MOBILITY THROUGH DROUGHTS: CROSS-SECTIONAL ANALYSIS OF FEMORA IN A SAN FRANCISCO BAY AREA PREHISTORIC NATIVE POPULATION

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ABSTRACT

MOBILITY THROUGH DROUGHTS: CROSS-SECTIONAL ANALYSIS OF FEMORA IN A SAN FRANCISCO BAY AREA PREHISTORIC NATIVE POPULATION

by Sarah Luce

This thesis aims to infer mobility patterns in the California prehistoric burial population of CA-ALA-329 (Ryan Mound) by conducting cross-sectional analysis on femoral bones. CA-ALA-329 is considered to be a burial ground used by precontact Ohlone natives in the San Francisco Bay Area. Glacial changes, pollen studies, and tree-ring data show shifts in climate change occurred during the Late Phase 1 Period, causing warmer and drier temperatures throughout California. Seventy-seven femora were analyzed in this study including 26 femora representing the Middle Period and 51 representing the Late Phase 1 Period. Cross-sectional geometric formulae were applied to measurements collected at the subtrochanteric and midshaft regions on each femora. Two second moments of area, Ix and Iy, were calculated and ratios were used to determine where mechanical stress was placed as a result of stress and strain. Supporting data, such as polar moment of area, cortical area, and total area, were calculated, but not standardized for body size. Results of the study demonstrated significant changes in mobility over time. Anteroposterior robusticity in the subtrochanteric region decreased from the Middle Period to the Late Phase 1 Period in males, and increased in females. Anteroposterior robusticity in the midshaft region increased in males from the Middle Period to the Late Phase 1 Period, and decreased with females. These findings suggest a shift in mobility between the two time periods.

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I would like to extend my deepest respect and appreciation for the likely descendants of the individuals handled within this study, the Muwekma Ohlone. The Muwekma Ohlone have continually given their blessing for students to conduct research such as this which has allowed people across the world to learn more about their ancestor's history in this region. Lastly, I would like to acknowledge all the sociological and anthropological thinkers that inspired me to continue to learn more and more about my fellow humans. I would not be who I am today had I not read their words.

"Herein lies the tragedy of the age: not that men are poor, — all men know something of poverty; not that men are wicked, — who is good? not that men are ignorant, — what is Truth? Nay, but that men know so little of men." (Du Bois, 1903)

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LIST OF ABBREVIATIONS

50%	Midshaft region of a femur, 50% of femoral length
80%	Subtrochanteric region of a femur, 80% of femoral length
A.D.	Anno Domini (beginning 1 A.D.)
AP	Anteroposterior
B.C.	Before Christ (ending before year 1 A.D.)
B.P.	Before Present (1950)
CA	Cortical Area
df	Degrees of Freedom
DV	Dependent Variable
F	Fisher’s F Ratio
Ix	Anteroposterior Second Moment of Area
Iy	Mediolateral Second Moment of Area
J	Polar Moment of Area
ML	Mediolateral
MS	Mean Square
N	Sample Size
P	Probability Value
SD	Standard Deviation
SS	Sum of Squares
TA	Total Area

INTRODUCTION

The study presented in this thesis aims to infer mobility through cross-sectional examination. It is reasonable to assume that the San Francisco Bay Area experienced periods of drought during the Late Phase 1 Period when looking at evidence suggesting the larger region experienced droughts and warmer weather. However, some archaeological studies show that the warming period impacts were region-specific (D'Oro, 1999) and that native populations within the Bay Area were not impacted by the warming period (West, Woolfenden, Wanket & Anderson, 2007). The burial population of CA-ALA-329 studied in this thesis represents the Middle Period, a period of time before the warming period occurred, and the Late Phase 1 Period, which parallels the documented warming period. While Late Phase 2 Period burials are represented in the collection housed at San José State University, they were not utilized in this study.

Cross-sectional analysis is a method used to calculate the amount and distribution of cortical bone as a result of mechanical force, and is based on both elementary engineering and biomechanical theories. Force placed on bone tends to thicken in areas that experience the most stress, which reinforces the layers of living bone and changes the morphology of the bone (Mays, 2010). In beam theory, stress is defined as force and applied pressure in the form of transverse loads (or weight) across a cross-section of a square beam (Kelly, 2015). For the purposes of this thesis, stress is referred to with this definition in mind, but is applied to cross-section of bone. Rather than being supported by additional beams, rollers, or pin supports, as would be a typical building, bone is supported by tissue in the form of muscle and tendons.

Due to degradation that transpires over time when bone is buried, and the difference between how living and dead bone reacts to stress, it is only possible to estimate strength where bone has been remodeled as a result of movement. Estimating strength from the bone can help anthropologists infer activity patterns of past populations (Mays, 2010). It is also important to take an individual's age into account. Muscle strength and body weight stabilize once skeletal maturity has been reached (Frost, 1997; Maggiano et al., 2008).

This thesis infers mobility patterns by analyzing femoral samples representing two different time periods from CA-ALA-329. The Ohlone of the San Francisco Bay Area were known to have exploited both marine and terrestrial resources since occupying the Bay. Habitual patterns likely to have impacted the strength of femoral bones within the population of CA-ALA-329 include activities such as traversing rough terrain, walking, swimming, climbing, and preparing food. Although some osseous studies have been conducted that conclude there was no change in health between the Middle Period and Late Phase 1 Period (Nechayev, 2007), it is uncertain if regional climate change required adaptation to less terrestrial game and trade, and more reliance on marine resources resulting in a decrease in mobility. The results of this thesis add to the body of knowledge surrounding the discussion of cross-sectional geometric analysis and activity pattern inference. This thesis also provides insight into mobility and activity patterns of the descendants of the Ohlone, adding to the cultural narrative of modern native populations. Figure 1 displays the location of CA-ALA-329 located in the southeast region of the San Francisco Bay Area.

Figure 1. Location of CA-ALA-329 in the San Francisco Bay Area (adapted from ©2018 Google LLC).

