The Rorschach butterfly, understanding bone biomechanics prior to using nomenclature in bone trauma interpretations

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Highlights

- Nomenclature and fracture characteristics are used to interpret broken bones.
- Nomenclature assumes an external loading condition making it inappropriate.
- Butterfly fracture describes an injury, limiting interpretative abilities.
- Modes of failure interpret bending direction of bone and total bone trauma patterns.

Abstract

Blunt traumas are the most common injuries observed and reported in medical examiner settings. Two common methods to describe bending bone fractures in the anthropological literature include the application of morphology nomenclature and describing characteristic fracture morphology. A nomenclature descriptor of blunt trauma, the butterfly fracture, is commonly used to describe broken long bones. In this paper, a case study of a fractured long bone in a pedestrian vehicle accident is used to highlight the complex interplay of factors involved in bone fracture formation. The application of a butterfly fracture pattern in trauma analysis is useful in establishing the bending direction of a bone, in identifying failure modes, and is valuable in teaching. Yet, butterfly fracture characteristics need to be examined in 3-dimensions for diagnosis of modes of failure, tension, shear and compression, and even then, the bending direction of a broken bone may not provide a reliable indicator of the point of impact (POI); this is especially true when a priori knowledge of the injury is unknown. Common fracture nomenclature, such as oblique, transverse and/or comminuted, as well as eponyms, are medical descriptions of an injury which are impractical to use for interpreting a broken bone from fleshed or skeletonized remains, in establishing a POI and in evaluating total bone trauma (TBT). The examination ofcharacteristic features on the surface of a broken bone associated with the modes of failure is the best approach for establishing the bending direction of a long bone.

Keywords

Blunt force injuries
Forensic anthropology
Fracture interpretation
Pedestrian vehicle accident
Fracture mechanics
Fractography

1. Introduction

Bone trauma as a discipline has flourished in the last 40 years, with trauma analysis being a standard part of a professional forensic anthropologists' skill set in many parts of the world [1]. The need to interpret traumatic injuries from bone grew from the development of an informal inter-professional teamwork in autopsy, where anthropologists, law enforcement, pathologists and archaeologists worked together to solve problems concerning the unnatural death of an individual, or a group. The idea of "*it takes two*" or more people to report on sustained bone injuries during autopsy and on skeletal remains developed from this collaborative engagement and marked a paradigm shift, or growth, of forensic anthropology and its contributions to the forensic sciences [1-3]. More recently, this web of inter-professional teamwork has spread to include biomechanical engineers and developments of finite element models for the analysis of stress responses in complex structures [4,5].

The benefit of teamwork among all anthropological disciplines to solve problems has been clearly defined in the four-field approach in all American anthropological tertiary curriculum. In this vein, interdisciplinary contributions of physical anthropology and their emphasis on human osteology has spilled-over into the medical professions, and particularly to trauma interpretations in forensic pathology. However, the major area of bone fracture interpretation, an area of concentration for forensic anthropology, is not fully realized in the USA on account of an absence of inter-professional discourse between the anthropological curriculum at tertiary institutions and the medical disciplines. Practical experience in the discipline of forensic anthropology is commonly obtained after formal education and usually after a practitioner has received a doctoral degree. The lack of emphasis on inter-disciplinary collaborations outside of anthropology fields leaves a disjoint in the concurrent development of academics and practitioners in forensic anthropology. While this void has caused discontentment among forensic anthropologists, particularly in mapping a road for their professional development, it has also led to two distinct schools of thought in how a practitioner should perform and present on bone trauma analyses to the public.

Two approaches for evaluating and interpreting bone impact and bending fractures currently exist in forensic anthropology and include the use of: (1) comparative morphology, which has stimulated the by-product of physician nomenclature in the medical literature, as compared to (2) application of fracture surface characteristics, or fractography, to identify modes of bone failure in a broken bone. The type of approach is highly dependent on their theoretical and practical training as well as hands-on experience in medico-legal casework

A common issue among many anthropological analyses is the application of medical terminology of specific fractures to broken bones. For example, bone failure of the distal radius can be described with numerous standard medical classifications, such as Monteggia, Colles', Smith's and Barton's fractures. However, diagnoses involving bone failure labels are often formulated from the patients' description of the event. Since anthropologists, like forensic pathologists, do not often obtain first-hand accounts of an injury, particularly from their patients, these morphological descriptors rarely contribute to interpretations during a forensic analysis. Therefore, the interpretation of long bone fractures in living patients rarely contributes to trauma interpretation of the dead. A fracture must be repaired in a living person so as to restore the patient's well-being (medical health) and mobility; whereas in the deceased, estimations of bone bending direction, as well as a possible point of impact (POI) is needed. Additionally, context of the injury is a required, but not often known, investigatory detail that contributes to prior knowledge and knowledge of fractures in the body.

Morphological diagnoses of fractures are also strongly founded in radiographic technology and in its application to a diverse array of medical fields, including forensic pathology. Forensic anthropologists and pathologists rely heavily on this time saving, non-invasive branch of the medical science, but practitioners also have to remember to examine not only the 2-dimensional bone but also its 3-dimensional structure. If the bone is removed from autopsy and processed free of soft tissues, the advantage of this 3-dimensional approach to analysis is readily apparent over both radiography and photography. The use and application of medical nomenclature designed around patient's histories and 2-dimensional images in forensic anthropology, particularly the butterfly fracture which is emphasized in this manuscript, presents with limitations for analysis and interpretation of an injury in a medico-legal setting.

