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REVIEW ARTICLE

Blunt Force Skeletal Trauma Research Methods
A Multidisciplinary Perspective

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ABSTRACT: A key component of the forensic anthropological examination is skeletal trauma analysis, which accounts for the majority of forensic anthropologists' expert testimonies. However, a major gap in the current knowledge surrounding skeletal trauma has been identified, specifically the data necessary to conduct comprehensive bone trauma analysis with established error rates are lacking. Current methods and standards of skeletal blunt force trauma analysis rarely meet Daubert guidelines that require: (1) validated studies, (2) peer review, (3) known or potential error rate, and (4) general acceptance, nor do they provide data or analyses that are comprehensible to the medicolegal community and the general public. Therefore, a multidisciplinary approach with a biomechanical emphasis is critical to improve the validity of skeletal trauma analysis and interpretation through precise, accurate, and repeatable analytical methods. The objectives of this review are to: (1) provide an overview of current approaches to blunt force skeletal trauma research across disciplines while highlighting the applications, strengths, and limitations of these methods, and (2) address gaps in discipline-specific methodologies to emphasize the importance of multidisciplinary scientific teams for improvement of skeletal trauma research. This review highlights the need for large-scale controlled experimental bone trauma studies utilizing human specimens and the various methodologies available for further skeletal trauma research.

KEYWORDS: forensic anthropology, experimental research, engineering, fracture research

Interpretations of skeletal trauma are one of the most important aspects of the forensic anthropological analysis and are critical for rigorous, scientific medicolegal testimony, the majority of which is related to skeletal trauma (Blau 2016; Christensen & Passalacqua 2018; Crowder et al. 2016; Dempsey & Blau 2020; Hulse et al. 2019; Kroman & Symes 2013; Lesciotto 2015; Murray & Anderson 2007; Simon et al. 2022; Symes et al. 2012; Ubelaker 2018). However, a major gap in the current knowledge surrounding skeletal trauma has been identified (OSAC 2016). Specifically, the methods are lacking to conduct comprehensive bone trauma analysis, and subsequently the data are often inadequate to statistically substantiate interpretations. As a response to fill the current gap in knowledge, forensic anthropologists are urged to incorporate biomechanical principles into their blunt force trauma injury analysis (Christensen et al. 2014; Love & Christensen, 2018; Passalacqua & Fenton 2012; Symes et al. 2012; Zephro & Galloway 2014); however, this is challenging, because understanding of complex bone biomechanics is generally lacking within the field of forensic anthropology (Symes et al. 2012). The standards outlined in the Trauma Analysis document of the Scientific Working Group for Forensic Anthropology (SWGANTH) highlight that "analysis of skeletal trauma should involve careful observation and thorough documentation, and interpretations should be based on scientifically valid methods and principles" (SWGANTH 2011). While the 2021 AAFS Standards Board (ASB) Standard for Analyzing Skeletal Trauma in Forensic Anthropology (ASB Standard 147, First Edition 2021) modified by peers and the committee is still under review, the draft version available at the time of this article's publication states that a distinction needs to be made between description and interpretation of skeletal trauma, and interpretation should be limited to instances where the findings are clearly supported by the evidence. Many of the current methods and standards utilized in skeletal blunt force trauma analysis may not explicitly meet *Daubert* guidelines that require: (1) validated studies, (2) peer review, (3) known or potential error rate, and (4) general acceptance (*Daubert v. Merrell Dow Pharmaceuticals* 1993), nor do they always provide data or analyses that are comprehensible to the medicolegal community and the general public. While *Daubert* standards are not utilized across all states, the National Institute of Justice considers

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these guidelines rules of evidence that must be considered when admitting scientific testimony. Regardless, the premise on which they are established (i.e., heavy reliance on rigor in conducting science) should be embraced by all scientists. Since the aim of skeletal trauma analysis is to offer professional, scientific interpretations that contribute to establishing the circumstances of death and any other forensically relevant questions (SWGANTH 2011), a multidisciplinary approach may offer opportunities for improvements in necessary objectivity and applicability. The analysis of skeletal trauma "requires the application of elements of physics, biomechanics, material engineering, ballistics, taphonomy, anatomy, and osteology" (SWGANTH 2011). Therefore, a multidisciplinary approach with a biomechanical emphasis is critical to improve the validity of skeletal trauma analysis and interpretation through precise, accurate, and repeatable analytical methods.

The intention of this manuscript is to provide a review of skeletal trauma research methods, specifically with a focus in forensic anthropology, to prompt discussion of how to improve research within our community. This review is designed to examine various skeletal trauma research methods across scientific fields, highlighting applications, strengths, and limitations, and to identify precise and accurate protocols for experimental research. Furthermore, it aims to address gaps in discipline-specific methodologies to emphasize the importance of multidisciplinary scientific teams for improvement of skeletal trauma research.

Paradigms

Skeletal trauma, specifically blunt force trauma, is studied using various methods across scientific fields. The overarching goal of each discipline is to investigate and understand fractures, yet the questions addressed in the specific fields and their general knowledge base differ. Symes et al. (2012, p. 343) describe a component of this dilemma: "Medical and anthropology experts often rely on summarizing the work of engineers as a means to explain the biomechanics of bone injury. However, forensic anthropologists differ from biomechanical engineers with respect to how bone trauma is described and explained. This is primarily due to the different contexts in which they observe traumatic fractures." Engineering, and specifically the field of injury biomechanics, utilizes systematic experimental methods. This approach to the design of the experiment, instrumentation, and data collection provides an excellent model of how to conduct trauma research, but is rarely attempted—or applied—in forensic anthropology contexts, likely because of its level of complexity and significant cost. Similarly, engineers are rarely trained in anatomy or skeletal biology and often do not have a comprehensive understanding of bone tissue, growth, senescence, and dynamic physiological processes that influence skeletal form and function. Likewise, the use of medical/clinical methodology is often disregarded in forensic anthropology trauma research due to differences in objectives and applications: to aid in treatment with little regard as to how the injury occurred. However, the medical field has produced valuable fracture classification and injury severity scoring systems that allow transdisciplinary use and comparisons through standardization of terminology. A paradigm combining expertise across all three fields would improve outcomes for trauma analysis.

Multidisciplinary Paradigm

A multidisciplinary paradigm is not simply borrowing aspects from different fields but instead provides a model that incorporates experts, including, but not limited to, engineers, anthropologists, anatomists, pathologists, physicians, computer modelers, and others, theories, methods, and analyses from across disciplines into one comprehensive scientific foundation. A multidisciplinary approach to skeletal trauma research does not address a specific forensic anthropology or engineering question but brings together a team to develop a research design, methods, data collection, and analysis that contributes to novel questions with applications across fields. This skeletal trauma research model is intended to encourage junior scholars and practitioners to take a broad approach to problem solving by embracing the multidisciplinary paradigm through more inclusive collaborations and integrated discussions to address questions across scientific fields.

Skeletal trauma interpretation has become an accepted forensic anthropological practice in the medicolegal community because of an "increase in graduate programs focusing on forensic anthropology and increasing collaborations between forensic anthropologists, forensic pathologists, and biomechanical engineers" (Passalacqua & Fenton 2012, p. 405). A multidisciplinary approach to skeletal trauma research should be more than a simple collaboration; it is an alteration to traditional discipline-centric methods and a path to an increased understanding of how bones fracture and the variables contributing to fracture behavior and characteristics. By disregarding the breadth of information and specialists researching different components of trauma analysis, or the multidisciplinary nature of a scientifically sound experimental research design, there will be persistent shortcomings that ultimately prevent a substantiated interpretation or full understanding of the causation of skeletal injuries. To understand the applications and limitations of current skeletal blunt force trauma research paradigms, methodologies in forensic anthropology, injury biomechanics, and medical disciplines are further examined here.

Forensic Anthropology Methodologies

The infrastructure of forensic anthropological skeletal trauma analysis has been examined through an exploration of foundational, interpretive, and methodological components (Berryman et al. 2018). The classic objective of skeletal trauma analysis is to use fracture characteristics or patterns observed on skeletal remains as interpretive tools to reconstruct traumatic events (Love & Symes 2004). Skeletal trauma analysis in forensic anthropology has largely been descriptive, with little or no interpretation; this is due to a lack of scientific data linking observed fracture characteristics to validated experimental trauma research identifying fracture mechanics. It is no longer sufficient to describe fracture patterns to infer how injuries occur (e.g., Ubelaker 2019). Forensic anthropologists must go beyond descriptions of skeletal trauma in order to identify quantifiable contributors to differential fracture characteristics (Blau 2016; Love & Christensen 2018). However, fracture mechanism, propagation, and the data required to interpret the loading mechanism have not been fully explored and are currently not well understood (Pechnikova et al. 2015). This gap in knowledge has led anthropologists to rely on a combination of prior experiences, casework, and experimental anthropological trauma research (e.g., Semeraro et al. 2012) to analyze and interpret skeletal trauma. While improvements have been made to incorporate principles of bone biomechanics and to consult with bioengineers to improve skeletal trauma research methods, efforts should continue to be made in this area.

