University of Nevada, Reno

Evaluation of Bone's Response to Force: Fracture Type, Fracture Location, and Fracture Severity Across the Female Lifespan

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in Anthropology

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Abstract

Trauma analysis and interpretation is a key component for forensic anthropologists and pathologists during any analysis of remains. Though studies have identified a positive relationship between increased age and higher risk of fracture, the field of anthropology is lacking a deeper understanding of how bone responds to force based on application of intrinsic and extrinsic factors. The current study evaluated the change in fracture type, location, and severity in women, exploring how endogenous hormones may impact bone's response to force. Data were collected from the Washoe County Regional Medical Examiner's Office and the Reno Orthopedic Clinic and included a sample of 263 women between the ages of 20 and 80 years. The analyses were separated by menopausal state (assumed by chronological age), by age decades, and by institution. The relationship between increased age and fracture location on bone was found to be statistically significant, indicating fracture location shifts with age. Additionally, fracture completeness is positively related to an increase in age. This research can be used to aid anthropologists in the future to facilitate a deeper understanding of trauma and how variation in intrinsic factors impact how bone responds to force.

Acknowledgements

Firstly, I would like to thank my advisor Dr. Kyra Stull, for her endless support and encouragement throughout these past two years. I would also like to thank forensic anthropologist Dr. Laura Fulginiti for taking me under her wing, believing in me, and advocating for me. I would not be the scientist I am today, nor possess the knowledge I do without the continued support from Dr. Stull and Dr. Fulginiti. Additionally, I would like to thank my parents and my sister for spending countless hours with me over the phone, encouraging me to persevere and believing in me.

For supporting my research, I would like to extend my thanks to the Reno Orthopedic Clinic, the Washoe County Regional Medical Examiner's Office, and Dr. Laura Knight. Without their assistance and collaboration my data collection and findings would not have been possible.

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Introduction

Trauma interpretations are critical in bioarchaeology (e.g., Martin & Harrod, 2015; Martin, Harrod, & Perez, 2012) , paleontology (e.g., L'Abbé et al., 2015), and forensic anthropology (e.g., Agnew et al., 2013; Agnew et al., 2014; Christensen, 2004; Christensen et al., 2019; Christensen et al., 2022; Harden et al., 2022; Hulse et al., 2019; Lesciotto, 2015; Love & Wiersema, 2016). Especially in forensic anthropology, it is imperative that the trauma interpretation is valid, and results are from a holistic understanding about the contribution of intrinsic and extrinsic factors of bone's response to force (Christensen et al., 2022; Kim, 2021). Externally applied force broadly categorizes trauma, such that there are differences in bone's response to rapid (gunshot trauma) and slow load forces (blunt trauma) (Kranioti, 2015; McNulty, 2016.). Most research is dedicated to further exploring blunt trauma, which is partly because of how complicated interpreting blunt force trauma can be and because it is frequently encountered by forensic anthropologists (Crowder et al., 2016). Efforts have been made to improve our understanding of blunt force injury patterns across the entire body (Hulse et al., 2019) and within specific elements, such as the ribs (Agnew et al., 2013; Agnew et al., 2014; Hulse et al., 2019), the tibia (Harden et al., 2022), and the crania (Isa et al., 2019). Trauma research generally follows a case-studies approach, that offers a large sample and real-life scenarios, or an experimental approach, that can control for demographic variables and/or external forces.

Trauma interpretations are recommended to be based on scientifically valid methods and principles, as for the latter, it usually implies biomechanical principles (Christensen et al., 2022; SWGANTH, 2019), which are dependent on the structural and material properties of bone, or the intrinsic factors. Bone has been described as viscoelastic, or that it exhibits both viscous and elastic characteristics under deformation. Young’s modulus, which is described as an object’s measure of elasticity when subjected to tensile or compressive forces, can be applied to bone when evaluating its resilience to stressors. A stress-strain curve demonstrates bone ductility in two phases. The first phase, elastic deformation occurs when stress is added to bone. In this phase bone will respond by bending and will return to its normal morphology if the stress is removed (Christensen et al., 2019; Lin & Kang, 2021; Symes et al., 2012). The second phase, plastic deformation occurs when continuous stress is added. During this phase, structural damage has occurred and if the stress is removed, bone will not return to its normal morphology. At the junction of the elastic and plastic deformation phases is the yield point, where properties of bone undergo an irreversible change, with no possibility of returning to normal morphology (Lin & Kang, 2021; Wolfram & Schwiedrzik, 2016). When the amount of stress applied to the bone exceeds the amount of force the bone can withstand, fracture occurs; this is deemed the fracture point. It is important to note that bone will not fracture until the amount of stress exceeds the forces bone can withstand. Bone will either make a full recovery or a partial recovery (depending on the phase) if stress is removed prior to the fracture point. The trajectory of failure in the young’s modulus is dependent on the structural and material properties of the bone. On a cellular level, bone consists of two matrices that lead it to be a brittle, yet ductile tissue with properties that require it to be stiff to resist loading, but also flexible to absorb and dissipate force (Symes et al., 2012; Seeman & Delmas, 2006). The organic matrix is composed of collagen, providing the bone with elasticity. The inorganic matrix is composed of minerals, primarily hydroxyapatite, providing the bone with strength and rigidity. The interaction between the matrices allows for the elastic and plastic behavior exhibited by bone, regardless of its size and shape (Burr, 2002; Florencio-Silva et al., 2015).

In addition to the cellular composition of bone, there are two types of bone that contribute to the overall morphology and structure. The first is cortical bone, which is present on the external surface of all bones. In bones such as the femur, the cortical bone is wider and denser on the diaphysis, which is required to prevent fracturing of the bone under weightbearing stress. There is a much thinner layer of cortical bone present at the epiphyseal and metaphyseal regions, where there is a larger proportion of the second type of bone, which is cancellous or trabecular bone (Seeman & Delmas, 2006). Cancellous bone is a highly vascularized and porous material that has a plate-like/needle-like structure, whereas cortical bone has little vascularization because of its dense nature. Because proper growth and development during the juvenile stage requires adequate blood flow, the highly vascularized nature of trabecular bone makes it the preferred option for optimal blood flow to the epiphyses and metaphyses (Hendriks & Ramasamy, 2020; Lafage-Proust et al., 2015; Ott, 2018). Histologically, cortical and cancellous bone demonstrate further differences in their composition of osteons and collagen. The basic structural units that comprise cortical bone are osteons. In long bones, the orientation of osteons are parallel as this provides the bone with the greatest amount of strength (Stockhausen et al., 2021). Contrary to the organized, structured pattern displayed by osteons in cortical bone, osteons in cancellous bone are laid down along the direction of force (Buchwald et al., 2012). While the orientation of osteons provides the bone with strength to resist added stress, the orientation of collagen fibers provide the bone with elasticity, and plays a crucial role in the ability of bone to resist fracture (Ritchie, 2011; Viguet-Carrin et al., 2006). In cortical bone, collagen fibers similar to osteons, are deposited in a parallel or circular orientation, allowing for the highest density of collagen per unit, ultimately increasing the strength of the bone (Moreira et al., 2000). In cancellous bone, the orientation of collagen fibers is random and unevenly spaced, giving a “woven” appearance

(Moreira et al., 2000). Though the two types of bone are compositionally similar, the orientation of the collagen fibers impacts how each type will respond to force. While collagen has an increased ability to absorb and dissipate energy, the inorganic matrix with high mineral content, is crucial in determining stiffness of a bone (Viguet-Carrin et al., 2006). Tightly packed lamellar bone (cortical bone) responds with a higher resistance to stress and a lower resistance to strain (Hart et al., 2017; Rho et al., 1997; Wu et al., 2012; Zysset et al., 1999), whereas the random, irregular deposition of collagen (trabecular bone) responds with a higher resistance to strain and a lower resistance to stress (Hart et al., 2017; Rho et al., 1997; Wu et al., 2012; Zysset et al., 1999). A higher resistance to strain indicates a greater ability to deform or displace, yet due to a decreased bone volume per total volume, failure is more likely to occur in the trabecular bone (Oftadeh et al., 2015).

Intrinsic factors, or the demographics of the individual, including age and sex, influence the way in which bone responds to stress. Recent anthropological literature highlights clear patterns between increase in fracture and increasing age in females (Hulse et al., 2018). An increase in fracture risk with age is not only commonly reported in the literature, but regularly stated (Gioffrè-Florio et al., 2018). The commonality of such a statement begs for a deeper understanding for the relationship among hormones, age, sex, and fracture morphology.

Bone and Endogenous Hormones

While the molecular composition of bone largely impacts how bone responds to force, the hormonal influence is also important to consider, and specifically how that modifies the molecular composition and the bone mineral density. Menopause occurs in women universally and is defined as the cessation of a menstrual cycle for twelve consecutive months (Gold et al., 2011). This cessation reflects the cessation of ovulation, resulting in reduced ovarian production of estradiol, decreased levels of inhibin, and increased levels of circulating follicular stimulating hormone (FSH) (Gold et al., 2011). Follicular stimulating hormone, inhibin, and estrogen work together in a negative feedback loop termed the HPG axis (hypothalamic-pituitary-gonadal axis). In this loop, the hypothalamus secretes gonadotropin releasing hormone (GnRH) which stimulates the anterior pituitary gland to release FSH and luteinizing hormone (LH). A rise in FSH and LH stimulate the gonads to release estrogen, testosterone, and inhibin. Inhibin affects both the hypothalamus and the anterior pituitary gland to prevent the release of GnRH, FSH, and LH. Blocking the release of FSH prevents the stimulation of the gonads to release estrogen, therefore estrogen levels decline, and FSH levels remain high (Klein, 2003). Estrogen functions in the body as a regulator of bone formation by aiding in osteoblastic activity and inhibiting osteoclastic activity at multiple cellular levels, ultimately leading to an increase in bone mineral density (BMD) (Khosla et al., 2012; Kim et al., 2021). With inhibition of estrogen at menopause, osteoclastic activity increases and osteoblasts are unable to match the rate at which bone is being broken down.