The purpose of this paper is to address the history of butterfly fracture nomenclature and its current application in forensic anthropology. The morphological characteristics of a butterfly fracture are also highlighted with the use of an exemplar fractured tibia and fibula from a pedestrian vehicle accident (PVA). This exemplar is used to demonstrate fracture variation and limitations of both a classificatory and fracture characteristics approach to the interpretation of broken bones, particularly blunt injuries, in a medico-legal investigation.

2. History of Bone Trauma Nomenclature and the Butterfly Fracture Pattern

In the late 19th century, Messerer [6,7] experimentally tested bone bending stresses on a series of disarticulated lower limbs (tibia and fibula), with an emphasis on fracture patterns on impacted tibial shafts. He consistently noted wedged-shaped fracture patterns on these tibiae which, at the time, he considered to be forensically significant for defining both the direction and location of an externally applied force. Wedged-shaped fractures on tibia became known as a *Messerer fracture* and this fracture pattern was featured in late 19th and early 20th century forensic pathology literature as often resulting from PVAs. The eponym is still used today among European forensic pathologists to describe fractures to the lower limb.

Today, and despite the fact that Messerer never used the terminology butterfly fracture, a Messerer fracture is a historical eponym for butterfly fracture morphology on the tibia. Other nomenclature for this fracture morphology includes wedged-shaped fracture; tibial/femoral wedged-shaped fracture; tension-wedged fracture; tension butterfly wedge fracture; butterfly fragment; comminuted fracture; and segmental fragments [[8], [9], [10], [11], [12]]. A butterfly fracture classification is applied when a bone has broken into two or more pieces and the associated shear failures sometimes form the shape of butterfly wings.

Additional descriptions for butterfly fracture morphology extend into modern medical/biomechanical nomenclature. Terminology such as transverse, oblique and comminuted, as well as medical eponyms, bumper fracture, and greenstick fracture (for example), are used in a similar manner to the *Messere*r fracture to describe an injury and to imply certain external loading conditions to a bone [13-15]. The practitioner simply observes the morphology of the broken bone and compares it to a suite of possible classification patterns for that bone. For example, in order to describe a fracture on a femur, a practitioner can select terminology such as "transverse, oblique, spiral, butterfly < 50% loss, butterfly >50% loss, comminuted butterfly, segmental, and comminuted" (Wedel and Galloway 2014:268). However, this terminology loosely refers back to the creation of a wedged-shaped fracture morphology associated with bending strain/stress placed on bone.

Butterfly fracture nomenclature is further complicated for practitioners with its use to describe ballistic injuries in the early 20th century. From 1893 to 1915, LeGarde [16] conducted experiments on the effects of small-arm weapons and various bullet calibers on the human body, with the intent on developing humane bullets for use in conflict situations. In his 1915 publication, he described a gunshot wound to a tibia, with a visible plug and spall and associated radiating fractures, as a butterfly fracture. The bullet struck the bone perpendicularly and the radiating fractures traversed around the long bone shaft creating what appeared to be a center (plug and spall) with two wing outlines (radiating fractures) which appeared to take on the morphological appearance of a butterfly. Makin [17] also used butterfly fracture nomenclature to describe stellate comminuted ballistic injuries on the long bones of soldiers from the Anglo-Boer War in South Africa. Makin likely obtained his use of butterfly fracture nomenclature from the earlier, and currently inaccessible, research and reports of LeGarde in 1893.

More recent ballistic research, experimental and descriptive, uses butterfly fracture nomenclature, along with other similar nomenclature such as divot fractures in cortical bone; drill-hole fracture; butterfly shaped radiating fractures; false butterfly fractures; and double butterfly fractures, to describe long bone fracture morphology from lower-velocity ballistic injuries [18-22]. In a text on skeletal trauma, Kimmerle and Baraybar (2008:428) describe how “a double-butterfly fracture occurs from penetrating injuries of the femoral shaft in which the projectile impacted perpendicular to the axis of the shaft and two to four radiating fractures extended away from the entrance defect, around the shaft, toward the exit.” The authors contend that the use of butterfly fracture or double-butterfly fracture for ballistic injuries focuses only on the appearance of the broken bone and not on the fracture characteristics which created the break.

While historical and modern literature used by anthropologists have applied butterfly fracture terminology to interpret blunt and ballistic injuries to long bones, bone fractures associated with gunshot wounds are unlike bending bone failures with blunt trauma. The former are radiating fractures associated with high kinetic energy whereas the latter are associated with bending bone failures. The “ballistic butterfly” fracture has rigid, straight “wings” (radiating fractures), whereas the “blunt butterfly fracture” has curved “wings” (shear failure). The creation of each fracture pattern, has completely different mechanisms, and therefore the terminology “butterfly fracture” is not interchangeable between the two trauma classifications. Furthermore, all these bone trauma analyses which make use of the butterfly fracture terminology are based on observing morphology of the injury and not evaluating the fracture characteristics of the injury. Additionally, historical anthropology literature in blunt trauma eludes to the idea that with the observation and classification of fracture morphology, such as a butterfly fracture, a practitioner is also able to interpret the external loading conditions to the bone, even without having prior knowledge of the injury [23-25].

