CHAPTER 19 Developments in Skeletal Trauma: Blunt-Force Trauma

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INTRODUCTION TO BLUNT-FORCE TRAUMA

The goal of this chapter is to briefly discuss the history of blunt-force trauma (BFT) research in forensic anthropology, and then present some of the current developments in the field. The draft guidelines on trauma analysis generated by the Scientific Working Group for Forensic Anthropology (SWGANTH) in 2011 states that "blunt force trauma is produced by low velocity impact from a blunt object (e.g., a beating, motor vehicle accident, concussive wave) or the low velocity impact of a body with a blunt surface (e.g., fall)" (SWGANTH 2011) As it concerns the forensic anthropologist, BFT can be understood as skeletal fractures that occur from a means of (relatively) slow-load application to bone. Slow loading results in more or less typical bony fracture characteristics in terms of the types and directions of forces applied that usually produce gross bony deformation. In contrast, projectile (sometimes referred to as "ballistic") trauma is generated by (relatively) *rapid*-load application (see Chapter 18 in this volume, and Berryman and Symes 1998 for further discussion). The difference between how bone reacts to BFT compared with projectile trauma has to do with the viscoelastic properties of fresh (wet) human bone (Harkness et al. 1984). Biomechanically speaking, when a force acts on a bone, the bone will react in predictable and consecutive stages: *stress*, the force applied to the bone; *strain* (*elastic deformation*), forces passing through the bending bone; *strain* (*plastic deformation*), forces bending the bone with permanent deformation; and *failure*, fracture of the bone (Gozna 1982). These stages occur at both the microscopic and macroscopic

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levels (see Berryman and Symes 1998; Smith et al. 2003 for further discussion). As noted by Smith et al. (2003), bony responses to blunt-force injuries will depend on a great number of both intrinsic factors (bone morphology, density, buttressing, microstructure, etc.) and extrinsic factors (object shape, weight, loading rate, loading duration, etc.), all of which must be taken into account when conducting a trauma analysis.

The difference in slow- versus rapid-load applications can be understood as how much time the bone has to bend and react (deform) before it fails. In slow-loading trauma, there is more time for the bone to bend, which is why significant deformation is so typical of BFT. Rapid loading, on the other hand, tends to have minimal deformation of skeletal tissue, which is why it is so typical of gunshot and blast injuries (and why reconstructions of these bony injuries fit together so much better).

Concerning the propagation of fractures in bone under blunt-force conditions, Kulin et al. (2008) tested equine bone at quasistatic and dynamic strain rates. In this case, the quasistatic (slower) rates produced much more tortuous fracturing throughout the bony microstructure as the fracture propagated. This basically occurs as a result of how the microstructural features of the bone deflect the propagating fracture away from the most direct crack-path, in essence limiting the overall fracture length and creating a very rough fracture surface as energy is dissipated. Under dynamic (faster) loading conditions, the fractures were much straighter with less peripheral damage and a smoother fracture surface. These results suggest a rate-dependent change in the properties of collagen from ductile to brittle as rates increase, the significance for forensic anthropology being the demonstration of the rate-dependent nature of fracture propagation.

Generally speaking, blunt-force injuries can be examined in terms of tension/compression for directionality of fracture (Figure 19.1). As bone is stronger in compression than tension (Curry 1970), bone usually fails under tension except under some unique circumstances (Love and Symes 2004). These simple principles often allow for fracture directionality to be determined; however, there are many other factors that can affect the direction and shape of bone fractures, and caution should be used whenever interpreting bone trauma (Galloway 1999; Gozna 1982; Smith et al. 2003).

