– 93.
- Britt, B. B., Scheetz, R. D., & Dangerfield, A. (2008). A suite of dermestid beetle traces on dinosaur bone from the Upper Jurassic Morrison Formation, Wyoming, USA. *Ichnos*, **15**(2), 59– 71.
- Bromley, R. G. (1975). Comparative analysis of fossil and recent echinoid bioerosion. *Palaeontology*, **18**(4), 725– 739.
- Bromley, R. G. (1994). The palaeoecology of bioerosion. In S. K. Donovan (Ed.), *The palaeobiology of trace fossils* (pp. 134– 154). Baltimore, MD: Johns Hopkins University Press.
- Bromley, R. G. (2004). A stratigraphy of marine bioerosion. In D. McIlroy (Ed.), *The application of ichnology to palaeoenvironmental and stratigraphic analysis* (pp. 455– 479). London, England: Geological Society of London Special Publication, 228.

- Bromley, R. G., & D'Alessandro, A. (1984). The ichnogenus *Entobia* from the Miocene, Pliocene and Pleistocene of southern Italy. *Revista Italiana Di Paleontologia e Stratigrafia*, **90**(2), 227– 296.
- Bromley, R. G., Hanken, N.-M., & Asgaard, U. (1990). Shallow marine bioerosion: Preliminary results of an experimental study. *Bulletin of the Geological Society of Denmark*, **38**, 85– 99.
- Bromley, R. G., & Heinberg, C. (2006). Attachment strategies of organisms on hard substrates: A palaeontological view. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **232**(2–4), 429– 453.
- Brothwell, D. R. (1976). Further evidence of bone chewing by ungulates: The sheep of North Ronaldsay, Orkney. *Journal of Archaeological Science*, **3**(2), 179– 182.
- Brothwell, D. R. (1992). Bones and beyond: Insects, stains and keratin remains. *Circa*, **9**(1), 15– 17.
- Buckland, W. (1823). *Reliquiæ Diluvianæ, or, observations on the organic remains contained in caves, fissures, and Diluvial gravel, and on other geological phenomena, attesting the action of an universal deluge*. London: John Murray.
- Buckland, W. (1836). *Geology and mineralogy considered with reference to natural theology*. London, England: William Pickering.
- Buikstra, J. E., & Swegle, M. (1989). Bone modification due to burning: Experimental evidence. In R. Bonnichsen & M. H. Sorg (Eds.), *Bone modification* (pp. 247– 258). Orono, Maine: Center for the Study of the First Americans.
- Bunn, H. T., Bartram, L. E., & Kroll, E. M. (1988). Variability in bone assemblage formation from Hadza hunting, scavenging, and carcass processing. *Journal of Anthropological Archaeology*, **7**(4), 412– 457.
- Bunn, H. T., & Kroll, E. M. (1986). Systematic butchery by Plio/Pleistocene hominids at Olduvai Gorge, Tanzania. *Current Anthropology*, **27**(5), 431– 452.
- Bunn, H. T. (1981). Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora and Olduvai Gorge. *Nature*, **291**(5816), 574– 577.
- Bunn, H. T. (1991). A taphonomic perspective on the archaeology of human origins. *Annual Review of Anthropology*, **20**, 433– 467.
- Burd, D. Q., & Kirk, P. L. (1942). Tool marks: Factors involved in their comparison and use as evidence. *Journal of Criminal Law and Criminology*, **32**(6), 679– 686.
- Burke, C. C. (2013). Neotaphonomic analysis of the feeding behaviors and modification marks produced by North American carnivores. *Journal of Taphonomy*, **11**(1), 1– 20.
- Byeon, W., Domínguez-Rodrigo, M., Arampatzis, G., Baquedano, E., Yravedra, J., Maté-González, M. A., & Koumoutsakos, P. (2019). Automated identification and deep classification of cut marks on bones and its paleoanthropological implications. *Journal of Computational Science*, **32**, 36– 43.



- Camarós, E., Cueto, M., Lorenzo, C., Villaverde, V., & Rivals, F. (2016). Large carnivore attacks on hominins during the Pleistocene: A forensic approach with a Neanderthal example. *Archaeological and Anthropological Sciences*, **8**(3), 635– 646.
- Carroll, E. L., & Smith, M. (2018). Burning questions: Investigations using field experimentation of different patterns of change to bone in accidental vs deliberate burning scenarios. *Journal of Archaeological Science: Reports*, **20**, 952– 963. <https://doi.org/10.1016/j.jasrep.2018.02.001>
- Cerutti, E., Magli, F., Porta, D., Gibelli, D. M., & Cattaneo, C. (2014). Metrical assessment of cutmarks on bone: Is size important? *Legal Medicine*, **16**(4), 208– 213.
- Cerutti, E., Spagnoli, L., Araujo, N., Gibelli, D., Mazzarelli, D., & Cattaneo, C. (2016). Analysis of cutmarks on bone: Can light microscopy be of any help? *The American Journal of Forensic Medicine and Pathology*, **37**(4), 248– 254.
- Child, A. M. (1995). Microbial taphonomy of archaeological bone. *Studies in Conservation*, **40**(1), 19– 30.
- Chisum, W. J., & Turvey, B. E. (2007). Preface: A holistic approach to crime reconstruction. In W. J. Chisum & B. E. Turvey (Eds.), *Crime reconstruction* (pp. ix– xx). Amsterdam, Netherlands: Academic Press.
- Christensen, A. M., Crowder, C. M., Ousley, S. D., & Houck, M. M. (2014). Error and its meaning in forensic science. *Journal of Forensic Sciences*, **59**(1), 123– 126.
- Cifuentes-Alcobendas, G., & Domínguez-Rodrigo, M. (2019). Deep learning and taphonomy: High accuracy in the classification of cut marks made on fleshed and defleshed bones using convolutional neural networks. *Scientific Reports*, **9**(1), 18933.
- Cleghorn, N., & Marean, C. W. (2007). The destruction of skeletal elements by carnivores: The growth of a general model for skeletal element destruction and survival in zooarchaeological assemblages. In T. R. Pickering, K. D. Schick, & N. Toth (Eds.), *Breathing life into fossils: Taphonomic studies in honor of C.K. (Bob) Brain* (pp. 37– 66). Gosport, IN: Stone Age Institute Press.
- Clua, E., & Reid, D. (2018). Contribution of forensic analysis to shark profiling following fatal attacks on humans. In K. H. Dogan (Ed.), *Post mortem examination and autopsy— Current issues from death to laboratory analysis* (pp. 57– 75). London, England: IntechOpen.
- Courtenay, L. A., Huguet, R., & Yravedra, J. (2020). Scratches and grazes: A detailed microscopic analysis of trampling phenomena. *Journal of Microscopy*, **277**(2), 107– 117.
- Courtenay, L. A., Yravedra, J., Huguet, R., Ollé, A., Aramendi, J., Maté-González, M. Á., & González-Aguilera, D. (2019). New taphonomic advances in 3D digital microscopy: A morphological characterisation of trampling marks. *Quaternary International*, **517**, 55– 66.
- Crader, D. C. (1983). Recent single-carcass bone scatters and the problem of “butchery” sites in the archaeological record. In J. Clutton-Brock & C. Grigson (Eds.), *Animals and*