The most common forensic anthropological approach to trauma interpretation is to reverse engineer, or to observe the injury and then re-create the traumatic event. This approach often comes in the form of case studies (Passalacqua & Rainwater 2015). Case studies offer useful insight into realistic, as well as extreme, scenarios, but they can be difficult for substantiating trauma interpretation and are rarely applicable to future forensic casework. On the other hand, forward engineering, where experiments are conducted with tightly controlled variables, provides an unequivocal link between observed skeletal trauma and resulting mechanical interpretation that case studies alone cannot provide. The challenge with such experiments is in ensuring they result in realistic injuries from actual injury scenarios. Advancements in trauma interpretation must originate from expertly conducted experimental research on large sample sizes that reflect representative variation in the human population. This approach is necessary in order to provide quantifiable methods to support expert testimonies and ultimately lead to a reconstruction of the traumatic event with the highest accuracy and precision. Reconstructing death events requires an understanding of the mechanisms behind fracture production and typical expressions of trauma patterns (Baraybar & Gasior 2006; Marinho & Cardoso 2016).

Case Studies and Retrospective Methods. Historically, case studies have been the primary source for documenting skeletal trauma, highlighting unique cases, identifying inadequacies in past methodologies, and assessing the applicability of new methods, and are often the basis for skeletal trauma research (Crudele et al. 2020; Dempsey et al. 2018; Love & Symes 2004; Passalacqua & Rainwater 2015). Case studies can provide useful documentation of skeletal trauma that may not have comparable experimental research and can offer valuable training for students and professionals. Additionally, case studies are critical for identifying and influencing future skeletal trauma research (Passalacqua & Rainwater 2015; Semeraro et al. 2012; Wedel et al. 2014). The benefit of case studies in the development of skeletal trauma analyses is demonstrated by Love and Christensen (2018). The authors conducted a case study review to validate the applicability of bone fractography analysis (examination of fracture surfaces to identify variables associated with specific fracture characteristics) for forensic casework and were successful in identifying the direction of fracture propagation in the four cases reviewed (Love & Christensen 2018). Another positive capability of case-based skeletal trauma research is the investigation of trends among a group or population or evaluation of aspects of injuries with substantiated information (e.g., confirming the interpretation of the skeletal trauma through video data of the event) (Kroman et al. 2011). Hulse et al. (2018) identified trends in skeletal trauma through a retrospective case study conducted in collaboration with the Washoe County Regional Medical Examiner's Office. The authors observed trends in location of trauma between the sexes and populations (White, Black, and Hispanic) (Hulse et al. 2018), which contributed valuable data applicable to the field of forensic anthropology and relevant for both practitioners and academics.

Because of the inherent retrospective approach in case-based research and lack of specific circumstances regarding the traumatic event, case-based analyses are often dependent upon knowledge gained through experience, intuition, and other contributors/specialists; instead of validated research *in conjunction with experience* (Berryman et al. 2018; Kroman & Symes 2013). Experience in skeletal trauma analysis is highly valued and critically important for an accurate interpretation of skeletal trauma (Passalacqua & Rainwater 2015). While experience and training are crucial, neither typically includes experimental trauma research data to validate the conclusions of skeletal trauma analyses. This is not to say that experience is not valuable; however, observing hundreds of cases of the same type of injury does not support interpretation of the mechanism of the injury (Porta 2005), which may often remain unknown. Several studies have demonstrated that the same mechanism can result in different injuries and vice versa (Harden et al. 2022a, 2022b).

Descriptive methodologies have enabled forensic anthropologists to contribute to the determination of cause and manner of death by providing important basic information and qualitative fracture pattern data in real casework. Controlled experimental skeletal trauma studies provide the "baseline data necessary to link biomechanical factors with fracture outcomes" (Kroman & Symes 2013; Semeraro et al. 2012; Ubelaker 2019, p. 236). More cohesive integration of these two approaches (case studies and experimental studies) has the potential to improve skeletal trauma analysis.

Experimental Methods. Skeletal trauma research has traditionally been associated with physics, biomedical engineering, and injury biomechanics (Berryman et al. 2018). The adoption of biomechanical principles and an engineering approach for forensic anthropological applications have recently led to increased collaborations with engineers in experimental skeletal trauma research; however, the utilization of a multidisciplinary team is not the current standard within forensic anthropology. Experimental methods are typically utilized to validate assumptions or support interpretations based on experience and/or case studies. Generally, forensic anthropological experimental methods are designed to re-create a specific traumatic event. While the goals of these studies are attainable in experimental studies, the data collected generally do not meet the standards of courtroom testimony because of methodological limitations, such as the use of nonhuman samples, small sample sizes, lack of instrumentation and data collection, and lack of biomechanical expertise.

In forensic anthropology, experimental skeletal trauma research has often been conducted using nonhuman specimens because of the difficulty of obtaining human specimens (monetary, practical, and ethical) (Christensen et al. 2012; DeLand et al. 2012; Dempsey et al. 2018; Dempsey & Blau 2020; Kulin et al. 2011; Passalacqua & Fenton 2012; Reber & Simmons 2015; Zephro et al. 2014). At present, it is unknown how intrinsic variation in human bone properties contributes to fracture pattern variance, let alone how to address variation inherent to other species. Utilizing nonhuman proxies may confound explanations of inter-individual variation and the applicability of these data to human bone fracture patterns because of the fundamental differences in human and nonhuman bone morphology and microstructure (Christensen et al. 2018; Hillier 2007; Kulin et al. 2011; Dempsey & Blau 2020; Zephro et al. 2014). For example, Wang et al. (1998) found significant differences in the fracture properties among species when studying the structural and material properties of humans, baboons, canines, bovines, and rabbits. Additionally, Franck and Franck (2016) detail significant differences in ultimate tensile strength in wet compact bone between human and various animal bone models horse, cattle, wild boar, pigs, and deer. Thus, utilizing nonhuman bone, which does not easily correlate to human structure (Passalacqua & Fenton 2012), in experimental studies is not recommended. Nonhuman bone studies are ideal to provide proof of concept or to perfect repeatability in experimental boundary conditions. However, human tissue should be utilized in experiments meant to strengthen interpretations of *human* skeletal trauma and to establish forensic significance (Dempsey & Blau 2020). Human tissue is the gold standard for experimental skeletal trauma research, and this standard should be upheld as the field continues to develop (Kroman & Symes 2013).

The four primary factors that affect the power of a statistical test are α level, difference between group means, variability among subjects, and sample size (e.g., Norton & Strube 2001). Small sample sizes reduce the power of a study and increase the margin of error, subsequently increasing the inability to detect an effect of the observed outcomes (i.e., fracture characteristics) and the likelihood of Type II errors. Daegling et al. (2008) conducted informative experimental research utilizing human ribs to investigate local deformations, failure location, and mode of fracture for forensic anthropology applications. However, the small sample size ($n = 8$), in addition to the lack of sample information (demographic and rib level data), prohibited comparisons and therefore was unable to yield statistical output to support the application of their conclusions to broader skeletal trauma interpretations. Another example of sample size limiting further application in the field is Isa et al. (2018), who assessed the impact direction in human femora through experimental three-point bending. Notably, the impact direction was accurately interpreted for the entire sample, yet the small sample size ($n = 13$) did not allow for statistically valid results or error rates associated with the research design. A third example of the effects of small sample sizes comes from a relatively new and promising method in skeletal trauma analysis: forensic fractography, which is the analysis of the fracture surfaces of bone (Christensen et al. 2018). This method was developed using a small sample of human femora ($n = 12$), which the authors note may have contributed to observed correlations between variables (Christensen et al. 2018). Experimental studies with small sample sizes contribute valuable knowledge to the field and can provide pilot data to inform a larger experimental design, but they often lack the statistical power necessary to develop error rates and therefore strengthen interpretations of skeletal trauma.

