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Skeletal trauma in forensic anthropology: Improving the accuracy of trauma analysis and expert testimony

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PROJECT SUMMARY

Abstract

Current analyses of skeletal trauma are largely dependent on descriptive methods with little or no interpretation. Such practice lacks any link from observed fracture patterns to validated, experimental skeletal trauma research identifying fracture mechanisms. This baseline for interpreting skeletal trauma and providing scientific testimony cannot satisfy Daubert guidelines. The proposed research will fill the identified gap in the current knowledge and methods of skeletal trauma research, analysis, and interpretation by providing controlled experimental bone trauma data focused on fracture mechanics to improve the validity of skeletal trauma analysis and interpretation through precise, accurate, and repeatable analytical methods. The goal of this research is to scientifically validate the relationship between long bone fracture characteristics and injury mechanisms. This will be accomplished by addressing the following specific aims throughout this research project; Aim 1: Analyze relationships between skeletal fracture characteristics and intrinsic variables of the individual or the tibia (e.g., age, sex, cross-sectional geometry), as well as evaluate covariation of intrinsic variables, and Aim 2: Analyze relationships between skeletal fracture characteristics and extrinsic experimental variables (e.g., loading rate, loading direction).

One-hundred human tibiae (50 females, 50 males) will by dynamically impacted at mid-shaft in 4-point bending testing scenarios in the proposed project. Intrinsic variables (e.g., age, sex, robustness), biomechanical parameters (e.g., force, energy), and fracture characteristics (e.g., location, type) will be collected before, during, and after

testing using multiple methodologies (e.g., QCT scans). Analyses will evaluate inter-relationships as well as the influence of each of the variables on outcome variables (biomechanical parameters and fracture characteristics). This research will provide forensic anthropologists a better understanding of biological variability and its impact on fracture mechanics, as well as offer statistically substantiated results to strengthen expert testimony. Strategic varying of extrinsic factors (Aim 2), will provide data to enable forensic anthropologists to further interpret traumatic injuries and legitimize or disprove common beliefs, such that higher loading rates result in more complex fractures. Data from this research will be organized into a publicly available Forensic Anthropology Skeletal Trauma (FAST) database, with the purpose of providing objective training resources for scholars and professionals to standardize trauma interpretations within and across disciplines.

Major Goals and Objectives

The goal of this research was to validate the relationship between long bone fracture characteristics and injury mechanisms. This was accomplished by quantifying the differential effects of intrinsic and extrinsic variables on fracture characteristics, thereby, establishing a blunt force trauma fracture classification system for long bones with empirically defined mechanistic links. Known intrinsic factors are related to the individual (e.g., sex, age, stature), or are bone specific (e.g., cross-sectional area) and will be calculated from computed tomography (CT) scans. Extrinsic factors relate to variability in experimental conditions (e.g., fleshed vs. defleshed, loading rate and direction). Core data from this study are available in the Forensic Anthropology Skeletal Trauma (FAST) database, which will ultimately provide objective trauma interpretation training for young scholars and professionals (https://ibrc.osu.edu/fast-database/).

Research Questions/Aims

***Specific Aim 1*: Analyze relationships between skeletal fracture characteristics and *intrinsic variables* of the individual or the tibia (e.g., age, sex, cross-sectional geometry), as well as evaluate covariation of intrinsic variables.**