- archaeology: I. Hunters and their prey* (pp. 107– 141) British Archaeological Reports. Oxford, England.
- Crowder, C., Rainwater, C. W., & Fridie, J. S. (2011). *Microscopic analysis of sharp force trauma in bone and cartilage: A validation study* (National Institute of Justice technical report no. 235611). Washington, DC: U.S. Department of Justice.
- Crowder, C., Rainwater, C. W., & Fridie, J. S. (2013). Microscopic analysis of sharp force trauma in bone and cartilage: A validation study. *Journal of Forensic Sciences*, **58**(5), 1119– 1126.
- Damann, F. E. (2017). Bacterial symbionts and taphonomic agents of humans. In E. M. J. Schotsmans, N. Márquez-Grant, & S. L. Forbes (Eds.), *Taphonomy of human remains: forensic analysis of the dead and the depositional environment* (pp. 155– 166). Chichester, England: John Wiley & Sons.
- Damann, F. E., & Jans, M. M. E. (2017). Microbes, anthropology, and bones. In D. O. Carter, J. K. Tomberlin, M. E. Benbow, & J. L. Metcalf (Eds.), *Forensic microbiology* (pp. 312– 327). Chichester, England: John Wiley & Sons.
- Danise, S., & Higgs, N. D. (2015). Bone-eating *Osedax* worms lived on Mesozoic marine reptile deadfalls. *Biology Letters*, **11**(4), 20150072.
- Dart, R. A. (1957). *The osteodontokeratic culture of Australopithecus prometheus*. Transvaal Museum: Pretoria.
- Daubert v. Merrell Dow Pharmaceuticals, Inc, 509 (US 1993).
- de Gibert, J. M., Domènech, R., & Martinell, J. (2004). An ethological framework for animal bioerosion trace fossils upon mineral substrates with proposal of a new class, fixichnia. *Lethaia*, **37**(4), 429– 437.
- de Graaff, G. (1961). Gross effects of a primitive hearth on bones. *The South African Archaeological Bulletin*, **16**(61), 25.
- de Gruchy, S., & Rogers, T. L. (2002). Identifying chop marks on cremated bone: A preliminary study. *Journal of Forensic Sciences*, **47**(5), 933– 936.
- de Rechter, G., & Mage, J. (1927). Considerations sur une méthode d'identification des objets. Son application a un cas particulier. *Revue de Droit Pénal et de Criminologie*, **7**, 269– 277.
- Delaney-Rivera, C., Plummer, T. W., Hodgson, J. A., Forrest, F., Hertel, F., & Oliver, J. S. (2009). Pits and pitfalls: Taxonomic variability and patterning in tooth mark dimensions. *Journal of Archaeological Science*, **36**(11), 2597– 2608.
- Derry, D. E. (1911). Damage done to skulls and bones by termites. *Nature*, **86**, 245– 246.
- Dettmeyer, R. B., Verhoff, M. A., & Schütz, H. F. (2014). Forensic osteology. In R. B. Dettmeyer, M. A. Verhoff, & H. F. Schütz (Eds.), *Forensic medicine: Fundamentals and perspectives* (pp. 377– 397). Berlin, Germany: Springer.

- DeVault, T. L., Rhodes, O. E., Jr., & Shivik, J. A. (2003). Scavenging by vertebrates: Behavioral, ecological, and evolutionary perspectives on an important energy transfer pathway in terrestrial ecosystems. *Oikos*, **102**(2), 225–234.
- Devlin, J. B., & Herrmann, N. P. (2015). Bone colour. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains* (pp. 119–138). Amsterdam, Netherlands: Elsevier.
- Dirkmaat, D. C., Cabo, L. L., Ousley, S. D., & Symes, S. A. (2008). New perspectives in forensic anthropology. *American Journal of Physical Anthropology*, **137**(S47), 33–52.
- Dirks, P. H. G. M., Berger, L. R., Roberts, E. M., Kramers, J. D., Hawks, J., Randolph-Quinney, P. S., ... Tucker, S. (2015). Geological and taphonomic context for the new hominin species *Homo naledi* from the Dinaledi Chamber, South Africa. *eLife*, **4**, e09561.
- Dirrigl, F. J., & Perrotti, L. (2014). Taphonomic study of Japanese Quail (*Coturnix japonica*) bone modification resulting from the burial and feeding behavior of the American burying beetle (*Nicrophorus americanus*). *International Journal of Osteoarchaeology*, **24**(3), 272–278.
- Domínguez-Rodrigo, M. (2019). Successful classification of experimental bone surface modifications (BSM) through machine learning algorithms: A solution to the controversial use of BSM in paleoanthropology? *Archaeological and Anthropological Sciences*, **11**(6), 2711–2725.
- Domínguez-Rodrigo, M., & Barba, R. (2006). New estimates of tooth mark and percussion mark frequencies at the FLK Zinj site: The carnivore-hominid-carnivore hypothesis falsified. *Journal of Human Evolution*, **50**(2), 170–194.
- Domínguez-Rodrigo, M., & Barba, R. (2007a). New estimates of tooth-mark and percussion-mark frequencies at the FLK Zinjanthropus level: The carnivore–hominid–carnivore hypothesis falsified (I). In M. Domínguez-Rodrigo, R. Barba, & C. P. Egeland (Eds.), *Deconstructing Olduvai: A taphonomic study of the Bed I sites* (pp. 39–74). New York, NY: Springer.
- Domínguez-Rodrigo, M., & Barba, R. (2007b). Five more arguments to invalidate the passive scavenging version of the carnivore-hominid-carnivore model: A reply to Blumenschine et al. (2007a). *Journal of Human Evolution*, **53**(4), 427–433.
- Domínguez-Rodrigo, M., de Juana, S., Galán López, A. B., & Rodríguez, M. (2009). A new protocol to differentiate trampling marks from butchery cut marks. *Journal of Archaeological Science*, **36**(12), 2643–2654.
- Domínguez-Rodrigo, M., & Pickering, T. R. (2010). A multivariate approach for discriminating bone accumulations created by spotted hyenas and leopards: Harnessing actualistic data from East and Southern Africa. *Journal of Taphonomy*, **8**(2–3), 155–179.
- Domínguez-Rodrigo, M., Pickering, T. R., & Bunn, H. T. (2010). Configurational approach to identifying the earliest hominin butchers. *Proceedings of the National Academy of Sciences*, **107**(49), 20929–20934.

- Domínguez-Rodrigo, M., Saladié, P., Cáceres, I., Huguet, R., Yravedra, J., Rodríguez-Hidalgo, A., ... Cobo-Sánchez, L. (2017). Use and abuse of cut mark analyses: The Rorschach effect. *Journal of Archaeological Science*, **86**, 14– 23.
- Domínguez-Rodrigo, M., Saladié, P., Cáceres, I., Huguet, R., Yravedra, J., Rodríguez-Hidalgo, A., ... Cobo-Sánchez, L. (2019). Spilled ink blots the mind: A reply to Merrit et al. (2018) on subjectivity and bone surface modifications. *Journal of Archaeological Science*, **102**, 80– 86.
- Domínguez-Rodrigo, M., Yravedra, J., Organista, E., Gidna, A., Fourvel, J.-B., & Baquedano, E. (2015). A new methodological approach to the taphonomic study of paleontological and archaeological faunal assemblages: A preliminary case study from Olduvai Gorge (Tanzania). *Journal of Archaeological Science*, **59**, 35– 53.
- Domínguez-Solera, S., & Domínguez-Rodrigo, M. (2009). A taphonomic study of bone modification and of tooth-mark patterns on long limb bone portions by suids. *International Journal of Osteoarchaeology*, **19**(3), 345– 363.
- Domínguez-Solera, S., & Domínguez-Rodrigo, M. (2011). A taphonomic study of a carcass consumed by griffon vultures (*Gyps fulvus*) and its relevance for the interpretation of bone surface modifications. *Archaeological and Anthropological Sciences*, **3**(4), 385– 392.
- Domínguez-Rodrigo, M. (1999). Flesh availability and bone modifications in carcasses consumed by lions: Palaeoecological relevance in hominid foraging patterns. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**(1–4), 373– 388.
- Domínguez-Rodrigo, M., & Piqueras, A. (2003). The use of tooth pits to identify carnivore taxa in tooth-marked archaeofaunas and their relevance to reconstruct hominid carcass processing behaviours. *Journal of Archaeological Science*, **30**(11), 1385– 1391.
- Donn, T. F., & Boardman, M. R. (1988). Bioerosion of rocky carbonate coastlines on Andros Island, Bahamas. *Journal of Coastal Research*, **4**(3), 381– 394.
- Drumheller, S. K., & Brochu, C. A. (2014). A diagnosis of *Alligator mississippiensis* bite marks with comparisons to existing crocodylian datasets. *Ichnos*, **21**(2), 131– 146.
- Drumheller, S. K., & Brochu, C. A. (2016). Phylogenetic taphonomy: A statistical and phylogenetic approach for exploring taphonomic patterns in the fossil record using crocodylians. *Palaios*, **31**(10), 463– 478.
- Dunlop, J. M. (1978). Traffic light discoloration in cremated bones. *Medicine, Science and the Law*, **18**(3), 163– 173.
- Dupras, T. L., & Schultz, J. J. (2013). Taphonomic bone staining and color changes in forensic contexts. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 315– 340). Boca Raton, FL: CRC Press.
- Efremov, I. A. (1940). Taphonomy: New branch of paleontology. *Pan-American Geologist*, **74**(2), 81– 93.