Experimental research conducted with forensic anthropological leads tends not to incorporate the extensive instrumentation utilized in experimental research conducted with engineering leads, since the research goals between the two likely differ. While this may not be relevant in observing simple fracture characteristics, the associated lack of data likely results in the inability to answer *how* or *why* fractures are initiating, propagating, or what is contributing to the variation observed. Therefore, the actual fracture mechanism remains elusive (Porta 2005). Isa et al. (2019) conducted experimental skeletal trauma research to examine fracture initiation in blunt impacts to human crania. The experimental design included the utilization of a force transducer to record the impact force-time response, but no instrumentation was applied to capture the bony response. Additional instrumentation such as strain gages on skeletal elements can provide data to quantitatively validate fracture initiation captured in the high-speed video data (Stark et al. 2019). Scheirs et al. (2018) utilized an experimental approach to examine blunt force fracture patterns in human ribs. The authors loaded anterolateral samples of fresh ($n = 18$) and dry ($n = 12$) four–six level ribs in three-point bending scenarios to inflict "slow and fast loading trauma" (Scheirs et al. 2018). The loading mechanism was controlled via a servo-hydraulic testing machine, but the ribs were not instrumented and therefore the fracture timing and strain mode(s) experienced by each rib could not be evaluated. Previous research demonstrated that fracture timing is significantly different between data collection methods and determined that strain gages were more accurate in determining fracture timing versus high-speed video data alone (Harden et al. 2020). Additionally, Harden et al. (2020) observed differences in failure mode in human ribs loaded to failure in the same loading conditions, demonstrating that strain mode should be directly measured and not assumed. While quantitative data collection was lacking, the qualitative data allowed Scheirs et al. (2018) to identify distinct characteristics that may contribute to the determination of perimortem trauma in human ribs. This methodological decision aligns with data historically collected in forensic anthropological skeletal trauma research, which is generally qualitative (i.e., fracture descriptions), not quantitative (i.e., output force or displacement).

Forensic anthropologists are urged to continue exploring and expanding the scientific infrastructure of trauma interpretation through experimental research and education, thus increasing our understanding of bony response, fracture characteristics, and linking these data back to traumatic events (Passalacqua & Fenton 2012; Wedel et al. 2014). As emphasized by Ubelaker (2019), forensic anthropologists are expected to go beyond the description and classification of fractures and explain failure strain modes (i.e., tension and/or compression) in order to interpret how fractures occurred. He states, "While description of the alterations is important, interpretation hinges on the understanding of bone strength, force, stress, tension, compression, load, strain, failure, deformation, fatigue, and other related factors" (Ubelaker 2019, p. 236). It is also recognized—and a point of concern—that over-interpretation is a problem in skeletal trauma analysis (Symes et al. 2012; Ubelaker 2018). This has led to the continued borrowing of basic engineering principles and assumptions to analyze skeletal trauma (Berryman et al. 2018; Isa et al. 2018). The increased push to incorporate engineering principles into forensic anthropology has sometimes resulted in general acceptance of broad concepts and statements, such as "bone fails first in tension" (Berryman et al. 2018; Blau 2016), that continue to prevail across scientific fields, but may be inaccurate in some skeletal elements and loading conditions. Harden et al. (2020) established through experimental research of human ribs loaded in the same anterior-posterior direction at two m/s that variation existed in the mode (e.g., tension or compression) of initial failure. This research highlights the issues and potential errors of utilizing general assumptions and demonstrates the need for further exploration of the validity of such assumptions (Harden et al. 2020). In order to properly utilize biomechanical principles, they must be fully understood, along with their inherent limitations. In general, this is not common knowledge that the typical forensic anthropologist obtains in academic or even specialized training, or through general experience; rather, it must be specifically sought out or be gained through extensive experience. The stagnant advancement of simultaneous developments in academia, research, and practice in forensic anthropology may be associated with the lack of emphasis on multidisciplinary collaborations (L'Abbe et al. 2019). To analyze and interpret fracture characteristics, observation and description must be coupled with a strong understanding of relevant biomechanical factors (Ubelaker 2019).

Engineering Methodologies

In engineering, materials are classified by their mechanical response to an applied load; this is also the standard approach for classifying biological materials, such as bone (King 2015). As a subfield of mechanical engineering, injury biomechanics investigates the relationships between physical mechanical properties and human injury to evaluate both the injury mechanisms and thresholds for the human body (Committee on Trauma Research 1985; King 2015). The overarching goal of injury biomechanics is usually to determine the responses to impact loading for civilian (e.g., motor vehicle crashes, vehicle vs. pedestrian crashes, or sport injuries) and military (e.g., blast events or ejection seat events) applications (Bolte et al. 2018; Danelson et al. 2015; Untaroiu et al. 2007; Yoganandan et al. 2014). Therefore, injury biomechanics relates data from experimental research such as fracture mechanics, bony response and failure, and injury criteria to real-world injuries to contribute to developing anthropomorphic test devices (ATD) and computational human body models (HBM) (Agnew et al. 2015; Agnew et al. 2018; Gabler et al. 2015; Kress & Porta 2001; Murach et al. 2017; Schafman et al. 2016; Untaroiu et al. 2008). Unlike in forensic anthropology, where the analysis begins with the skeletal trauma, in injury biomechanics the analysis begins with an experimental test setup and should result in injuries consistent with those found in real-world occurrences. A substantial underlying limitation of classic biomechanical principles is that they were not developed for osteological material and therefore cannot provide *direct* applications to predict and understand the bony response. However, a forensic anthropologist can strengthen injury biomechanics interpretations by contributing their expertise in skeletal anatomy and biology.

Experimental Methods and Design. The experimental method must replicate traumatic events or result in injuries comparable to real-world data and injuries in order to be applicable and significant. As Hardy (2002, p. 12) states: "After a problem has been identified and adequately characterized, the researcher must create a representative and repeatable test event, measure the appropriate parameters, and analyze the measurements such that meaningful conclusions may be drawn." Experimental methods provide the unique opportunity to determine injury mechanisms as the loading scenario is known, and both mechanical and biological data can be collected. The success of experimental research is contingent upon sample selection and astute experimental design (Hardy 2002).

When designing a research study, engineers utilize databases (e.g., Crash Injury Research and Engineering Network [CIREN], National Trauma Data Bank [NTDB]) and compiled injury or traumatic event data (e.g., Special Crash Investigations [SCI], The National Automotive Sampling System/Crashworthiness Data System [NASS/CDS]) to develop an epidemiological study of the real-world injuries and scenarios of the previously identified problem to create a relevant experimental design. While this may appear similar to the case-study approach in forensic anthropology, these epidemiological studies reference data from thousands of similar cases with similar injuries to inform on the experimental design and to provide expected outcomes based on large-scale, real-world data across populations. In most cases, forensic anthropologists are working with a small sample of case studies with unknown injury mechanisms. Prior to evaluating the necessary sample, it must first be determined whether the research design calls for component (single element) or whole-body testing. The underlying limitation for all experimental research using postmortem human subjects (PMHS) is they are not living humans and do not have muscle response or exhibit any other living physiological functions. However, the utilization of PMHS provides more realistic results than nonhuman models do and are as comparable as possible to an injurious real-world scenario in living humans. Whole body tests enable the researcher to account for variables such as body mass and inertia, while component tests are more controlled and therefore generally even more repeatable. Whether component or whole-body tests are performed depends on the specific research questions identified in the research design.

Once the sample type (component vs. whole body) has been determined, each potential PMHS is reviewed using inclusion and exclusion criteria, which are developed based on each project's requirements. Inclusion criteria, utilized as a prescreening method to determine whether a PMHS is appropriate for a specific project, are often dictated by sex, age, height, and weight ranges. Once a PMHS has met the inclusion criteria, exclusion criteria are explored via imaging methodologies (e.g., computed tomography, dual-energy X-ray absorptiometry [DXA], and X-ray) to ensure no previous skeletal trauma is present and there are no observed anatomical anomalies or pathological conditions that would interfere with the experimental test results. While these criteria allow for the development of a controlled sample, they also exist as limitations to the study, especially in a small sample. Specific inclusion/exclusion criteria and population-focused research (e.g., average-sized male based on weight and height in a given population) often result in small sample sizes, specifically in whole-body research, which can result in a lack of statistical power. The data and results collected are also limited to the specific population represented and cannot be universally applied to a broader population. For example, data collected from a mid-sized male in a frontal crash scenario would likely not be appropriate for informing or predicting the response of a small elderly female in the same loading condition. This ultimately leads to population-specific applications of finite element (FE) models, developed from validated experimental research, and limits the applicability of models across populations. FE models can only predict injuries in the testing scenarios with the exact boundary conditions in which they have been conducted and validated. Once the sample has been determined and the test design (ideally, based on real-world injuries) has been identified, it is necessary to determine which data should be collected. Biomechanical information, such as loading parameters (e.g., input energy and velocity), bony response (e.g., displacement, force, stress, and strain), and the relationships between these variables, are critical to blunt force skeletal trauma research design (Kress & Porta 2001).