HYPOTHESES

While many studies have been conducted on the burial and archaeological assemblages of CA-ALA-329 (e.g., Leventhal, 1993; D'oro, 1999; Weiss, 2007; Bartelink, 2006; Jurmain et al., 2009), no cross-sectional data have been studied to infer mobility patterns during the warming period. The warming period was characterized by droughts that may have impacted mobility of the coastal population of CA-ALA-329 through resource depletion, requiring a higher reliance on marine resources. Two hypotheses were developed prior to statistical analysis of the cross-sectional geometric data.

1) Late Period Phase 1 burials will reveal thinner cortical thickness in both cross-sectional locations compared to Middle Period burials, which may be especially pronounced in males. It was hypothesized that during the warming period, Late Period Phase 1 males were less mobile than Middle Period males due to diminishing terrestrial resources (e.g., deer, acorns) and began exploiting more marine resources (i.e., shellfish, otter). This would be supported by lower ratio values of Ix/Iy and lower CA, TA, and J values when compared to Middle Period femora.
2) Middle Period burials will show greater differences between the sexes than Late Phase 1 burials, as evidenced by cortical thickness. It was hypothesized that prior to the warming period, males were more mobile when compared to females. Due to assumed abundance of resources prior to the warming period, males would have been more mobile to hunt available terrestrial resources and travel to trade.

This would be evidenced by Middle Period males having higher ratio values of Ix/ly values when compared to Middle Period females. Conversely, Late Phase 1 Period femora would reveal smaller differences in Ix/Iy values between males and females due to decreased mobility in males and heavier reliance on marine resources.

BACKGROUND LITERATURE

Cross-sectional analysis

Second moments of area (also known as second moments of inertia) measurements, called "I," are the most important geometric characteristic to analyze 'beam' strength and rigidity under bending (i.e., force, stress). Length measurements from the anterior and posterior (AP) direction (sagittal plane) of the cross-section are taken together and are termed Ix. The medial and lateral (ML) directions (frontal plane) are also measured together and are termed Iy (Ruff & Hayes, 1983; Weiss, 1998). Two additional second moments of area measure the thickest part of the cortical area (Imax) and thinnest I minimum (Imin) cortical areas (Weiss, 1998; Stock, 2006). This study is only concerned with two of the four second moments of area (i.e., Ix and Iy).

To evaluate torsional strength in rigidity, it is most important to look at the polar moment of area, or J (Ruff & Hayes, 1983). J is measured by totaling the two second moments of area (i.e., Ix and Iy). This allows researchers to estimate bending and torsional strength of the overall bone using only geometry (Mays, 2010). Cortical area (CA) and total area (TA) are ideal to analyze structural resistance, or compressive strength, to loads applied perpendicular to the cross-section surface with the resulting force passing through the center of the cross-section (Ruff &Hayes 1983). Ix, Iy, Imax, Imin, CA, TA, and medullary area are all traditional and standard measurements used in cross-sectional analysis. This study is only concerned with CA and TA compressive strength measurements. Figures 2 and 3 provide examples of bending strength and compressive strength measurements.

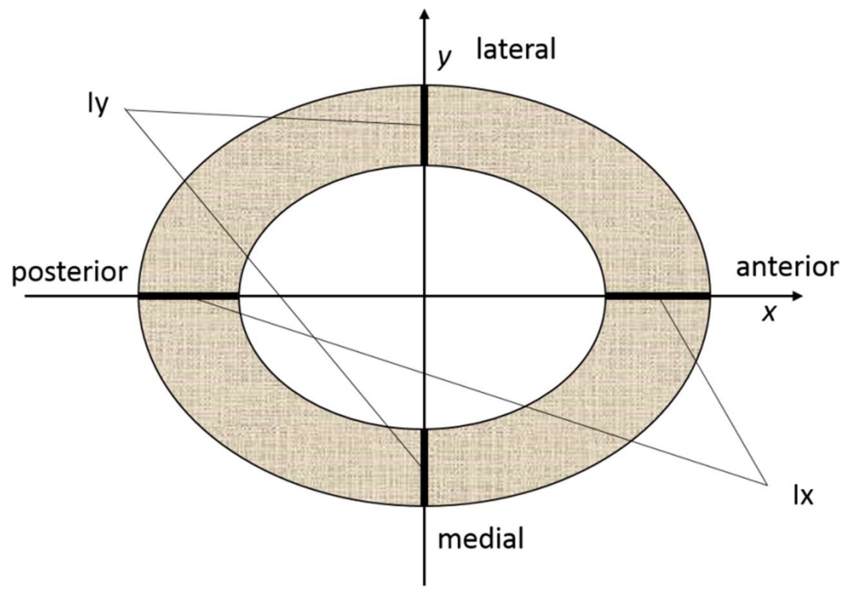

Figure 2. Bending strength measurements (image created by author).

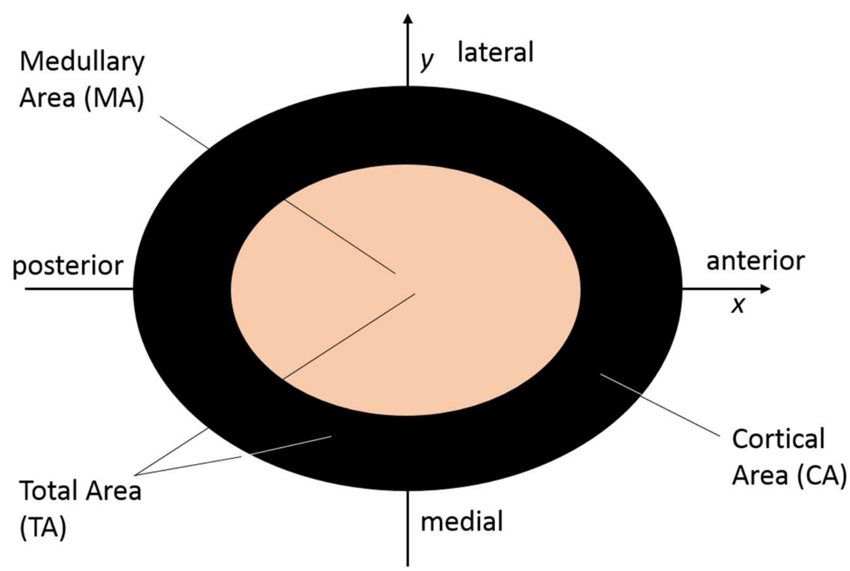

Figure 3. Compressive strength measurements (image created by author).