Differences in fracture characteristics are also important for the determination of timing of injury, especially when determining whether the fractures occurred perimortem or postmortem. Sauer's (1998) article on the timing of injuries distinguishes among antemortem, perimortem, and postmortem trauma. Sauer (1998) states that "any injury directly associated with the manner of death is considered a perimortem injury." This view aligns closely with the use of the term by forensic pathologists, where perimortem is defined as "at or around the time of death." Nawrocki (cited as a personal communication in Symes et al. 2008) argues that the *perimortem interval* lasts until the skeletal remains exhibit dry-bone characteristics. Nawrocki's viewpoint is based on the fact that as skeletal remains lose their organic content and viscoelastic properties, they change from a wet (perimortem) to dry (postmortem) state (also see Wieberg and Wescott 2008). This is complicated, however, as different elements in a single body may be able to shift from wet to dry phases at different times depending on differential decomposition or heat alteration (Symes et al. 2008).

The disagreement on the definition of perimortem is an issue that the SWGANTH has grappled with in the trauma analysis draft document (SWGANTH 2011). The

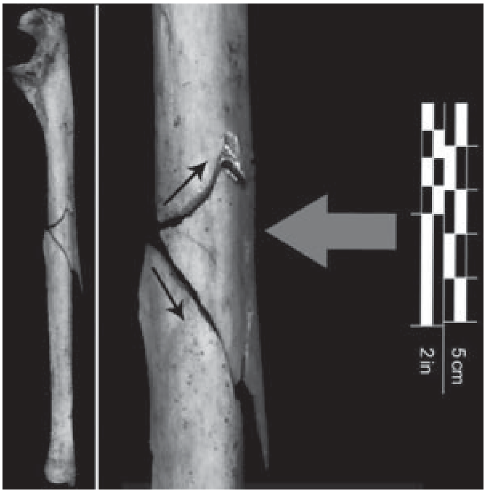

Figure 19.1 Butterfly fracture on a right ulna (often referred to as a "parry fracture" suggesting it is a defensive wound; Ortner 2003: 137). The large arrow indicates direction of impact. Compression forces occur at the impact site, whereas tension forces (small arrows) occur on the opposite side. The bone fails first in tension (at the body of the butterfly), then sheers towards the site of impact (the butterfly wings). See also Berryman and Symes (1998).

first draft document posted on the SWGANTH website in February of 2010 stated "Perimortem trauma refers to an injury occurring around the time of death (i.e., slightly before or slightly after). Within the anthropological realm, perimortem is determined on the basis of evidence of the biomechanical characteristics of fresh bone and *does not take into consideration the death event*" (SWGANTH 2011). Using the term "perimortem" in this way, however, potentially creates a problematic situation where the forensic anthropologist's definition of "perimortem" differs from that of the forensic pathologist's.

This is a serious concern because there may be occasions when a fracture identified as perimortem by the forensic anthropologist is misinterpreted by the forensic pathologist as being related to cause of death when it is not. Forensic anthropologists are not experts in death, but in how bones break. We can determine whether a fracture occurred in fresh bone and exhibits healing, if it occurred in fresh bone with no healing, or if the fracture occurred when the bone was in a dry state. Certainly, most fresh bone fractures with no healing occur perimortem; however, there are unique instances where bones remain fresh long past the death event. Thus, the use of the term "perimortem," which specifically refers to the death event, may misrepresent the type of analysis a forensic anthropologist is capable of performing on skeletal remains. This has prompted some forensic anthropologists to suggest that we abandon the term perimortem as it relates to bone fracture, and instead refer to it as "fresh bone fracture."

The issue of postmortem interval then becomes additionally cloudy as most taphonomic modification to human remains occurs in terms of slow loading. While some taphonomic modification is easy to identify, such as carnivore chewing or rodent gnawing (see Haglund 1997, 1997), other factors may be more difficult, especially with fragile remains. For instance, Ubelaker and Adams (1995) noted that butterfly fractures also occur in dry bone. Further, Wheatley (2008) examined deer (*Odocoileus virginianus*) long bones and found that fresh bone required more energy to produce fractures and that fresh bone absorbed more energy at impact than dry bone. Important to note is that while bone may fail in slightly different ways due to differences in organic content present, the acting forces are still the same. Tension and compression will always be present and bone fractures will always propagate in the same directions. Thus, failure and fracture of the bone occurs in predictable ways because there are only so many ways a bone can fail.

