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Estimating the Timing of Long Bone Fractures: Correlation Between the Postmortem Interval, Bone Moisture Content, and Blunt Force Trauma Fracture Characteristics*

ABSTRACT: There is very limited knowledge about how long perimortem fracture characteristics persist into the postmortem interval (PMI). Therefore, in this study, 60 porcine long bones were exposed to natural taphonomic conditions and fractured with a steel bone breaking apparatus every 28 days throughout a 141-day period. Differences between macroscopic blunt force trauma fracture characteristics (fracture angle, surface morphology, and outline) were examined to determine if they varied over time or in relationship to bone moisture content (ash weight) and overall assessment. There are significant relationships between (1) PMI and percent ash weight (%AW), fracture surface, and fracture angle and (2) %AW and fracture surface and fracture angle. Bone moisture content correlates significantly with fracture morphology and other characteristics commonly used by forensic anthropologists to determine the timing of traumatic injuries. However, fracture characteristics normally associated with perimortem trauma can persist long into the PMI.

KEYWORDS: forensic science, forensic anthropology, trauma, perimortem, postmortem

Anthropologists are frequently asked to determine when skeletal fractures occurred in relation to an individual's death. Using characteristics of bone, anthropologists typically report the timing of traumatic events as occurring antemortem, perimortem, and postmortem. Antemortem trauma occurs before death and is recognized by active healing of the injured site (1,2). The term perimortem is used by anthropologists to indicate events occurring near (around) the time of death. Classifying trauma as perimortem often implies that the injury is directly associated with the manner of death or the handling of the remains (1). Postmortem fractures are those occurring after death and are usually considered to be associated with taphonomic processes.

Numerous forensic anthropologists (e.g., 1–3) have defined the characteristics of bone that distinguish antemortem, perimortem, and postmortem skeletal fractures. However, the majority of morphological characteristics used to differentiate between perimortem and postmortem fractures are actually discussed in terms of occurring in "green" or "fresh" bone versus "dry" bone. Bones retain their moisture content and flexible collagen matrix well after death. This increases the interval during which skeletal fractures can occur while still exhibiting typical fresh bone or perimortem fracture characteristics (4). This makes distinguishing between pathological events and early postmortem taphonomic events problematic (1). Few authors discuss explicitly how long perimortem fracture characteristics persist into the postmortem interval (PMI) or the causes of the changes in characteristics. Therefore, it is unclear what exactly constitutes "near death" in terms of skeletal modification, or how "dry" a bone must be before it exhibits postmortem rather then perimortem fracture characteristics. Maples (3) suggested that perimortem fracture characteristics can be observed in fractures created several weeks after death. He did not, however, give any specific temporal limits or an explanation as to why bones stop exhibiting perimortem characteristics when fractured and instead exhibit postmortem features. In fact, Maples (3:221) defines the perimortem interval as "an elastic interval at best and a vague concept at worst."

Clearly there is a need to define the perimortem interval so that it is more useful in medicolegal cases involving long bone fractures. Therefore, this study endeavors to do this by examining changes in long bone fracture characteristics when fractures are created monthly over a 5-month period. First, we documented the macroscopic differences in fracture morphology occurring in bones fractured every 28 days throughout a 141-day period. Second, we examined the relationship between bone moisture content and fracture morphology. Third, we looked at the correlation between overall assessment (i.e., perimortem or postmortem), PMI, and moisture content. Finally, we documented the characteristics commonly used by forensic anthropologists to determine the timing of bone fractures.

Perimortem Versus Postmortem Fracture Characteristics

Once antemortem trauma is ruled out based on the lack of healing at or near the injury site, three primary characteristics are commonly cited as useful when attempting to establish whether an injury was sustained perimortem or postmortem: color variation, fracture morphology (outline, surface appearance, and angle), and microscopic characteristics.