The process of bone remodeling is necessary to maintain bone strength and stability. During remodeling, osteoclastic activity is increased at sites of microfracture caused by natural stress and aging. Naturally, the loss of bone volume is compensated by periosteal apposition via osteoblasts. Loss of endogenous estrogen inhibits osteoblastic activity, leading to continuous uptake of bone via osteoclasts without reciprocating osteoblastic activity (Aeberli & Schett, 2013). Ultimately, bone density is lost and bone strength is compromised. It has been found that compared to pre-menopausal women who still have adequate bone mineral density, post-menopausal women are two times more likely to sustain fractures (Cauley et al., 2015). In post-menopausal women, fracture risk continues to increase as an individual ages; there is a 7x more likely risk of fracture in women 70 to 74 years of age compared to women 50 to 54 years of age (Banks et al., 2009).

The knowledge of fracture risk is informative, but it does not facilitate the interpretation for the anthropologist, which is why there is a gap in the knowledge regarding how fracture location and morphology change with increasing age among females. By documenting blunt force injury patterns (severity, location, and type) through the lifespan, one can elucidate trends to facilitate interpretation that considers both biology and biomechanics, moving anthropologists beyond a descriptive analysis of injuries and towards probabilistic interpretations. The overall objective of the current study is to create a foundation for understanding the variation of traumatic injuries and how they vary through the female lifespan by evaluating their type, location, and severity. The specific aims of the project are: 1) a quantification of fracture patterns in the female lifespan, 2) an understanding of how bone fails differently because of hormone changes and bone density loss, and 3) statistical substantiation for interpretation of fracture patterns.

Materials

Data were collected from a total of 353 fractures from two collaborating institutions: the Reno Orthopedic Clinic (ROC) and the Washoe County Regional Medical Examiner's Office (WCRMEO). Of the total sample, 258 (73.09%) women were living individuals from the ROC, and 95 (26.91%) women were decedents from the WCRMEO (see Table 1).

Inclusion criteria was used in the process of selecting individuals from each institution. These consisted of:

1) individuals that were biologically female;
2) individuals between the ages of 20 and 80 years at the time of fracture (born between 1940 and 2000);
3) individuals who sustained a fracture between 01/01/2015 and 12/31/2020;
4) individuals who sustained a fracture in one of the six long bones being evaluated (humerus, radius, ulna, femur, tibia, fibula);
5) individuals who were not pregnant at the time of fracture; and
6) a) living sample (ROC): data must be collected on initial radiograph, prior to corrective surgical intervention;
   b) deceased sample (WCRMEO): individuals must have been x-rayed and the case must have been reviewed by the Medical Examiner.

If all inclusion criteria were met, the individual was included in the study. The Institutional Review Board (IRB) at University of Nevada, Reno determined this study qualified for exemption in category 4(ii) under the IRB at the University of Nevada, Reno because of collection of data with no identifiers and no possible means of re-identification, even if some of the individuals were living at the time the medical images were generated. Therefore, notification in the study was not required for those who had been selected.

Methods

Fracture data were collected from X-ray images of each individual’s injury was obtained using the institutions’ respective DICOM software, and demographic and incident information was collected from the medical chart of the individual. Demographic information included age (years), height (inches), weight (pounds), and social/health factors, such as diabetes, obesity, smoking, etc. Because of the interest to explore hormonal changes, age was used differently for different analyses. Age at fracture was used to categorize the sample into menopausal groups (pre-, peri-, and post-menopausal) and age groups by decades were also utilized. Menopause was not a known variable in the sample, so the age at menopause was estimated based on statistical findings from the Study of Women's Health Across the Nation (SWAN, 2022). Though not exact, multiple studies have found that the age at natural menopause is approximately 51 years, with menopausal changes occurring one year prior and two years after the final menstrual period (Cauley et al., 2015; Gold et al., 2013; Karlamangla et al., 2018; Peacock & Ketvertis, 2022). Age at natural menopause is highly variable and dependent on social, demographic, and biological factors, therefore a slightly wider range was needed. The pre-menopausal age group comprised of women ages 20 to 45 years; the peri-menopausal age group comprised of women ages 46 to 51 years; and the post-menopausal age group comprised of women ages 52 to 80 years. Age was also explored on a more nuanced level, which is why some analyses used age decades for additional tests. The age decades in the current study consisted of nine year differences (20 to 29 years, 30 to 39 years, etc.), except for the final decade which had a difference of ten years (70 to 80 years).

Fracture data included: bone, fracture location on bone, type of fracture, and severity of fracture. Initial classifications began by noting the bone that was fractured and its general location on the bone, which was identified by its distance measured from the nearest anatomical landmark (*e.g.*, most lateral point on the lesser trochanter, or most distal point on the lateral malleolus). The fracture type was classified using common forensic anthropological fracture classifications (transverse, oblique, spiral, comminuted, and butterfly), as well as longitudinal and avulsion (Christensen et al., 2019). The fracture location on each bone was estimated according to the total length of the bone and was categorized as proximal, midshaft, or distal. Fractures occurring approximately in the upper fourth section of the bone were classified as proximal. Likewise, fractures occurring approximately in the lower fourth section of the bone were classified as distal. Fractures occurring between the margins of the proximal and distal segments were classified as diaphyseal.

The common anthropological fracture classifications were then compared to the classifications system from the American Journal of Orthopedic Trauma Fracture and Dislocation Classification Compendium (simple, multi-fragmentary, wedge, and avulsion) (Meinberg et al., 2018), which is a standardized system used by orthopedists. Differences between the Orthopedic Trauma Association's (OTA) classification of fractures and classification of fractures made by forensic anthropologists are apparent. Classifications in the Fracture Compendium consist of highly descriptive definitions and the classes are highly structured, whereas anthropological classifications are rather broad categorizations.

Following classification and identification of the fracture, variables such as angulation (in degrees), impaction/distraction (in centimeters), and displacement (anatomical direction in centimeters) were measured using tools provided in the institutions DICOM system. Greater measurements of these variables would be suggestive of higher force, leading to more severe fractures. In addition to classifying severity by measurement, use of the Fracture Compendium also provided a scale of severity. A broad categorization of severity was interpreted using letters (A,B,C) and these categories were further broken down into numbers (1,2,3). A progression of letters and numerical values indicated a greater severity of fracture.

Statistical Analysis

The data comprises continuous and discrete variables. The following variables were considered discrete: 1) bone; 2) fracture type; 3) age decade; 4) fracture location; and 5) menopausal group. The remainder of the variables: 1) weight; 2) height; 3) angulation in degrees; 4) impaction/distraction in centimeters; and 5) displacement in centimeters, were considered continuous variables. For statistical comparison, age decade was also used as a continuous variable.

The fracture data (*i.e.*, bone, fracture type, fracture location) was explored primarily by menopausal group and age decade using a chi-squared test of independence. A Fisher's exact test was used with variables containing smaller amounts of data, specifically less than five observations within a category. Fisher's exact test was primarily used in analyses evaluating fracture patterns by institution (*i.e.*, ROC vs WCRMEO). Both the chi-squared test of independence and the Fisher's exact test are used to identify a relationship between two variables, computing their degree of relatedness (Soetewey, 2020; Kim, 2017). Because the chi-squared test of independence applies an approximate relationship between two variables, a Fisher's exact test is preferred as it provides an exact result, rather than an estimation (Sotewey, 2020; Kim, 2017). One difference with the Fisher's exact test is that it can only be used with small samples, whereas a chi-squared test of independence can be used for samples of any size. Age was categorized for the Chi-squared and Fisher Exact tests, but because it is also a continuous variable, a Kruskal-Wallis test, which is used for identifying relationships between two or more groups, was also utilized. A significant ($p < 0.05$) Kruskal-Wallis test would indicate there were different median ages per categorical variables used in the test. A p-value of less than 0.05 was considered significant for all analyses. A significant p-value verified a dependent relationship between the two variables being tested (*e.g.*, an increase in age is directly correlated to an increase in fracture risk) (Nahm, 2017).

The *stats* (R Core Team, 2022) package was used for statistical analyses. Functions *chisq.test*, *fisher.test, and kruskal.test* were used to obtain the p-value between the desired variables. Analyses were visualized using the *ggplot2* (Wickham, 2016) package. Visualizations included bar graphs, scatterplots, and bubble plots. R and RStudio version 1.4.1103 were used to identify statistical relationships between the variables as well as visual interpretations of the data.

Results

A total number of 353 fractures were evaluated on 263 individuals (Table 1). Most of the individuals had one fracture, however 90 individuals sustained two or more fractures (n = 72/ROC, n = 18/WCRMEO). Only one individual (1.39%) at the ROC sustained six or more fractures, while seven individuals at the WCRMEO sustained six or more fractures (38.89%). All bones exhibited fractures though the tibia and fibula presented with the largest number of fractures (24.93% and 25.5% respectively), closely followed by the radius (17.85%); the ulna presented with the smallest number of fractures (5.95%). Even though some fractures occurred on the same individual, for the purpose of this study, all fractures were evaluated as independent events. Future research will evaluate the covariation among fracture types, location, severity on the same individual. The following analyses exploring bone fractured, fracture location, severity of fracture, and fracture type are all presented based on the menopausal state, by age decades, and by institution. The age was categorized into decades because the sample of peri-menopausal women was significantly smaller than the pre- and post-menopausal samples as well as knowing the negative effects of modified hormones has an accumulated effect, the sample was separated into decades.