- Egeland, C. P. (2012). The use of bone surface modifications to model hominid lifeways during the Oldowan. In M. Domínguez-Rodrigo (Ed.), *Stone tools and fossil bones: Debates in the archaeology of human origins* (pp. 80– 114). Cambridge, England: Cambridge University Press.
- Ellingham, S. T. D., Thompson, T. J. U., Islam, M., & Taylor, G. (2015). Estimating temperature exposure of burnt bone—A methodological review. *Science & Justice*, **55**(3), 181– 188.
- Erickson, D., & Thompson, T. J. U. (2016). Animal attacks and injuries: Anthropological findings. In J. Payne-James & R. G. Byard (Eds.), *Encyclopedia of forensic and legal medicine* (pp. 143– 147). New York, NY: Elsevier.
- Fay, J. M., Carroll, R., Kerbis Peterhans, J. C., & Harris, D. (1995). Leopard attack on and consumption of gorillas in the Central African Republic. *Journal of Human Evolution*, **29**(1), 93– 99.
- Feldman, A. D. (2015). *From trauma to trial: Proposing new methods for examining the variability of sharp force trauma on bone*. (M.A. thesis). San José State University, San Jose, CA.
- Fernández-Jalvo, Y., & Andrews, P. (2016). *Atlas of taphonomic identifications*, Dordrecht, Netherlands: Springer.
- Fiorillo, A. R. (1989). An experimental study of trampling: Implications for the fossil record. In R. Bonnichsen & M. H. Sorg (Eds.), *Bone modification* (pp. 61– 72) Center for the Study of the First Americans . Orono, Maine.
- Fisher, J. W. (1995). Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory*, **2**(1), 7– 68. <https://doi.org/10.1007/BF02228434>
- Galtés, I., Gallego, M. Á., Giménez, D., Padilla, V., Subirana, M., Fumadó-Martín, C., & Medallo, J. (2014). A body, a dog, and a fistful of scats. *Forensic Science International*, **241**, e1– e4.
- Gardner, R. M., & Bevel, T. (2009). *Practical crime scene analysis and reconstruction*, Boca Raton, FL: CRC Press.
- General Electric Co. V. Joiner, 522 (US 1997).
- Gidna, A., Domínguez-Rodrigo, M., & Pickering, T. R. (2015). Patterns of bovid long limb bone modification created by wild and captive leopards and their relevance to the elaboration of referential frameworks for paleoanthropology. *Journal of Archaeological Science: Reports*, **2**, 302– 309.
- Gidna, A., Yravedra, J., & Domínguez-Rodrigo, M. (2013). A cautionary note on the use of captive carnivores to model wild predator behavior: A comparison of bone modification patterns on long bones by captive and wild lions. *Journal of Archaeological Science*, **40**(4), 1903– 1910.
- Gifford-Gonzalez, D. (1991). Bones are not enough: Analogues, knowledge, and interpretive strategies in zooarchaeology. *Journal of Anthropological Archaeology*, **10**(3), 215– 254.

- Gilchrist, R., & Mytum, H. C. (1986). Experimental archaeology and burnt bone from archaeological sites. *Circa*, **4**(1), 29– 38.
- Glover, A. G., Källström, B., Smith, C. R., & Dahlgren, T. G. (2005). World-wide whale worms? A new species of *Osedax* from the shallow North Atlantic. *Proceedings of the Royal Society B: Biological Sciences*, **272**(1581), 2587– 2592.
- Go, M. (2018). A case of human bone modification by ants (Hymenoptera: Formicidae) in The Philippines. *Forensic Anthropology*, **1**(2), 117– 123.
- Greenfield, H. J. (1988). Bone consumption by pigs in a contemporary Serbian village: Implications for the interpretation of prehistoric faunal assemblages. *Journal of Field Archaeology*, **15**(4), 473– 479.
- Greenfield, H. J. (1999). The origins of metallurgy: Distinguishing stone from metal cut-marks on bones from archaeological sites. *Journal of Archaeological Science*, **26**(7), 797– 808.
- Greer, S. (2018). Quantifying variation in kerf wall striations created by hacksaws and reciprocating saws. *Forensic Anthropology*, **1**(3), 160– 169.
- Greiner, M., Rodríguez-Navarro, A., Heinig, M. F., Mayer, K., Kocsis, B., Göhring, A., ... Schmahl, W. W. (2019). Bone incineration: An experimental study on mineral structure, colour and crystalline state. *Journal of Archaeological Science: Reports*, **25**, 507– 518.
- Guilday, J. E., Parmalee, R. W., & Tanner, D. P. (1962). Aboriginal butchering techniques at the Escheiman site (36 La 12), Lancaster County, Pennsylvania. *Pennsylvania Archaeologist*, **32**(2), 59– 83.
- Haglund, W. D. (1992). Contribution of rodents to postmortem artifacts of bone and soft tissue. *Journal of Forensic Sciences*, **37**(6), 1459– 1465.
- Haglund, W. D. (1997). Dogs and coyotes: Postmortem involvement with human remains. In W. D. Haglund & M. H. Sorg (Eds.), *Forensic taphonomy: The postmortem fate of human remains* (pp. 367– 381). Boca Raton, FL: CRC Press.
- Haglund, W. D., & Sorg, M. H. (1997). Method and theory of forensic taphonomy research. In W. D. Haglund & M. H. Sorg (Eds.), *Forensic taphonomy: The postmortem fate of human remains* (pp. 13– 26). Boca Raton, FL: CRC Press.
- Haglund, W. D., & Sorg, M. H. (2002). Human remains in water environments. In W. D. Haglund & M. H. Sorg (Eds.), *Advances in forensic taphonomy: Method, theory, and archaeological perspectives* (pp. 201– 218). Boca Raton, FL: CRC Press.
- Harris, J. A., Marean, C. W., Ogle, K., & Thompson, J. (2017). The trajectory of bone surface modification studies in paleoanthropology and a new Bayesian solution to the identification controversy. *Journal of Human Evolution*, **110**, 69– 81.
- Hart, D. (2007). Predation on primates: A biogeographical analysis. In S. L. Gursky & K. A. I. Nekaris (Eds.), *Primate anti-predator strategies* (pp. 27– 59). Boston, MA: Springer.