Color change or staining of the bone can be caused by fluids of decomposition, blood, soil, water, and organic matter. Staining from hemorrhage can occur at or near the fracture location (1), but

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decomposition can eliminate or obscure this perimortem indicator (5). Hence, anthropologists often look for color differences between the bone fracture surface (cross-section of compact bone exposed by the passage of force) and the internal and external cortical bone surfaces. If the fracture surface and cortical bone surfaces are homogeneous in color, the fracture is considered to have occurred before the postmortem period. That is, it occurred before decomposition and taphonomic staining (2). Conversely, a fracture surface free from staining and/or a different color than the internal and external surface of cortical bone indicates a postmortem modification. However, it is possible that the color could equalize between the fracture surface and the bone surface over time, thus creating the appearance of perimortem injury. Unfortunately, no known research has addressed this question.

Fracture morphology can also provide information as to whether the injury occurred to fresh or dry bone. Fresh bone, unlike dry bone, is highly pliable and possesses considerable tensile strength. Table 1 lists some of the major differences observed by Johnson (6) between fractures occurring in fresh and dry bones. Usually, when fresh bone is fractured dynamically it will splinter, creating irregular fracture surfaces or edges and fragments of bone that may remain attached to the fracture surface margins (3). Concentric, circular, and spiral fractures are usually only observed when a bone is broken while fresh (2). Additionally, fractures that display "greenstick" qualities (splintering, unclean breaks) and oblique transverse fractures with a "butterfly" pattern are most likely due to trauma during the perimortem interval. Frequently, transverse impacts cause butterfly patterns (7). Ubelaker and Adams (8), however, have shown that butterfly fractures can occur in long bones more than 1 year after death.

As bone and its collagen matrix decompose and moisture is lost, the fracture morphology the bone exhibits will change. Trace element analysis and scanning electron microscope (SEM) images suggest that dry mineralized bone tissue has undergone structural changes that cause it to break differently than fresh bone (9). A dry bone exhibits horizontal tension failure where the fracture front cuts across the diaphysis and produces perpendicular, parallel, or diagonal breaks (6). Typical fracture characteristics of modified dry bone also include production of several small fragments, brittle flaking or shattering, and surface cracking (3).

Fracture outline is difficult to evaluate because it is highly variable between individual bones. Villa and Mahieu (10) document this character using three basic categories: (1) transverse, (2) curved or V-shaped, and (3) intermediate. Transverse fractures are straight and perpendicular to the long bone's longitudinal axis and are more commonly associated with fractures of dry bone. Curved fractures are spiral or partial spiral fractures while V-shaped fractures are pointed. These two types of fracture outlines are complex and multidirectional in their morphology. Spiral fractures observed in fresh bone are the result of the tensile-shear failure along a helical path (6,11). Spiral fractures are often disrupted from continuing around the shaft by the longitudinal orientation of collagen fibers, resulting in fragments that are longer than they are wide (12). Finally, intermediate fractures are a combination of fractures with a straight morphology and with a stepped outline.

Villa and Mahieu (10) and Johnson (6) characterize fracture surface morphology as either smooth or jagged. Fresh bone fractures tend to have smooth fracture surfaces, while dry bone breaks have jagged or stepped fracture surfaces (9,10,13,14). These differences between fresh and dry bone fracture surfaces may result from the more heterogeneous nature of dry bone (9). The stepped edges are due in large part to the fact that weathering cracks appear along the surface of the bone as it dehydrates, which cause new fracture fronts to terminate upon intersection with another crack. This will create a step-like appearance along the edge of the fracture (12,15). Micro-step fractures can also occur in fresh bone if the fracture front splits to bypass structural irregularities of the bone (12). In addition, hackle marks can sometimes be observed on the fracture surface of a fresh bone. These marks are small fissures that penetrate the fracture, usually near the impact site, and parallel the principle direction of the fracture (12).

Fracture angle is another characteristic that is often used when examining blunt force trauma. The angle category is established by determining the angle between the fracture surface and the cortical bone. Fracture angles are characterized as being right, obtuse, or acute. Obtuse and acute angles are associated with fresh bone fractures. Right angles are most often associated with dry bone fractures (6,10), yet Bonnichsen (9) and Morlan (13,14) indicate that right angles are also frequently observed on fresh bone fractures.