The confusion in fracture interpretation may have arisen from *Messerer's* original experimental work [6,7], and later researchers [14,15] where a fracture to a long bone was useful in providing information on both the direction of bending strain/stresses, the location of the POI and the possible external loading conditions. For example, the 5th metacarpal has been observed to break during fist fights (Boxer’s fracture) and the hyoid has been shown to fracture in manual strangulations; yet, the appearance of fractures on these bones cannot be used to indicate that such an external loading condition occurred to the individual, without prior knowledge of the event and/or mechanical testing of other types of loading conditions that could produce the observed breaks.

Another example of blunt trauma limitations would be with situational evidence. If scattered skeletal remains found in the woods, a forensic anthropologist's interpretations of long bone fractures is severely limited, such that establishing a POI is not possible without a corresponding tool mark. In this situation, the use of classification nomenclature based on the location of failures in the skeleton, such as a dancer's fracture, a toddler's fracture, or a hangman's fracture, leads to suspected external loading conditions that, without a known context of the body or which a break was produced, contribute to inaccurate diagnoses. The relationship between fracture pattern and external loading condition should be considered in an analysis but is neither self-evident nor absolute. Butterfly fractures, while not associated with a certain external loading condition, are descriptive not interpretative. In essence, all bending bone fractures in the body (including hyoids and ribs) will form variations of a butterfly fracture pattern, or a rather more accurately, a pattern associated with failure in bending bone. Therefore, a butterfly fracture classification only describes an injury, but it cannot be used to interpret an injury.

In the 21st century, the idea of a practitioner being able to define a POI from a butterfly fracture pattern, tibia or otherwise, was given more scrutiny, and criticized [26]. Researchers stated that on account of considerable variation within butterfly fracture morphology, it was not always possible to define a POI without prior knowledge of how the break occurred [23-28]. Butterfly fracture morphology is highly variable in long bones as intrinsic factors such as shape of the bone, location on the bone, as well as biological parameters such as age and sex, along with stress risers and resistors affect fracture propagation, and ultimately its morphology, under external bending strain/stress [10, 25]. Recently, researchers suggest that the amount of observable variation in butterfly fracture morphology may also negate a practitioner's ability to estimate the direction a bone had bent prior to failure [26, 29, 30]. In essence, the morphology of long bone bending fractures are highly variable and cannot be accurately interpreted from its 2-dimensional appearance.

However, evaluation of bone biomechanics and modes of failure in a broken bone is useful in establishing the direction of bending [23 – 27]. A 3-dimensional analysis of fracture characteristics on a broken bone are highlighted in the following case study so as to demonstrate the use of these characteristics in establishing the direction of bending on a broken lower limb (tibia and fibula) in a medico-legal investigation.

3. Pedestrian Vehicle Accident: Tibia-Fibula Fracture

The victim ran between two cars into heavy 4-lane traffic and was struck on his left side at approximately 40 mph (65 kph) by a police SUV. The police officer had no warning before the impact. According to the officer's dash video, the victim was impacted near the driver side headlight and was thrown forward and left of the SUV into more oncoming traffic. In his attempt to save the victim from further injuries, the police officer immediately left his vehicle in the median of the road, ran back to the victim and began dragging the severely injured victim out of the oncoming traffic lane. The police officer was also struck by a second hit and run motor vehicle. He sustained survivable injuries and fractures to his arm and shoulder, but the original pedestrian struck was killed on impact.

In autopsy, no biomechanical assessment was conducted to test the possible external loading conditions, such as the bumper to the left, weight-bearing leg, so as to better evaluate the response of the lower limb to a 4-point bending situation. However, fracture characteristics on the damaged surfaces of the bone, such as ridges and valleys as opposed to mottled, smooth bone, associated with compressive and tensile modes of failure, respectively, were