The methodology of applying cross-sectional analysis of geometric properties to past populations was first developed and applied in research as early as the 1970s (Lovejoy, Burstein & Heiple, 1976). Since then, numerous studies have been conducted to explore mobility patterns and sexual dimorphism in past populations and over time around the world (Trinkaus & Ruff, 1999; Stock & Pfeiffer, 2001; Weiss, 2002; Sladek, Berner & Sailer, 2006; Westcott & Cunningham, 2006; Maggiano et al., 2008; Marchi, 2008; Ogilvie & Hilton, 2011; Trinkaus & Ruff, 2012; Stock & Macintosh, 2015). Modern cross-sectional research on living populations has given insight into bone related diseases, such as osteoporosis and bone development (Nelson, Barondess, Hendrix & Beck, 2009; Neu, Rauch, Manz & Schoenau, 2001). The following is a discussion of studies in which traditional cross-sectional geometric properties were applied to explore characteristics in prehistoric and modern people.

In 1999, Trinkaus and Ruff examined femora from two populations dated to the Middle Paleolithic time period. The first sample included a group of late archaic Neandertals (n = 5) and compared the results with an early modern human sample (n = 7). Trinkaus and Ruff (1999) tested if scaling diaphyseal measurements to ecogeographically (the study of how unique environments interact with living things) documented body proportions would provide insight into previous findings that Middle Palaeolithic archaic humans and early modern humans were starkly different in robusticity. Trinkaus and Ruff (1999) took measurements at several locations of the femur: 20%, 35%, 50%, 60%, and 80% of total femoral length by using polysiloxane molding putty and biplanar radiographs. After accounting for ecogeographic body proportions, the results indicated little difference in overall shaft hypertrophy between the two populations. However, the results showed that while midshaft shape remained the same, the early modern humans showed more anteroposterior strength compared to the Early Middle Palaeolithic sample. Trinkaus and Ruff (1999) concluded that it is still unclear how body shape (i.e., hip and pelvic proportions) may have played a role in the differences found in the study.

Stock and Pfeiffer (2001) analyzed the relationship between cross-sectional properties and evidenced behavior in two Holocene human foraging populations. The study included samples including a Prehistoric Later Stone Age dated to 10,000 to 2,000 B.P. (or years before present, where present is defined as 1950) from Southern Africa (n = 65) and a sample of indigenous Andaman Islanders dated to the 19th century (n = 39). Cross-sectional properties were taken from femora, tibiae, humeri, clavicles, and first metatarsals by using computed tomography scanning (CT scanning), for a part of the sample while molding and biplanar radiographs were used for the remaining samples. The result showed that the South African samples had greater robustness in their lower limbs compared to the Andaman Island populations. These findings are consistent with prior evidence that supports the idea that the South African populations were highly mobile terrestrial and marine foragers. Conversely, the Andaman Island population showed greater robusticity in their upper limbs. Historic evidence suggests that the Andaman populations were off-shore foragers (i.e., exploited water resources by swimming and canoeing).

In a study of a California prehistoric native population in the San Joaquin Valley (CA-SJO-91), Weiss (2002) examined drought-related changes as evidenced by cortical thickness, age at death, and pathology/trauma for two different cemeteries representing two different time periods. Cemetery 1 predated the drought period and was dated to 2895 to 1845 B.P. Cemetery 2 was dated to 1110 B.P. to 1220 B.P. and corresponds to periods of known drought. Sixty-four femoral midshaft cross-sections were analyzed using CT scans including 53 from Cemetery 1 (predating the drought), and 11 from Cemetery 2 (during periods of drought). Six measurements were taken from each cross-section to calculate a cortical thickness value. Weiss (2002) found that the Cemetery 2 population had less cortical thickness when compared to Cemetery 1. Weiss (2002) concluded that the lack of cortical thickness, age at death and pathologies/trauma found in Cemetery 1 indicate that the population within the drought period sample was impacted.

Sladek et al. (2006) studied cross-sectional geometric properties of femoral midshafts to determine mobility patterns in a population thought to have practiced a pastoral subsistence strategy and compared it to a sample known to have been generally sedentary. The Late Eneolithic sample (n = 57) represented two populations dated between 2900-2000 B.C. The Early Bronze Age sample (n = 94) was represented by three populations dating between 2200-1700 B.C. The results provide evidence to support that the Late Eneolithic sample was not highly mobile compared to the early Bronze Age sample.

Westcott and Cunningham (2006) investigated temporal trends using cross-sectional geometric properties in paired samples of humeri at 35% of humeral length and femora at 50% and 80% of femoral length. The sample size (N) represented the Arikara, an American Great Plains tribe from South Dakota, over three different time periods including 1500-1640 A.D. (n = 30), 1650-1780 A.D. (n = 53), and 1780-1845 A.D. (n = 12). The Arikara were known horticulturists who also hunted and gathered. Females were expected to show more asymmetrical cross-sections compared to males overtime due to their primary role in cultivation and maintenance of domestic plants. The results showed significant changes in left femoral strength and asymmetry among females when compared to the first period sample and the last, with females showing increased asymmetry over time. The increased asymmetry found in the study may reflect increased used of tools required in a horticulture subsistence pattern (Westcott & Cunningham, 2006).

Maggiano et al. (2008) analyzed humeral and femoral cross-sectional properties from an early Maya settlement, Xcambó, near the Northern Gulf coast of the Yucatan. The sample size (N = 79) represented two time periods including the Early Classic dated to 250-550 A.D. (n = 21) and the Late Classic 550-700 A.D. (n = 58). Cross-sectional properties were taken using destructive analysis of 2-centimeter samples of humeral and femoral diaphyseal midshaft sections. The results showed that the femoral and humeral cortical areas were significantly higher in males when compared to females throughout the Early Classical period. The findings decreased by fifty percent when analyzed with samples from the Late Classical period. In addition, the results showed a general decrease in robusticity in both femoral and humeral cross-sections, across both sexes temporally. The researchers infered that this was due to an improved and stable period of settlement resulting in less mobility (Maggiano et al., 2008).