Little research has been published on the microscopic differences between perimortem and postmortem skeletal fractures, but both Johnson (6) and Shipman (16) discuss microscopic examination of fracture surfaces using SEM. While the fracture surfaces of bones broken fresh appear smooth macroscopically, Shipman (16) found that perimortem fractures appear roughened and string-like microscopically. The reason for this microscopic appearance is that the fracture front either follows the predominant direction of collagen bundles or breaks the bonds between adjacent bundles. Conversely, fractures of dry bone will have a roughened and stepped appearance both macroscopically and microscopically because the fracture front perpendicularly intersects the collagen bundles (6,16).

The interpretation of blunt force trauma to bones can have a significant medicolegal impact, thus it is important that anthropologists have a clear understanding of the relationship between the PMI, bone moisture content, and fracture characteristics. Therefore, we examined monthly changes in long bone moisture content and fracture characteristics over a 5-month period to help clarify these relationships. While color changes and weathering may also play a vital role in the anthropologist's decision about the timing of fracture events, we chose to focus on fracture morphology, especially fracture outline, surface morphology, and fracture angle.

TABLE 1—*Fracture analysis characteristics of fresh and dry bone.**

Morphology	Fresh Bone Characteristic	Dry Bone Characteristic
Outline	Radial pattern circling diaphysis	Fracture perpendicular or horizontal fracture surface
Surface	Homogeneous color with external cortical bone	Heterogeneous color with external cortical bone
Surface	Smooth	Rough
Angle	Obtuse and acute angles	Right angles
Other	Loading point present	Loading point absent
Other	Fracture fronts never crosscut epiphyseal ends	Fracture front can crosscut epiphyis

*After Johnson (6).

Materials and Methods

Sixty long bones were obtained from ten 150- to 200-pound domestic pigs (*Sus scrofa*). Ulnae, femora, and tibiae were collected from each animal. Pig bones were used because they provide an acceptable substitute for human bones in fracture research (1,17) and are readily obtainable. Each bone was given a unique alphanumeric identification.

Processing and Fracturing of the Bones

The bones were collected from animals that died of natural causes within 1–8 h of death. After death, the fore- and hind-limbs of the animals were removed leaving the soft tissue intact. The limbs were then wrapped in black plastic and paper sacks and immediately frozen until all specimens were collected. This method protected the bones from freezer damage and eliminated differential preservation by maintaining a constant environment for all bones. Evans (11) reported that freezing and subsequent controlled thawing has no significant effect on the mechanical properties of bone. At the commencement of the experimental phase of the research project, the frozen limbs were placed in a temperature-controlled room and allowed to steadily thaw until the soft tissue reached room temperature (22°C or 72°F).

An initial sample of 10 bones was fractured immediately upon thawing and served to represent trauma occurring at the time of death. The initial sample was designated as PMI 0. The remaining bones were placed on the ground in a fenced area in central Missouri at the beginning of the summer (June 19, 2005) to decompose. Ten bones were removed and fractured every 28 days for a period of 141 days. Each PMI was designated by the number of days the bones were allowed to decompose: PMI 0, 28, 57, 85, 115, and 141. The fenced enclosure allowed normal surface decomposition processes to occur (exposure to climatic events and insects) but prevented animals from carrying off the remains. See Miller Wieberg (18) for a detailed description of the fenced structure.

Climatic data including average monthly precipitation, daily precipitation, and average monthly minimum and maximum temperatures were obtained from the National Climatic Data Center (19). Daily minimum and maximum temperatures at the decomposition site were recorded using a digital thermometer.

Bones were fractured using a custom drop impact bone breaking apparatus, which consisted of a steel strike bar and a steel base. The strike bar was made from a 10.2-kg steel pipe with a sealed end. The base consisted of plate steel with a cradle for the bones constructed of 3-inch diameter steel pipe cut in half lengthwise. When the strike bar was dropped from a height of 0.48 m, it produced a sudden dynamic force of *c.* 106 kg/cm^2.