Instrumentation, Testing Equipment, and Data Collection. A variety of instrumentation, either selected or custom designed, is utilized in injury biomechanical experimental studies (Hardy 2002). Table 1 summarizes commonly utilized instrumentation.

The type of impacting or loading equipment utilized in experimental research depends upon the loading mechanism the researcher is re-creating. The loading rate is a critical element of experimental research design. In order to conduct realistic experiments, the loading rate in the experiment must replicate the rates observed in real traumatic events. For example, conducting quasi-static loading to examine the effects of a dynamic event does not replicate the real-world

TABLE 1—*Instrumentation and imaging modalities utilized in engineering experimental research.*

Instrumentation or Imaging Type	Measurement Purpose	Experimental Research
Accelerometer	Acceleration	Kang et al. 2011; Bolte IV et al. 2018; Murach et al. 2018
Angular Rate Sensor	Rotational velocity	Danelson et al. 2015; Kang et al. 2015; Cristino et al. 2017
Chestband	Thoracic deflection	Kemper et al. 2016; Kang et al. 2017; Shurtz et al. 2018
High-speed Camera	Displacement	Bolte IV et al. 2003; Kang et al. 2013; Tillis et al. 2020
High-speed X-ray Fluoroscopy	Fracture propagation	Ono et al. 1997; Deng et al. 2000; Hardy et al. 2001
Strain Gage	Strain	Kerrigan et al. 2004; Ebacher et al. 2007; Agnew et al. 2018
Load Cell	Forces and moments	Rudd et al. 2004; Kang et al. 2012; Agnew et al. 2015
Potentiometer	Linear displacement and rotation	Kemper et al. 2011; Schafman et al. 2016; Kang et al. 2021
Motion Capture System (e.g., Vicon)	3D motion	Shaw et al. 2009; Hauschild et al. 2016; Stark et al. 2019

data and will not result in comparable injuries. Bone is viscoelastic, meaning it responds differently to quasi-static and dynamic loading, and it is well established that bone has rate-dependent properties (Hansen et al. 2008; Katzenberger et al. 2020; McElhaney 1966). There are numerous types of testing equipment available in various injury biomechanics laboratories throughout the world. Testing equipment utilized in bioengineering experimental research is dependent upon the loading scenario being replicated and varies between laboratories due to customization of systems. Experimental research utilizing specialized instrumentation and testing equipment provides results comparable to real-world injuries; however, traumatic events are rarely simple or straightforward in terms of loading mechanism and bony response (Love & Christensen 2018). Yet, until fracture characteristics in simplified loading conditions can be statistically linked to specific events, these more complex situations cannot begin to be analyzed and interpreted.

Standard data collected in an injury biomechanics experimental research study on bone include output force (peak and yield), displacement (percent peak and percent yield), linear stiffness, energy (total, plastic, and percent plastic), and strain. Data are collected using the instrumentation described in Table 1 along with a data acquisition system that allows for high rate (over 10,000 Hz) simultaneous collection of data from various types of instrumentation. Additionally, most studies incorporate at least one high-speed video camera to capture the event and provide displacement data (Table 1). These data are then utilized in various statistical analyses, determined in the experimental design, to examine relationships between the intrinsic (e.g., age, sex), extrinsic (e.g., loading rate), and biomechanical (e.g., energy) variables. These results can identify and explain injury mechanisms and provide data for ATD development and computational human body models (HBM) (Agnew et al. 2015; Agnew et al. 2018; Danelson et al. 2015; Murach et al. 2017; Schafman et al. 2016; Untaroiu et al. 2008).

Modeling Methods. Finite element modeling is a technique utilized in injury biomechanics to conduct finite element analysis (FEA) of a specific loading event (Fig. 1). This method is dependent upon the data collected in experimental methods, which are then employed in FE software to evaluate biofidelity. In other words, an HBM can remain the same for each test (unlike PMHS tests, which require a different individual every time an injury is induced), but the researcher has the capability of altering external components such as restraint systems and seat designs. These models have been utilized to aid in the development of vehicle safety designs for both occupants and pedestrians (Beillas et al. 2001; Schuster et al. 2000; Takahasi et al. 2000; Untaroiu et al. 2005; Untaroiu et al. 2007). The applicability of an HBM is contingent upon the validation of the model through experimental research. For example, if the HBM was only validated in a low-speed rear impact scenario, the model is appropriate only for low-speed rear impact simulations. Current expectation of model developers is validation of their model against complementary experimental data, which has aided in improving the scientific rigor and legitimacy of FE models (King 2015).

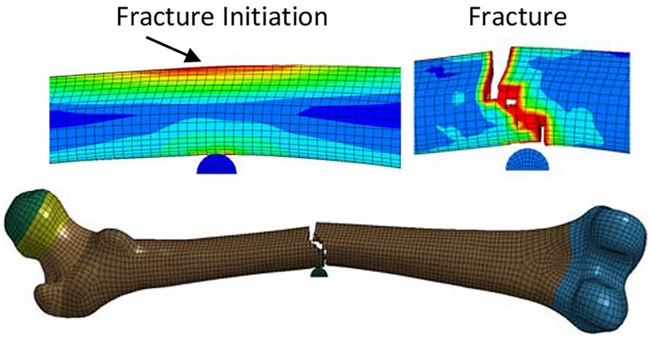

FIG. 1—*Finite element model of three-point bend test simulation. Adapted from Khor et al. (2016). Copyright 2016 by the International Research Council on Biomechanics of Injury.*

Current understanding of injury mechanisms can be advanced through the application of HBMs that incorporate fundamental data, such as validated material properties and failure criteria (Khor et al. 2017). For models to be sophisticated enough to predict injuries, the investigation and validation of their ability to produce realistic responses in a large range of scenarios beyond standard crash configurations, still needs to be examined (Yang & Chou 2015). As more experimental data become available and technological advances in terms of computational power and storage capabilities in computer software develop, models are becoming more complex and exhibit more detail (King 2015). Yang and Chou (2015) state that "future development of a well-validated HBM requires: (1) more material property data on human tissues. These biomaterials exhibit anisotropic behaviors under tensile/compressive loadings, and have time-dependent properties under dynamic impacts, and (2) better experimental testing methods (i.e., reproducible experimental tests) to reduce and/or minimize biological variations at high-speed test conditions." Previous and perhaps current consensus is that researchers in injury biomechanics have more confidence in experimental data than in FE model predictions; however, rapid improvements in computational and mathematical models are resulting in more reliable human responses and injury interpretations (King 2015).

Medical Methodologies

The medical field has provided numerous well-developed and comprehensive fracture classification systems for most skeletal elements (AO Foundation 2019; Bernstein et al. 1997; Kellam et al. 2018; Love et al. 2013); these can be applied to forensic anthropology or injury biomechanics research. The most common of these systems are the AO Foundation/Orthopaedic Trauma Association (AO/OTA) Fracture and Dislocation Compendium and the AO Foundation Craniomaxillofacial (AOCMF) Classifications (AO Foundation 2019; Audige et al. 2014; Cornelius et al. 2014; Di Ieva et al. 2014; Kellam et al. 2018). These systems were designed to overcome the obstacles of non-uniform language and variation in data collection across fields to construct a multistructure fracture classification system using systemic methodology to describe a skeletal injury (Kellam et al. 2018). Standardized definitions and terminology allow for precise and consistent classifications that can be utilized across disciplines. These classification systems are designed to be evolving systems that update and improve based on research, feedback, criticism, and the needs of the medical community (Kellam et al. 2018). Both the AO/OTA and AOCMF classification systems are based on a hierarchical design in which the user determines the level of detail to record for each injury. For example, each classification in the AO/OTA Fracture and Dislocation Compendium (Kellam et al. 2018) begins with identifying the injured element. This is followed by determining the location of the fracture and assigning the fracture to types, groups, and subgroups, then adding in any qualifications and universal modifiers. If at any point the practitioner does not have the additional information, the fracture can be classified with only the data available (e.g., humerus, diaphyseal segment, middle third of humerus, simple fracture). Both the AO/OTA and the AOCMF classification systems provide a mechanism to convert the description into an alphanumeric code, which can be used for data storage, trauma databases, and data coding (AO Foundation 2019; Audige et al. 2014; Cornelius et al. 2014; Di Ieva et al. 2014; Kellam et al. 2018). These fracture classification systems were developed to provide information for assessment and treatment of trauma and inherently lack the level of detail or fracture surface morphology that forensic anthropologists require in order to interpret the loading event from the fracture characteristics. For this reason, the utilization of medical fracture classification systems has been discouraged for forensic anthropological analyses (Galloway et al. 2014).