What may be important to note is the fact that any antemortem or perimortem damage to skeletal tissues must first have damaged the overlying soft tissues. Skeletal tissues are by definition much more robust in the nature of traumatic data that they record. Due to this fact, soft tissue may often be more accurate in recording data such as minimum number of blows, but skeletal tissue may better preserve tool marks (or general object shape) (Bonte 1975), or the sequence of blows. Unfortunately, while the sequence of blows may often be determined from skeletal remains, in BFT it is a challenging endeavor. Further, the estimation of first, second, and third impact in BFT is not frequently important and thus acts as a piece of information that, while possible to estimate, is associated with too much uncertainty with regard to its evidentiary value. In addition, while bone can record tool marks, without direct association of the blunt instrument involved or unique class characteristics present, tool marks are often too general to be indicative of blunt-instrument shape or type.

Historical Trends in Trauma Analysis

Trauma analysis did not become a common component in forensic anthropology casework until surprisingly late in the development of the field. This is most easily inferred by looking at the most prominent textbooks of the past – Krogman (1962) and Stewart (1979) – where the job of the forensic anthropologist was described as identifying human bone and developing a biological profile of an individual for purposes of *identification*. When bone trauma or "damage" was found, it was superficially described and measured. For instance, Stewart states: "a forensic anthropologist should simply describe any evidence of bone damage, point out its location in relation to vital centers, explain the possibility of its having been sustained at the time of death or otherwise, and discuss the likely objects that produced the damage" (Stewart 1979: 76). Only with the introductory text by Byers (2002) did the analysis of trauma take an equal footing with age, sex, ancestry, and stature in a textbook on forensic anthropology.

What may be helpful is to consider the evolution of trauma analysis in our discipline using the "Eras of Forensic Anthropology" as roughly defined by Stewart (1979) and Sledzik et al. (2007).

1. *Pioneering era*: pre-World War II. Characterized by anatomists and physical anthropologists consulting on forensic cases without formal instruction, research, or positions.
2. *Formative era*: 1940s–early 1970s. Forensic anthropology as a *subfield* of anthropology begins to emerge with recognition by government agencies and the

medicolegal community (may also be considered as Stewart's "Modern Period"; Stewart 1979: 11).

3. *Professionalization era*: late 1970s–1990. This era begins with the founding of the Physical Anthropology section of the American Academy of Forensic Scientists (AAFS) and the creation of the American Board of Forensic Anthropology (ABFA), but is better characterized by an increase in professional forensic anthropology training, research, and practice.
4. *Standardization era*: 1990–present (2010). This era is characterized by the establishment of forensic anthropology as its own *discipline* and the broadening of the scope of forensic anthropological work (also referred to as Sledzik et al.'s "Fourth Era"; Sledzik et al. 2007).

It was not until the professionalization era that trauma analysis in forensic anthropology casework began to become mainstream. This delay in taking a systematic and scientific examination of bone trauma may be explained by the evolving role of the forensic anthropologist in the medicolegal death investigation. As it is the responsibility of the forensic pathologist to determine cause and/or manner of death, the idea that forensic anthropologists had important knowledge to contribute to understanding cause and manner was slow in coming. The first PhD programs training students in forensic anthropology, established in the late 1970s and early 1980s, played an important role in expanding the scope of forensic anthropology in medicolegal death investigation. Namely, programs at the University of Tennessee, the University of Arizona, the University of Florida, and the University of New Mexico (under the directorships of Dr Bill Bass, Dr Walt Birkby, Dr Bill Maples, and Dr Stan Rhine, respectively) established strong bonds with the local medical examiner offices and worked closely with the forensic pathologists in those offices on a large range of cases, including cases involving skeletal trauma. Over time in those offices it became protocol for the forensic anthropologist to consult on most cases involving skeletal trauma, whether the case was a skeleton or a fresh body. This was certainly the case for Dr Birkby at the University of Arizona, where he averaged 100 cases a year during the 1980s and 1990s, with many of those cases involving the analysis of skeletal trauma.