In 2008, Marchi compared a sample of femora and tibiae (*N* = 16) in a Neolithic population thought to be pastoralists from Liguria, Italy (dated 6th millennium B.P. to other European samples ranging from the Late Upper Paleolithic (19,000 B.P.), Mesolithic (10,000 B.P.) to Late Neolithic (4,000 B.P.). The study was conducted to attempt to explain why a previous study of Liguria specimens showed buttressing in male anteroposterior femoral cross-sectional planes, when other cross-sectional studies throughout the Neolithic showed this as a time of decreased mobility (i.e., the adoption of agriculture and movement away from hunting and gathering). Marchi (2008) used polysiloxane molds and measurements of biplanar radiographs of the shaft to take cross-sectional measurements on the femora and tibiae. Marchi's (2008) results showed that while cortical areas of male femora in the Neolithic pastoral sample were not significantly different to the Late Upper Paleolithic and Mesolithic samples, male pastoralist femora showed increased bending strength anteroposteriorly. The greater robusticity and sexual dimorphism of both the femora and tibiae indicated to Marchi that the pastoralists' bones looked closer to populations of much earlier periods who were highly mobile (i.e., Late Upper Paleolithic and Mesolithic) compared the other Late Neolithic samples who were less mobile. Marchi (2008) stated that the results do not invalidate the general trend of decreased mobility over time, rather they infer the results of studies such as these must take subsistence patterns (i.e., pastoralism) and terrain into consideration.

Ogilvie and Hilton (2011) used cross-sectional geometric properties to examine sexual division of labor in two populations. The first population sample was from mobile foragers in Lower Pecos region in Texas (*n* = 27) dating to 2300-1300 years B.P. The second population represented a sample of known agriculturists from Pottery Mound Pueblo (*n* = 65) in New Mexico dating to 700-500 years B.P. The researchers utilized both biplanar radiographs/molding and CT scans to analyze humeri at 35% of humeral length to calculate traditional cross-sectional properties. Ogilvie and Hilton (2011) found that Pottery Mound females exhibited the least asymmetry compared to males from Pottery Mound and compared to the foraging population. Males from the Lower Pecos region exhibited the greatest asymmetry compared to the other samples. The results indicated that Pottery Mound females possessed greater resistance to maximum bending strength and torsional strength. The findings were corroborated by ethnographic data that indicated females engaged in strenuous activity not limited to farming, but also carried heavy loads, including children.

Trinkaus and Ruff (2012) examined cross-sectional geometric properties from femoral and tibial bones of the genus *Homo* in five temporal samples including Early Pleistocene (*n* = 6), Middle Pleistocene (*n* = 8), Neandertals (*n* = 14), Middle Paleolithic modern humans (*n* = 6), and Early/Middle Upper Paleolithic (*n* = 28). Traditional cross-sectional geometric properties were calculated for several diaphyseal locations on the femora and tibiae (i.e., 20%, 35%, 50% and 80% of femoral and tibial length). Significant changes were observed in femoral disaphyseal shape including a decrease in mediolateral orientation to anteroposterior orientation between archaic and early modern humans and several shifts were observed in cross-sectional geometric properties. However, little change was observed in overall anteroposterior robustness throughout the Pleistocene femora. Trinkaus & Ruff (2012) discussed the findings as being a result of a continuous foraging subsistence strategy throughout the Pleistocene.

Stock and Macintosh (2015) compared cross-sectional properties between two mid-Holocene hunter-gatherer populations to infer mobility and biomechanical loading patterns. The first sample represented a population from Early Neolithic Kitoi Culture (n = 50) dated to 6800 B.C. The second sample represented a population from the Bronze Age Isakovo, Servo and Glazkovo cultures (n = 30) dated to 4200-1000 B.C. Traditional cross-sectional properties were calculated from measurements taken at 50% of total femoral and tibial length. The results revealed a decrease in femoral compressive and torsional strength between the Kitoi and Bronze Age samples indicating a decrease in terrestrial mobility between the two periods. Tibial midshaft values also revealed the same findings in females, but not with males. Differences between the orientation of the bone between males and females, one characteristic of sexual dimorphism, increased and was indicated by increased compressive strength and torsional strength in the males of the Bronze Age sample. Sexual dimorphism is defined by differences between the sexes beyond sexual organs (e.g., height, weight, and bone morphology).

Cross-sectional analysis of living populations has provided medical professionals with understanding of bone disease (Nelson et al., 2000; Neu et al., 2001). Nelson and colleagues (2000) used x-ray absorptiometry to analyze cross-sections and bone mass between Black and White postmenopausal women. The results revealed significant differences between the groups in the femoral neck region, with Black women having more resistance to mechanical loading. However, fewer differences were found in the midshaft regions between the groups. In 2001, Neu et al. conducted a temporal study of living individuals ($N = 469$) aged 6-40 years old to gain a better understanding of how bone development plays a role in bone mass related diseases (i.e., osteoporosis). The research included calculating CA and TA cross-sectional geometric properties. The study found that bone mineral content was higher in males and periosteal remodeling continued longer in males, while females exhibited more bone mass density. The researchers concluded that hormones like estrogen likely played a role in the differences observed between males and females (Neu et al., 2001).

Beam theory

In mechanical engineering, the term "beam" refers to a structural component designed to support transverse loads; that is, loads that act perpendicular to the longitudinal axis of the beam (Kelly, 2015). Engineering beam theory typically assumes that the cross-section of the beam is uniform and symmetrical, with simple or fixed supports, and experiences transverse loading. Beam theory states that these conditions produce bending loads, denoted by “M,” and are independent of torsion or twisting of the beam (Kelly, 2015). Consider the horizontal beam in Figure 4. When downward force is applied over the cross-sectional area of the beam, the bottom of the beam extends in reaction to this stress, while the top half shortens (Kelly, 2015; Boston University Mechanical Engineering, n.d.). Within this theory, the lengthening and shortening produces internal loads, or stresses, parallel to the long axis of the beam. Stress in this scenario is defined as the internal pressure produced by transverse loads (or weight) across the cross-section of the beam (Kelly, 2015) (see Figure 4).