While the discipline-specific needs for fracture classification and identification of fracture characteristics vary (e.g., broad descriptions in engineering and detailed descriptions in forensic anthropology), a hierarchical approach, similar to the structure of bone, is advantageous across scientific fields. The ability of fracture classification and injury severity systems to support and strengthen skeletal trauma analyses and interpretation is dependent upon the user. If simply used as a description of the observed trauma, these qualitative assessments do not necessarily contribute to the determination of how the injury occurred or address questions about the traumatic event. However, if these systems are used as a research and comparative tool, they can contribute to analyses by providing the frequency and severity of an observed injury.

The Abbreviated Injury Scale (AIS) is an international anatomy based coding dictionary that associates injury descriptions to a severity scale (AAAM 2016). The AIS was originally developed as a standardized system for classifying type and severity of vehicular crash injuries (AAAM 2016) and is commonly used in injury biomechanics. Injuries are coded based on anatomic region, type of anatomical structure, specific nature of injury, and severity level. The AIS is intended for professional and research use, is compatible with large and small scale datasets, and is applicable for detailed and/or limited injury data (AAAM 2016). Kang et al. (2017) employed the abbreviated injury scale to classify skeletal and soft tissue trauma in PMHS from a frontal impact experimental study. The injury assessment and AIS scores allowed the authors to quantify and compare the injury severity between subjects, additionally allowing for the data to be compared to real-world injuries. Unger et al. (2020) utilized the AIS Revision 2015 to predict the number of road users with moderate to serious injuries in Germany and found that the application of AIS allowed for a better understanding of motor vehicle crash occupants and pedestrians injury severity. However, AIS was developed and is intended for use on a living population, which limits the applications for bone trauma and/or PMHS research. When utilized in PMHS injury analyses, AIS scores should be reported as minimum scores (e.g., ≥AIS2) due to the inherent limitations of identifying increased injury severity based on blood loss, neurologic symptoms, presence of air outside of lungs, etc. in a non-living population. Harden et al. (2019) developed an interdisciplinary rib fracture classification system utilizing the hierarchical classification methods of the AO/OTA system, an adaptation of the standard language for rib fractures, and a method of determining severity of trauma based on the AIS (AAAM 2016). The goal of the research was to provide an interdisciplinary, validated, and standardized rib fracture classification system that incorporated both qualitative and quantitative data to allow for both comparable data across disciplines and the detail required for forensic anthropological analyses.

In addition to AIS, there are other injury severity score calculations that assess the maximum severity to an individual or the severity of multiple regions of the body combined. These methods include the Maximum Abbreviated Injury Scale (MAIS), the Injury Severity Score (ISS), and the New Injury Severity Score (NISS). The AIS is utilized in trauma centers across the United States and throughout the world. A limitation to using AIS is that it is recommended to be used by trained and board-certified users to promote proficient, reliable, and consistent injury classifications and injury databases. In order to ensure correct skeletal trauma classifications and injury severity scores, researchers would require additional training and certification or should collaborate with a Certified Abbreviated Injury Scale Specialist (CAISS). Nonetheless, utilizing the same system to capture skeletal trauma provides the opportunity for large-scale trauma comparisons and demonstrates the severity of the injury to both the medicolegal community and the general public when presented in the courtroom.

Discussion

A literature review of abstracts from the American Academy of Forensic Sciences proceedings from 2018 to 2022 was conducted to examine the frequency of experimental blunt-force trauma research utilizing human specimens with contributions from authors across disciplines. During the period reviewed, 121 abstracts featured blunt-force trauma/injuries and of these, nine were experimental studies that included authors from multiple disciplines. Five were from Michigan State University and four were from The Ohio State University. The examples in the discussion section below will focus on research from the Injury Biomechanics Research Center, The Ohio State University.

A multidisciplinary approach to skeletal trauma research supports several of the principles outlined in the AAFS Position Statement (AAFS 2009) in response to the National Academy of Sciences Report *Strengthening Forensic Science in the United States: A Path Forward* (National Research Council 2009), specifically: (1) all forensic science disciplines must have a strong scientific foundation, and (2) forensic science terminology should be standardized. A multidisciplinary approach to experimental skeletal trauma research facilitates the evaluation of relationships between biological and mechanical variables to attempt to explain which factors are contributing to variations in fracture characteristics (Harden et al. 2017; Harden et al. 2019). If researchers continue to utilize an exclusively discipline-focused research design, relationships between force (input and output), strain, and other biomechanical variables will not be explored to their full potential. Without a multidisciplinary method, the characterization of strain modes in blunt force rib trauma would not have been investigated to explore and understand where fractures are initiating and capture the data that demonstrate that it differs from traditional assumptions (Harden et al. 2020).

Single datasets have been utilized to answer research questions across scientific disciplines, albeit rarely. Utilizing methodologies from multiple fields offers the opportunity to explore different gaps of knowledge and discipline-specific questions (Kroman & Symes 2013); however, combining approaches from across scientific fields allows for different research questions to be addressed within one comprehensive study. This is best accomplished if the various applications are included in the experimental design from the start. For example, in Agnew et al. (2018), the aim of the study was to identify biological sources contributing to differential rib mechanical properties. This study explored the effects of demographics (age, sex, body size, and aBMD [areal bone mineral density]) and rib geometry (global and cross-sectional) on human rib structural properties (force, displacement, stiffness, and energy at failure and yield). Utilizing the same dataset as Agnew et al (2018), the aim of Harden et al (2019) was to then validate an interdisciplinary rib fracture classification system. Kang et al. (2021) also used this dataset to generate biomechanical human rib response corridors with respect to age, sex, and body size. A subset of the same dataset was also utilized by Dominguez et al. (2016) to evaluate the influence of intracortical porosity on rib structural properties. The aforementioned research was published in various journals across disciplines including engineering, forensic anthropology, and skeletal biology research. In addition, multiple other publications have resulted from subsets of the same dataset (Agnew et al. 2015; Albert et al. 2018; Dominguez et al. 2016; Harden & Agnew 2018; Harden et al. 2019; Holcombe et al. 2019; Iraeus et al. 2019; Murach et al. 2017; Schafman et al. 2016; Sreedhar et al. 2020), each addressing a different objective and utilizing different data, but collected from one larger experimental research project. The caveat to the success of utilizing one dataset to address knowledge gaps across disciplines is that the team and the approach should be multidisciplinary from the outset.

Conclusions

This review has highlighted the critical need for large-scale controlled experimental bone trauma studies utilizing human specimens and the various approaches available for skeletal trauma research. This is vital to the continued development of the field of forensic anthropology, whose multidisciplinary nature necessitates "constant reevaluation of methods" (Passalacqua & Rainwater 2015, p. 3). In order to provide statistical substantiation (i.e., error rates and validated comparable studies) to forensic anthropological interpretations in the courtroom, in turn, meeting the needs of better forensic science (National Research Council 2009), a multidisciplinary approach to skeletal trauma research is imperative. The National Institute of Justice has recently reiterated the importance of replicability in scientific research, specifically in forensic sciences (Muhlhausen 2020). Replicability is a fundamental principle of the reliability of scientific research through the validation of previous studies and experimental methodologies (Muhlhausen 2020). The critical need in skeletal trauma research is not necessarily in more research, but in better research (Dempsey & Blau 2020), a need that can partially be addressed by utilizing a multidisciplinary methodology. As such, there has been increased pressure on forensic anthropologists to understand and apply biomechanics to their research (Kroman & Symes 2013). However, forensic anthropologists are not engineers, and vice versa, and experts in both fields inherently lack the education, training, and specialized knowledge to incorporate principles, applications, and analyses beyond their disciplines that are necessary to conduct thorough and scientifically relevant experimental research. A paradigm shift to building a collaborative multidisciplinary team to assess skeletal trauma allows for the incorporation of scientific data, both qualitative and quantitative, to not only re-create traumatic events but to address larger gaps in knowledge such as fracture mechanics and what variables are contributing to variation in fracture characteristics. A multidisciplinary approach should be the foundation of any scientific study conducting skeletal trauma research.

The authors acknowledge the challenges in conducting large-scale human specimen skeletal trauma research. However, many of these obstacles can be overcome through increased collaborations with established injury biomechanics research laboratories, institutions with anatomical donation programs, forensic practitioners, and researchers specializing in human injury tolerances and skeletal trauma. The authors also recognize the difficulty in identifying and connecting with experts and laboratories to develop a multidisciplinary research team. Therefore, the authors encourage researchers interested in conducting multidisciplinary skeletal trauma research but would like some assistance in identifying laboratories or individuals with specific areas of expertise to contact us; we encourage questions and further discussion. It is our hope this review fosters newfound collaborations and innovative ideas to advance the science of skeletal trauma analysis across all disciplines.