- Haynes, G. (1980). Prey bones and predators: Potential ecologic information from analysis of bone sites. *Ossa*, **7**, 75– 97.
- Haynes, G. (1983). A guide for differentiating mammalian carnivore taxa responsible for gnaw damage to herbivore limb bones. *Paleobiology*, **9**(2), 164– 172.
- Higgs, N. D., Glover, A. G., Dahlgren, T. G., Smith, C. R., Fujiwara, Y., Pradillon, F., ... Little, C. T. S. (2014). The morphological diversity of *Osedax* worm borings (Annelida: Siboglinidae). *Journal of the Marine Biological Association of the United Kingdom*, **94**(7), 1429– 1439.
- Higgs, N. D., Little, C. T. S., Glover, A. G., Dahlgren, T. G., Smith, C. R., & Dominici, S. (2012). Evidence of *Osedax* worm borings in Pliocene (~3 Ma) whale bone from the Mediterranean. *Historical Biology*, **24**(3), 269– 277.
- Higgs, N. D., & Pokines, J. T. (2013). Marine environmental alterations to bone. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 143– 179). Boca Raton, FL: CRC Press.
- Hill, A. (1987). Appendix B: Damage to some fossil bones from Laetoli. In M. D. Leakey & J. M. Harris (Eds.), *Laetoli: A Pliocene site in Northern Tanzania* (pp. 543– 545). Oxford, England: Clarendon Press.
- Hockett, B. (2018). Taphonomic comparison of bones in mountain lion scats, coyote scats, golden eagle pellets, and great-horned owl pellets. *Quaternary International*, **466**, 141– 144.
- Höpner, S., & Bertling, M. (2017). Holes in bones: Ichnotaxonomy of bone borings. *Ichnos*, **24**(4), 259– 282.
- Horwitz, L. K., & Smith, P. (1988). The effects of striped hyaena activity on human remains. *Journal of Archaeological Science*, **15**(5), 471– 481.
- Huchet, J.-B., Deverly, D., Gutierrez, B., & Chauchat, C. (2011). Taphonomic evidence of a human skeleton gnawed by termites in a Moche-civilisation grave at Huaca de la Luna, Peru. *International Journal of Osteoarchaeology*, **21**(1), 92– 102.
- Humphrey, J. H., & Hutchinson, D. L. (2001). Macroscopic characteristics of hacking trauma. *Journal of Forensic Sciences*, **46**(2), 228– 233.
- Hutson, J. M., Burke, C. C., & Haynes, G. (2013). Osteophagia and bone modifications by giraffe and other large ungulates. *Journal of Archaeological Science*, **40**(12), 4139– 4149.
- Hutton, J. (1794) (Eds.), *An investigation of the principles of knowledge and of the progress of reason, from sense to science and philosophy*. Edinburgh and London: A. Strahan and T. Cadell.
- Ihama, Y., Ninomiya, K., Noguchi, M., Fuke, C., & Miyazaki, T. (2009). Characteristic features of injuries due to shark attacks: A review of 12 cases. *Legal Medicine*, **11**(5), 219– 225.

- Imaizumi, K. (2015). Forensic investigation of burnt human remains. *Research and Reports in Forensic Medical Science*, **5**, 67– 74.
- Işcan, M. Y., & McCabe, B. Q. (1995). Analysis of human remains recovered from a shark. *Forensic Science International*, **72**(1), 15– 23.
- Jans, M. M. E. (2008). Microbial bioerosion of bone: A review. In M. Wisshak & L. Tapanila (Eds.), *Current developments in bioerosion* (pp. 397– 413). Berlin, Germany: Springer.
- Johnson, E. (1985). Current developments in bone technology. *Advances in archaeological method and theory*, **8**, 157– 235.
- Junod, C., & Pokines, J. (2013). Subaerial weathering. In J. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 287– 314). Boca Raton, FL: CRC Press.
- Kaiser, T. M. (2000). Proposed fossil insect modification to fossil mammalian bone from Plio-Pleistocene hominid-bearing deposits of Laetoli (Northern Tanzania). *Annals of the Entomological Society of America*, **93**(4), 693– 700.
- Kelly, S. R. A., & Bromley, R. G. (1984). Ichnological nomenclature of clavate borings. *Palaeontology*, **27**(4), 793– 807.
- Keough, N., L'Abbé, E. N., Steyn, M., & Pretorius, S. (2015). Assessment of skeletal changes after post-mortem exposure to fire as an indicator of decomposition stage. *Forensic Science International*, **246**, 17– 24.
- Keyes, C. A., Myburgh, J., & Brits, D. (2019). Taphonomic bone trauma caused by Southern African scavengers. *International Journal of Legal Medicine*. **134**(3), 1227– 1238.
- Kierdorf, U. (1994). A further example of long-bone damage due to chewing by deer. *International Journal of Osteoarchaeology*, **4**(3), 209– 213.
- Kockel, R. (1900). Ueber die Darstellung der Spuren von Messer-Scharten. *Archiv für Kriminal-Anthropologie Und Kriminalistik*, **5**(1), 126– 130.
- Komar, D., & Beattie, O. (1998). Identifying bird scavenging in fleshed and dry remains. *Canadian Society of Forensic Science Journal*, **31**(3), 177– 188.
- Krap, T., Ruijter, J. M., Nota, K., Karel, J., Burgers, A. L., Aalders, M. C. G., ... Duijst, W. (2019). Colourimetric analysis of thermally altered human bone samples. *Scientific Reports*, **9**(1), 8923.
- Krap, T., van de Goot, F. R. W., Oostra, R.-J., Duijst, W., & Waters-Rist, A. L. (2017). Temperature estimations of heated bone: A questionnaire-based study of accuracy and precision of interpretation of bone colour by forensic and physical anthropologists. *Legal Medicine*, **29**, 22– 28.
- Krogman, W. M. (1939). A guide to the identification of human skeletal material. *FBI Law Enforcement Bulletin*, **8**(8), 3– 31.



- Krogman, W. M. (1943a). Role of the physical anthropologist in the identification of human skeletal remains. *FBI Law Enforcement Bulletin*, **12**(4), 17– 40.
- Krogman, W. M. (1943b). Role of the physical anthropologist in the identification of human skeletal remains—Part II. *FBI Law Enforcement Bulletin*, **12**(5), 12– 28.
- Krogman, W. M. (1962). *The human skeleton in forensic medicine*, Springfield, IL: Charles C Thomas.
- Kumho Tire Co. V. Carmichael, 526 (US 1999).
- Lartet, É. (1860). On the coexistence of man with certain extinct quadrupeds, proved by fossil bones, from various Pleistocene deposits, bearing incisions made by sharp instruments. *Quarterly Journal of the Geological Society*, **16**(1–2), 471– 479.
- Lewis, J. E. (2008). Identifying sword marks on bone: Criteria for distinguishing between cut marks made by different classes of bladed weapons. *Journal of Archaeological Science*, **35**(7), 2001– 2008.
- Linares-Matás, G. J., Yravedra, J., Maté-González, M. Á., Courtenay, L. A., Aramendi, J., Cuartero, F., & González-Aguilera, D. (2019). A geometric-morphometric assessment of three-dimensional models of experimental cut-marks using flint and quartzite flakes and handaxes. *Quaternary International*, **517**, 45– 54.
- Lloveras, L., Cosso, A., Solé, J., Claramunt-López, B., & Nadal, J. (2018). Taphonomic signature of golden eagles (*Aquila chrysaetos*) on bone prey remains. *Historical Biology*, **30**(6), 835– 854.
- Locard, E. (1923). *Manuel de technique Policière*, Paris, France: Payot.
- Lopes, R. P., & Pereira, J. C. (2019). Molluskan grazing traces (Ichnogenus *Radulichnus* Voigt, 1977) on a Pleistocene bivalve from southern Brazil, with the proposal of a new ichnospecies. *Ichnos*, **26**(2), 141– 157.
- Love, J. C. (2019). Sharp force trauma analysis in bone and cartilage: A literature review. *Forensic Science International*, **299**, 119– 127.
- Love, J. C., Derrick, S. M., & Wiersema, J. M. (2013). *Independent validation test of microscopic saw mark analysis* (National Institute of Justice technical report no. 241745). Washington, DC: U.S. Department of Justice.
- Love, J. C., Derrick, S. M., Wiersema, J. M., & Peters, C. (2015). Microscopic saw mark analysis: An empirical approach. *Journal of Forensic Sciences*, **60**(1), S21– S26.
- Lubbock, J. (1913). *Prehistoric times: As illustrated by ancient remains and the manners and customs of savages*, London, England: Williams and Northgate.
- Lyell, C. (1830). *Principles of geology: Being an attempt to explain the former changes of the earth's surface, by reference to causes now in operation*. John Murray.
- Lyman, R. L. (1994). *Vertebrate Taphonomy*, Cambridge, England: Cambridge University Press.