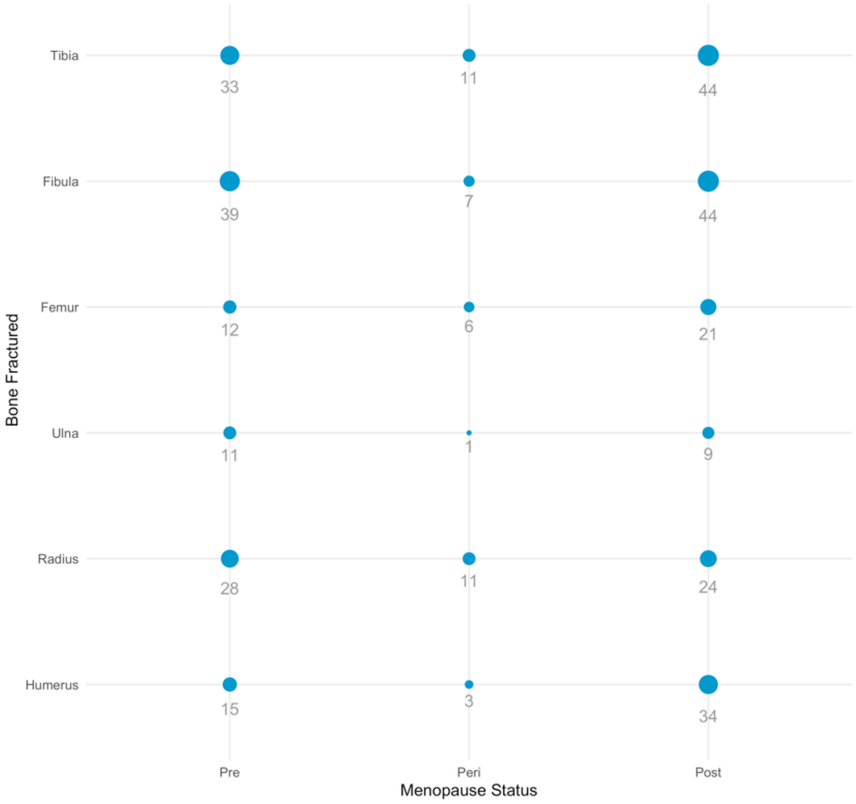
Table 1: Number of individuals at each institution per decade of life							
	Decade (Years)						
Institution	20-29	30-39	40-49	50-59	60-69	70-80	Total
WCRMEO (ME)	7	32	8	9	17	22	95
ROC	35	38	43	51	51	40	258
Total	42	70	51	60	68	62	353

Bone Fractured

The number of bones fractured in each menopausal stage allows us to understand how the relationship between menopausal stage and risk of bone fracture may change (Table 2, Figure 1). Raw counts reveal that the tibia, fibula, and radius present with the largest number of fractures. Because the menopausal subsets have such different sample sizes, especially the peri-menopausal group having such fewer individuals, the counts were calculated into percentages. From the percentages of fractures, one can conclude that the tibia and the fibula are two of the most fractured bones regardless of life history stage.

Table 2: Counts and percentages of fractures per bone and menopausal group.

	Bone						
Menopausal Group	Humerus	Radius	Ulna	Femur	Tibia	Fibula	Total Count/ Total Percentage
Pre-Menopausal	15 4.25%	28 7.93%	11 3.12%	12 3.40%	33 9.35%	39 11.05%	138 39.09%
Peri-Menopausal	3 0.85%	11 3.12%	1 0.28%	6 1.70%	11 3.12%	7 2.0%	39 11.05%
Post-Menopausal	34 9.63%	24 6.80%	9 2.55%	21 5.95%	44 12.46%	44 12.46%	176 49.86%
Total Count/Total Percentage	52 14.73%	63 17.85%	21 5.95%	39 11.05%	88 24.93%	90 25.51%	353 100%



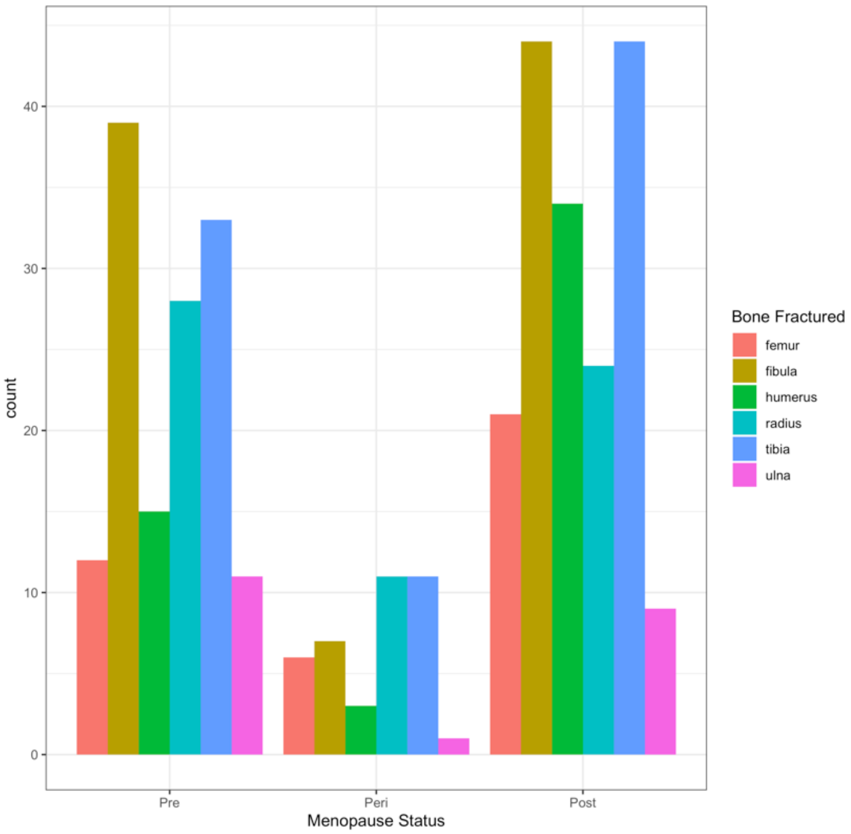


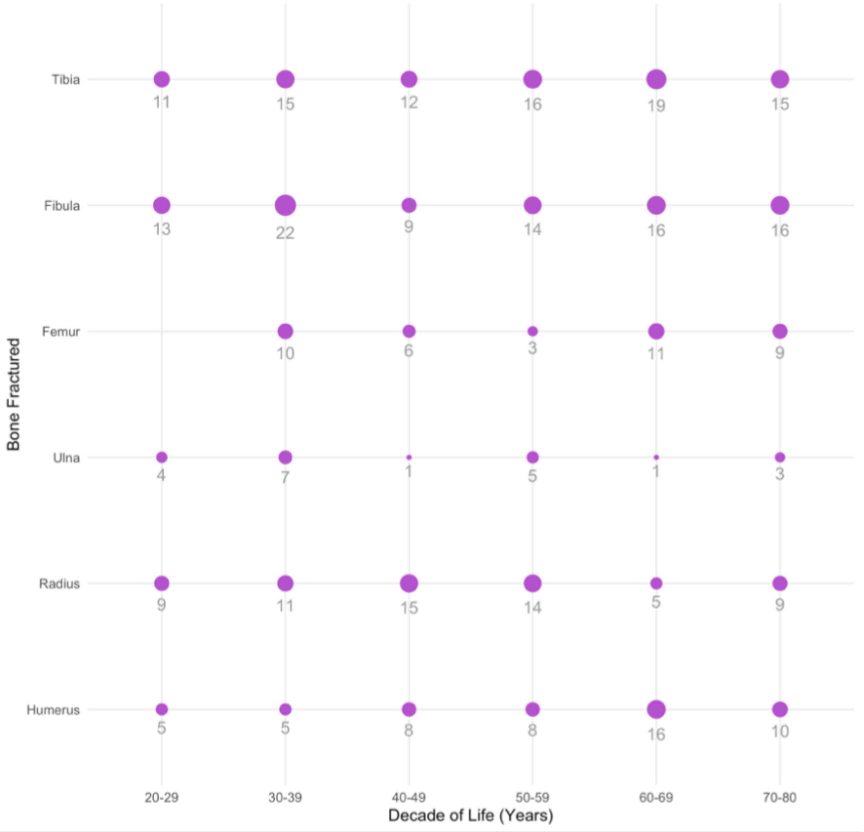
Figure 1: Visualization of number of fractures per bone per menopausal stage using a bubble plot (top) and bar plot (bottom).

Table 3 and Figure 2 show that even with expansion of the data into decades, the tibia and fibula were consistent in their fracture rate regardless of age though there is a slight increase of fractures from ages 20 to 69 years. Instances of radial fractures increased with age until the sixth decade (60 to 69 years) with their highest occurrence from ages 40 to 49 years. Instances of humeral fractures almost doubled from the fifth to the sixth decade after slight increases up to the fifth decade. Femoral fractures did not demonstrate the expected pattern, and instead displayed fluctuations among age groups.

The relationship between menopausal status and bone fractured were not found to be statistically significant (p-value = 0.14) in the chi-squared test. However, when using decade of life and age as a continuous variable, the relationships were significant. Specifically, decade of life and bone were found to be statistically significant with a p-value = 0.03 in the Fisher's exact test and age as a continuous variable and bone fractured were statistically significant with a p-value = 0.04 in a Kruskal-Wallis test.

Table 3: Counts and percentages of bone fractured during each decade.