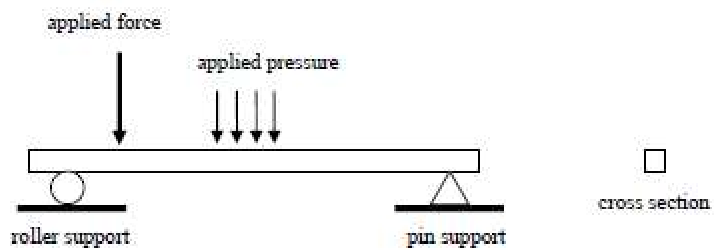

Figure 4. Beam theory (adapted from Kelly, 2015).

Elementary beam theory can be applied to long bones because they are weight bearing and approximately hollow with relatively uniform cross-sectional area over the shaft. However, when we apply the theory to bone, rather than using a square symmetrical model for the cross-section, we apply an ellipse model (Katoozian and Davy, 2000). This model allows us to infer bone behavior, and its response to stress (weight loads) by assigning appropriate axis to the bone (for purposes of the femur, AP and ML), and calculating moments of area. Second moments of area tell us what level of strain has been applied to the bone to make the structure of the bone remodel to maintain weight bearing proportionally and in response to mechanical stimuli (Turner, 1998). Where a beam is supported by other beams or fixtures to keep it in place, bone is supported by surrounding muscles that contract and apply force through locomotion. An example of this can be found in Figure 5.

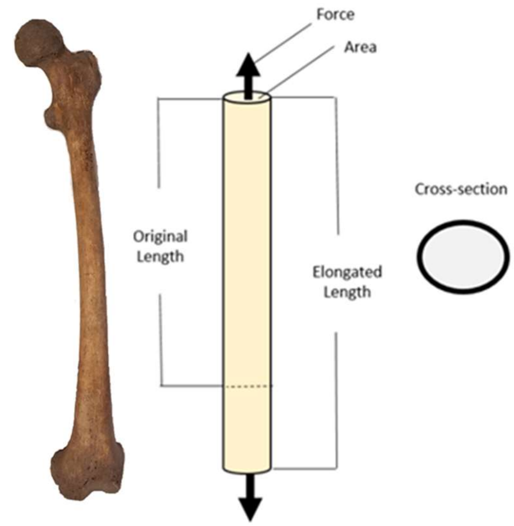

Figure 5. Stress (force/area) and resulting strain (image created by author).

Biomechanics

The femur is a long bone in the lower limb, with proximal attachment to the hip (pelvis), and distal attachment to the knee joint. The proximal femur is made up of the joint surface, the epiphyses and metaphysis. The shaft of the femur is termed the diaphysis, and consists of trabecular bone (cancellous or spongy bone) surrounded by cortical bone (compact bone). The transition between the ends of the bone (epiphyses) and diaphysis is termed the subtrochanteric region. The midshaft of the diaphysis is strictly cortical bone surrounding a hollow medullary cavity that stores fat and red blood cells in living bone (Mays, 2010). The diaphyseal portion of the femoral bone includes the inferior metaphysis, epiphyses and the joint surface. Cross-sectional locations on the femora are measured from the distal end at 0% to the proximal end at 100%. This study is concerned with the subtrochanteric region located at 80% (distally to proximally) of total femoral length, and the midshaft, located at 50% of total femoral length. An example of this can be seen in a photograph of burial 273's left femur resting on an osteometric board (See Figure 6).

Figure 6. Cross-section locations (image created by author).

Stress is nominally defined as force divided by area. In response to stress being placed on bone by the connecting muscles and ligaments, the bone lengthens or shortens. The lengthening and shortening is referred to as strain. As muscles contract to produce locomotion, the contractions of the muscle attached to the bone place strain on the bone (Nagaraja & Jo, 2014). Muscles that have undergone increase in mass as a result of physical activity such as hunting and traveling over rough terrain (i.e., foothills and mountains) will be larger, and will place more stress on bone, requiring the bone to remodel to adapt to the strain (Turner, 1998). Greater strain in the anteroposterior planes will result in an increase in cortical bone thickness in that direction.

Bones are complex structures that function to aid in mechanical movement of the body. Bone tissue will lay down new bone cells and replace old bone cells to retain its efficiency in weight bearing (Mays, 2010). This process is accelerated or decelerated in response to mechanical stimuli (Nagaraja & Jo, 2014). When a bone, such as the femur, is broken (fractured), the bone cells will respond to heal tissue to allow the bone to continue to mechanically function as it normally would. When a bone is under strain, it will remodel its architecture to accommodate the resulting stress and maintain its structural integrity, including resorbing bone material in directions that are not being used (Seeman, 2003).

For the purposes of this thesis, strain is defined as change in cross-sectional shape due to stretching, compression, torsion, and bending placed on bone at the studied cross-sections (Frost, 2001). This process in which bone remodels where strain is placed is often referred to as Wolff's law (Frost, 2001). Wolff developed this theory in the 19th century and years later it was supported by Bonner Thompson in 1962 who elaborated that a condition of strain, the result of stress, is a direct stimulus to growth itself (Turner, 1998). Harold Frost added to this body of knowledge by asserting there is a threshold that must be reached in order for bone to remodel (Frost, 1964; Turner, 1998). Dynamic strain, rather than static strain, is said to be the primary impetus of bone remodeling. Dynamic strain is defined as recurring internal strain due to repeated loads (Nagaraja & Jo, 2014). Turner (1998) proposed three rules for bone adaptation to mechanical stimuli:

> *"1. Bone adaptation is driven by dynamic, rather than static, loading.*
>
> *2. Only a short duration of mechanical loading is necessary to initiate an adaptive response. Extending the loading duration has a diminishing effect on further bone adaptation.*
>
> *3. Bone cells accommodate to a customary mechanical loading environment, making them less responsive to routine loading signals."*

Several studies have validated the conclusions of Turner's (1998) paper. Heinonen et al. (1995) used the general principal that physical loading increases with increasing strain rates and peak forces to study competitive female athletes. The athletes included females that played three sports including aerobic dancers, squash players, and speed skaters with each sport represented differing loading patterns on the skeleton. The sample included women who reported conducting activity five days a week, a more sedentary group that engaged in activity twice a week, and a physically inactive reference group. Skeletal elements of the lumbar spine, femoral neck, distal femur, patella, proximal tibia, calcaneus and distal radius were analyzed using x-ray absorptiometry. The results found that squash players had the highest bone mass density compared to the other groups. Both the aerobic dancers and the speed skaters also had higher bone mass density compared to the reference groups. Heinonen et al.'s (1995) study supports that high strain rates and high peak forces are more effective in bone formation compared to low-force repetition. The researchers noted that the training involved to prepare athletes for these sports played a role in the results.