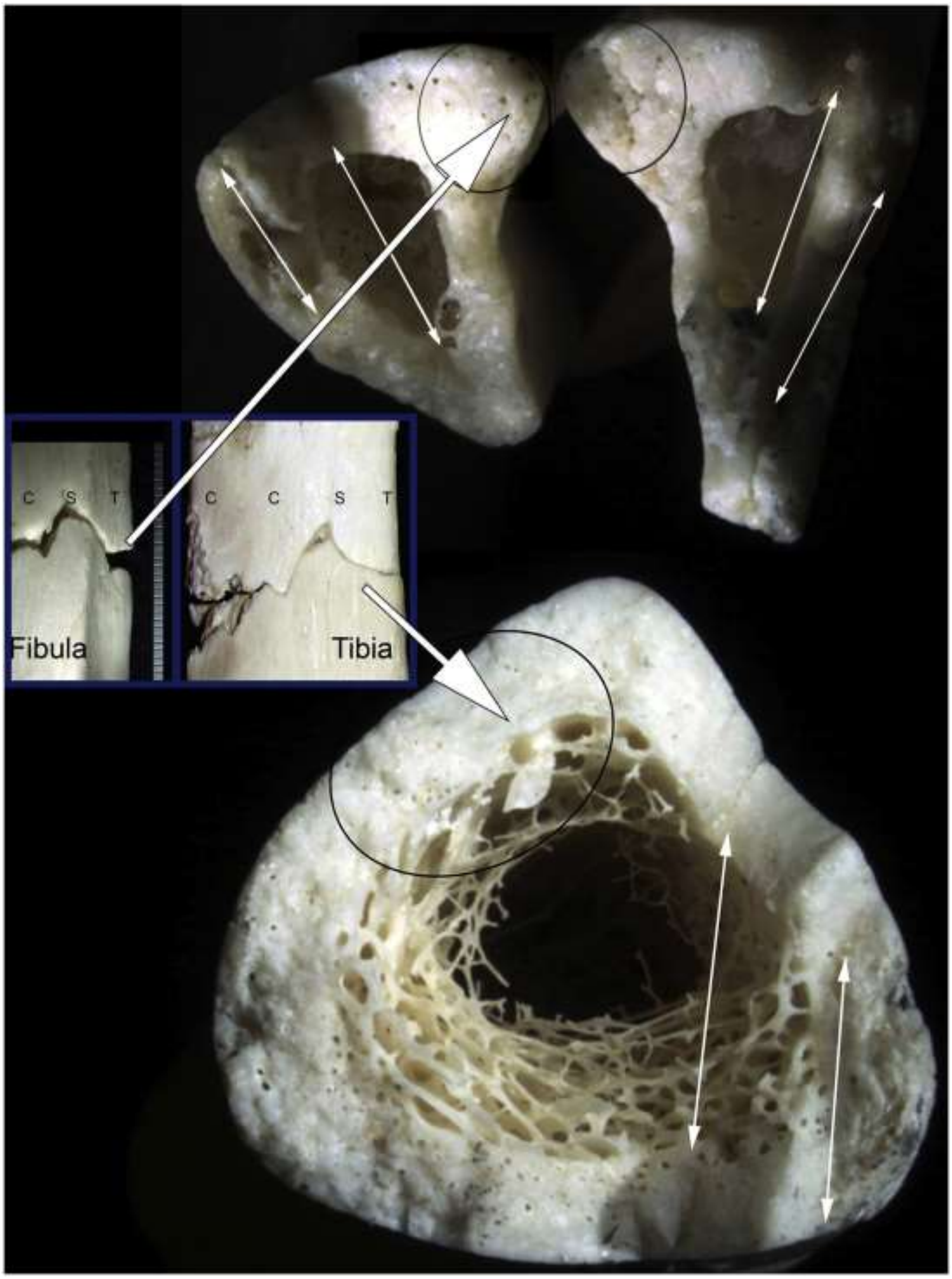

Fig. 1. Exemplar of a tibia and fibula fracture from the side and in cross-section. The image in the box shows the tibia and fibula from the side. Labels T, S and C are used to denote expressions of fracture characteristics for tension, shear and compressive modes of failure. Cross-section of a long bone shaft of a fibula (top) and tibia (bottom). The small, double-headed arrows denote the areas of ridges and valleys created from break up and crushing of bone under compressive modes of failure. The pin pricks and mottling of bone opposite the area of ridges and valleys (black circle and large arrows), indicates tearing of bone under a tensile mode of failure.

examined on the broken left tibia and fibula and were compared with soft tissue damaged at the proposed POI (see Fig. 1). In the absence of soft tissue or recovery context, interpretation of a POI is discouraged, as a practitioner cannot reliably propose the location of impact without soft tissue evidence. However, in the absence of soft tissue and recovery context, the practitioner can evaluate the bending direction of a long bone, the process of which is described below.

All cortical bone fractures present with morphological characteristics that can be used to identify modes of failure, namely tension (T), shear (S) and compression (C). Fracture characteristics associated with failure under tensile stress create pulling tears in bone. These mottled bone surface tears are roughly perpendicular edges of pulled apart bone (Fig. 1). Whereas ridges and valleys on bone surfaces and crushing are features of bone failure under compressive stress (Fig. 1) [2,3,24,25,31,32]. Shear stresses are often identified between the areas of tensile and compressive stresses and represent a separating and sliding of the material against itself. These characteristics form the basis for all bone fracture interpretations associated with blunt trauma. The combination of these failures result in the creation of a butterfly fracture pattern, which is a classic failure in bending bone.

Soft tissue destruction to the victim’s lower left limb includes lacerations and bruising from the kneecap to the ankle, mainly on the lateral surface (Fig. 2). Bruising is also noted on the opposite right lower leg and on the medial side of the ankle, superior to the ID tag (Fig. 2). While examination of injuries are documented, before autopsy, the whole right leg reveals lateral rotation and shortening of the limb, despite the apparent lack of bone fractures, at least from the midshaft of the femur down. The right leg likely indicates a dislocation (femoral head from acetabulum) or a complete fracture in the upper femur with muscular shrinking, drawing the whole leg up toward the hip. Additionally, the right lower limb probably avoided the destructive characteristics of the left leg because it was non-weight bearing, which allowed it to survive the impact without fractures. All of these features on the body, which are observed during autopsy, provide prior knowledge, in the form of soft tissue, as to the possible type and location of the injury.