	Bone						
Decade (Years)	Humerus	Radius	Ulna	Femur	Tibia	Fibula	Total Count/ Total Percentage
20-29	5 1.42%	9 2.55%	4 1.13%	0 0.00%	11 3.12%	13 3.68%	42 11.90%
30-39	5 1.42%	11 3.12%	7 1.98%	10 2.83%	15 4.23%	22 6.23%	70 19.83%
40-49	8 2.23%	15 4.25%	1 0.28%	6 1.70%	12 3.40%	9 2.55%	51 14.45%
50-59	8 2.23%	14 3.97%	5 1.42%	3 0.85%	16 4.53%	14 3.97%	60 17.00%
60-69	16 4.53%	5 1.42%	1 0.28%	11 3.12%	19 5.38%	16 4.53%	68 19.26%
70-80	10 2.83%	9 2.55%	3 0.85%	9 2.55%	15 4.25%	16 4.53%	62 17.56%
Total Count/Total Percentage	52 14.73%	63 17.85%	21 5.95%	39 11.05%	88 24.93%	90 25.49%	353 100%


Tibia
11
15
12
16
19
15
Fibula
13
22
9
14
16
16
Femur
10
6
3
11
9
Ulna
4
7
1
5
1
3
Radius
9
11
15
14
5
9
Humerus
5
5
8
8
16
10
Bone Fractured
20-29
30-39
40-49
50-59
60-69
70-80
Decade of Life (Years)

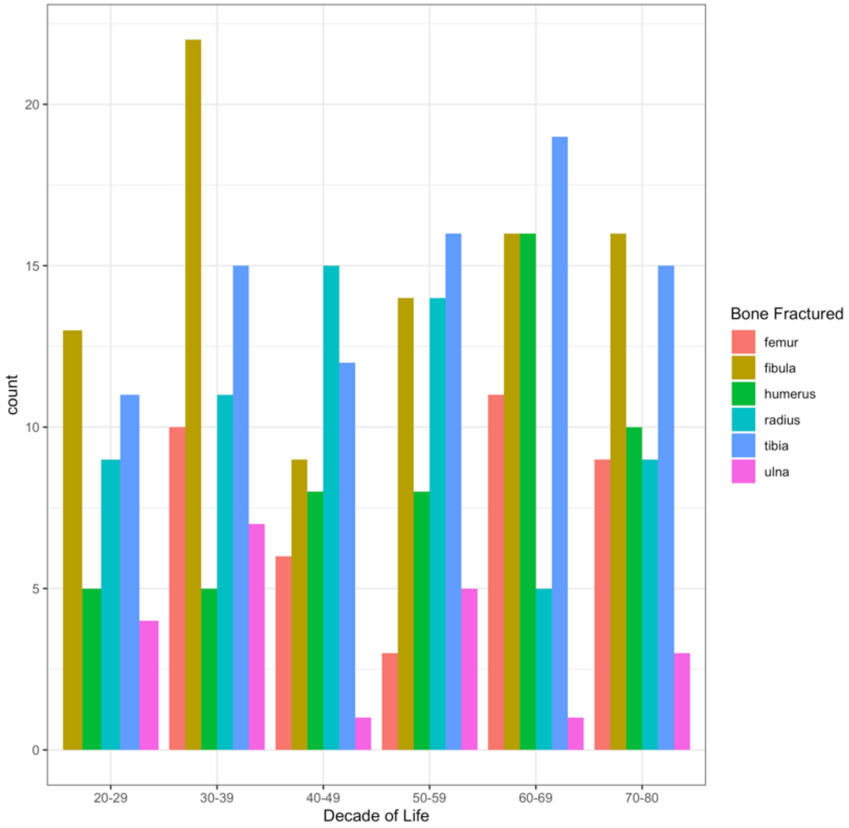


Figure 2: Visualization of number of fractures per bone per decade of life using a bubble plot (top) and bar plot (bottom).

Figure 3 displays the difference between bones fractured during each decade separated by institutions. In the ROC sample, which is a living sample, there is an increase in fracture occurrence from the fourth to seventh decade (40 to 69 years). In the deceased sample (WCRMEO), all weightbearing bones have the highest occurrence of fractures. A chi-squared test of independence identified a statistically significant relationship between which bones are fractured during each decade when the samples are first separated by institution (p-value < 0.001).

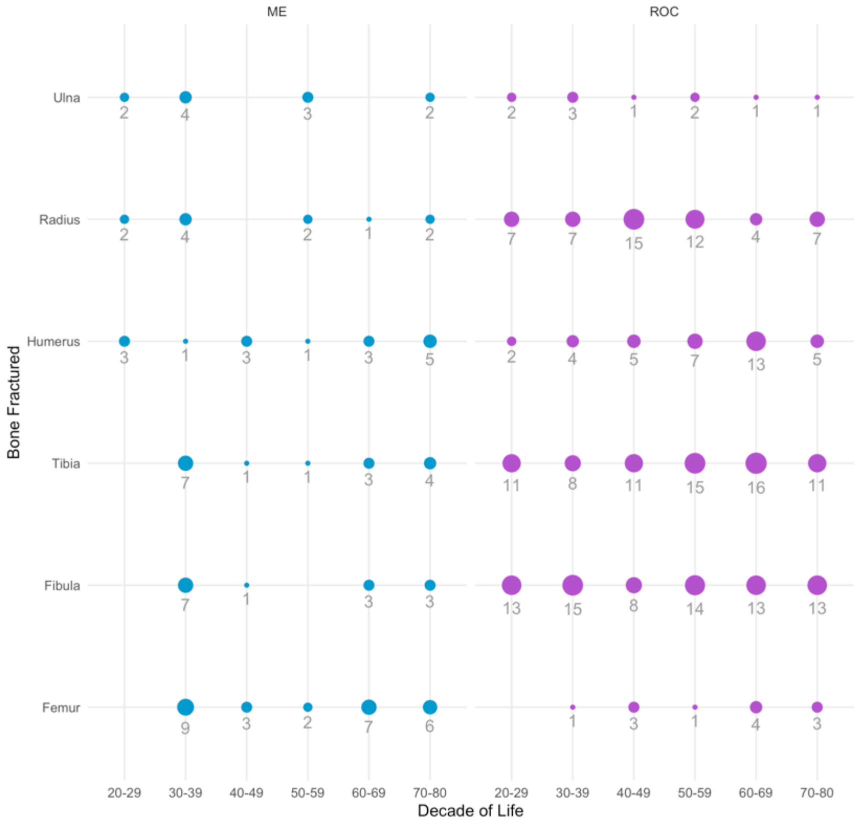


Figure 3: Relationship between bone fractured during each decade
(years) separated by institution

Fracture Location on Bone

Table 4 and Figure 4 reveal that prior to the menopausal transition, most fractures occur at the midshaft and distal locations. In contrast, the post-menopausal group displays a shift in locations. Instances of fractures located at the midshaft are surpassed by instances of fractures located at proximal locations; the distal location remained consistently high regardless of menopausal state. A chi-squared test between menopausal status and fracture location is statistically significant, with a p-value < 0.001.

Table 4: Counts and percentages of fracture location on the bone in each menopausal group.

	Fracture Location			
Menopausal Group	Proximal	Midshaft	Distal	Total Count/Total Percentage
Pre-Menopausal	19 5.38%	57 16.15%	62 17.56%	138 39.09%
Peri-Menopausal	5 1.42%	10 2.83%	24 6.80%	39 11.05%
Post-Menopausal	55 15.58%	39 11.05%	82 23.23%	176 49.86%
Total Count/Total Percentage	79 22.38%	106 30.03%	168 47.59%	353 100%

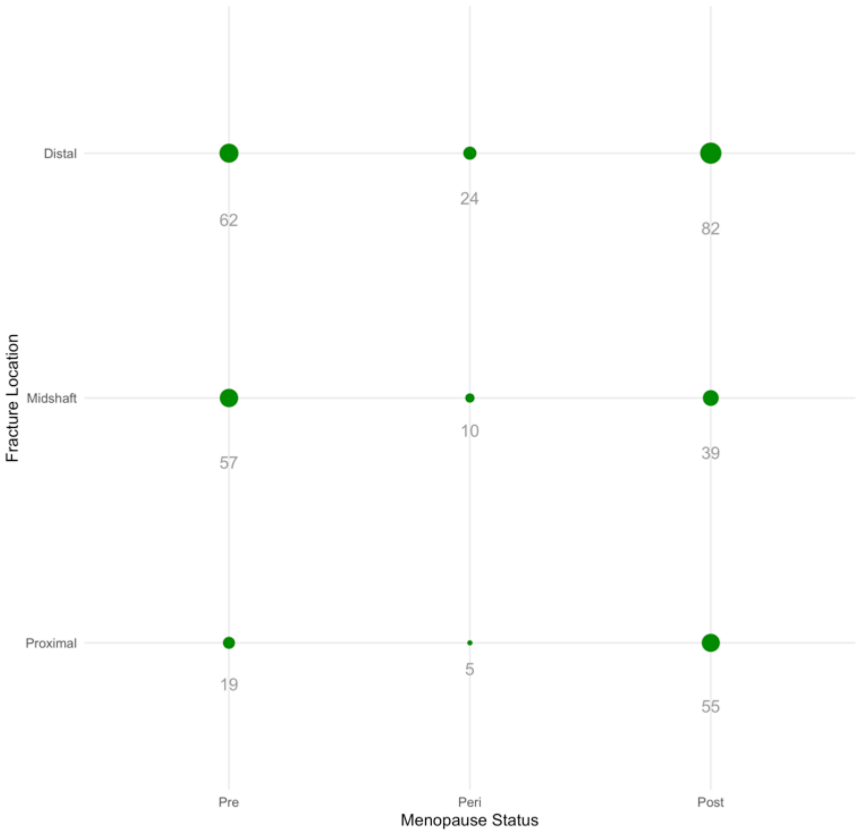
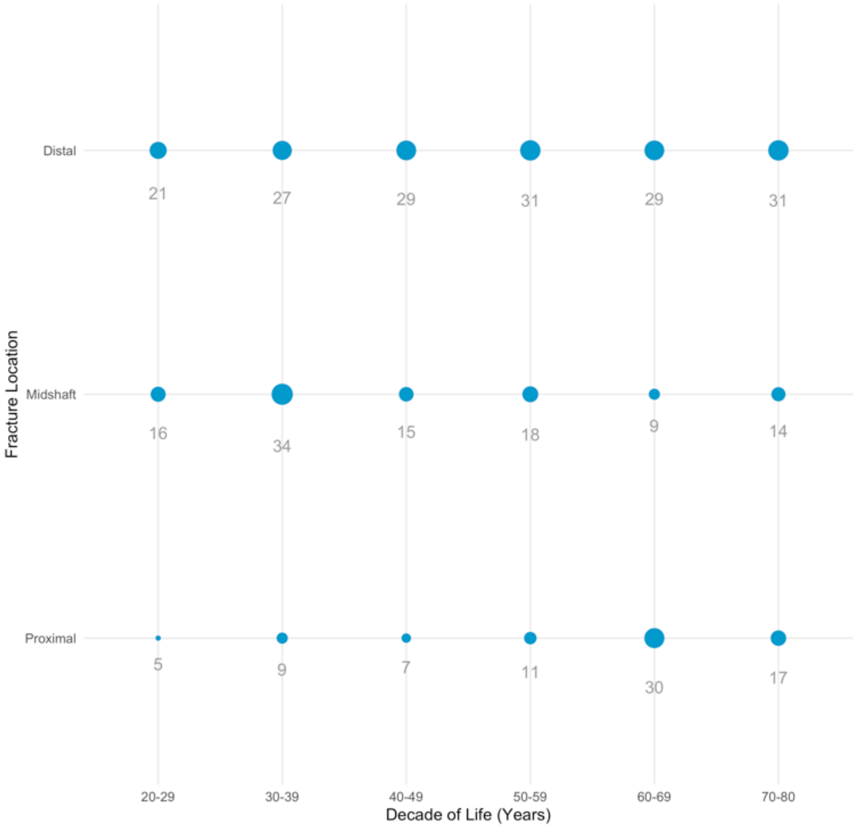