Once a bone was removed from the fenced enclosure, it was placed in the bone breaking apparatus designed to produce a complete midshaft fracture perpendicular to the long axis of the bone. After fracturing the bone, a small section of bone was removed from one end using a hacksaw and preserved for ash weight analysis. To ensure that the fracture location was clean enough to thoroughly examine, soft tissue was removed manually and then macerated in a standard detergent and water solution. Upon completion of the maceration process the bones were air dried.

Bone Moisture Content

The bone section removed prior to cleaning was sacrificed to determine moisture content. For each trial, 10 specimens (one from each bone) were placed separately into standard crucibles that had been placed in the oven for 2 h at 100°C prior to use to eliminate excess moisture. The wet weight of the bone was measured to the nearest 0.1 mg using a Metter AK160 balance. Next, the crucibles containing the specimens were dried for 12–14 h in an oven at 100°C. They were then heated in a Fisher Scientific Isotemp Muffle furnace at 600°C for 24 h to remove all organic components of the bone. Upon removal from the furnace, the bones were placed in a desiccator to cool for 12 h, which prevented any outside moisture from accumulating in the samples. Finally, the bone ash was weighed and percent ash was determined by dividing the ash weight of the specimen by the wet weight of the specimen.

Fracture Characteristics

Fracture outline, surface morphology, and angle were examined and recorded by the first author. In addition, weathering stages and the color of the fracture surface and external cortical bone were recorded, and all fragments were weighed, measured, and described. The focus of this paper is on fracture morphology, so weathering and bone color will not be discussed. Fracture outline was recorded as transverse, curved or V-shaped, or intermediate. Fracture surface morphology was observed at four locations on each specimen. Each surface was assigned to one of three categories: smooth, jagged, or intermediate. A score of intermediate was used when the fracture surface possessed both smooth and jagged characteristics. Fracture angle was observed at the same locations used to determine fracture surface morphology and was recorded as (1) acute, (2) obtuse, (3) acute and obtuse, (4) right, (5) right and acute, or (6) right and obtuse by visually examining the angle between the fracture surface and the cortical bone. In a few cases less than four locations of the fracture were examined because of high fragmentation, angles being present only in the metaphyseal region, or the presence of three or less fragments. Categories containing two types of angles merely indicate that both types of angles were present, usually along the same fracture. Fracture angle categories 1–3 were later combined during analysis because they were all considered to be associated with fresh bone fractures. Likewise, fracture angle categories 5 and 6 were combined for statistical analyses.

Overall Assessment

The characteristics of each bone were used to determine if the bone appeared to have been fractured perimortem, postmortem, or during an intermediate interval. Bones classified as "intermediate" show a mixture of perimortem and postmortem fracture characteristics. The "overall assessment" was evaluated by the first author and determined using the combination of fracture outline, fracture angle, and fracture surface morphology. Color was not used in the decision. The overall assessment was meant to replicate the examination and determination of the fracture timing that would be conducted by a forensic anthropologist during a medicolegal investigation, with the exception of using information based on bone coloration or microscopic appearance.

Assessment by Forensic Anthropologists

In order to get a more accurate grasp of the characteristics used by practicing forensic anthropologists to assess the timing of fracture events, participants were sought to examine 10 bones from the study sample and determine the timing of the failure event. The protocol was approved by the University of Missouri Institutional Review Board (# 1054957). After examining each bone, participants were asked to characterize the blunt force trauma as either perimortem or postmortem and list the primary characteristics used to make this determination. Participants were primarily limited to anthropologists attending the annual meeting of the American Association of Forensic Scientists in 2006 held in Seattle, WA.