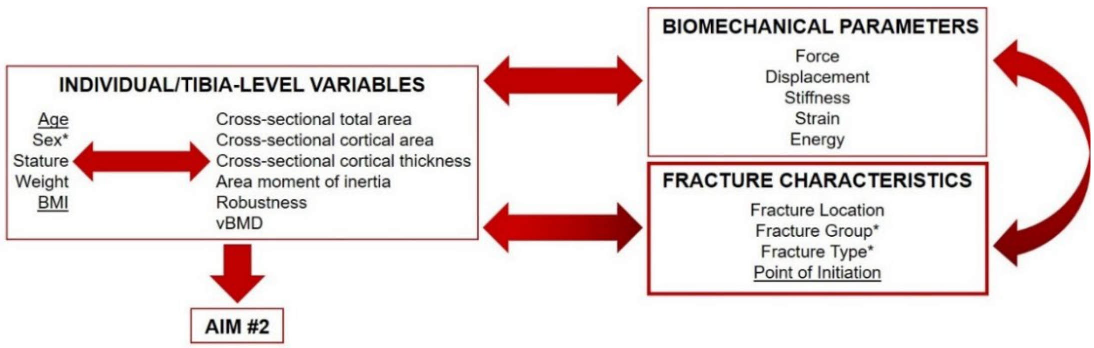

Figure 1. Schematic of Aim 1.

***Specific Aim 2*: Analyze relationships between skeletal fracture characteristics and *extrinsic experimental variables* (e.g., loading rate, loading direction).**

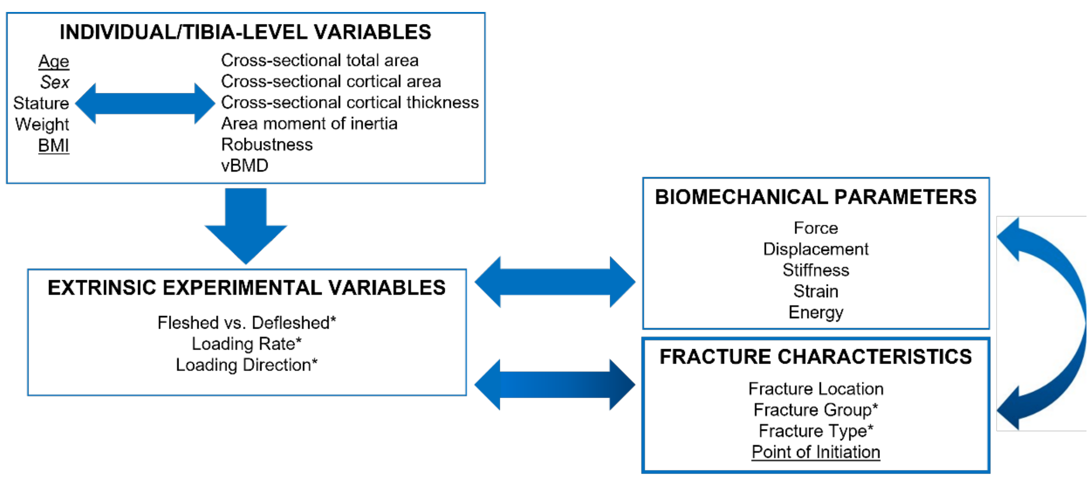

Figure 2. Schematic of Aim 2.

Research Design, Methods, Analytical and Data Analysis Techniques

Samples

One-hundred human tibiae ethically acquired from The Ohio State University Body Donation Program were dynamically impacted at mid-shaft in 4-point bending testing scenarios. No sample was eliminated based on previous conditions or trauma, unless it would interfere with the mechanical tests (e.g., fracture or hardware in the region of interest). To understand mechanisms of fracture characteristics and deviations from expected norms, it is necessary to conduct experiments that reflect a broad range of human variation (i.e., not eliminate samples based on health conditions, size, etc.). The results of this research capture real world variation and the role of this variation in determining fracture characteristics. Sex and age are known, stature and weight are recorded upon arrival into the program, and generally the complete medical history is unknown for the sample.

Sixty tibiae from the previously collected 100 tibiae, were utilized to address Aim #1. An equal distribution of males and females was ensured (25 females, 25 males) and were age-matched. Significant differences in CT morphometrics have been found between sexes (Hunter, Briley, & Agnew 2019), which supports the need for an age-matched sex sample. Right versus left side elements were randomized in the sample. Aim #2 included a total of 40 tibiae equally distributed into five different testing scenarios.