Figure 4: Relationship between fracture location and menopause status

All bones have more fractures located at the distal end, except for the humerus (Figure 6). Until the fifth decade (50 to 59 years) the humerus presented with primarily distal and midshaft fractures, then shifted primarily to the proximal location. There are a large amount of midshaft fractures occurring throughout the life history (Figure 5), until the sixth decade (60 to 69 years) where both proximal and distal fractures surpass the instances of midshaft fractures. Notably, the radius and ulna present with the least number of proximal fractures overall (Figure 6). The tibia and fibula, two of the most fractured bones in the current study, primarily exhibited distal fractures, and particularly in decades five through eight (50 to 80 years) (Figure 6).

The relationship between decade of life and fracture location was found to be statistically significant, with a $p\text{-value} < 0.001$ when using the chi-squared test of independence.


Fracture Location
Distal
Midshaft
Proximal
21
27
29
31
29
31
16
34
15
18
9
14
5
9
7
11
30
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20-29
30-39
40-49
50-59
60-69
70-80
Decade of Life (Years)

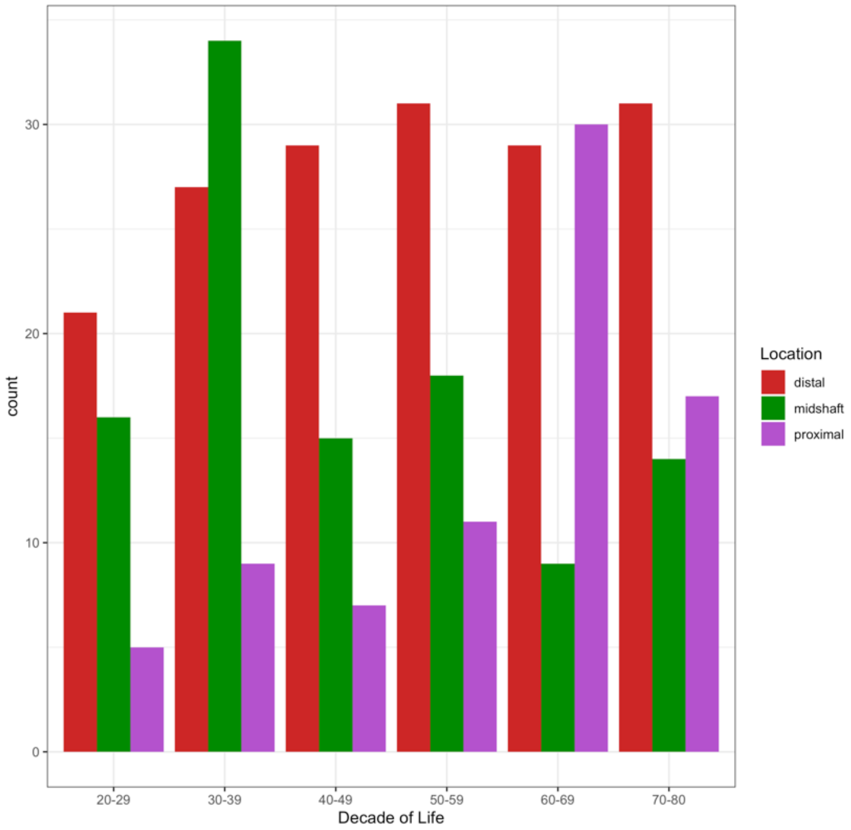

Figure 5: Visualization of location of fracture per decade of life (years) using a bubble plot (top) and bar plot (bottom).

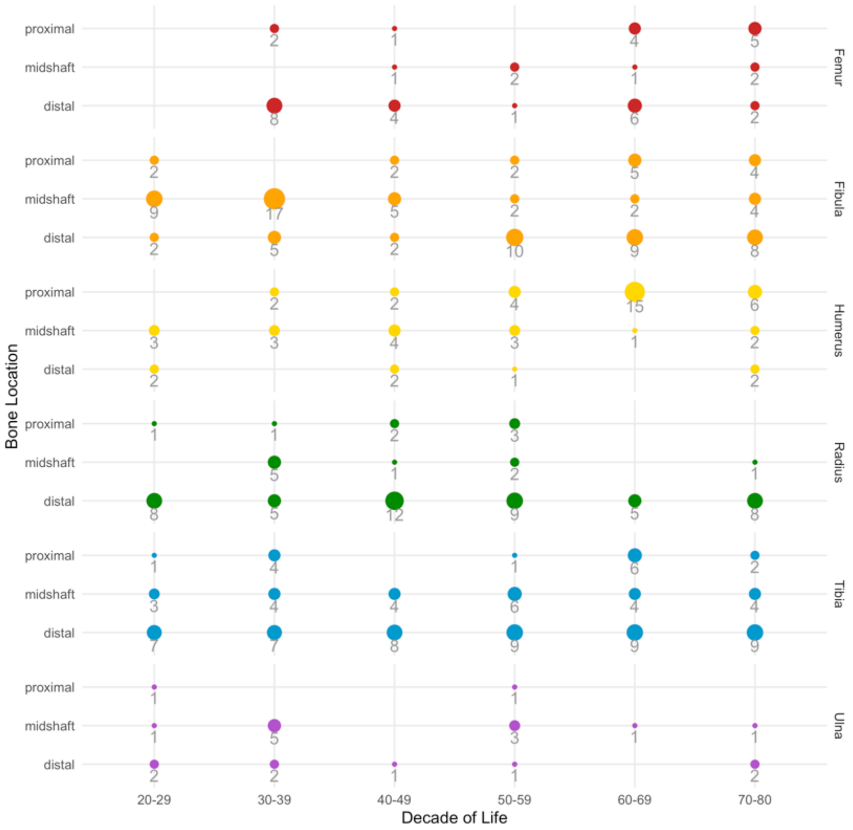

Figure 6: Relationship between bone fractured, the location on the bone, and the decade of life (years)

Severity of Fracture

Statistical analyses of most variables scored to indicate severity (displacement (cm), angulation (°), and impaction/distraction (cm)) were not found to be statistically significant when using a chi-squared test (p-value > 0.05). Severity of fracture was also analyzed using completeness of fracture; however, the relationship between age (decade of life) and fracture severity (completeness of fracture) was not found to be statistically significant (p-value = 0.10) when using the Fisher's exact test.

When comparing the statistical relationship between decade of life and category/subcategory, both were found to be statistically insignificant with p-values > 0.05 in a chi-squared test of independence. Similar insignificant results (p-value > 0.05) were found when comparing the relationship between menopause status and category/subcategory using a chi-squared test of independence.

Figure 7 demonstrates the relationship between the severity of a fracture and the institution in which the data were collected. Living samples from the ROC demonstrate higher occurrences of mild-moderate fractures, while deceased samples from the WCRMEO (ME) demonstrate higher occurrences of severe-severe fractures. The relationship between institution and fracture severity as well as institution and type of fracture, were the only two comparisons with institution found to be statistically significant. P-values < 0.001 for both analyses were obtained when using the chi-squared test of independence and the Fisher's exact test.