References

Agnew AM, Murach MM, Dominguez VM, Sreedhar A, Misicka E, Harden A, et al. Sources of variability in structural bending response of pediatric and adult human ribs in dynamic frontal impacts. *Stapp Car Crash Journal* 2018 Nov;62:119–92.

Agnew AM, Schafman M, Moorhouse K, White SE, Kang Y-S. The effect of age on the structural properties of human ribs. *Journal of the Mechanical Behavior of Biomedical Materials* 2015;41:302–14.

Albert DL, Kang YS, Agnew AM, Kemper AR. The effect of injurious whole rib loading on rib cortical bone material properties. International Research Council on Biomechanics of Injury. 2018:680–687.

American Academy of Forensic Sciences Position Statement 2009. https://news.aafs.org/policy-statements/the-american-academy-of-forensic-sciences-approves-position-statement-in-response-to-the-national-academy-of-sciences-forensic-needs-report/. Accessed December 12, 2020.

AO Foundation. AO CMF Classification System—2019. https://aocmf.aofoundation.org/clinical-library-and-tools/classification (accessed January 12, 2020)

Association for the Advancement of Automotive Medicine. Abbreviated injury scale: 2015 Revision. 6th ed. Chicago, IL; 2018.

Audigé L, Cornelius CP, Ieva A Di, Prein J. The first AO classification system for fractures of the craniomaxillofacial skeleton: Rationale, methodological background, developmental process, and objectives. *Craniomaxillofacial Trauma & Reconstruction* 2014;7(3):S6–14.

Baraybar JP, Gasior M. Forensic anthropology and the most probable cause of death in cases of violations against international humanitarian law: An example from Bosnia and Herzegovina. *Journal of Forensic Sciences* 2006;51(1):103–8.

Beillas P, Begeman PC, Yang KH, King AI, Arnoux PJ, Kang HS, et al. Lower limb: Advanced FE model and new experimental data. *Stapp Car Crash Journal* 2001 Nov;45:469–94.

Bernstein J, Monaghan BA, Silber JS, DeLong WG. Taxonomy and treatment: A classification of fracture classifications. *Journal of Bone and Joint Surgery* 1997 Sept;79(5):706–707.

Berryman HE, Berryman JF, Saul TB. Bone trauma analysis in a forensic setting: Theoretical basis and a practical approach for evaluation. In: Boyd CC Jr, Boyd DC, eds. *Forensic Anthropology: Theoretical Framework and Scientific Basis*. John Wiley & Sons Ltd, 2018:213–34.

Blau S. How traumatic: A review of the role of the forensic anthropologist in the examination and interpretation of skeletal trauma. *Australian Journal of Forensic Sciences* 2017;49(3):261–80.

Bolte JH, Gustafson H, Agnew AM, Kang Y-S. Injuries due to lower spine blunt force impacts associated with the planetary suit Body Seal Closure (BSC). International Research Council on the Biomechanics of Injury. 2018:170–172.

Bolte JH IV, Hines MH, Herriott RG, McFadden JD, Donnelly BR. Shoulder impact response and injury due to lateral and oblique loading. *Stapp Car Crash Journal* 2003 Oct;47:35–53.

Christensen AM, Hefner JT, Smith MA, Webb JB, Bottrell MC, Fenton TW. Forensic fractography of bone: A new approach to skeletal trauma analysis. *Forensic Anthropology* 2018;1(1):32–51.

Christensen AM, Passalacqua NV. *A Laboratory Manual for Forensic Anthropology*. 1st ed. Academic Press; 2018.

Christensen AM, Passalacqua NV, Bartelink EJ. Analysis of skeletal trauma. In: Christensen AM, Passalacqua N V, Bartelink EJ, eds. *Forensic Anthropology: Current Methods and Practice*. Elsevier Inc.;2014:341–377.

Christensen AM, Smith VA, Ramos V, Shegogue C, Whitworth M. Primary and secondary skeletal blast trauma. *Journal of Forensic Sciences* 2012;57(1):6–11.

Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. *Strengthening Forensic Science in the United States: A Path Forward*. 2009. https://www.ojp.gov/pdffiles1/nij/grants/228091.pdf. Accessed December 12, 2020.

Cornelius CP, Kunz C, Neff A, Kellman RM, Prein J, Audigé L. The comprehensive AOCMF classification system: Fracture case collection, diagnostic imaging work up, AOCOIAC iconography and coding. *Craniomaxillofacial Trauma & Reconstruction* 2014 Dec;7 (Suppl 1):S131–5.

Cristino D, Pietsch H, Bolte IV JH, Kemper A, Danelson K, Hardy W. Response of female and male PMHS to blast-induced vertical accelerative loading. International research. In: Proceedings of the Injury Biomechanics Symposium 2017.

Crowder CM, Wiersema JM, Adams BJ, Austin DE, Love JC. The utility of forensic anthropology in the medical examiner's office. *Academic Forensic Pathology* 2016;6(3):349–60.

Crudele GDL, Merelli VG, Vener C, Milani S, Cattaneo C. The frequency of cranial base fractures in lethal head trauma. *Journal of Forensic Sciences* 2020;65(1):193–195.

Daegling DJ, Warren MW, Hotzman JL, Self CJ. Structural analysis of human rib fracture and implications for forensic interpretation. *Journal of Forensic Sciences* 2008;53(6):1301–7.

Danelson KA, Kemper AR, Mason MJ, Tegtmeyer M, Swiatkowski SA, Bolte JH, et al. Comparison of ATD to PMHS response in the under-body blast environment. *Stapp Car Crash Journal* 2015 Nov;59:445–520.

Daubert v. Merrell Dow Pharmaceuticals (92–102), 509 U.S. 579; 1993.

DeLand TS, Kendell AE, Fenton TW, Haut RC. Fracture patterns from three-point bending of sheep femora. In: Proceedings of the ASME 2012 Summer Bioengineering Conference; 2012 June 20–23;Fajardo, Puerto Rico. 2012:655–656.

Dempsey N, Blau S. Evaluating the evidentiary value of the analysis of skeletal trauma in forensic research: A review of research and practice. *Forensic Science International* 2020:307.

Dempsey N, Gilbert FM, Miszkiewicz J, Oxenham MF. Biomechanical analysis of controlled tibial blunt force trauma. *Australian Journal of Forensic Sciences* 2019;51(5):538–548.

Deng B, Begeman PC, Yang KH, Tashman S, King AI. Kinematics of human cadaver cervical spine during low speed rear-end impacts. *Stapp Car Crash Journal* 2000 Nov;44:171–88.

Di Ieva A, Audigé L, Kellman RM, Shumrick KA, Ringl H, Prein J, et al. The comprehensive AOCMF classification: Skull base and cranial vault fractures: Level 2 and 3 tutorial. *Craniomaxillofacial Trauma & Reconstruction* 2014 Dec;7(Suppl 1):S103–13.

Dominguez VM, Kang Y-S, Murach MM, Crowe N, Agnew AM. Bone area

vs. cortical area: Considering intracortical porosity when predicting rib structural properties. International Research Council on Biomechanics of Injury; 2016:933–934.

Ebacher V, Tang C, McKay H, Oxland TR, Guy P, Wang R. Strain redistribution and cracking behavior of human bone during bending. *Bone* 2007;40(5):1265–75.

Franck H, Franck D. *Forensic Biomechanics and Human Injury: Criminal and Civil Applications - An Engineering Approach*. CRC Press; 2016.

Gabler HC, Weaver AA, Stitzel JD. Automotive field data in injury biomechanics. In: Yoganandan N, Nahum AM, Melvin JW, eds. *Accidental Injury: Biomechanics and Prevention*. 3rd ed. Springer, 2015;33–50.

Galloway A, Zephro L, Wedel VL. Classification of fractures. In: Wedel VL, Galloway A, eds. *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. 2nd ed. Charles C Thomas; 2014:59–71.

Hansen U, Zioupos P, Simpson R, Currey JD, Hynd D. The effect of strain rate on the mechanical properties of human cortical bone. *Journal of Biomechanical Engineering* 2008;130(1):1–8.

Harden A, Kang Y-S, Agnew A. Rib fractures: Validation of an interdisciplinary classification system. *Forensic Anthropology* 2019;2(3):158–67.

Harden AL, Kang Y-S, Moorhouse K, Agnew AM. Variation in fracture location of human ribs subjected to dynamic anteroposterior bending. International Research Council on Biomechanics of Injury; 2017:749–50.

Harden AL, Kang Y-S, Moorhouse K, Stammen J, Agnew AM. Human rib fracture characteristics and relationships with structural properties. International Research Council on Biomechanics of Injury; 2019:465–474.