Specimen Preparation

Following removal of all soft tissue, except the periosteum, which was left intact, fresh (un-embalmed) tibiae were wrapped in normal saline soaked gauze and stored at

-20˚C until testing. Freezing of the specimens to -20˚C does not significantly affect the mechanical properties of cortical bone (Hamer et al. 1996; Griffon, Wallace, & Bechtold 1995; Linde & Sorenson 1993; Reilly & Burstein 1975; Frankel 1960). Prior to potting and mounting the strain gages, standard measurements of each tibia were recorded, following *Data Collection Procedures for Forensic Skeletal Material 2.0* (Langley et al. 2016). To quantify fracture mechanics and mechanism of injury, the tibia must be defleshed to visually record fracture initiation and propagation. Testing of fleshed specimens would result in an experiment that is limited to only external data collection. Therefore, it is best practice to have the bone visible during experimentation in order to accomplish Aim #1 and Aim #2. However, because fleshed specimens are more representative of reality, a small subsample of fleshed specimens were explored in Aim #2.

The proximal and distal ends of the tibiae were rigidly potted after measurements were recorded. To ensure each tibia was potted in the same orientation, an anatomically relevant coordinate system established by Danelson et al. (2015) was utilized. The tibiae were positioned and held in place with nylon set screws that were screwed into each of the potting fixtures. The potting fixtures were then filled with Fast Cast resin and the position of the tibiae were maintained until the resin cured.

Prior to testing, tri-axial rectangular rosette strain gages were mounted on the tibial diaphysis of each specimen. Each tibia had six strain gages mounted on the proximal and distal mid-shaft; two gages on each of the following surfaces: interosseous (lateral) surface, medial surface, and posterior surface. Adherence of this instrumentation began with careful removal of the periosteum at the attachment site of the gages, followed by degreasing the surface with diethyl ether. A thin coat of cyanoacrylate was applied to the bone surface and the gage, which is then mounted to the surface of the bone. Tibiae were kept well hydrated with normal saline throughout preparation and testing, since several studies have shown that properties of dry bone differ significantly from wet bone (Evans 1973; Zioupos and Currey 1998).

Imaging Methodology

Radiographs (X-ray) and quantitative computed tomography (QCT) scans were obtained from both pre- and post- four-point bending test specimens. Additionally, extensive and consistent macro (gross) photography was utilized to capture detailed post-test still images of the resulting fractures. Whole bone QCT scans were obtained prior to mechanical testing to quantify bone morphometric data and determine the role of these cortical bone properties in fracture mechanics, and to investigate variation in and relationships among these measurements.

Controlled Experimental Tests

Since 74% of pedestrians struck by vehicles are struck on the lateral side (Chidester & Isenberg 2001), the direction of loading for Aim #1 was lateral to medial. All tibiae were tested to failure at 6 m/s, which is equivalent to 13.4 mph. According to the National Highway Traffic Safety Administration (NHTSA), approximately 80% of pedestrian impacts occur with vehicles moving less than 35 mph (NHTSA 1993). The testing set-up created dynamic bending of the tibial midshaft. This type of fracture mechanism is observed in pedestrian vs. motor vehicle crashes, sports injuries, and any direct injury to the tibia through blunt force trauma impact (Grütter et al., 2000; Ivarsson et al., 2008; Kuppa et al., 2001; Wedel & Galloway, 2014).

Bending tests were conducted using a custom build high-rate MTS machine (15kN High Strain-Rate Material Testing System, MTS Systems Corporation). The MTS is displacement-controlled for safety and is highly repeatable. Two six-axis load cells were utilized to measure reaction loads at the supports. Displacement was measured using a linear variable differential transformer (LVDT) (MTS 308.50-30/LVDT, Eden Prairie, MN) pre-installed in the high-rate MTS machine. The on-board MTS data acquisition (BNC-2090, National Instruments, Austin, TX) and an external high-rate data acquisition system (DTS SLICE PRO, Seal Beach, CA) provide velocity, force, and displacement over time profiles. High-speed video data was collected with a Phantom VEO 710L at a minimum frame rate of 10,000 fps.