Fig. 2. Lower limbs of the victim of a pedestrian vehicle accident, Note the bruising and lacerations. Disruptions on the lower left leg (arrows) indicate how the leg likely wrapped around the bumper of the police car. Notice how the right leg also has bruising, but is not deformed except for the lateral rotation of the whole leg. An indication of the proximal femur dislocation and/or a fracture.

The anthropologist's bone trauma assessment concentrated on identifying fracture characteristics to bone surfaces of the lower left tibia and fibula (Fig. 2, Fig. 3) where soft tissue injuries were observed with prior knowledge of a bumper impact. A pre-existing skin laceration on the left lower limb revealed extensive soft tissue damage and numerous bone fractures (Fig. 3). At this point, an anthropologist's diagnosis of bending direction of bone is difficult at best, due to the dishevelled mix of tissues and fluids. Further analysis requires incision and debridement of the soft from the hard tissue, with eventual removal of the left tibia and fibula. Macerated and processed bone is much easier to evaluate fracture characteristics associated with modes of failure (tension, compression and shear) which can assist an anthropologist in interpreting the bending direction of a bone.

Figure 3. Complex fractures associated with blunt force injury in the proximal left tibia and distal third of the left tibia and fibula. The left image is the initial examination with the knee flexed in autopsy and the skin laceration retracted revealing the complexity of the wound. The right image exposes the length of the left tibia and fibula as the skin is incised and retracted to reveal complex fractures (ovals). Notice bruising on medial left ankle, right image.

3.1. Anthropological Examination of Tibia and Fibula Fractures

Three complete fractures of the tibia and fibula were observed at autopsy, with the tibia and fibula failing in the same plane in the distal third of the bone shaft. A third fracture occurs in the proximal third of the tibia shaft (Fig. 3, white circles).

The left tibia and fibula were processed and reconstructed minus the proximal metaphysis which was left with the body, see Fig. 4. Fractures on the lateral surface of the proximal tibia and the distal one-third of the tibia and fibula present with a classic butterfly fracture morphology (Fig. 4). In order to evaluate the bending direction of the bone, a closer examination of fracture surface characteristics used to identify modes of failure, namely tension (T), shear (S) and compression (C) is required. As shown in Fig. 1, fractures associated with tension failure are often straight (in 2-dimensions) with a mottled bone surface in cross-section where perpendicular edges of pulled apart bone are noticeable. Areas of compressive failure present with clearly defined crushing often visualized as zipper like tears in bone (2-dimensional) with distinct ridges and valleys in cross-section (Fig. 1). Shear stresses form between the areas of tensile and compressive stresses and can form curved, diagonal lines across a long bone, classically representing the wings of a butterfly.

Fig. 4. Three images of the left posterior lower leg with proximal and distal bone fractures (left image with proximal bone removed in autopsy). The upper leg (right image) reveals the reconstructed tibia and the lower fractures (middle image) show the reconstructed tibia and fibula. The upper tibia fracture is approximately 10 cm above the paired fractures distally, and present with similar fracture mechanisms (labelled tension T, shear S, and compression C). The middle insert demonstrates a close –up of the distal third fracture patterns with labelling revealing areas of fracture characteristics associated with compression (C), shear (S), and tension (T) modes of failure.

Fracture characteristics observed in crack development of a bone (as described above in Fig. 1) can assist a forensic anthropologist in identifying the modes of failure which can be further used to determine 1) the direction in which the bone bends, 2) the weak points (stress risers) in the tubular bone shafts and, with prior knowledge, the POI [32]. As long bones vary in shape and size, all bones present with different stress risers (weakness) and stress resistors (strengths) which, combine with a variety of external loading conditions that create distinct fracture morphology. The variation may or may not represent the 2-dimensional distinct morphology of a classic butterfly fracture. Thus, biomechanical interpretations of fractures in terms of tension (T), shear (S), and compression (C) are of more value than nomenclature in interpreting broken bone failure [24, 25, 32].

In an examination of the tibia and fibula (Fig. 4), bone surface characteristics consistent with tensile failure (T) were noted on the medial surface, such as a gaping fracture and a straight tear in bone, while surface characteristics associated with compressive failure (C) were noted on the lateral surface, including zipper-like crushing of the material. On the distal one-third of the tibia (Fig. 4, middle), a gaping fracture propagated through the cortical bone and into the medullary cavity, with straight surface characteristics that can be used to indicate a failure under tensile stress. Propagation of the fracture across the shaft is also noted with an incomplete fracture radiating from the tensile side at an approximate 30–45° angle initially and terminating as the cracks path turns along the long-axis of the bone. This curved lined is consistent with shear failure (S) within the compressive stress region of the bending bone since maximum shear stress has been known to occur at approximately 45 ° angles to the long-axis of the bone in bending experiments. A similar fracture pattern is also noted superiorly at the mid-shaft of the tibia (first insert, Fig. 1).