Harden AL, Kang Y-S, Stammen J, Moorhouse K, Agnew AM. Characterization of strain mode in human ribs subjected to anterior-posterior loading. International Research Council on Biomechanics of Injury; 2020:819–820.

Harden AL, Agnew AM. Classification of fractures in human ribs subjected to dynamic bending. *American Journal of Physical Anthropology* 2018;165(S66):112.

Harden AL, Kang Y-S, Agnew AM. Comparison of the effect of two dynamic loading rates on fracture characteristics of human ribs in bending: An experimental study. *Forensic Anthropology* 2022a:1-10.

Harden AL, Kang Y-S, Bendig A, Bolte IV J, Goldsmith C, Agnew AM. The frequency of wedge fractures in experimental bending of the tibia. In: Proceedings of the American Academy of Forensic Sciences 74th Annual Scientific Conference, February 21–25, 2022b; Seattle, Washington.

Hardy WN. Instrumentation in experimental design. In: Nahum AM, Melvin JW, eds. *Accidental Injury: Biomechanics and Prevention*. 2nd ed. Springer-Verlag, 2002:12–39.

Hardy WN, Foster CD, Mason MJ, Yang KH, King A, Tashman S. Investigation of head injury mechanisms using neutral density technology and high-speed biplanar x-ray. *Stapp Car Crash Journal* 2001 Nov;45:337–68.

Hauschild HW, Humm JR, Pintar FA, Yoganandan N, Kaufman B, Kim J, et al. Protection of children in forward-facing child restraint systems during oblique side impact sled tests: Intrusion and tether effects. *Traffic Injury Prevention* 2016;17(S1):156–62.

Hillier ML, Bell LS. Differentiating human bone from animal bone: A review of histological methods. *Journal of Forensic Sciences* 2007;52(2):249–63.

Holcombe SA, Kang YS, Derstine BA, Wang SC, Agnew AM. Regional maps of rib cortical bone thickness and cross-sectional geometry. *Journal of Anatomy* 2019;235(5):883–91.

Hulse CN, Stull KE, Knight LD. Determining common skeletal injury locations based on manner of death (MOD). In: Proceedings of the 70th Annual Scientific Meeting of the American Academy of Forensic Sciences; 2018 Feb 19–24; Seattle, WA. A30;67.

Hulse C, Stull K, Weaver A. rib fracture frequency and location using vehicular crash data. *Forensic Anthropology* 2018;2(1):1–8.

Institute of Medicine (US) and National Research Council (US) Committee on Trauma. Injury biomechanics research and the prevention of impact injury. In *Injury in America: A Continuing Health Problem*. 1985. https://www.ncbi.nlm.nih.gov/books/NBK217482/. Accessed December 15, 2019.

Iraeus J, Lundin L, Storm S, Agnew A, Kang YS, Kemper A, et al. Detailed subject-specific FE rib modeling for fracture prediction. *Traffic Injury Prevention* 2019;20(2 Suppl):S88–95.

Isa MI, Fenton TW, Deland T, Haut RC. Assessing impact direction in 3-point bending of human femora: Incomplete butterfly fractures and fracture surfaces. *Journal of Forensic Sciences* 2018;63(1):38–46.

Isa MI, Fenton TW, Wei F, Haut RC. Experimental investigation of cranial fracture initiation in blunt human head impacts. *Forensic Science International* 2019;300:51–62.

Kang Y-S, Bolte JH IV, Moorhouse K, Donnelly B, Herriott R, Mallory A. Biomechanical responses of PMHS in moderate-speed rear impacts and development of response targets for evaluating the internal and external biofidelity of ATDs. *Stapp Car Crash Journal* 2012 Oct;56:105–70.

Kang Y-S, Moorhouse K, Icke K, Stricklin J, Herriott R, Bolte J IV. Rear impact head and cervical spine kinematics of BioRID II and PMHS in production seats. International Research Council on Biomechanics of Injury; 2015:246–260.

Kang Y-S, Agnew AM, Hong CB, Icke K, Bolte JH. Elderly PMHS thoracic responses and injuries in frontal impacts. International Research Council on the Biomechanics of Injury; 2017: 539–557.

Kang Y-S, Kwon HJ, Stammen J, Moorhouse K, Agnew AM. Biomechanical response targets of adult human ribs in frontal impacts. *Annals of Biomedical Engineering* 2021 Feb;49(2):900–911.

Kang Y-S, Moorhouse K, Bolte IV JH. Measurement of six degrees of freedom head kinematics in impact conditions employing six accelerometers and three angular rate sensors (6aω configuration). *Journal of Biomechical Engineering* 2011;133(11): 1–11.

Kang Y-S, Moorhouse K, Herriott R, Bolte JH IV. Comparison of cervical vertebrae rotations for PMHS and BioRID II in rear impacts. *Traffic Injury Prevention* 2013;14 Suppl S136–47.

Katzenberger MJ, Albert DL, Agnew AM, Kemper AR. Effects of sex, age, and two loading rates on the tensile material properties of human rib cortical bone. *Journal of the Mechanical Behavior of Biomedical Materials* 2020;102:103410.

Kellam J, Meinberg E, Agel J, Karam M, Roberts C. Fracture and dislocation classification compendium. *Journal of Orthopaedic Trauma* 2018;32(1):S1-S170.

Kemper AR, Kennedy EA, McNally C, Manoogian SJ, Stitzel JD, Duma SM. Reducing chest injuries in automobile collisions: Rib fracture timing and implications for thoracic injury criteria. *Annals of Biomedical Engineering* 2011;39(8):2141–51.

Kemper AR, Beeman SM, Porta DJ, Duma SM. Non-censored rib fracture data during frontal PMHS sled tests. *Traffic Injury Prevention* 2016 Sept;17:131–140.

Kerrigan JR, Drinkwater DC, Kam CY, Murphy DB, Ivarsson BJ, Crandall JR, et al. Tolerance of the human leg and thigh in dynamic latero-medial bending. *International Journal of Crashworthiness* 2004;9(6):607–23.

Khor F, Cronin D, Van Toen C. Lower cervical spine hard tissue injury prediction in axial compression. International Research Council on Biomechanics of Injury; 2017:645–647.

Khor F, Watson B, Glerczycka S, Panzer M., Cronin D. Effect of cortical bone material asymmetry using a three- point bend test simulation. International Research Council on Biomechanics of Injury; 2016:18–19.

King AI. Introduction to and applications of injury biomechanics. In: Yoganandan N, Nahum AM, Melvin JW, eds. *Accidental Injury: Biomechanics and Prevention*. 3rd ed. Springer; 2015:1–32.

Kress TA, Porta DJ. Characterization of leg injuries from motor vehicle impacts. SAE Technical Paper 2001-06-0025; 2001: 1–14.

Kroman AM, Symes SA. Investigation of skeletal trauma. In: DiGangi EA, Moore MK, eds. *Research Methods in Human Skeletal Biology*. Academic Press; 2013:219–239.

Kroman, AM, Symes, S. Investigation of skeletal trauma. In: DiGangi EA, Moore MK, eds. *Research Methods in Human Skeletal Biology*. Elsevier Inc; 2013:219-240.

Kulin RM, Jiang F, Vecchio KS. Effects of age and loading rate on equine cortical bone failure. *Journal of the Mechanical Behavior of Biomedical Materials* 2011;4(1):57–75.

L'Abbé EN, Symes SA, Raymond DE, Ubelaker DH. The Rorschach butterfly, understanding bone biomechanics prior to using nomenclature in bone trauma interpretations. *Forensic Science International* 2019;299:187–94.

Lesciotto KM. The impact of daubert on the admissibility of forensic anthropology expert testimony. *Journal of Forensic Sciences* 2015;60(3):549–55.

Love J, Christensen A. Application of bone fractography to a medical examiner sample: A case series. *Forensic Anthropology* 2018;1(4):221–7.

Love JC, Derrick SM, Wiersema JM, Pinto DC, Greeley C, Donaruma-Kwoh M, et al. Novel classification system of rib fractures observed in infants. *Journal of Forensic Sciences* 2013;58(2):330–5.

Love JC, Symes SA. Understanding rib fracture patterns: Incomplete and buckle fractures. *Journal of Forensic Sciences* 2004;49(6):1153–8.

Marinho L, Cardoso HFV. Comparing known and reconstructed circumstances of death involving a blunt force trauma mechanism through a retrospective analysis of 21 skeletonized individuals. *Journal of Forensic Sciences* 2016;61(6):1416–30.

McElhaney JH. Dynamic response of bone and muscle tissue. *Journal of Applied Physiology* 1966;21(4):1231–1236.