- Lyman, R. L., & Fox, G. L. (1989). A critical evaluation of bone weathering as an indication of bone assemblage formation. *Journal of Archaeological Science*, **16**, 293– 317.
- Mamede, A. P., Gonçalves, D., Marques, M. P. M., & Batista de Carvalho, L. A. E. (2018). Burned bones tell their own stories: A review of methodological approaches to assess heat-induced diagenesis. *Applied Spectroscopy Reviews*, **53**(8), 603– 635.
- Mann, R. W., & Owsley, D. W. (1992). Human osteology: Key to the sequence of events in a postmortem shooting. *Journal of Forensic Sciences*, **37**(5), 1386– 1392.
- Maples, W. R. (1986). Trauma analysis by the forensic anthropologist. In K. J. Reichs (Ed.), *Forensic osteology: Advances in the identification of human remains* (pp. 219– 228) Charles C. Thomas. Springfield, IL.
- Marean, C. W., Abe, Y., Frey, C. J., & Randall, R. C. (2000). Zooarchaeological and taphonomic analysis of the Die Kelders Cave 1 Layers 10 and 11 Middle Stone Age larger mammal fauna. *Journal of Human Evolution*, **38**(1), 197– 233.
- Martin, L. D., & West, D. L. (1995). The recognition and use of dermestid (Insecta, Coleoptera) pupation chambers in paleoecology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **113**(2–4), 303– 310.
- Maté-González, M. Á., Courtenay, L. A., Aramendi, J., Yravedra, J., Mora, R., González-Aguilera, D., & Domínguez-Rodrigo, M. (2019). Application of geometric morphometrics to the analysis of cut mark morphology on different bones of differently sized animals. Does size really matter? *Quaternary International*, **517**, 33– 44.
- Maté-González, M. Á., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F., & Domínguez-Rodrigo, M. (2015). Micro-photogrammetric characterization of cut marks on bones. *Journal of Archaeological Science*, **62**, 128– 142.
- May, L. S. (1930). The identification of knives, tools and instruments: A positive science. *American Journal of Police Science*, **1**(3), 246– 259.
- Mayne Correia, P. M. (1997). Fire modification of bone: A review of the literature. In W. D. Haglund & M. H. Sorg (Eds.), *Forensic taphonomy: The postmortem fate of human remains* (pp. 275– 293). Boca Raton, FL: CRC Press.
- McCardle, P., & Lyons, T. (2015). Machete cut marks on bone: Our current knowledge base. *Foresic Research & Criminology International Journal*, **1**(2), 00007.
- McGraw, W. S., Cooke, C., & Shultz, S. (2006). Primate remains from African crowned eagle (*Stephanoaetus coronatus*) nests in Ivory Coast's Tai Forest: Implications for primate predation and early hominid taphonomy in South Africa. *American Journal of Physical Anthropology*, **131**(2), 151– 165.
- Merritt, S. R., Pante, M. C., Keevil, T. L., Njau, J. K., & Blumenschine, R. J. (2019). Don't cry over spilled ink: Missing context prevents replication and creates the Rorschach effect in bone surface modification studies. *Journal of Archaeological Science*, **102**, 71– 79.
- Miller, G. J. (1975). A study of cuts, grooves, and other marks on recent and fossil bone: II weathering cracks, fractures, splinters, and other similar natural phenomena. In E. H.

- Swanson (Ed.), *Lithic technology: Making and using stone tools* (pp. 211– 226). Boston, MA: Mouton Publishers.
- Miller, J. H. (2009). *The large mammal death assemblage of Yellowstone National Park: Historical ecology, conservation biology, paleoecology*. (Ph.D. dissertation). University of Chicago, Chicago, IL.
- Motovilin, Y. G. (1965). Ustanovleniye nekotorykh svoystv klinka po kolotomu povrezhdeniyu v kosti (Some properties of the blade established by stab injury to the bone). *Sudebno-Meditsinskaya Ekspertiza (Forensic-Medical Examination)*, **12**(3), 52– 54.
- Murad, T. A. (1997). The utilization of faunal evidence in the recovery of human remains. In *Forensic taphonomy: The postmortem fate of human remains* (pp. 395– 404). Boca Raton, FL: CRC Press.
- Nicholson, R. A. (1993). A morphological investigation of burnt animal bone and an evaluation of its utility in archaeology. *Journal of Archaeological Science*, **20**, 411– 428.
- Nicholson, R. A. (1996). Bone degradation, burial medium and species representation: Debunking the myths, an experiment-based approach. *Journal of Archaeological Science*, **23**(4), 513– 533.
- Njau, J. K., & Blumenschine, R. J. (2006). A diagnosis of crocodile feeding traces on larger mammal bone, with fossil examples from the Plio-Pleistocene Olduvai Basin, Tanzania. *Journal of Human Evolution*, **50**(2), 142– 162.
- Nogueira, L., Alunni, V., Bernardi, C., & Quatrehomme, G. (2018). Les lésions osseuses par scies dans les démembrements: Résultats préliminaires. *La Revue de Médecine Légale*, **9**(4), 168– 173.
- Nogueira, L., Quatrehomme, G., Rallon, C., Adalian, P., & Alunni, V. (2016). Saw marks in bones: A study of 170 experimental false start lesions. *Forensic Science International*, **268**, 123– 130.
- Norman, D. G., Baier, W., Watson, D. G., Burnett, B. A., Painter, M., & Williams, M. A. (2018). Micro-CT for saw mark analysis on human bone. *Forensic Science International*, **293**, 91– 100.
- Olsen, S. L., & Shipman, P. (1988). Surface modification on bone: Trampling versus butchery. *Journal of Archaeological Science*, **15**(5), 535– 553.
- Otárola-Castillo, E., Torquato, M. G., Hawkins, H. C., James, E., Harris, J. A., Marean, C. W., ... Thompson, J. C. (2018). Differentiating between cutting actions on bone using 3D geometric morphometrics and Bayesian analyses with implications to human evolution. *Journal of Archaeological Science*, **89**, 56– 67.
- Ousley, S. D. (2016). Forensic classification and biodistance in the 21st century: The rise of learning machines. In M. A. Pilloud & J. T. Hefner (Eds.), *Biological distance analysis: Forensic and bioarchaeological perspectives* (pp. 197– 212). Amsterdam, Netherlands: Elsevier.