In 1997, Frost proposed why marathon runners have less bone mass compared to weight lifters. Frost (1997) stated that due to weight lifters reaching higher modeling thresholds to increase muscle mass faster, the acceleration of stress and resultant strain on the bone induces remodeling. Conversely, runners tend to stay below the remodeling threshold resulting in less occurrence of strain. Frost (1997) concluded that as muscle mass plateaus, remodeling does too. Those who do not engage in activities that challenge remodeling thresholds will have weaker muscles and therefore smaller bones.

Andreoli et al. (2001) studied bone and muscle mass in adult males who engaged in high-intensity sports including judo, karate, water polo, and a more sedentary reference group. It was found that the judo athletes had higher bone mineral density compared to the other groups. Judo involves dynamic high-intensity and weight bearing including picking up and throwing opponents on their backs. All of the athletes were found to have more bone mass when compared to the reference group. Andreoli et al.'s (2001) research validates the importance of dynamic force being placed on bone for it to remodel and for researchers to infer activity.

RYAN MOUND

Temporal dating

The individuals curated at San José State University, and therefore the individuals used in this study, were previously assigned to one of three periods or phases based on Bennyhoff and Hughes' alternative dating scheme. The three temporal classifications are the Middle Period 200 B.C. – 900 A.D. (1100-900 years B.P.), Phase 1A-1C (Phase 1) 900 A.D. – 1500 A.D. (900-450 years B.P.), and Phase 2A-2B 1500 A.D. to 1800 A.D. (450-150 years B.P.) (Leventhal, 1993). These dates are based on a temporal marine shell bead typology classification system supported by radiocarbon dating and obsidian hydration created by Bennyhoff and Hughes in 1987 and, where necessary, supported by obsidian hydration studies from the archaeological assemblage from CA-ALA-329. The obsidian hydration studies were conducted by Watts (1984), Homen (1967), Origer (1966), and Wilson (1993) (see Leventhal, 1993).

Bennyhoff and Hughes' dating scheme has been used to date temporal aspects of archaeological sites throughout California. The scheme is based on radiocarbon dates from charcoal, shell, and collagen from archaeological sites throughout the region. The radiocarbon dates were used to classify 180 beads into temporal classifications (Milliken et al., 2007). Bead typology has allowed researchers to not only assign temporal dating, but to also infer trading relationships between regions. The theory behind obsidian hydration is that when a piece of obsidian has been altered by a human (e.g., to make an obsidian projectile point) or otherwise, it will cause the obsidian to create a water signature called the hydration rim. The depth of the hydration rim in the unaltered part of the obsidian is what is studied and used to assign a date (Friedman, Trembour & Hughes,1997). Based on Bennyhoff and Hughes' dating scheme and supporting obsidian hydration studies, 85% of burials from CA-ALA-329 were assigned to the Late Phase Periods while the Middle Period is represented by 15% of the collection.

The warming period

The Late Phase 1 Period burials range temporally from 900 A.D. to 1500 A.D., as classified by Leventhal (1993). This time period roughly corresponds to a climate warming period, also termed by some as the Medieval Warm Period, Medieval Warm Epoch, and by others as the Medieval Climatic Anomaly (Hughes & Diaz, 1994). Several region-specific studies have been conducted to determine periods of drought throughout California. The following studies include climate data inferred from glacial events and tree-ring data followed by discussions of how the warming period may have or may not have impacted regions in California.

There are several ways researchers have reconstructed prehistoric climates. Tree-ring data are valuable to infer climate because they provide a continuous record, are easily dated, and can be compared to modern records (Moratto, King & Woolfenden, 1978). Temperatures can then be reconstructed to analyze temporal shifts (Scuderri, 1993). Glacial events are useful to corroborate tree-ring data due to deposits (e.g., soils and rocks) left behind that can be dated (Moratto et al., 1978). Pollen samples taken from dated deposits can also give evidence of regional flora that was thriving at the time and therefore can help to infer climate (D'Oro, 1999).

In 1978, Moratto et al. examined the impact that California's climate had on its inhabitants. The authors used glacial events, tree-ring data, and pollen analysis as a baseline for climatic changes that go back several millennia. Moratto et al. 1978 conducted studies on 67 native archaeological sites and excavated 27 of the sites. The researchers developed three temporal phases based on their findings, Chowchilla Phase (2800 – 1200 B.P.), the Raymond Phase (1400 to 500 B.P.) and the Madera Phase (500 to 100 B.P.). The Raymond Phase represents the time period of the Medieval Climatic Anomaly (MCA) (roughly 1176 to 717 B.P.). The authors discuss the Raymond Phase as a period of climatic warming, social chaos and violence, and with a cooling trend towards the end of it (Moratto et al., 1978).

In 1993, Scuderi analyzed approximately 4,400 year-old tree-rings from a foxtail pine tree to infer climatic variation in the southern Sierra Nevada Mountains of California. The tree-ring data indicated that the warmest period in the region was between 425 A.D. and 1569 A.D. Scuderi (1993) also stated that altitude should be considered when analyzing tree-ring data to infer regional climate studies.

Graumlich (1993) used juniper and pine tree-ring data from three sites going back to 800 A.D. to examine precipitation in the Sierra Nevada. Graumlich's (1993) results showed that there was a warmer period from 1100 to 1375 A.D., but stated that other studies showed the timing and occurrence of this varies regionally. Graumlich (1993) also stated that the increase in warmth could be a result of volcanic activity that may have impacted oscillation patterns. Graumlich (1993) concluded by inferring that there were periods of droughts from 800-859 A.D., 1197-1217 A.D., and 1249-1365 A.D.