Muhlhausen D. Replication studies are vital to science we can count on—2020. https://nij.ojp.gov/general-message/replication-studies-are-vital-science-we-can-count/ Accessed January 10, 2019.

Murach MM, Kang Y-S, Bolte JH, Stark D, Ramachandra R, Agnew AM, et al. Quantification of skeletal and soft tissue contributions to thoracic response in a dynamic frontal loading scenario. *Stapp Car Crash Journal* 2018;62:193–269.

Murach MM, Kang Y-S, Goldman SD, Schafman MA, Schlecht SH, Moorhouse K, et al. Rib geometry explains variation in dynamic structural response: Potential implications for frontal impact fracture risk. *Annals of Biomedical Engineering* 2017;45(9):2159–2173.

Murray EA, Anderson BE. Forensic anthropology in the courtroom: Trends in testimony. In: Proceedings of the 59th Annual Meeting of the American Academy of Forensic Sciences, 2007; San Antonio, Texas. H4;322–23.

Norton BJ, Strube MJ. Understanding statistical power. *Journal of Orthopaedic & Sports Physical Therapy* 2001;31(6):307–15.

Ono K, Kaneoka K, Wittek A, Kajzer J. Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear impacts. SAE Technical Paper 973340; 1997 Nov.

Organization of Scientific Area Committees for Forensic Science (OSAC). *OSAC Research Needs Assessment Form* (Controlled experimental bone trauma studies), F.S.S. Board. 2016.

Passalacqua NV, Fenton TW. Developments in skeletal trauma: Blunt-force trauma. In: Dirkmaat DC, ed. *A Companion to Forensic Anthropology*. Blackwell Publishing; 2012:400–411.

Passalacqua NV, Rainwater CW, eds. *Skeletal Trauma Analysis: Case Studies in Context*. John Wiley & Sons, Ltd.; 2015.

Passalacqua NV, Rainwater CW. Introduction. In: Passalacqua NV, Rainwater CW, eds. *Skeletal Trauma Analysis: Case Studies in Context*. John Wiley & Sons, Inc.; 2015:1–6.

Pechníková M, Mazzarelli D, Poppa P, Gibelli D, Scossa Baggi E, Cattaneo C. Microscopic pattern of bone fractures as an indicator of blast trauma: A pilot study. *Journal of Forensic Sciences* 2015;60(5):1140–5.

Porta DJ. Biomechanics of impact injury. In: Rich J, Dean DE, Powers RH, eds. *Forensic Science and Medicine: Forensic Medicine of the Lower Extremity: Human Identification and Trauma Analysis of the Thigh, Leg, and Foot*. The Humana Press Inc.; 2005:279–310.

Reber SL, Simmons T. Interpreting injury mechanisms of blunt force trauma from butterfly fracture formation. *Journal of Forensic Sciences* 2015;60(6):1401–1411.

Rudd R, Crandall J, Millington S, Hurwitz S, Höglund N. Injury tolerance and response of the ankle joint in dynamic dorsiflexion. *Stapp Car Crash Journal* 2004 Nov;48:1–26.

Society of Automotive Engineers (SAE). J211/1 instrumentation for impact test-part 1-electronic instrumentation. Warrendale, PA; 2007.

Schafman MA, Kang Y-S, Moorhouse K, White SE, Bolte JH, Agnew AM. Age and sex alone are insufficient to predict human rib structural response to dynamic A-P loading. *Journal of Biomechanics* 2016;49(14):3516–22.

Scheirs S, Langenhorst W, Malgosa A, Ortega-Sánchez M, McGlynn H, Santos C, et al. Perimortem fracture pattern in ribs by blunt force trauma. *International Journal of Legal Medicine* 2018;132(4):1205–13.

Schuster PJ, Chou CC, Prasad P, Jayaraman G. Development and validation of a pedestrian lower limb non-linear 3- D finite element model. *Stapp Car Crash Journal* 2000 Nov;44: 315–34.

Scientific Working Group For Forensic Anthropology (SWGANTH). Trauma analysis—2011. https://www.nist.gov/system/files/documents/2018/03/13/swganth_trauma.pdf (accessed January 5, 2020).

Semeraro D, Passalacqua NV, Symes S, Gilson T. Patterns of trauma induced by motorboat and ferry propellers as illustrated by three known cases from Rhode Island. *Journal of Forensic Sciences* 2012;57(6):1625–1629.

Shaw G, Parent D, Purtsezov S, Lessley D, Crandall J, Kent R, et al. Impact response of restrained PMHS in frontal sled tests: Skeletal deformation patterns under seat belt loading. *Stapp Car Crash Journa*. 2009 Nov;53:1–48.

Shurtz BK, Agnew AM, Kang Y-S, Bolte J. Application of scaled deflection injury criteria to two small, fragile females in side impact motor vehicle crashes. SAE Tech Pap 2018-01-0542 2018 Apr;1–8.

Simon L, Lopez R, King K. Blunt force trauma. In: StatPearls—2022. https://www.ncbi.nlm.nih.gov/books/NBK470338/ (accessed January 15, 2022).

Sreedhar A, Kang Y, Iv JHB, Murach MM, Stammen J, Ramachandra R, et al. A hierarchical exploration of rib strain in dynamic frontal thoracic impacts. International Research Council on Biomechanics of Injury; 2020:746–769.

Stark DB, Willis AK, Eshelman Z, Kang Y-S, Ramachandra R, Bolte JH IV, et al. Human response and injury resulting from head impacts with unmanned aircraft systems. *Stapp Car Crash Journal* 2019 Nov;63:29–64.

Symes SA, L'Abbe EN, Chapman EN, Wolff I, Dirkmaat DC. Traumatic injury to bone in medicolegal. In: Dirkmaat DC, ed. *A Companion to Forensic Anthropology*. 1st ed. John Wiley & Sons, Inc.; 2012:340–389.

Takahashi Y, Kikuchi Y, Konosu A, Ishikawa H. Development and validation of the finite element model for the human lower limb of pedestrians. *Stapp Car Crash Journal* 2000 Nov;44: 335–355.

Tillis M, Stuckey S, Sreedhar A, Stammen J, Moorhouse K, Agnew A. Preliminary methods for modeling stress-strain curves of human ribs from structural dynamic bending tests. International Research Council on Biomechanics of Injury; 2020:732–745.

Ubelaker DH. A history of forensic anthropology. *American Journal of Physical Anthropology* 2018;165(4):915–23.

Ubelaker DH. Recent advances in understanding hard tissue alterations related to trauma. *Forensic Science International* 2019;299:235–237.

Unger T, Liers H, Schuster R, Kleber PDC. Impact of the new diagnostic dictionary (AIS 2015) for traffic accident research. International Research Council on Biomechanics of Injury; 2020:27–36.

Untaroiu CD, Darvish K, Crandall J, Deng B, Wang JT. A finite element model of the lower limb for simulating pedestrian impacts. *Stapp Car Crash Journal* 2005 Nov;49:157–181.

Untaroiu CD, Ivarsson J, Genovese DR, Bose D, Crandall JR. Biomechanical injury response of leg subjected to combined axial compressive and bending loading. *Biomedical Sciences Instrumentation* 2008 Apr;44:141–146.

Untaroiu C, Kerrigan J, Kam C, Crandall J, Yamazaki K, Fukuyama K, et al. Correlation of strain and loads measured in the long bones with observed kinematics of the lower limb during vehicle-pedestrian impacts. *Stapp Car Crash Journal* 2007 Oct;51:433–66.

Wang X, Mabrey JD, Agarwal C. An interspecies comparison of bone fracture properties. *Bio-Medical Materials and Engineering* 1998;8:1–9.

Wedel VL, Galloway A, Zephro L. Trauma analysis: Training, roles, and responsibilities. In: Wedel VL, Galloway A, eds. *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. 2nd ed. Charles C. Thomas; 2014:5–10.

Yang KH, Chou CC. Mathematical models, computer aided design, and occupational safety. In: Yoganandan N, Nahum AM, Melvin JW, eds. *Accidental Injury: Biomechanics and Prevention*. 3rd ed. Springer, 2015;143–182.

Yoganandan N, Arun MWJ, Pintar FA. Normalizing and scaling of data to derive human response corridors from impact tests. *Journal of Biomechanics* 2014;47(8):1749–1756.

Zephro L, Galloway A. The biomechanics of fracture production. In: Wedel VL, Galloway A, eds. *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. 2nd ed. Charles C. Thomas; 2014:33–45.

Zephro L, Galloway A, Wedel VL. Theoretical considerations in designing experimental trauma studies and implementing their results. In: Wedel VL, Galloway A, eds. *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. 2nd ed. Charles C. Thomas; 2014:73–87.