Fracture Characteristics

Fracture characteristics include the location, type, group, and point of initiation. Static high-quality still photographs were taken of each fracture. Fracture *location* was quantified as a percentage of the length of the tibia (e.g., 56%) (Agnew et al. 2018; Harden & Agnew 2018; Harden et al. 2019). Classification of the observed fractures was conducted based on guidelines established in AO/OTA Fracture and Dislocation Classification (AO Foundation 2018), earlier editions of the classification system have been utilized in previous studies (Grutter et al. 2000; Ebacher et al. 2007). This system is designed for application across skeletal elements, highlights the use of a hierarchical classification approach, and standardizes descriptive terminology. Fracture classification begins with the area of the bone in which the trauma appears (e.g., diaphyseal segment, middle 1/3), followed by a broad description of the fracture *type* (e.g., simple, wedge, multifragmentary), then each fracture is assigned to a specific *group* (e.g., simple oblique) within each type. The *point of initiation* for each fracture was identified utilizing high-speed video and strain gage data. Location of the point of initiation is quantified as a percentage of the length of the tibia (e.g., 63%).

<u>Forensic Fractography</u>

After mechanical tests and post-test imaging, the fractured portion of the tibia were carefully separated in order to conduct a forensic fractographic examination. The fracture surfaces were analyzed according to the methods established in *Forensic Fractography of Bone: A New Approach to Skeletal Trauma Analysis* (Christensen et al., 2018). Each fracture surface was examined and photographed utilizing an Olympus SZ61 Stereo Microscope (0.67-4.5x zoom optics) equipped with a 5MP digital color camera and external LED lights.

Expected Applicability of the Research

The most common reason for testimony by forensic anthropologists is trauma analysis. While the number of trauma-associated publications has increased over the past few years, the incorporation of methods that can be used to substantiate interpretations has not increased. This research will fill an acknowledged gap in the forensic anthropology discipline. By providing controlled experimental bone trauma data focused on fracture mechanics, this research will improve the validity of skeletal trauma analysis and interpretation. Through precise, accurate, and repeatable analytical methods, the proposed research will impact criminal justice policy and practice in the United States by providing methods and analyses that satisfy *Daubert* guidelines.

This project resulted in an extensive amount of data – from experimental testing parameters to fracture characteristics. The large and varied sample is uncommon for forensic anthropological trauma research and will provide extensive contributions to the current knowledge and methods of skeletal trauma analysis and interpretation. Data from this study are incorporated into the Forensic Anthropology Skeletal Trauma (FAST) database (https://ibrc.osu.edu/fast-database/). The FAST database is a searchable database comprised of images and test variables, with the intent of providing objective trauma interpretation for young scholars and professionals. To date, few researchers get quality hands-on training with trauma cases. Even fewer have experience with known cases. Therefore, the ability for students and professionals, at all stages in their career, to be exposed to skeletal trauma with known parameters has the potential to be transformative for the field.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

Name	Role	Affiliation	Research Identifier
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OUTCOMES and ARTIFACTS

Activities/Accomplishments

Activities and Milestones – Year 1
Specimen Procurement and Preparation
Controlled Experimental Tests (50 tests)
Data Collection and Analysis (Intrinsic Variables [Individual- and Tibia-Level])
Data Collection and Analysis (Test Output Variables and Fracture Characteristics)
FAST Database (Create Layout and Code for Database)

Activities and Milestones – Years 2-3
Aim #1 Complete
Specimen Procurement and Preparation
Controlled Experimental Tests (50 tests)
Data Collection and Analysis (Intrinsic Variables [Individual- and Tibia-Level])
Data Collection and Analysis (Test Output Variables and Fracture Characteristics)
FAST Database (upload all data from Aim #1 and Previous Research)

Activities and Milestones – Years 3-4
Aim #2 Complete

Activities and Milestones – Years 3-4
FAST Database (Upload all data from Aim #2)
Finalize FAST Database

Results and Findings

Ultimately, the success of this research provides forensic anthropologists a better understanding of biological variability and its impact on fracture mechanics as well as offer statistically substantiated results that can strengthen expert testimony. Essentially, moving trauma interpretation from heuristically based to empirically based and ultimately to meeting the NAS recommendations of conducting 'good science' (National Research Council 2009). Therefore, anthropologists will be able to better interpret injury patterns and their probability of occurrence based on individual demographics and the tibia-level variables.