Classic butterfly fracture morphology is also visible on the fracture of the distal fibula in the same plane as the tibia fracture (middle insert of Fig. 4 and Fig. 5). Examination of the fractured surfaces demonstrated failure under tensile stress (T) on the medial aspect of the fibula with a straight line and gapping fracture, shear failure (S) as indicated with curved lines across the long axis of the bone and crushing failure due to compressive stress (C) on the lateral aspect of the bone As posterior aspect of the left tibia and fibula are shown, the convex area of bending is on the medial side, whereas the concave area of bending is on the lateral side of the two bones. If the direction of bending is compared with the soft tissue bruising (Fig. 2), then a practitioner can suggest that the lateral side of the leg (fibula) was the POI with the bumper of the police vehicle. However, variation in the observed fracture pattern is noted on the inferior fracture of the left fibula, which demonstrates surface characteristics of tensile failure (straight lines and gapping tears) on the lateral aspect and compressive failure (zipper-like crushing of bone) on the medial aspect (Fig. 5). These fracture characteristics on the inferior fibula exhibits an interesting pattern which suggests a bending failure of opposite direction of that of the superior fibula and tibia fractures (Fig. 4, Fig. 5). This would seem to defy biomechanical principles associated with the distribution of bending stress in an impact coming from the lateral-to-medial direction if one were to assume these fibula fracture regions occurred simultaneously under the same bending stresses. How can this fracture pattern be explained in order to accurately determine the direction in which the bone was bending?

An explanation requires both prior knowledge of the injury and anatomical context of the injury. First, the inferior failure on the left fibula is *likely* to have been below the bumper line of the vehicle, even though this was not biomechanically examined, and is *possibly* a consequence of this bone being medially shifted after its initial failure from the impact. Second is the relationship of the fibula to the rest of the skeleton. The fibula is paired with a larger, denser tibia which is axial loaded. The two bones are interacting with each other during the momentum and fracture events. With relatively high kinetic energy, such as a motor vehicle accident, a thin bone often fails more than once and usually in an accordion style where each consecutive fracture reveals opposite bending directions to the one next to it. This has been seen in fibulae of post-mortem human subject pedestrian experiments [33].