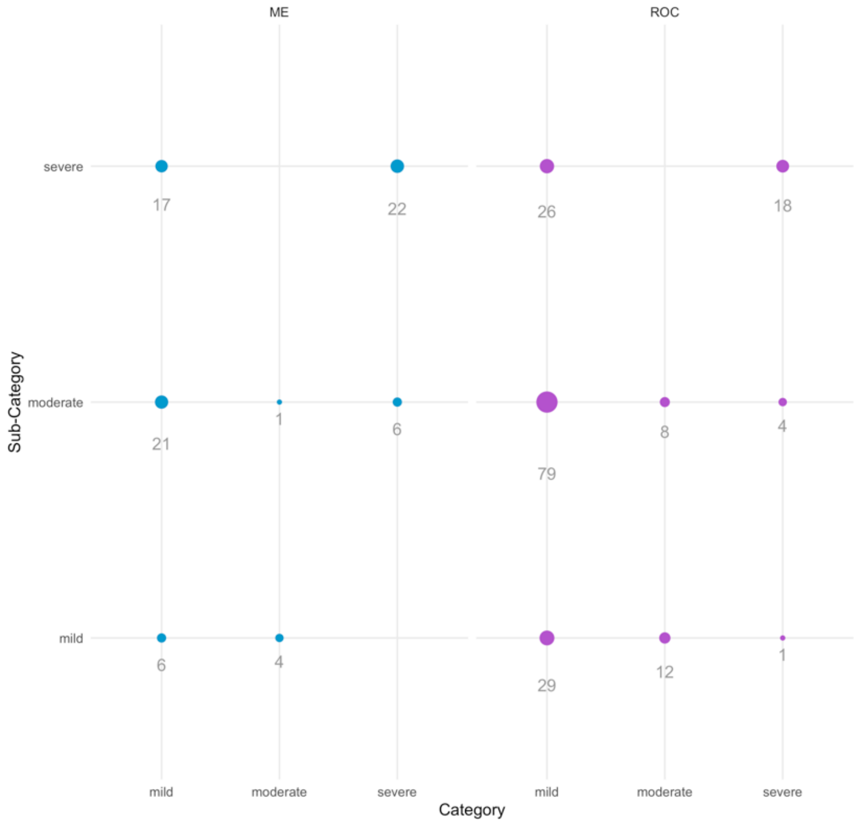

Figure 7: Relationship between institution, category, and subcategory (severity)

Fracture Type

Fracture type was classified using two systems, the common anthropological trauma classifications, as well as the American Orthopedic Trauma Association's Fracture and Dislocation Classification Compendium. Both systems are presented as there is not a consistent approach used in biological anthropology. Common anthropological trauma classifications include: transverse, oblique, butterfly, comminuted, avulsion, longitudinal, and spiral. Classifications from the OTA are broader, with classifications of: simple, multi-fragmentary, wedge, and avulsion.

Regardless of age, three types of fractures presented as most common: comminuted (n = 118), oblique (n = 98), and transverse (n = 96) (Tables 5 and 6). Tables 5 and 6 and Figure 8 demonstrate that instances of simple fractures increase throughout the life history. Figure 9 corroborates the findings in Figure 8, with an apparent increase in simple fractures with age.

Table 5: Counts and percentages of anthropological fracture type occurrence per menopausal group.

	Menopausal Group			
Fracture Type	Pre-Menopausal	Peri-Menopausal	Post-Menopausal	Total Count/Total Percentage
Avulsion	2 0.56%	0 0.00%	1 0.28%	3 0.85%
Butterfly	4 1.13%	1 0.28%	3 0.85%	8 2.27%
Comminuted	53 15.01%	11 3.12%	54 15.30%	118 33.43%
Oblique	35 9.92%	11 3.12%	52 14.73%	98 27.76%
Segmental	4 1.13%	3 0.85%	7 1.98%	14 3.97%
Spiral	10 2.83%	1 0.28%	5 1.42%	16 4.53%
Transverse	30 8.50%	12 3.40%	54 15.30%	96 27.20%
Total Count/Total Percentage	138 39.1%	39 11.05%	176 49.85%	353 100%

Table 6: Counts and percentages of anthropological fracture type occurrence per decade of life.

	Decade of Life (Years)						
Fracture Type	20-29	30-39	40-49	50-59	60-69	70-80	Total Count/ Total Percentage
Avulsion	1 0.28%%	1 0.28%	0 0.00%	0 0.00%	0 0.00%	1 0.28%	3 0.85%
Butterfly	1 0.28%	2 0.57%	1 0.28%	2 0.57%	2 0.57%	0 0.00%	8 2.27%
Comminuted	12 3.40%	30 8.50%	19 5.38%	15 4.25%	23 6.52%	19 5.38%	118 33.43%
Oblique	15 4.25%	17 4.82%	10 2.83%	16 4.53%	16 4.53%	24 6.80%	98 27.76%
Segmental	1 0.28%	3 0.85%	2 0.57%	4 1.13%	2 0.57%	2 0.57%	14 3.97%
Spiral	2 0.57%	4 1.13%	4 1.13%	3 0.85%	3 0.85%	0 0.00%	16 4.53%
Transverse	10 2.83%	13 3.68%	15 4.25%	20 5.67%	22 6.23%	16 4.53%	96 27.19%
Total Count/Total Percentage	42 11.90%	70 19.83%	51 14.45%	60 17.00%	68 19.26%	62 17.56%	353 100%

Table 7: Counts and percentages of OTA fracture type occurrence per menopausal group.

	Menopausal Group			
Fracture Type	Pre-Menopausal	Peri-Menopausal	Post-Menopausal	Total Count/Total Percentage
Avulsion	2 0.56%	0 0.00%	1 0.28%	3 0.84%
Wedge	4 1.13%	1 0.28%	3 0.85%	8 2.27%
Multi-fragmentary	57 16.15%	14 3.97%	61 17.28%	132 37.40%
Simple	75 21.25%	24 6.80%	111 31.44%	210 59.49%
Total Count/Total Percentage	138 39.09%	39 11.05%	176 49.86%	353 100%

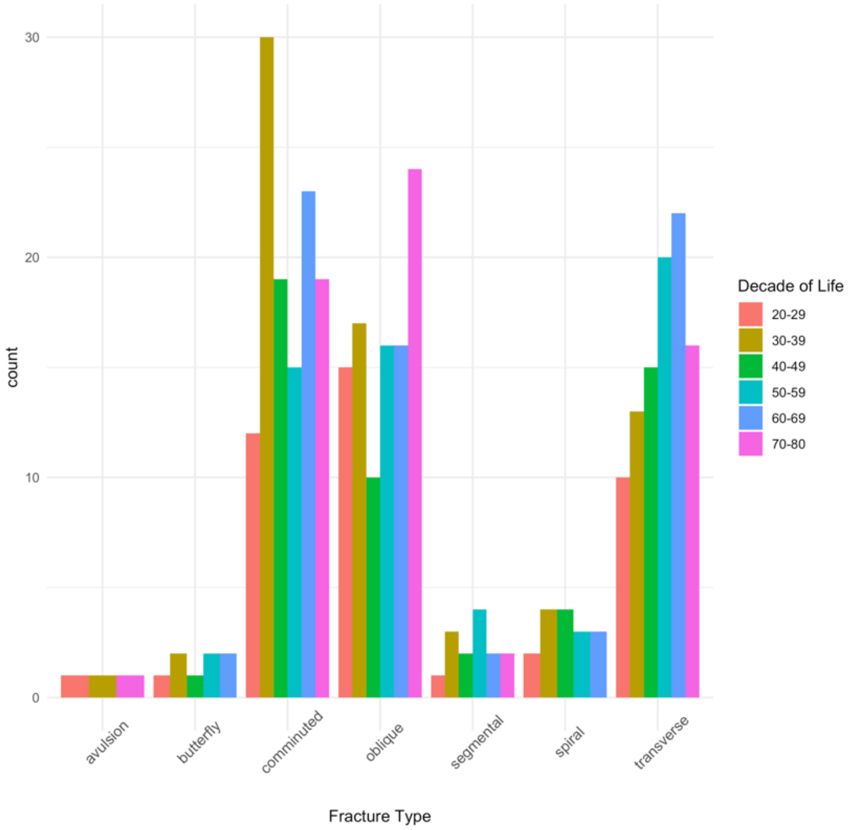

Figure 8: Relationship between fracture type and decade of life (years)

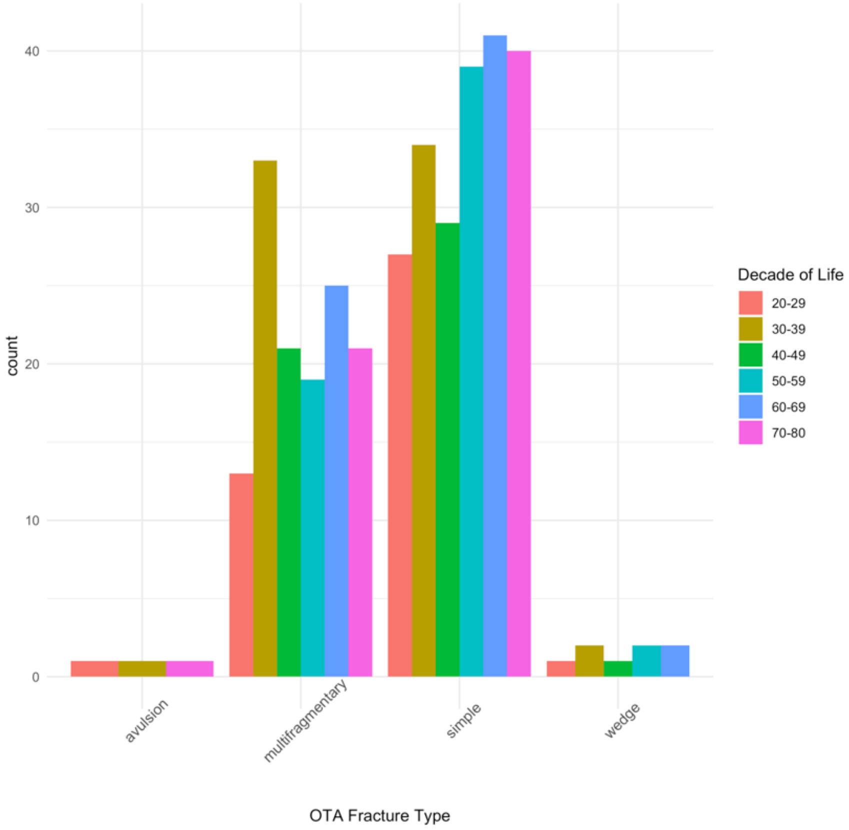

Figure 9: Relationship between OTA fracture type and decade of life (years)

Using a chi-squared test of independence, fracture type was found to be statistically insignificant when evaluating the relationship between both classification systems (anthropological and OTA) and menopause status/decade of life (p-value > 0.05). Though statistically insignificant, there are some practically significant trends. Especially that using two different classification systems, there is an increase in occurrence of simple fractures with age. These analyses demonstrate that each age group is experiencing these types of fractures, but where the statistical significance occurs is at the institutional level (see Figure 10). The most common fracture types are comminuted, oblique, and transverse, regardless of institution (Tables 8 and 9 and Figure 10). There is an increased number of comminuted fractures with the deceased sample, and an increased number of simple fractures (oblique, and transverse) with the living sample. The relationship between fracture type and institution was found to be statistically significant (p-value = 0.00) when using a chi-squared test of independence.