A total of 22 individuals participated. Bones selected for assessment by forensic anthropologists were not chosen at random, but instead chosen by the authors to represent different time intervals, specific fracture morphologies, and taphonomic conditions. In addition, the bones were lightly bleached with hydrogen peroxide to reduce the use of color as an indicator for determining the timing of the injury. The specimens used in this study were not left to further decompose once they were fractured so color differences between the external cortical bone surface and the fracture surface were often distinct.

Statistical Methods

All statistical analyses were carried out using SAS 9.1.3 (20). Regression analysis was used to examine the relationship between percent ash weight (%AW) and days after death. Analysis of variance (ANOVA) was conducted to determine the following correlations: (1) overall assessment to PMI, %AW, fracture surface, and fracture angle; (2) PMI to %AW, fracture surface and fracture angle; (3) and %AW to fracture surface and fracture angle. Chi-square analysis was conducted for the following comparisons: PMI and fracture surface, PMI and fracture angle, overall assessment and fracture surface, and overall assessment and fracture angle. Before performing statistical analyses, the categorical data were scored as 1, 2, or 3 (see Table 2). Agresti (21) suggests that it is often advantageous to treat ordinal/qualitative data in a quantitative manner when assessing correlative strengths and values.

Results

Bone Moisture Content

The average ash percentage of the bones increased dramatically from PMI 0 to PMI 28 (17–40%) and then generally leveled off. In other words, moisture content decreases rapidly for nearly 2 months, after which the drying process continues but at a slower rate (Fig. 1). Using linear regression, the correlation (R^2) between %AW and PMI is only 0.45, but it increases to 0.76 when a third power polynomial regression is utilized. The curved nature of the data is apparent in Fig. 1. However, even this correlation may be artificially low because of above average precipitation during August and the heavy precipitation on two collection days (Table 3). The samples from PMI 57 and PMI 141 were collected on days with precipitation. Like other collection days, the bones were placed directly into plastic bags and then analyzed for %AW. This process most likely artificially deflated the %AW of these particular samples. To determine how the collection method affected the ash weights, a small sample of dry porcine long bones (from animals dead more than 4 years) was examined under different conditions. Ash weight was determined on a fragment of one of the dry bones to represent "dry" postmortem bone. Two other bones were soaked for 24 h to simulate a long rain. After 24 h, the bones were

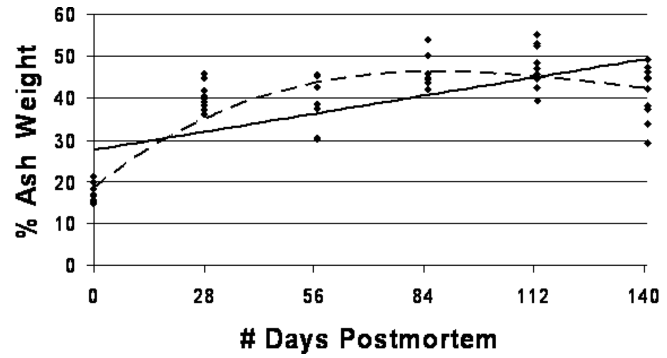

FIG. 1—*Plot illustrating changes in percent ash weight with time with linear (solid) and 3rd degree polynomial (dash) regression lines.*

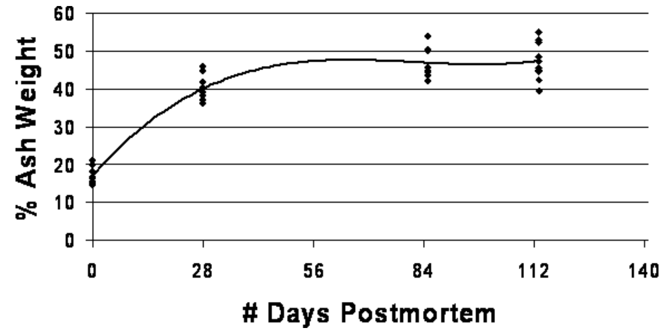

FIG. 2—*Plot illustrating changes in percent ash weight and 3rd degree polynomial regression line when PMI 57 and 141 data are removed.*

removed from the water, and two sections of each bone were removed. A section of each soaked bone was air dried for 24 h, while the other was damp dried with a paper towel and placed in a plastic bag. The bone soaked in water for 24 h and not dried prior to ashing had a significantly lower %AW than the "dry" bone or the "air dried" soaked bone. This suggests that the correlation between bone moisture content (%AW) and PMI is even greater than indicated. If these two trials are dropped as shown in Fig. 2, the correlation between bone moisture content and length of decomposition increases significantly ($R^2 = 0.93$). However, the small sample size should be taken into consideration here.