Hughes and Brown (1992) inferred periods of severe drought for the past 2,000 years from Giant Sequoia rings at three sites in the San Joaquin Basin. The authors proposed that by looking at 20th century records of drought occurrence and comparing written historical records to rings of sequoia trees, researchers can subsequently establish a baseline of what droughts years look like in rings of Sequoias and use this to infer droughts in previous centuries. The authors found that across all three sites, the most common drought-stricken centuries were 707-797A.D., before the MCA, and 1500-1580 A.D., after the MCA (Hughes & Brown, 1992). However, consistent and high periods of droughts were found from 800-1100 A.D. which decline gradually from 1100-1350 A.D., with the 13th century displaying the least number of low growth years (indicating lack of drought). The results changed when not incorporating all three sites, which show consistent intense drought events throughout the warming period (Hughes & Brown, 1992).

In 1994, Hughes and Diaz argued against intensified climatic change during the warming period. They found that rather than a global warming trend, there was spatial differentiation between climates across the world. The article points out an extremely wet period in the White Mountains of California (inferred from a bristlecone pine) from 1080 – 1129 A.D. The article concludes that there may have been a warmer period between the 9th and 15th Centuries A.D., but only in comparison to the five centuries that followed. The article emphasized that through climate variability, we can still study human interaction with these variations which will help further our knowledge of past populations.

Raab and Larson (1997) focused on cultural evolution during climatic change in coastal southern California. The authors discussed the ways in which the native Chumash evolved culturally as an adaptation to paleoenvironmental shifts. They suggested that elevated sea temperatures and droughts from 1150 A.D. to 1300 A.D. allowed the coastal Chumash to gain control over marine resources in the region, giving them advantage over terrestrial drought-stricken populations. The authors provided climatic data sources from tree-rings and pollen counts to substantiate the climatic changes that occurred during the warming period. In addition to paleoenvironmental data, Raab and Larson (1997) provided osteological and archaeological records indicating that many of the southern native populations experienced episodes of violence and disease throughout the proposed transitional period (1150 A.D. to 1300 A.D.) (Raab & Larson, 1997).

Gamble (2005) looked at climatic changes between 400 A.D. and 1500 A.D. that may have influenced social change. The author argued that hunter-gatherer societies were less impacted by climate change than previously thought, and that climatic changes were gradual rather than abrupt. Gamble referenced studies that indicated drought periods created resource stress (which led to a reliance on marine subsistence) and heightened violence. The author suggested that social systems evolved as a response to and preparation for periods of droughts. Osteological studies also validate these data by showing evidence of violence during this period and a decline in violence in the record towards the end of it, potentially indicating climate stability (Gamble, 2005). The author also discussed the recurrence of El Nino/Southern Oscillations as occurring every two to seven years, lasting for one to years, as a pattern that has existed for thousands of years, which may have also contributed to intense climate change.

In summary, Juniper and pine tree-ring precipitation data from three sites in the Sierra Nevada, California going back to 800 A.D. analyzed by Graumlich (1993) show periods of drought in 800-859 A.D., 1197-1217 A.D., and 1249-1365 A.D. Giant sequoia tree-rings at three sites in the San Joaquin Basin analyzed by Hughes and Brown (1992) show the most common drought stricken centuries were 707-797 A.D., before the warming period, and 1500-1580 A.D., after the warming period (Hughes & Brown, 1992). However, there are consistent and high periods of droughts from 800-1100 A.D. which decline gradually from 1100-1350 A.D., with the 13th century showing the least number of droughts. The research presented here suggests that climate change was likely regionally specific and gradual which may have allowed natives to adapt to change in availability of resources.

San Francisco Bay Area and the Ohlone

According to contemporary literature, natives arrived in California between 15,000 to 11,000 years B.P. (Erlandson, Jones, Rick & Porcasi, 2007). Although it is nearly impossible to pinpoint when California was first occupied, environmental factors such as retreating of glaciers, abundance of pine, Douglas fir and cedar forests (West et al., 2007), and stable sea levels (Aiello & Masters, 2007) around 11,000 to 12,000 years ago may have turned California into a temperate climate suitable for occupation. Two sites within the San Francisco Bay Area (SCR – 177 and SCL-178) indicated occupation as early as 6,000 to 7,000 years ago (Erlandson et al., 2007). Additionally, shell middens found throughout the Bay Area date to around 5,000 years ago (Aiello & Masters, 2007). However, it is well known that sea levels were much lower in previous centuries, meaning previously habited sites are likely underwater (Aiello & Masters, 2007). It has been speculated that proto-Utian peoples, assumed ancestors of all Ohlone, came to the Bay Area around 4,500 years ago and integrated with Hokan speaking people to enable new kinship systems that furthered socioeconomic relationships (Milliken et al., 2007).

When the Spanish made contact with the natives in the San Francisco Bay Area in the middle of the 18th century, they estimated there to be 7,000 to 10,000 people inhabiting the region from Point Sur to the San Francisco Bay Area (Kroeber, 1925; Margolin, 1978). The Spanish labeled the natives Costanoan, or "people of the coast," (Kroeber, 1925; Margolin, 1978) but descendants of these peoples prefer to be referred to as Ohlone. According to observations made by missionaries, the Ohlone were made up of 40 nations averaging about 250 individuals per nation and each nation spoke one of 8 to 10 dialects (Margolin, 1978).

Limited ethnographic information is available to reveal past lifestyles of the Ohlone. European explorers and missionaries who found themselves within this region observed a moist climate with vast marshes, thick oak bay forests, and redwoods coating the hills. Terrestrial mammals such as antelope, deer, rabbits, bears, wolves, and mountain lions were common. Marine life, from shellfish to whales, was observed to be in abundance. Temporary and permanent villages throughout the coastline suggested that the Ohlone travelled in small bands to accommodate harvesting seasons (Margolin, 1978; Milliken et al., 2007). According to the records Margolin (1978) summarizes, the Ohlone had no need to practice conservation nor were they struggling to retain adequate resources. These resources included marine life such as shellfish, sea lions, salmon, acorn and seeds (Kroeber, 1925).