Table 8: Counts and percentages of fracture type (anthropological) per institution

	Institution		
Fracture Type	WCRMEO (ME)	ROC	Total Count/Total Percentage
Avulsion	1 0.28%	2 0.57%	3 0.85%
Butterfly	1 0.28%	7 1.98%	8 2.27%
Comminuted	48 13.60%	70 19.83%	118 33.43%
Oblique	19 5.38%	79 22.38%	98 27.76%
Segmental	7 1.98%	7 1.98%	14 3.96%
Spiral	0 0.00%	16 4.53%	16 4.53%
Transverse	19 5.38%	77 21.81%	96 27.20%
Total Count/Total Percentage	95 26.91%	258 73.09%	353 100%

Table 9: Counts and percentages of fracture type (OTA) per institution

	Fracture Type				
Institution	Avulsion	Multi-fragmentary	Simple	Wedge	Total Count/Total Percentage
WCRMEO (ME)	1 0.28%	55 15.58%	38 10.76	1 0.28%	95 26.90%
ROC	2 0.57%	77 21.81%	172 48.73%	7 1.98%	258 73.09%
Total Count/Total Percentage	3 0.85%	132 37.39%	210 59.49%	8 2.27%	353 100%

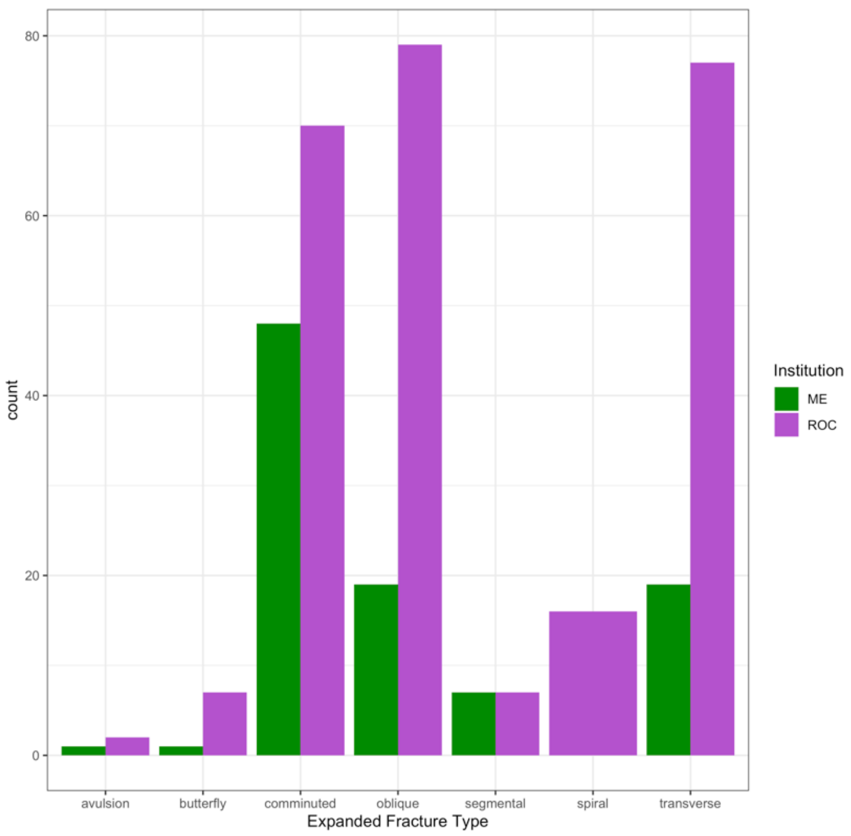

Figure 10: Relationship between fracture type and institution

Discussion

The current research moved beyond the general concept of increased risk or rate of fracture with age and explored the fracture patterns in a large sample of pre-, peri-, and postmenopausal women. The findings from the current study reveal differential location and severity of fractures across the female adult life history stages, which emphasizes and reinforces the relationship between fracture morphology and the material and structural properties and how that can be captured in the demographics of the individual. Location of the fracture on the bone appeared to have the most clear and distinguishable difference between the life history stages (Table 4, Figure 4). Life history stages are defined by changes in age and demographic/biological qualities and patterns and in the current research refers to pre-, peri- and post-menopausal (Baldini, 2015). Proper placement of an individual into a life history stage offers insight into the trauma event (*i.e.*, do the demographics of the individual suggest greater susceptibility to fragility fractures or a trauma mechanism associated with external force). Identification of demographics, and incorporating a life history framework, prior to trauma analysis of remains may provide an anthropologist with the information needed to accurately assess the bone's response.

Previous anthropological and clinical sciences research has identified clear patterns between the increase of fracture risk with progressing age (Cauley et al., 2015; Hulse et al., 2019; Karlamangla et al., 2018), noting that instances of fracture increases with age and the majority of fractures having been sustained by women ages 50 years and older. Very unique to female life histories is menopause, which is a consequence of reproductive aging and follicular depletion (ovarian failure), that yields low circulating estrogen serum (Pollycove et al., 2011). Because endogenous sex hormones have a profound effect on the strength and maintenance of bone, it was expected that fluctuations in hormone levels will also impact how bone responds to force.

Quantification of fracture patterns throughout the life history stages demonstrated an increase in women sustaining fractures of the femur and humerus over the menopausal transition whereas prior to the menopausal transition, fracture occurrence was highest in the tibia and fibula (Figure 2). An institution level analysis was conducted in the current study to identify trends between living and deceased samples in reference to fracture type, location, and severity (Figure 3, Figure 7, Figure 10). The institutional analysis demonstrated differences between which bone is fractured during each decade (Figure 2, Table 3). Fracture occurrence in the tibia and fibula of the living sample, as well as the humerus increased during age 40 to 69 years, suggesting an obvious change in intrinsic factors leading to the increased number of fractures (Figure 3). The same trend was noted in the WCRMEO sample, with instances of tibial and fibular fractures increasing, though not nearly as notably because of the small sample size. Instances of femoral fractures decreased in the fifth decade (50 to 59 years) and rose again in the sixth decade (60 to 69 years), which was also noted in the pooled sample.

In the current study, location on the bone in which the fracture occurred was found to be statistically significant when age groups were separated by decade, as well as when separated by bone, location, and decades (Figure 4, Figure 5, Figure 6). It was most common for women in the pre-menopausal period (ages 30 to 39 years) to sustain midshaft fractures, while women in the post-menopausal period (ages 60 to 80 years) demonstrated more epiphyseal and metaphyseal (proximal and distal) fractures. The current study found that the distal tibia (14.6%), distal fibula (14.6%), and the proximal humerus (13.5%) were the most common fracture locations in women over 50 years of age (Figure 6), while the distal tibia, distal fibula, and the distal radius were most common overall. Largely contradictory to the current study, one previous study identified the three most common fragility fractures in women over 50 years as the distal radius, proximal femur, and the proximal humerus (Bergh et al., 2020). The only similarity with the current study is the proximal humerus. Another study indicated that ankle fractures (distal tibia and distal fibula) are the third most common fracture location amongst those greater than 55 years (Simske et al., 2020). While the current research does not fully corroborate or disprove the findings of previous research, it does demonstrate the patterned variability of fracture location throughout the female life history.

To further understand and more accurately identify the trends present throughout the life history, the data were separated into decades. This separation yielded slightly different results. Until the sixth decade of life (ages 60 to 69 years) fracture location presented mainly in the distal and diaphyseal aspects of the bone. Further evaluation of the decades demonstrates that instances of proximal fractures surpass instances of distal fractures from the sixth to seventh decade (60 to 69 year age group). Because proximal fractures are fairly uncommon throughout the decades, the surpassing of both distal and midshaft fractures by proximal fractures in the sixth decade (60 to 69 years) is highly suggestive of a statistical significance, demonstrating that fracture location shifts proximally as an individual ages (Figure 5). The only bone that did not follow this trend was the humerus, which demonstrated a different pattern; the humerus presented with the most instances of fractures occurring proximally from ages 30 to 80 years. Because the proximal and distal aspects of the bone occur in the epiphyseal and metaphyseal regions, the composition is mainly trabecular bone and these regions present with an increased susceptibility to fracture because of the lack of surrounding cortical bone, as well as the natural lack of collagen present in the trabecular bone (Hart et al., 2017; Moreira et al., 2000; Rho et al., 1997; Wu et al., 2012; Zysset et al., 1999). The lack of density of collagen per unit of bone explains the strain resistant behavior of the trabecular bone and contrasting lack of strength. The difference presented by the humerus must be discussed. The proximal humerus is noted as one of the most common locations for fragility fractures (Adachi et al., 2021; Borgström et al., 2020; Pietri & Lucarini, 2007), yet prior research identifies the hip as the most common location for fragility fractures. While both considered ball-and-socket joints, the glenohumeral joint presents with a greater range of motion than the femoroacetabular joint. Because of the multiaxial nature of the glenohumeral joint, the tendons, ligaments, and muscles surrounding the proximal humerus are subject to increased strain. This could provide reasoning behind why the humerus is prone to sustaining proximal fractures.