- Pante, M. C., Muttart, M. V., Keevil, T. L., Blumenschine, R. J., Njau, J. K., & Merritt, S. R. (2017). A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record. *Journal of Human Evolution*, **102**, 1– 11.
- Parkinson, A. H. (2012). *Dermestes maculatus and Periplaneta americana: Bone modification criteria and establishing their potential as climatic indicators*. (Ph.D. dissertation). University of the Witwatersrand, Johannesburg, South Africa.
- Peale, T. R. (1872). On the uses of the brain and marrow of animals among the Indians of North America. In *Annual report of the board of regents of the Smithsonian Institution showing the operations, expenditures, and condition of the institution for the year 1870* (pp. 390– 391). Washington, DC: Government Printing Office.
- Pei, W.-C. (1933). Preliminary note on some incised, cut and broken bones found in association with *Sinanthropus* remains and lithic artifacts from Choukoutien. *Bulletin of the Geological Society of China*, **12**(1–2), 105– 112.
- Pei, W.-C. (1938). Le rôle des Animaux et des Causes Naturelles dans la Cassure des Os. *Palaeontologica Sinica*, **7**, 1– 32.
- Pelletti, G., Viel, G., Fais, P., Viero, A., Visentin, S., Miotto, D., ... Giraud, C. (2017). Micro-computed tomography of false starts produced on bone by different hand-saws. *Legal Medicine*, **26**, 1– 5.
- Pickering, T. R. (2001). Carnivore voiding: A taphonomic process with the potential for the deposition of forensic evidence. *Journal of Forensic Sciences*, **46**(2), 406– 411.
- Pickering, T. R., & Carlson, K. J. (2004). Baboon taphonomy and its relevance to the investigation of large felid involvement in human forensic cases. *Forensic Science International*, **144**(1), 37– 44.
- Pickering, T. R., Domínguez-Rodrigo, M., Egeland, C. P., & Brain, C. K. (2004). Beyond leopards: Tooth marks and the contribution of multiple carnivore taxa to the accumulation of the Swartkrans Member 3 fossil assemblage. *Journal of Human Evolution*, **46**(5), 595– 604.
- Pickering, T. R., & Wallis, J. (1997). Bone modifications resulting from captive chimpanzee mastication: Implications for the interpretation of Pliocene archaeological faunas. *Journal of Archaeological Science*, **24**(12), 1115– 1127.
- Piepenbrink, H. (1986). Two examples of biogenous dead bone decomposition and their consequences for taphonomic interpretation. *Journal of Archaeological Science*, **13**, 417– 430.
- Pijoan, C. M., Mansilla, J., Leboreiro, I., Lara, V. H., & Bosch, P. (2007). Thermal alterations in archaeological bones. *Archaeometry*, **49**(4), 713– 727.
- Pittoni, E. (2009). Necropoli of Pill'e Matta Quartucciu (Cagliari, Sardinia): Wild bee and solitary wasp activity and bone diagenetic factors. *International Journal of Osteoarchaeology*, **19**(3), 386– 396.

- Pobiner, B. L. (2008). Paleoecological information in predator tooth marks. *Journal of Taphonomy*, **6**(3–4), 373– 397.
- Pobiner, B. L., & Blumenschine, R. J. (2003). A taphonomic perspective on Oldowan hominid encroachment on the carnivores paleoguild. *Journal of Taphonomy*, **1**(2), 115– 141.
- Pokines, J. T. (2013a). Faunal dispersal, reconcentration, and gnawing damage to bone in terrestrial environments. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 201– 248). Boca Raton, FL: CRC Press.
- Pokines, J. T. (2013b). Introduction: Collection of macroscopic osseous taphonomic data and the recognition of taphonomic suites and characteristics. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 1– 17). Boca Raton, FL: CRC Press.
- Pokines, J. T., & Baker, S. E. (2013). Avian taphonomy. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 427– 446). Boca Raton, FL: CRC Press.
- Pokines, J. T., & Higgs, N. D. (2015). Macroscopic taphonomic alterations to human bone recovered from marine environments. *Journal of Forensic Identification*, **65**(6), 953– 984.
- Pokines, J. T., Sussman, R., Gough, M., Ralston, C., McLeod, E., Brun, K., ... Moore, T. L. (2017). Taphonomic analysis of Rodentia and Lagomorpha bone gnawing based upon incisor size. *Journal of Forensic Sciences*, **62**(1), 50– 66.
- Potts, R., & Shipman, P. (1981). Cutmarks made by stone tools on bones from Olduvai Gorge, Tanzania. *Nature*, **291**(5816), 577– 580.
- President's Council of Advisors on Science and Technology. (2016). *Forensic science in criminal courts: Ensuring scientific validity of feature-comparison methods*, Washington, DC: Executive Office of the President.
- Queiroz, R. A., Carvalho, M. V. D., Caldas-Junior, A. F., Souza, E. H. A., Coelho-Junior, L. G. T. M., Campello, R. I. C., ... Vasconcellos, A. (2017). First forensic records of termite activity on non-fossilized human bones in Brazil. *Brazilian Journal of Biology*, **77**(1), 127– 131.
- Rathbun, T. A., & Rathbun, B. C. (1984). Human remains recovered from a shark's stomach in South Carolina. *Journal of Forensic Sciences*, **29**(1), 269– 276.
- Reeves, N. M. (2009). Taphonomic effects of vulture scavenging. *Journal of Forensic Sciences*, **54**(3), 532– 528.
- Reichs, K. J. (1998). Postmortem dismemberment: Recovery, analysis and interpretation. In K. J. Reichs (Ed.), *Forensic osteology: Advances in the identification of human remains* (pp. 353– 388) Charles C. Thomas. Springfield, IL.
- Roberts, E. M., Rogers, R. R., & Foreman, B. Z. (2007). Continental insect borings in dinosaur bone: Examples from the Late Cretaceous of Madagascar and Utah. *Journal of Paleontology*, **81**(1), 201– 208.

- Rolfe, W. D. I., & Brett, D. W. (1969). Fossilization processes. In G. Eglinton & M. T. J. Murphy (Eds.), *Organic geochemistry: Methods and results* (pp. 213– 244). Berlin, Germany: Springer.
- Rometti, C., Nogueira, L., Quatrehomme, G., & Alunni, V. (2020). Comparaison des lésions osseuses par « feuille de boucher » et hachette: Résultats préliminaires. *La Revue de Médecine Légale*, **11**(2), 63– 67.
- Ross, A. H., & Radisch, D. (2019). Toolmark identification on bone. In A. H. Ross & E. Cunha (Eds.), *Dismemberments: Perspectives in forensic anthropology and legal medicine* (pp. 165– 182). London, England: Elsevier.
- Rouse, G. W., Goffredi, S. K., & Vrijenhoek, R. C. (2004). *Osedax*: Bone-eating marine worms with dwarf males. *Science*, **305**(5684), 668– 671.
- Rudwick, M. J. S. (1992). *Scenes from deep time: Early pictorial representations of the prehistoric world*, Chicago, IL: University of Chicago Press.
- Sala, N., Arsuaga, J. L., & Haynes, G. (2014). Taphonomic comparison of bone modifications caused by wild and captive wolves (*Canis lupus*). *Quaternary International*, **330**, 126– 135.
- Savazzi, E. (1994). Functional morphology of boring and burrowing invertebrates. In S. K. Donovan (Ed.), *The palaeobiology of trace fossils* (pp. 43– 82). Baltimore, MD: Johns Hopkins University Press.
- Savazzi, E. (1999). Boring, nestling and tube-dwelling bivalves. In E. Savazzi (Ed.), *Functional morphology of the invertebrate skeleton* (pp. 205– 237). New York, NY: John Wiley & Sons.
- Saville, P. A., Hainsworth, S. V., & Rutty, G. N. (2007). Cutting crime: The analysis of the “uniqueness” of saw marks on bone. *International Journal of Legal Medicine*, **121**(5), 349– 357.
- Schmitt, D. N., & Juell, K. E. (1994). Toward the identification of coyote scatological faunal accumulations in archaeological contexts. *Journal of Archaeological Science*, **21**, 249– 262.
- Schneider, C. S. (2019). *Alligator (Alligator mississippiensis) taphonomy: Analysis of gnawed and digested bone*. (M.S. thesis). Boston University, Boston, MA.
- Schönberg, C. H. L. (2008). A history of sponge erosion: From past myths and hypotheses to recent approaches. In M. Wisshak & L. Tapanila (Eds.), *Current developments in bioerosion* (pp. 165– 202). Berlin, Germany: Springer.
- Schultz, J. J., Hawkins, M. M., & Mitchell, A. T. (2018). Skeletal weathering in Central Florida: A preliminary approach for developing a scoring protocol to estimate time since death. *Forensic Science International*, **290**, 85– 93.
- Schulz, A. (1906). Die forensisch-kriminalistische Bedeutung von Schartenspuren an Beilverletzungen des menschlichen Skeletts, insbesondere des Schädels. *Archiv Für Kriminal-Anthropologie Und Kriminalistik*, **23**, 222– 244.