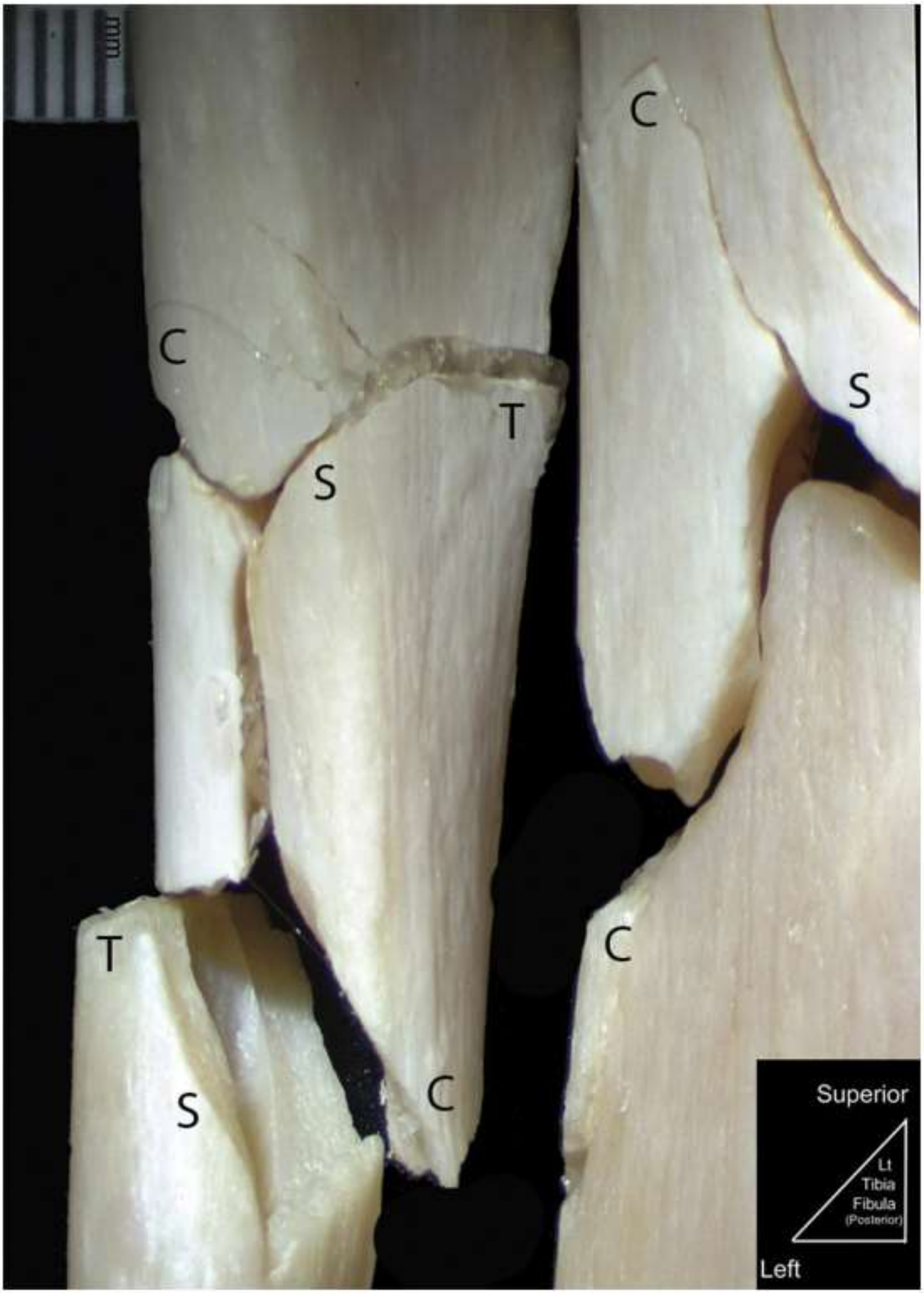

Figure 5. Extreme close up of the complex fracture pattern on the distal one-third of the left fibula. The partial view of the tibia (lateral third) is also visible. The fibula actually presents with multiple fractures to the shaft, where fracture characteristics of tension, shear, and compression modes of failure are in opposition.

Anatomical context is critical in fracture interpretation of a total bone trauma pattern (TBT) as well as being particularly useful in evaluating perimortem and postmortem injuries [34]. If the fibula was assessed in isolation, a practitioner would have difficulties estimating a bending direction for this bone. However this unusual fracture morphology on the fibula, and its bending direction, is interpretable in association with the tibia, as the tibia provides anatomical context for evaluating and understanding the propagation of this fracture. For example, the shaft of the fibula was likely driven into the tibia, causing a failure in tension on the medial crest, which is a stress riser, as noted on the superior aspect of the fibula in Fig. 5. As bone failure is dynamic, the initial broken tibia and fibula readjusted such that the more distal part of the broken fibula was driven into the tibia shaft. A chip of bone is also noted in the lateral surface tibia which may have been a result of the fibula impacting it.

A practitioner must remember that the fracture morphology associated with a blunt force injury is a dynamic process such that areas of stress/strain change throughout the loading and in response to breaks, and that fracture characteristics, particularly those associated with tension and compression, may not necessary occur directly opposite each other, depending on the complexity of tissues and combined loading to the limb. This includes anatomical and biomechanical stress risers/resistors in the bone.

In this case, the soft tissue examination performed by the pathologist, and substantiated in Figs. 2 to 5, confirms (among other injuries) a broad and massive impact to the lower left leg. Since the skin wounds emphasize the left sides of the legs as the point of impact, our prior knowledge includes injuries consistent with a pedestrian struck on the left, where the weight bearing supporting leg was impacted. Medial failure in tension and lateral failure in compression is consistent with this scenario and thereby substantiates prior knowledge of the injury and anatomical context (meaning that the bones were not disarticulated when fractured).

As simplistic as it seems, prior knowledge significantly increases a practitioner’s ability to interpret the injury, and we know that the victim was either struck by bumper in the lower leg, or run over by a vehicle, each of which is a common affliction examined by forensic pathologists from fatal pedestrian vehicle accidents. If soft tissue bruising is not available for analysis, nor is any other prior injury knowledge known, then the practitioner can only provide the bending direction of the bone and cannot associated the injury with an external loading condition (in this case the bumper of a motor vehicle).

4. Discussion

Failure of bone is a dynamic process and multiple factors lead to deviation from the idealized loading and response conditions described in most anthropological texts as the classic butterfly fracture pattern. The interpretation of a butterfly fracture pattern from bone is a challenge as considerable morphological variation can exist in failure on a single long bone due to intrinsic (age, size, location, shape, stress risers and resistors) and extrinsic features (magnitude, duration, velocity and number of impacts). On account of this variation, a 2-dimensional classification of fracture appearance (such as depressed fracture, Messerer’s fracture, dancer’s fracture, or even butterfly fracture) can only be used to describe an injury, not to interpret it. Furthermore, many descriptive eponyms, such as boxer’s fracture or dancer’s fracture, imply a certain external loading condition which an anthropologist cannot surmise from a blunt force injury without prior knowledge.

A practitioner needs to interpret fracture characteristics, tension, compression and shear, rather than describing fracture pattern morphology so as to establish bending direction and, if possible, a POI, as well as to evaluate the TBT, prior to drawing final conclusions about possible reasons behind the injuries, all of which may potentially contribute to the forensic pathologist's evaluation of cause and manner of death.

Classification nomenclature is currently a popular method for practicing forensic anthropologists to use when evaluating blunt force injuries [13, 14]. Yet, because of the complex variation in fracture patterns and morphology, no interpretative value exists in applying fracture classifications, such as oblique, transverse, comminuted; in using eponyms to describe a fracture without prior knowledge of the injury; or worse yet, in making lists of possible objects such as baseball bats, gym weights, bricks, hammers, and even "catapults," in a bone trauma analysis. Without a further biomechanical assessment of the external loading conditions, a forensic anthropologist cannot reliably or validly pick from any of these classifications systems or suggested items to include in the interpretation of observed skeletal injuries on a single bone or throughout a body. Finally, the lists of items are not valid in a court of law, and therefore, have no validity to forensic science. Simplified classification systems ignore fracture variation and thereby can lead to inaccurate conclusions in bone trauma analysis.