In the current study, the nature of trabecular bone can be used to explain the high proportion of proximal and distal fractures throughout the life history, yet its' relationship to the significant rise in diaphyseal fractures during the third decade remains unexplained (Figure 5). It could also be explained by the level of risk-taking activity engaged in during this life history stage. Studies suggest that risk taking activity increases throughout young adulthood and peaks around middle adulthood (Josef et al., 2016). Participation in risk taking behavior declines into older adulthood, however, the decline in risk taking behavior does not explain the increase that is seen when evaluating fracture susceptibility with age, and rather relates more to the severity of the fracture instead of the occurrence of fracture.

Fracture types also varied across the life history stages. Simple fractures (oblique and transverse) occurred more (63.07%) in the post-menopausal period compared to multi-fragmentary (34.66%), avulsion (0.57%), and wedge (1.70%). In contrast, a higher occurrence of multi-fragmentary fractures (40.11%) compared to simple (55.93%), wedge (2.82%), and avulsion (1.13%) in pre- and peri-menopausal periods (Table 7). Fracture classification categories included transverse, oblique, spiral, butterfly, avulsion, longitudinal, and comminuted. In the current study, and considering all ages, the most common fracture types were comminuted (33.43%), oblique (27.76%), and transverse (27.20%) (Table 6) (which are reported by the OTA as multi-fragmentary and simple (transverse and oblique). Though these three fracture types present as the most common in each age group, there was a difference noted in the amount of each occurring in each decade. Though not statistically significant, this comparison demonstrated that individuals in the post-menopausal age groups presented with more instances of simple fractures (transverse and oblique), and individuals in the pre-menopausal age groups presented with more instances of comminuted or multi-fragmentary fractures (Table 5, Figure 8, Figure 9). The differential propensity for a type of fracture across the ages is likely related to the change in material properties related to bone density changes and the loss of elasticity (Boskey & Coleman, 2010; Boskey & Imbert, 2017; Zdzieblik et al., 2021). As estrogen levels decrease through the menopausal transition osteoblastic activity is reduced, leading to decreased resilience to added stress and strain via loss of bone density in the cortical and cancellous bone. Collagen fibers present in the organic matrix are also reduced during the menopausal transition leading to a loss of elasticity (Zdzieblik et al., 2021). As bone transitions through the elastic and plastic phases as described by Young's modulus, the loss of strength, density, and elasticity associated with hormonal changes impacts the amount of elastic and tensile stress the bone can withstand prior to reaching the fracture point (Leng et al., 2013; Zimmermann et al., 2011). The amount of time spent in the elastic and plastic phases is shortened in aged bone (Zimmermann et al., 2011), as the amount of tolerated stress is decreased.

When examining fracture type with institutional separation, the same fracture types as the pooled sample were visualized, however, they were present in different proportions in each institution (Table 8, Table 9). The living sample from the ROC demonstrated more instances of simple fractures, and the deceased sample from the WCRMEO demonstrated more instances of multi-fragmentary fractures (Figure 10). Though statistically significant, this conclusion would be expected considering the relationship to injury severity and mortality (Liem et al., 2013; Sattui & Saag, 2014); therefore, one would expect increased instances of multi-fragmentary fractures, as fragmentation is suggestive of higher force. Because the samples at the WCRMEO are deceased, it can be assumed that fractures sustained at their time of death were associated with high levels of force. Severity of the fracture was expected to decrease with an increase in age because of the loss of trabecular and cortical bone, however, the relationship was found to be statistically insignificant. Rather, a statistically significant relationship was discovered upon institutional separation, where individuals in the WCRMEO sample presented with a higher number of severe fractures than the ROC sample (Figure 7).

Potential bias may have been incorporated regarding sample severity and institutions in which data were collected from. At the WCRMEO increased severity is expected; initial visits at the ROC were found to be associated with less severe fractures (*i.e.*, individuals who sustained more severe but non-life-threatening fractures would have likely been primarily evaluated at the hospital; many times, the initial x-ray images taken at the hospital were not available in the ROC database, and therefore the individual was excluded from the sample). Though institution was found to have a direct correlation with the type and severity of fracture, an increase in age did not display the same trend. Age was not found to have any impact on the variables initially associated with severity (angulation, displacement, and impaction/distraction). Considering this, evaluation of severity was based generally on the completeness of the fracture (full transection or partial transection). Though statistically insignificant, most fractures sustained by post-menopausal women (greater than 52 years of age) demonstrated full transection of the bone, while those prior to menopause (less than 52 years of age) demonstrated higher occurrences of incomplete fractures.

When analyzing fracture severity using the Fracture Compendium categorization, most fractures were found to be either mild or severe, regardless of age (Figure 7). Very little instances of fractures classified as “moderately severe” were found. When interpreting this finding in relation to Young’s modulus, it is understandable that few instances of “moderate severity” were discovered. Based on the stress-strain curve, bone transitions through two phases prior to fracturing. Depending on the density of the bone and the quality of the matrices, the time between the yield point and failure could be greatly diminished. Less time spent in the plastic phase correlates to more rapid fracturing. As bone spends more time in the plastic deformation phase, it has more time to resist the applied force, indicating a bone of high strength or potentially a slow loading force. Though not proven, a shortened plastic phase could also be linked to the type of fracture sustained. Some studies suggest that the severity of the fracture is increased when using bone from older individuals (Harden et al., 2022), however, the current research suggests the opposite. Though the current research contradicts the findings in Harden et al., 2022, the increasing incidents of simple fractures with age in the current study was corroborated by the former study. It is worth considering if the presence of flesh and muscular tissue at the time of fracture affects the severity of the fracture, as the samples used in the Harden et al., 2022 study consisted of wet bone devoid of muscle and flesh, while the current study incorporated fully fleshed subjects. The lack of severity increasing with age presented by this research could also suggest that women greater than 52 years of age become progressively more sedentary, therefore their activities become less risky and their risk of overall fracture decreases.

Limitations and Future Directions

Potential drawbacks of the study incorporate aspects of biases such as under coverage and observer bias. Under coverage occurred in the sampling obtained at the different institutions. Though the sample consisted of a decent number of individuals (n=353), statistical findings could have been further substantiated with a larger number of individuals comprising the peri-menopausal group, as well as increasing the number of individuals from the WCRMEO. Observer bias was incorporated when classifying fracture type based on common anthropological trauma classifications. The anthropological classifications do not have well-defined descriptors, but rather broad categorizations. Therefore, anthropological classification was based solely off the observer’s interpretation of the fracture. Ideally, an interobserver error would be performed to verify the findings and identify any shortcomings of the categorization process. The field of anthropology as a whole is lacking in interobserver error research surrounding blunt trauma and fracture morphology. Comparison of the anthropological classifications with the OTA classifications is necessary to ultimately strengthen findings and potentially change the way anthropologists classify blunt force trauma.

Another drawback of the current study is its use of cross-sectional data. Because cross-sectional data incorporates a different random sample of individuals in each subset (*i.e.*, age decade or menopausal group), certain patterns could be a result of sampling rather than reality. For example, in the current study if a pattern such as severity of fracture demonstrates an increase in the sixth decade (60 to 69 years), but not from the sixth to the eighth decade (60 to 80 years) an assumption could be made that there is an outside force acting on the variables during only in that decade, where in reality because it is not a consistent increase there is no statistical findings to corroborate the increase. Ideally, this type of research question would have a prospective research design where the date of menopause would be known, and the sampling could yield comparable numbers of individuals in all subsets. Random sampling of individuals is appropriate, but not knowing the biological and hormonal data from each individual does not facilitate linear explanations between fracture and biological data.

Though the current study does provide corroborating evidence to previous research (Bergh et al., 2020; Harden et al., 2022; Simske et al., 2020), further research must be done with incorporation of males in the sample, not only to increase sample size but to visualize population trends, as well as trends between sexes.

Future studies could delve deeper into the relationship between nutrition and bone health. Though numerous studies have evaluated how malnutrition and loss of endogenous vitamins and minerals impacts the overall health of bone (Amir & Donath, 2012; Calleja-Agius, 2017; Cauley et al., 2015; Laird et al., 2010; Moffat & Prowse, 2010), examining how chronic malnutrition impacts fragility of bone and risk of fracture could provide further information to substantiate exactly how bone with various deficiencies respond to force. Due to lack of demographic data, health conditions and social factors were not evaluated in the current study, however, the increase of fracture occurrence with age does suggest that with an increase in fragility comes an increased risk of fracture. Though, it should be noted that increased bone fragility does not correlate to greater severity of fracture, but rather increased mortality.

Conclusion

The results of the statistical analyses led to four conclusions: 1) different bones fracture in different decades of life; 2) fracture location on bone changes throughout the life history; 3) fracture type consists primarily of comminuted and simple fractures regardless of life history stage; and 4) fracture patterns are present in different institutions. This research brings to light the importance of trauma analysis in the field of forensic anthropology, and encourages anthropologists to deepen their understanding of traumatic events to bone, and in what ways intrinsic and extrinsic factors impact how bone responds to force. Evaluation of how fracture patterns differ throughout the life history allows for comparisons to be made between aging bone and risk of fracture.

The fields of anthropology and others such as paleontology and more so, bioarchaeology can benefit from further evaluation of fracture patterns throughout female life history stages by providing a statistical and alternate option for identification of chronological age of past human populations. The field of paleodemography is in search of methods to assist in skeletal age identification (Roksandic & Armstrong, 2011), therefore through knowledge of fracture patterns and how bone responds differently to stress with age, the current research could prove useful in sparking interest in linking the relationship between trauma indicators and life history age estimations.

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