- Scientific Working Group for Forensic Anthropology (2011). Trauma analysis. Washington, DC: National Institute of Standards and Technology.
- Shipman, P. (1981). *Life history of a fossil: An Introduction to taphonomy and paleoecology*, Cambridge, MA: Harvard University Press.
- Shipman, P., Foster, G., & Schoeninger, M. (1984). Burnt bones and teeth: An experimental study of color, morphology, crystal structure and shrinkage. *Journal of Archaeological Science*, **11**(4), 307– 325.
- Shipman, P., & Rose, J. (1983). Early hominid hunting, butchering, and carcass-processing behaviors: Approaches to the fossil record. *Journal of Anthropological Archaeology*, **2**(1), 57– 98.
- Simpson, G. G. (1970). Uniformitarianism. An inquiry into principle, theory, and method in geohistory and biohistory. In M. K. Hecht & W. C. Steere (Eds.), *Essays in evolution and genetics in honor of Theodosius Dobzhansky* (pp. 43– 96). Amsterdam: North-Holland Publishing Company.
- Sincerbox, S. N., & DiGangi, E. A. (2018). *Forensic taphonomy and ecology of North American scavengers*, London, England: Academic Press.
- Smith, O. C., Pope, E. J., & Symes, S. A. (2009). Look until you see: Identification of trauma in skeletal material. In D. W. Steadman (Ed.), *Hard evidence: Case studies in forensic anthropology* (pp. 190– 204) Pearson. Upper Saddle River, NJ.
- Snow, C. C. (1982). Forensic anthropology. *Annual Review of Anthropology*, **11**, 97– 131.
- Snow, C. C., & Luke, J. L. (1970). The Oklahoma City child disappearances of 1967: Forensic anthropology in the identification of skeletal remains. *Journal of Forensic Sciences*, **15**(2), 125– 153.
- Sorg, M. H., Dearborn, J. H., Monahan, E. I., Ryan, H. F., Sweeney, K. G., & David, E. (1997). Forensic taphonomy in marine contexts. In W. D. Haglund & M. H. Sorg (Eds.), *Forensic taphonomy: The postmortem fate of human remains* (pp. 567– 604). Boca Raton, FL: CRC Press.
- Steadman, D. W., & Worne, H. (2007). Canine scavenging of human remains in an indoor setting. *Forensic Science International*, **173**(1), 78– 82.
- Stephoe, D. P., & Wood, W. B. (2002). The human remains from HMS *Pandora*. *Internet Archaeology*, (11). <https://doi.org/10.11141/ia.11.4>
- Stewart, T. D. (1951). What the bones tell. *FBI Law Enforcement Bulletin*, **20**(2), 2– 5 19.
- Stiner, M. C., Kuhn, S. L., Weiner, S., & Bar-Yosef, O. (1995). Differential burning, recrystallization, and fragmentation of archaeological bone. *Journal of Archaeological Science*, **22**, 223– 237.
- Stock, M. K., Winburn, A. P., & Burgess, G. H. (2017). Skeletal indicators of shark feeding on human remains: Evidence from Florida forensic anthropology cases. *Journal of Forensic Sciences*, **62**(6), 1647– 1654.

- Sutcliffe, A. J. (1973). Similarity of bones and antlers gnawed by deer to human artefacts. *Nature*, **246**(5433), 428– 430.
- Symes, S. A. (1992). *Morphology of saw marks in human bone: Identification of class characteristics*. (Ph.D. dissertation). University of Tennessee.
- Symes, S. A., Berryman, H. E., & Smith, O. C. (1998). Saw marks in bone: Introduction and examination of residual kerf contour. In K. J. Reichs (Ed.), *Forensic osteology: Advances in the identification of human remains* (pp. 389– 409) Charles C. Thomas. Springfield, IL.
- Symes, S. A., Chapman, E. N., Rainwater, C. W., Cabo, L. L., & Myster, S. M. T. (2010). *Knife and saw toolmark analysis in bone: A manual designed for the examination of criminal mutilation and dismemberment* (National Institute of Justice technical report no. 232227). Washington, DC: U.S. Department of Justice.
- Symes, S. A., L'Abbé, E. N., Chapman, E. N., Wolff, I., & Dirkmaat, D. C. (2012). Interpreting traumatic injury to bone in medicolegal investigations. In D. C. Dirkmaat (Ed.), *A companion to forensic anthropology* (pp. 340– 389). Ltd: John Wiley & Sons.
- Symes, S. A., L'Abbé, E. N., Pokines, J. T., Yuzwa, T., Messer, D., Stromquist, A., & Keough, N. (2013). Thermal alteration to bone. In J. T. Pokines & S. A. Symes (Eds.), *Manual of forensic taphonomy* (pp. 367– 402). Boca Raton, FL: CRC Press.
- Symes, S. A., Rainwater, C. W., Chapman, E. N., Gipson, B. A., & Piper, A. L. (2015). Patterned thermal destruction in a forensic setting. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains* (pp. 17– 59). Amsterdam, Netherlands: Elsevier.
- Symes, S. A., Williams, J. A., Murray, E. A., Hoffman, J. M., Saul, J. M., & Pope, E. J. (2002). Taphonomic context of sharp-force trauma in suspected cases of human mutilation and dismemberment. In W. D. Haglund & M. H. Sorg (Eds.), *Advances in forensic taphonomy: Method, theory, and archaeological perspectives* (pp. 403– 434). Boca Raton, FL: CRC Press.
- Tappen, M. (1994). Bone weathering in the tropical rain forest. *Journal of Archaeological Science*, **21**, 667– 673.
- Tegtmeyer, C. E. (2012). *A comparative analysis of serrated and non-serrated sharp force trauma to bone*. (M.A. thesis). Texas State University, San Marcos, TX.
- Thomas, F., & Cuelenaere, A. (1952). Identification de l'arme du crime dans un assassinat par coups de marteau assésés sur la tête. *Acta Medicinae Legalis et Socialis*, **5**(3), 171– 181.
- Thomas, F., & Gallent, G. (1947). Homicide by blows dealt to the head by means of an axe and identification of the weapon. *International Criminal Police Review (Reprinted in the Association of Firearm and Tool Mark Examiners Journal)*, **39**(2), 88– 94.
- Thompson, J. E., Martín-Vega, D., Buck, L. T., Power, R. K., Stoddart, S., & Malone, C. (2018). Identification of dermestid beetle modification on Neolithic Maltese human bone: Implications for funerary practices at the Xemxija tombs. *Journal of Archaeological Science: Reports*, **22**, 123– 131.