Without prior knowledge of an injury, medical eponyms, should not be "used as a stand-alone description for an injury or a pathology process" but rather an interpretation should focus on the combination of [approaches] with soft and hard tissues [9], in effect, an inter-disciplinary approach, with an evaluation of bone biomechanics assessment, is warranted for the interpretation of a bone fracture. In order to further these interpretations beyond the direction of the bending bone, a biomechanical model (finite element) is recommended and can be used to conduct simulations in evaluating the stress-response and failure, which could then be correlated to what was observed with the fracture characteristics.

For example, our exemplar of the pedestrian vehicle accident (PVA), the tibia and fibula were affected as a unit, and due to their shape and buttressing, these bones had distinct stress risers (interosseous crest) and stress resisters (soleus line and muscle attachment sites), which affected the propagation of the butterfly fracture morphology [10, 25, 27]. Each of the tension failures on the tibia and fibula first occurred on a stress riser, or the angled part of the bone, which was the weakest point, and not necessarily across from the point of impact (see Fig. 4, proximal and distal tibia failure). Initial failure on bending cortical bone is the area closest to the point of most severe bending (tension) combined with the weakest point of that structure. While this failure is generally opposite the point of impact, it may show variation.

Despite the direction of bending, the bone resists/succumbs to tension and compression failure depending on (besides direction of bending) the bone stress risers/resistors. In bending cortical bone, fracture characteristics associated with tensile failure occur on one side of the bending material with compressive failure opposite to it. This is simply because the bone has a lower ultimate stress in tension; which means it succumbs more easily to tension as compared to compression. Compression and tension failure will not necessarily be exactly opposite from each other within a bone but should be explainable using known principles of bending and failure mechanics.

Is it possible for an anthropologist to interpret fractures observed during an unobserved single vehicle accident, vs. a pedestrian struck by vehicle, vs. a fall from heights? If so, how?

Without prior knowledge of external factors involved in the production of an injury, such as a body decomposed in an automobile wrapped around a tree or scattered skeletal remains found with postmortem disruption in the woods; an anthropologist's (and for that matter, a forensic pathologist's) interpretation of long bone fractures is limited. An anthropologist can only evaluate the direction in which the bone was bending on each fracture and provide an analysis of TBT. Obviously, a TBT pattern will be dependent on the condition of the body and/or skeleton for analysis; however, an anthropologist has to be stringent concerning examining the whole body, and willing to accept limitations of their interpretations should an analysis of the entire body (skeleton) not be possible. TBT assessment is important so as to potentially contribute to the final interpretation of cause and manner of death.

5. Conclusions

A butterfly fracture pattern is often an anthropology student's first exposure to the biomechanics of bone trauma. But merely recognizing the 2-dimensional morphology of a butterfly fracture does not lead to success in bone trauma interpretations. The highly variable fracture pattern in long bones is attributable to numerous intrinsic and extrinsic factors. Tubular bone failure may provide an indicator of direction of the failure but not necessarily the exact point of impact of the contacting object, or further information about the external loading conditions, unless prior knowledge of the context of the injury is available. The context of the injury, or the absence thereof, dictates the extent to which the fracture can be interpreted.

In the analysis of a butterfly fracture pattern, an anthropologist needs to: (1) evaluate the fracture characteristics, or the modes of failure (tension, compression and shear) on the bone, and (2) assess the TBT from the body or the skeleton, so as to be able to provide useful evidence in evaluating cause and manner of death in a medico-legal situation. Interpretation of modes of failure, as opposed to the reconstructed 2-dimensional bone fracture morphology, is the foundation for interpreting injury through the bending direction of the bone.

The authors encourage anthropologists to closely examine characteristics of bone failure, note natural stress risers and resistors, consult with biomechanical engineers as needed to gain additional insight into the dynamics and material response of the bone under various combined loading conditions for correlation to fracture surface characteristics and to create a complete picture of the external loading condition. Merely assigning an overall classification to the injury is discouraged and it is recommended to avoid over-reaching assumptions and predictions regarding impact sites prior to working collaboratively with engineers, pathologists, first responders and other that can add context to the injury in question. Anthropologists need to understand the considerable depth of variation in fracture patterns associated with blunt force injuries and try to avoid creating new classifications or categories from what seems like a ‘unique’ fracture pattern. This will reduce error in the interpretations, particularly cause and manner of death, and will reduce repercussions for inaccurate analysis of blunt force injuries; the eventual goal in the forensic sciences.

Fractography of bone also holds significant promise for interpretation of fractured bone. As this methodology matures, terminology associated with surface features specific to forensic analysis of fractured bone will likely become of primary interest, as these features are likely linked to the fundamental failure mechanisms of the bone [31]. Such terminology has recently been proposed by Christensen and colleagues. and includes features such as “arrest ridges,” “bone hackle,” “bone mirror,” and “wake features”. While these terms have been proposed, additional work is needed and agreement in the discipline will be key in the future.

Future collaborations with biomechanical engineers on experimental and computational stress analyses on bone will also continue to play an important role so as to gain better understanding of the relationship between externally-applied forces to the leg and resulting internal stress response under various loading conditions. Internal stress responses will also need correlation to fractography studies.

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