Limitations

This research will foster improvements in current forensic practices of interpreting skeletal trauma; however, there are limitations worth acknowledging. The sample does not permit us to explore the impact of ancestry on fracture characteristics and biomechanical parameters. We acknowledge that a limitation to this study is that only one skeletal element will be tested as well as only two loading mechanisms; however, this is also a strength. This project cannot address the entirety of the massive gap identified by OSAC, which extends to every possible fracture mechanism of every skeletal element. In order to interpret more complicated loading mechanisms and fracture characteristics on every element, it is necessary to follow a research design that is less complex such that robust interpretations can be made. Additionally, future research should build from the findings of the current project and should focus on conducting controlled experimental bone trauma studies on a variety of skeletal elements, including the cranium, under various loading mechanisms.

Products

Harden A, Kang YS, Baker G, Stull K, Agnew A. (2023). Exploring the Effects of Sex and Size on Dynamic Tibia Properties. *International Research Council on Biomechanics of Injury*. Paper IRC-23-53, 477–498. Presented at the International Research Council on Biomechanics of Injury Annual Meeting, Cambridge, UK.

Harden, Angela L.; Stull, Kyra E.; Kang, Yun-Seok; Bolte IV, John H.; Agnew, Amanda M. (2023): Forensic Anthropology Skeletal Trauma Database. Figshare. Dataset. https://doi.org/10.6084/m9.figshare.21948419

Harden A, Stull K, Kang YS, Bendig A, Bolte J IV, Agnew A. (2022). Relationships between Age, Sex, and Number and Type of Fractures in Human Tibiae. *International Research Council on Biomechanics of Injury*. Short Communication IRC-22-50, 361–362. Presented at the International Research Council on Biomechanics of Injury Annual Meeting, Porto, Portugal.

Harden A, Kang YS, Hunter R, Bendig A, Bolte J IV, Eckstein N, Smith A, Agnew A. (2021). Sex-specific relationships between fracture force and cortical bone morphometrics in human tibiae subjected to lateral loading. *International Research Council on Biomechanics of Injury*. Paper IRC 21-33, 232–248. Presented at the International Research Council on Biomechanics of Injury Annual Meeting, online.

Dissemination Activities

Harden AL, Stull KE, Kang Y-S, Agnew AM. (2024). Tibia size and the contribution to variance in fracture outcomes. American Academy of Forensic Sciences.

Harden AL, Weisensee K. Improving Methods using Machine Learning and Databases in Forensic Anthropology. National Institute of Justice, Forensic Technology Center of Excellence, Webinar, December 5, 2023.

Harden AL, Agnew AM, Bolte JH, Kang Y-S, Stull KE. Development of the Forensic Anthropology Skeletal Trauma (FAST) Database. In *2023 National Institute of Justice Forensic Science Research and Development Symposium: American Academy of Forensic Sciences 75th Annual Scientific Conference.* DiEmma G, Fornaro E (Eds.). 2023, p. SA210. RTI Press Publication No. CP-0016-2304. https://doi.org/10.3768/rtipress.2023.cp.0016.2304

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Harden AL, Kang YS, Bolte JH IV, Stull KE, Agnew AM. (2023). Examination of Strain Mode at Fracture in Experimentally Loaded Human Tibiae. *American Academy of Forensic Sciences.* Presented at the American Academy of Forensic Sciences 75th Annual Scientific Meeting, Orlando, Florida. A40.

Harden A, Kang YS, Bendig A, Bolte JH IV, Goldsmith C, Agnew A. (2022). Frequency of Wedge Fractures in Experimental Bending of the Tibia. *American Academy of Forensic Sciences.* Presented at the American Academy of Forensic Sciences 73rd Annual Scientific Meeting, Seattle, Washington. A178.

Harden A, Agnew A. Experimental Skeletal Trauma Research in Forensic Anthropology. *National Institute of Justice Forensic Science Research and Development Symposium*, *American Academy of Forensic Sciences 73rd Annual Scientific Meeting,* February 16, 2021.