During this period, the earliest publications on trauma by forensic anthropologists are case-study-based (e.g., Kerley 1976, 1978; Maples 1986; Maples et al. 1989). But beginning in the late 1980s systematic skeletal trauma research began to take shape in forensic anthropology, pioneered by the work of Hugh Berryman, Steve Symes, and O.C. Smith and colleagues (based on a collaboration of forensic pathologists and forensic anthropologists in the medical examiner's office in Memphis, TN). Spurred on by their casework at Memphis, Berryman and Symes published the landmark 1998 book chapter titled "Recognizing gunshot and blunt cranial trauma through fracture interpretation" (Berryman and Symes 1998). Based on their overall contributions that helped to establish the analysis of trauma in forensic anthropology, we see the late 1980s and 1990s as the Berryman–Symes era.

On the heels of the first wave of research on skeletal trauma came the first major volume dealing with blunt-force skeletal trauma, the book *Broken Bones: Anthropological Analysis of Blunt Force Trauma* (1999) edited by Alison Galloway. This publication, often referred to as the "bible" of BFT, is an essential reference on the fundamentals of BFT description and interpretation, including fracture biomechanics, fracture patterns, and the various circumstances of BFT.

Today, with the increase in graduate programs focusing on forensic anthropology and increasing collaborations between forensic anthropologists, forensic pathologists, and biomechanical engineers, the analysis of skeletal trauma by the forensic anthropologist has become an accepted practice in many jurisdictions. An outcome of the early research by Berryman, Symes, and Smith is the current framework that most forensic anthropologists use when identifying the mechanism of perimortem skeletal trauma, classifying trauma into these categories: blunt force, projectile, sharp force, and thermal. This medicolegal classification scheme of skeletal trauma uses biomechanical, pathological, and anthropological principles to classify causes of bony fracture. This is also the framework used in the SWGANTH draft guidelines on trauma analysis (SWGANTH 2011).

The trend of increasing research and education in skeletal trauma is clearly displayed in a review of past issues of *Journal of Forensic Sciences* (1972–2009). There is a large increase in articles involving BFT and projectile trauma research beginning in the early 1990s, with trauma research diversifying as time goes on. Over the years, research on BFT was almost always the leading type of trauma. Additionally, there is an obvious increase in trauma research by students in relation to PhDs. There is also an increase in experimental versus actualistic (case) studies, accompanied by a large increase in nonhuman models for bone trauma research. These same trends are found in surveys of abstracts from proceedings of annual meetings of the American Academy of Forensic Scientists.

RESEARCH IN BFT

The history of BFT research in forensic anthropology is a confusing issue, mainly because the first experimental researchers were not forensic anthropologists, but multidisciplinary teams of engineers led by the neurosurgeon and anatomist E.S. Gurdjian, beginning in the 1940s (Gurdjian 1975; see also Kroman 2003). Gurdjian and colleagues published numerous manuscripts on the subject of blunt-force cranial trauma generated from human cadaver experiments (summarized in Gurdjian 1975). Gurdjian and colleague’s theories were largely based on experimental research using the “stress-coat technique,” which involved preparation of cranial bones and the application of a brittle lacquer, which would fracture under their loading conditions. Among this productive team’s conclusions were that there were no biomechanical differences between dry, fresh, and living bone, and that fractures initiate away from the point of impact in areas of outbending and then propagate back towards the impact site (Gurdjian 1975). These studies were quite groundbreaking in scale, as well as documentation and scientific rigor, and they still set the standard for experimental trauma research today.

Another avenue of bone trauma research involves the application of biomechanics to either known trauma cases (e.g., Fenton et al. 2003), or fracture initiation or propagation experimentation (e.g., Gurdjian 1975; Kroman 2007; Baumer et al. 2010). These studies often have a more theoretical focus and attempt to explain larger questions (i.e., *bone fractures like this because…*; not, *bone will tend to fracture like this* *in this scenario…*). However, this experimental research is also problematic for various reasons, one of the greatest obstacles being the fact that human skeletal tissue is difficult to obtain without a high price tag and animal models do not easily correlate to human morphology. Further, these highly controlled laboratory experiments generate large amounts of data which often do not recreate observed circumstances of human fracture patterns, the greatest example being the Gurdjian versus Kroman debate (see Kroman 2003 for a full discussion).