Fracture Characteristics

The majority of fractures were complete resulting in two or more fragments, with many specimens displaying comminuted fractures and 20 or more fragments. Fracture appearances changed throughout the study from fractures with smooth surfaces and obtuse or acute angles and curved or V-shaped outlines to fractures with jagged surfaces, more right angles, and fewer curved or V-shaped outlines (Table 4).

Ash weight, fracture surface appearance, and fracture angle all show a significant positive correlation with PMI (Table 5). However, the *post hoc* tests do not indicate an entirely consistent pattern. The lower than expected ash weight means for PMI 57 and PMI 141 may be due to collection procedures. Fracture surface means also fluctuate but still separate the bones in early decomposition from those in more advanced stages, and the most advanced stages from bones in the other PMIs. Fracture angle shows the

TABLE 2—*Fracture characteristics recorded.*

Observation	Abbreviation	Categories
Fracture angle	FA	Acute, obtuse, acute & obtuse (1), right & acute, right & obtuse (2), right only (3)
Fracture surface	FS	Intermediate (1), jagged (2), smooth (3)
Fracture outline	FO	Curved and v-shaped (1), intermediate (2), transverse (3)

TABLE 3—*Monthly precipitation and temperature data from the National Climatic Data Center website* for the study location.*

Month	Total Precipitation†	Deviations from Average†	Days with Precipitation	Daily Average Precipitation†	Average Maximum Temperature‡	Average Minimum Temperature‡
June	4.66	+0.64	2	0.16	86.5	64.5
July	0.62	−3.18	5	0.02	92.4	66.8
August	10.19	+6.44	10	0.33	88.5	67.7
September	5.60	+2.18	4	0.19	81.5	61.0
October	2.97	−0.21	5	0.10	66.8	46.9
November	1.08	−2.39	7	0.04	57.2	36.2
Average	4.19	–	5.5	0.14	68.8	57.2

*http://www.ncdc.noaa.gov/oa/ncdc.html.
†Inches.
‡Degrees Fahrenheit (°F).

TABLE 4—*Summary of bone assessment and fracture surface, angle, and outline appearances.*

Trial	Assessment			Surface Appearance			Angle Appearance			Outline Appearance		
	PER*	Inter†	PST‡	Smooth	Inter†	Jagged	Obtuse and Acute	Right Mix§	Right	Curved or V-Shaped	Inter†	Trans¶
PMI 0	10	0	0	33	0	4	33	0	4	10	0	0
PMI 28	9	0	1	31	1	3	35	0	0	9	0	1
PMI 57	6	2	2	18	8	12	32	3	3	8	0	2
PMI 85	1	4	5	15	9	13	26	2	9	5	3	2
PMI 113	1	3	6	19	1	14	20	2	12	4	3	3
PMI 141	0	0	10	0	0	31	16	9	6	6	3	1
Total	27	9	24	116	19	77	162	16	34	42	9	9

*Perimortem.
†Intermediate.
‡Postmortem.
§Right Mix—either right and acute or right and obtuse.
¶Transverse.

TABLE 5—*Relationship between PMI and primary fracture characteristics.*

Variable	F-statistic	*p*-value	R^2	Paired Group Differences*
%AW	46.53	<0.0001	0.4356	$113^A > 85^A > 141^B > 28^B > 57^B > 0^C$
FS	79.17	<0.0001	0.5699	$141^A > 113^B > 85^B > 57^B > 0^C > 28^C$
FA	18.84	0.0002	0.2452	$113^A > 141^{AB} > 85^{AB} > 57^{BC} > 0^{BC} > 28^C$

*PMI ordered from largest to smallest mean value. Intervals with the same letter superscript do not differ significantly.

most overlap between PMI trials and inconsistent groupings (Table 5).