- Thompson, T. J. U. (2004). Recent advances in the study of burned bone and their implications for forensic anthropology. *Forensic Science International*, **146**, S203– S205.
- Thompson, T. J. U., & Inglis, J. (2009). Differentiation of serrated and non-serrated blades from stab marks in bone. *International Journal of Legal Medicine*, **123**(2), 129– 135.
- Thompson, T. J. U., & Ulguim, P. F. (2016). Burned human remains. In S. Blau & D. H. Ubelaker (Eds.), *Handbook of forensic anthropology and archaeology* (pp. 391– 401). New York, NY: Routledge.
- Thomson, G., & Black, S. (2017). Principles of tool mark analysis and evidential best practice. In S. Black, G. N. Ruty, S. V. Hainsworth, & G. Thomson (Eds.), *Criminal dismemberment: Forensic and investigative analysis* ( 1st ed., pp. 79– 95). Boca Raton, FL: CRC Press.
- Trammell, L. H. (2020). Dismembered, burned, and dumped: But in what order? In H. M. Garvin & N. R. Langley (Eds.), *Case studies in forensic anthropology: Bonified skeletons* (pp. 81– 89). Boca Raton, FL: CRC Press.
- Tucker, B. K., Hutchinson, D. L., Gilliland, M. F. G., Charles, T. M., Daniel, H. J., & Wolfe, L. D. (2001). Microscopic characteristics of hacking trauma. *Journal of Forensic Sciences*, **46**(2), 234– 240.
- Turner, A., & Antón, M. (2000). *The big cats and their fossil relatives*, New York, NY: Columbia University Press.
- Turner-Walker, G. (2012). Early bioerosion in skeletal tissues: Persistence through deep time. *Neues Jahrbuch Für Geologie Und Paläontologie— Abhandlungen*, **265**(2), 165– 183.
- Turner-Walker, G. (2019). Light at the end of the tunnels? The origins of microbial bioerosion in mineralised collagen. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **529**, 24– 38.
- Ubelaker, D. H. (2009). The forensic evaluation of burned skeletal remains: A synthesis. *Forensic Science International*, **183**(1), 1– 5.
- Ubelaker, D. H. (2018). A history of forensic anthropology. *American Journal of Physical Anthropology*, **165**(4), 915– 923.
- Ullinger, J., & Sheridan, S. G. (2015). Bone color changes in a burned burial structure from Early Bronze Age Bab adh-Dhra', Jordan. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains*, Amsterdam, Netherlands: Elsevier.
- Viero, A., Montisci, M., Pelletti, G., & Vanin, S. (2019). Crime scene and body alterations caused by arthropods: Implications in death investigation. *International Journal of Legal Medicine*, **133**(1), 307– 316.
- Voigt, E. (1977). On grazing traces produced by the radula of fossil and recent gastropods and chitons. In T. P. Crimes & J. C. Harper (Eds.), *Trace fossils 2: Proceedings of an International Symposium Held at Sydney, Australia, 23, August 24, 1976 as Part of the 25th International Geological Congress* (Vol. 2, pp. 335– 347). Liverpool, England: Seel House Press.

- von Bertalanffy, L. (1968). *General system theory: Foundation, development, application*, New York, NY: George Baziller.
- Wahl, J. (1981). Beobachtungen zur Verbrennung Menschlicher Leichname. *Archäologisches Korrespondenzblatt*, **11**, 271– 279.
- Walker, P. L., Miller, K. W. P., & Richman, R. (2008). Time, temperature, and oxygen availability: An experimental study of the effects of environmental conditions on the color and organic content of cremated bone. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains* (pp. 129– 135). Amsterdam, Netherlands: Academic Press.
- Wärmländer, S. K. T. S., Varul, L., Koskinen, J., Saage, R., & Schlager, S. (2019). Estimating the temperature of heat-exposed bone via machine learning analysis of SCI color values: A pilot study. *Journal of Forensic Sciences*, **64**(1), 190– 195.
- Washburn, S. L. (1957). Australopithecines: The hunters or the hunted? *American Anthropologist*, **59**(4), 612– 614.
- Watson, J. A. L., & Abbey, H. M. (1986). The effects of termites (Isoptera) on bone: Some archeological implications. *Sociobiology*, **11**(3), 245– 254.
- Weitzel, M. A., & McKenzie, H. G. (2015). Fire as a cultural taphonomic agent. In C. W. Schmidt & S. A. Symes (Eds.), *The analysis of burned human remains* (pp. 203– 217). Amsterdam, Netherlands: Elsevier.
- Wenham, S. J. (1989). Anatomical interpretations of Anglo-Saxon weapon injuries. In S. C. Hawkes (Ed.), *Weapons and warfare in Anglo-Saxon England* (pp. 123– 139). Oxford, England: Oxford University Committee for Archaeology.
- West, D. L., & Martin, L. D. (2002). Insect trace fossils as environmental/taphonomic indicators in archaeology and paleoecology. In D. Wakefield (Ed.), *Institute for Tertiary-Quaternary studies, TER-QUA symposium series* (Vol. **3**, pp. 163– 173) Nebraska Academy of Sciences. Lincoln, NE.
- Whelan, C. J., Şekercioğlu, Ç. H., & Wenny, D. G. (2015). Why birds matter: From economic ornithology to ecosystem services. *Journal of Ornithology*, **156**(S1), 227– 238.
- Williams, J. A., & Davis, R. W. (2017). Thinking outside the box: Theory and innovation in sharp trauma analysis. In C. C. Boyd & D. C. Boyd (Eds.), *Forensic anthropology: Theoretical framework and scientific basis* (pp. 235– 249). Chichester, England: John Wiley & Sons.
- Wood, W. B., & Hodgson, G. P. (1996). The skeleton from the wreck of HMS *Pandora*. In *History, heritage and health: Proceedings of the fourth biennial conference of the Australian Society of the History of Medicine* (pp. 303– 307). Brisbane, Australia: Australian Society of the History of Medicine.
- Wylie, F. R., Walsh, G. L., & Yule, R. A. (1987). Insect damage to Aboriginal relics at burial and rock-art sites near Carnarvon in Central Queensland. *Australian Journal of Entomology*, **26**(4), 335– 345.

- Wyman, J. (1868). An account of some kjoekkenmoeddings, or shell-heaps, in Maine and Massachusetts. *American Naturalist*, **1**(11), 561– 584.
- Yellen, J. E. (1977). Cultural patterning in faunal remains: Evidence from the !Kung Bushmen. In D. Ingersoll, J. E. Yellen, & W. MacDonald (Eds.), *Experimental archaeology* (pp. 271– 331). New York, NY: Columbia University Press.
- Young, A., Stillman, R., Smith, M. J., & Korstjens, A. H. (2015). Scavenger species-typical alteration to bone: Using bite mark dimensions to identify scavengers. *Journal of Forensic Sciences*, **60**(6), 1426– 1435.
- Zanetti, N. I., Visciarelli, E. C., & Centeno, N. D. (2014). Taphonomic marks on pig tissue due to cadaveric Coleoptera activity under controlled conditions. *Journal of Forensic Sciences*, **59**(4), 997– 1001.
- Ziemke, E. (1921). Zur Erkennung des verletzenden Werkzeuges aus Schädelwunden. *Vierteljahrsschrift für Gerichtliche Medizin Und öffentliches Sanitätswesen*, **61**(2), 185– 203.