As forensic anthropologists began to be employed in medical examiner's offices, forensic blunt trauma cases with known circumstances did not appear to agree with the Gurdjian finding of fracture initiation in areas away from the point of impact (Berryman and Symes 1998). Kroman and colleagues retested the Gurdjian theories using adult human cadaver heads and found fractures initiating at the site of impact (in this case, the center of the parietal), and propagating away from this area (Kroman 2004, 2007).

While Gurdjian found no differences in fracture production between fresh and dry bone, the utility of rehydrating bone and testing it assuming "fresh" conditions is questionable (Rappazzo 2006) attempted to rehydrate nonhuman ribs in a saline solution in order to examine differences in fresh-fractured versus rehydrated-fractured bones. Here the rehydrated bones all fractured in atypical patterns; however, another study by Daegling et al. (2008) applied a similar method with more encouraging results.

While most methods developed to generate the components of the biological profile of an unknown individual involve statistical evaluations of their reliability as required by the Daubert criteria (*Daubert v. Merrell Dow Pharmaceuticals* 1993), research on skeletal trauma is still in its infancy. Although some work has been done attempting to generate statistics in order to back up autopsy observations of trauma (e.g., Hart 2005; Love and Symes 2004; Quatrehomme and İşcan 1999; Tomczack and Buikstra 1999), large sample sizes of known trauma cases are only starting to be compiled (Fenton et al. 2011; Kimmerle et al. 2009). Further, these observational studies are more difficult to analyze, as there are many independent variables that must be indirectly approached by the practitioner unless circumstances of injury are known. This observational research, while exceedingly important, tends to generate qualitative results, which are helpful only to match patterns of trauma, not to explain the how and why of the resulting fracture patterns.

BFT Research Using Nonhuman Animal Models

Recent experimental blunt-force research using infant porcine skulls (*Sus scrofa*) was carried out by a team of scientists from Michigan State University consisting of forensic anthropologists and biomechanical engineers. This research used infant porcine crania (specifically the parietal) as a nonhuman model for testing both material properties and fracture patterns. The results suggest that infant pig cranial material properties are similar to those of infant humans (Baumer et al. 2009; Coats and Margulies 2006; Margulies and Thibault 2000). These results are limited, however, because, as seen in bony measurements acquired from human infant computed tomography (CT) scans and comparable gross bony measurements of the porcine crania, cranial shape differs significantly as age increases; thus the infant porcine skull may only be comparable up to human infants aged to about 22 days (Baumer et al. 2010).

A primary goal of the Michigan State team was to establish baseline data on fracture initiation and propagation from experimental impacts with a flat surface to the center of the parietal. There were several significant findings using the immature porcine animal model. First, fracture initiation consistently occurred away from the site of impact at the surrounding suture margins and propagated back toward the site of impact (Baumer et al. 2010). Second, a single impact commonly produced two or more separate fractures away from the site of impact. Third, with increased energy, more fractures (in terms of overall fracture length) are produced. Fourth, for a given impact site, fractures occur at common locations across individuals of the same age and interface. Fifth, blunt-force impacts from rigid and compliant interfaces display different amounts of fracturing that change with age. And sixth, analysis of material properties of the developing porcine cranial vault suggests an age correlation of days in the pig to months in the human infant.

It is currently unclear how these data correlate to human infants, as both age and geometry (gross head shape) are key variables in the mechanism and pattern of bony fracture. This is, however, an important baseline in the experimental study of fracture patterns, which will only grow with the acquisition of infant human tissue for experimental research. Other research utilizing an animal model includes Marceau (2007), who examined the cortical density and cross-sectional geometry of human (*Homo sapiens*), pig (*S. scrofa*), and deer (*O. virginianus* and *Odocoileus hemionus*) long bones. Marceau concluded that "both deer and pig skeletons can serve as suitable models in forensic experiments based on their geometric and densitometric similarities to human bone" (Marceau 2007: 63). Interestingly, Marceau then compared taphonomic weathering characteristics of each species and found differences in the patterns of deer and pigs, with deer long bones acting in a way more similar to human bone. This example of using a nonhuman model is quite pertinent as nonhuman models are the norm in experimental trauma and taphonomic research due to the many problems of acquiring human tissue for destructive purposes.