Chi-square results show that significant changes in fracture surface morphology ($\chi^2 = 113.4$, DF = 10, $p < 0.0001$) and fracture angle ($\chi^2 = 48.0$, DF = 10, $p < 0.0001$) occur during decomposition. As the bone decomposes and dries, the occurrence of fractures with smooth fracture surfaces decreases and the frequency of jagged surfaces increases (Table 4). The occurrence of fractures with an acute or obtuse angle also decreases, but acute/obtuse angles remain predominate throughout the study period. Although there is a general trend towards less curved or V-shaped fracture outlines as PMI increases, the overwhelming majority of the specimens analyzed manifested curved or V-shaped outlines. Furthermore, the Chi-square results do not show a significant relationship between fracture outline and PMI ($\chi^2 = 15.5$, DF = 10, $p = 0.1125$).

Overall Assessment of Fracture Timing

Each bone was assessed to determine if the fracture characteristics were more typical of those described as perimortem, intermediate, or postmortem. ANOVA results suggest a significant correlation between the PMI and the predicted category or overall assessment ($F = 45.18$, $p < 0.0001$, $R^2 = 0.61$) and between ash weight and the overall assessment ($F = 15.93$, $p < 0.0001$, $R^2 = 0.36$). Fractures assessed as perimortem had a significantly shorter PMI and lower %AW.

Bone Moisture Content and Fracture Characteristics

Analysis of variance was conducted to determine if ash weight percentage correlated with the way bones fractured when subjected to blunt force. Results indicate that there is a significant positive correlation between %AW and both fracture surface appearance ($F = 9.31$, $p = 0.0034$, $R^2 = 0.14$) and fracture angle ($F = 7.39$, $p = 0.0086$, $R^2 = 0.11$). The correlation is not particularly high for either, but this may be attributed to collection protocol (collection on rainy days).

Assessment by Forensic Anthropologists

Twenty-two forensic anthropologists examined a set of 10 bones and assessed if the fracture was perimortem or postmortem in appearance. Correct assignment of the bones ranged from three to ten, with an average score of 6.8. The participants were also asked to provide information on the characteristics they used in the evaluation. The main characteristics reported, in order of frequency, were: the appearance of the fracture margin or edges, the primary shape of the fracture outline, color differences between fracture surface and bone surface, whether or not the fracture was complete, the appearance of the fracture surface itself, whether or not there was a visible impact site on the bone, and whether or not the bone showed evidence of plastic deformation near the fracture location. Fracture edge was used by 12 participants and fracture outline and color were used by nine. Only one participant reported using plastic deformation as a characteristic to determine the timing of the fracture. Participants that used fracture surface morphology as an indicator had the highest number of correctly assigned bones.

Discussion

Anthropologists use a variety of characteristics to distinguish between perimortem and postmortem skeletal fractures (e.g., color, fracture outline, fracture surface appearance, and fracture angle). Yet, little research has been conducted to determine how bone changes over time and how these changes relate to fracture morphology. This study examined the rate at which bone dries after death when allowed to decompose on the surface during the summer and autumn months in mid-Missouri, and how changes in moisture content affect fracture characteristics commonly used to distinguish between perimortem and postmortem fractures.