Calce and Rogers (2007) attempted to examine the affects of taphonomy when interpreting blunt-force impacts to juvenile pig heads (juveniles because they were livestock animals and were thus slaughtered before they reached maturity). Ten pig heads were used, five of which were defleshed prior to impacting and exposure. All the specimens were then "impacted" using a hammer on the right and left parietals until the ectocranial surface was "perforated," or assumed perforated in the case of the fleshed specimens. The heads were then exposed for 52 weeks in different microenvironments, but within the same enclosure in southern Ontario, Canada. Unfortunately the taphonomic variables in this study are hardly quantified, and it is unclear how certain variables such as freeze–thaw cycles were differentiated from others like presence or weight of rain or snow (variables that are very interdependent). More problematic is the fact that the authors claim that freeze–thaw cycles and soil erosion have the ability to "completely obliterate" evidence of BFT after an exposure period of 52 weeks (Calce and Rogers 2007: 522, 524). Other research into freeze–thaw cycles and cryoturbation using deer long bones (*O. virginianus*) found that bone will exhibit taphonomic weathering patterns only *after* it has passed from the wet to dry state, thus making it possible to differentiate between perimortem trauma and postmortem damage even after 52 weeks of exposure (Passalacqua and Rainwater 2006). In addition, Herrmann and Bennett (1999) were able to discern BFT after severe burning of porcine remains in a majority of their cases with only partial recoveries, and Symes et al. (2008) were able to distinguish perimortem blunt-force fractures from postmortem thermal damage in forensic cases, demonstrating that bone will retain characteristics of BFT even after the thermal alterations of calcification and fragmentation.

Other research has focused on artificial models of infant and adult human crania with limited success. A full-body infant model of a 1.5-year-old was developed by Coats and Margulies (2008) and demonstrated similar data to previous impact experiments; however, the correlation of impact load to fracture initiation and propagation has yet to be made. Similarly Desantis et al. (2002) and Roth et al. (2007, 2008) have also failed to successfully build a computational model that can be used as a substitute for human crania.

LOOKING TO THE FUTURE

Skeletal trauma analysis is one of the most challenging tasks confronting the forensic anthropologist. Looking back, it becomes apparent that the field of forensic anthropology emerged with the need for bone specialists in the medicolegal field. As forensic anthropology casework progressed, deficiencies in knowledge regarding bone trauma began to be filled first by actualistic case studies, then by experimental research, verifying and refining earlier work. These same themes continue today. As we encounter more trauma cases and increase our knowledge of bone biomechanics, we are constantly looking to refine our ability to make confident statements about the mechanisms of injury and contribute to the cause of death via the skeletal remains. Current research demonstrates that while we know more about BFT to the human skeleton than ever before, we are still confronted by many challenges that require extensive additional research. Finally, it is our charge to further the field of forensic anthropology by developing collections, references, standards, and practices for analyzing skeletal trauma, and that we do so through scientific rigor and validation built upon actualistic data and not via post hoc assumptions or untested models. We have to move beyond our reliance on experience as the only way to inform us in the analysis of trauma, and develop a strategy for the future of trauma analysis in order to advance our abilities in this area. We need new directions in trauma interpretation to include further experimental work in which fracture patterns are better understood and thus utilized for future trauma interpretation. What we are suggesting is a paradigm shift in how we approach skeletal trauma analysis: moving toward a science of trauma that involves the testing of hypotheses and the establishment of baseline parameters on how bones break in numerous scenarios. We are convinced this paradigm shift needs to include scientists from outside of forensic anthropology, such as biomechanical engineers, and computer learning experts. We also need validation where we set up systematic tests to validate our techniques in trauma analysis.

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