In general, there is a continuous transition in fracture morphology associated with the time after death. Fracture appearance changed from fractures with predominately smooth surfaces, obtuse or acute angles, and curved or V-shaped outlines to fractures with jagged surfaces, more right angles, and fewer curved or V-shaped outlines over 5 months. As a result of these changes, bones fractured near death (PMI 0) appear to be detectable as perimortem and bones fractured 5 months postmortem (PMI 141) have clear dry bone fracture characteristics. However, bones fractured between the two terminal intervals present significant ambiguity in terms of injury timing determination. Bones fractured at 28 days postmortem are almost indistinguishable from those fractured at PMI 0. Bones broken at PMI 57–113 often exhibit both perimortem and postmortem characteristics—or, more precisely, "fresh" and "dry" bone characteristics. For example, of the 10 bones fractured at 57 days (PMI 57), six exhibited primarily perimortem, two postmortem, and two intermediate characteristics. These results suggest there is likely a long period when determining the timing of a fracture event is imprecise at best.

Fracture surface appearance showed the greatest degree of difference between the trials with fracture surfaces changing from smooth to jagged with increasing PMIs. Likewise, the forensic anthropologists that indicated using fracture surface morphology as a definitive character when making an injury timing determination had the greatest success (greatest number of correct responses). Nevertheless, jagged surfaces occurred in bones broken immediately after death and smooth surfaces persisted in bones fractured at 141 days. The smooth fracture surface appearance in fresh bone is related to the structure of collagen.

Bones fractured while fresh are widely assumed to manifest acute or obtuse angles, while bones fractured when dry exhibit right angles. Fracture angle appearance did change significantly during the decomposition process in this study. However, bones broken perimortem did exhibit some (less than 25%) right angles, and bones fractured at 141 days postmortem possessed some acute and obtuse angles (Table 4). It is clear that the frequency of acute and obtuse fracture angles decreases as the bone dries, but it is probably not until a bone is mineralized that the fracture angles are exclusively right (9,13,14).

Relationship Between Bone Moisture and Fracture Characteristics

Fracture surface appearance and fracture angle both correlate significantly with the moisture content of bone. Bone moisture content decreases rapidly for the first few months after death and then continues to dry (albeit at a much slower rate) for at least 5 months and probably longer. The rate at which the bone dries and how it affects fracture characteristics is probably dependent on local environmental conditions. However, the results of this study suggest that bone does not cease to react like living tissue at the moment of death. As a material, bone retains moisture and organic compounds that allow it to maintain many of the properties (e.g., ductility, pliability, and elasticity) it possessed during the organism's life that affects how bone reacts to traumatic blunt force.

While there is a significant correlation between bone moisture content and fracture characteristics, the relatively low correlation suggests that moisture content is probably not a causal factor in fracture pattern, but instead a related factor. Intact collagen gives bone a homogeneous nature and greatly affects the way the bone reacts to strain resulting from blunt trauma. Moisture content is probably an indicator of collagen decomposition. In this study, part of the low correlation is probably also associated with not allowing samples collected on days with precipitation to fully dry.

Forensic Anthropological Implications

The results of this study indicate that bone retains "fresh" properties long after death. Our results indicate that bones do not consistently manifest "postmortem" characteristics until 141 days postmortem. As bones maintain fresh bone properties long after death and these properties are associated with perimortem fractures, caution should be exercised when determining fracture timing.

No single morphological characteristic of a skeletal fracture appears to provide an accurate injury timing determination. As a result, anthropologists should use multiple characteristics that are weighted based on their accuracy. Not all fracture characteristics endorsed by anthropologists provide the same insight into trauma timing.

Perhaps the use of the terms "postmortem" and "perimortem" are not analytically useful terms in forensic anthropology for describing fracture morphology. The term perimortem, while well defined, is ineffective because it refers to a temporal period instead of a physical condition (fresh or dry). Maybe it is more appropriate for forensic anthropologists to discuss fractures only as occurring on fresh or dry bone. Morin et al. (22) correctly point out, "identifications of green- versus dry-bone fractures are no more than probability statements." Yet, anthropologists do not have a valid method for assigning a probability to the likelihood of a fracture being perimortem or postmortem. The results of the assessment of the porcine bones by forensic anthropologists suggest that there is not even a consensus among anthropologists regarding the best characteristics to use when attempting to determine fracture timing. There is a marked need for clear terminology and research on the relationship between fracture characteristics and decomposition processes.

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