The diary entries and retold accounts summarized within Margolin's (1978) book and the observations made by Kroeber (1925) would be over two centuries past the time of the known warming period. We, therefore, cannot project the book's contents onto the people who lived prior to documented histories. Margolin (1978) stated in his book that it is problematic to label the natives (the Ohlone) as one homogenous group considering the diverse vast array of cultures and language dialects as one whole group. It is also problematic to interpret subjective interpretations of history as truth. However, it is somewhat useful to receive these written accounts as a glimpse into the past of the Ohlone.

The archaeological and osteological record has provided evidence of complex societies of hunter-gathers in the San Francisco Bay Area at approximately 4,000 years ago. Dietary reconstruction of paleo-coastal people in the San Francisco Bay Area has revealed that coastal peoples relied heavily on shell-fish and plant material, and consumed marine mammals (Milliken et al., 2007). Faunal records have indicated that northern fur seal was prevalent during the Early Period (4500-2500 B.P.). Dietary reconstruction studies also showed that the Middle Period was characterized by terrestrial mammals, with an increase in sea otter and harbor seals in the Late Period (Milliken et al., 2007). These findings are supported by isotopic research conducted by Bartelink in 2006. Bartelink (2006) found changes in dietary signatures from the Early and Middle periods. The Early Period dietary analysis showed high consumption of marine resources (i.e., marine and anadromous fish, and marine mammals) with less evidence of terrestrial resources being consumed. Dietary signatures in the Middle Period showed less consumption of marine protein compared to the Early Period, with more signatures indicating lower consumption of proteins like shellfish and high consumption of terrestrial resources. The results also showed that the Late Periods are "nearly identical" to the Middle Period, with a slight increase in marine resource consumption (Bartelink, 2006).

Prehistoric activity patterns of the Ohlone have been lifted from archaeological and osteological data. Burial assemblages with associated artifacts have revealed a sexual division of labor was practiced by the Ohlone. Research conducted using cross-sectional analysis indicated female upper arm bone mass was more mediolaterally oriented compared to males, indicating the use of pestles and mortars to process plant material such as acorns, nuts, and seeds (Leventhal, 1993; Weiss, 2007). Males have been found to be more anteroposteriorally robust in their humeri, which may imply that males were primarily responsible for hunting or engaging in violence (Weiss, 2007; Weiss, 2009).

Cultural complexity in the Ohlone region can be gleaned from mortuary practices observed in the region. Individuals were either interred within or near villages, or in dedicated cemeteries (Milliken et al., 2007). Offerings were sometimes placed with the dead and included items such as ornamentally shaped mortars, bird bone whistles, *Olivella* beads, and *Haliotosis* shell bead pendants (Leventhal, 1993; Milliken et al., 2007). *Olivella* beads constructed from shells are found throughout the prehistoric archaeological record in California. It is widely accepted that *Olivella* beads, *Haliotosis* ornaments, and clamshell ornaments held socioeconomic and ceremonial value within prehistoric societies in California. The production of each shell has been estimated to have taken over an hour of labor (Milliken et al., 2007). This would have made these artifacts a valuable aspect of trade relationships. The burial assemblages of CA-ALA-329 in particular showcase the vast amounts of shell beads that were circulating in the Bay Area region. However, mortuary treatment is not consistent across the region or even within sites. Burials have been found with no offerings, indicating differential treatment of the dead.

The differential treatment of the dead may infer a socioeconomic and class component within the region. Elite people were likely adorned with items associated with wealth (Leventhal, 1993). There is evidence that at least some groups of the Ohlone practiced the Kuksu religion, as evidenced by several effigy abalone pendants found throughout the region (Leventhal, 1993). The Ohlone buried their dead in several different positions throughout the Bay Area over time ranging from face down and tightly flexed with knees tucked to the chest, to face up and fully extended (Milliken et al., 2007). The cultural shifting of burial positioning and beads may indicate the region was filled with culturally and genetically different people over time, as proposed by Weiss (2018) in her study of biological continuity in the collection. Interpersonal violence and trophy taking has been documented throughout the region and seems to have increased temporally, though it is not certain if this was a result of territory or scarcity of resources (Milliken et al., 2007; Jurmain et al., 2009).

Climatic impacts have been studied in the San Francisco by comparing archaeological assemblages to southern California native sites established to have been impacted by the warming period. D'Oro (2009) concluded that when comparing Bay Area sites to southern California sites, the Bay Area was not impacted by the warming period. Furthermore, a study conducted on health indicators in the region observed no significant changes in health from the Middle Period to the Late Phase 1 Periods (Nechayev, 2007). This thesis provides additional insight through cross-sectional analysis that infers mobility patterns during warming the period in the Late Phase 1 Period.

CA-ALA-329

CA-ALA-329, also referred to as Ryan Mound, is a large earthen mound site in the eastern Coyote Hills of the San Francisco Bay Area. The site is bounded to the west by San Francisco Bay and to the east by Diablo Mountain Range (Leventhal, 1993; Jurmain et al,. 2009). CA-ALA-329 has been excavated several times beginning in 1935 by Waldo Wedel, by University of California, Berkeley in 1948, by Stanford University in 1959, and by San José State College in 1962 (now San José State University) (Leventhal, 1993). Stanford University excavated 139 burials from CA-ALA-329. Stanford chose to repatriate the burials to the Ohlone community in 1991 (Leventhal, 1993). San José State's collection reflects excavations from 1962-1968 and consists of 284 (71 subadults; 212 adults) burials discovered in-situ (Leventhal, 1993).

In 1993, Leventhal conducted a study on the entire archaeological assemblage from CA-ALA-329. The study inventoried hundreds of artifacts and assigned each burial temporally. The assemblage is rich in artifacts that reflect social, economic and subsistence patterns. A vast majority of artifacts were found to be burial associated. Mortars and pestles were generally found to be associated with female burials, indicating females were involved with the processing of plant material and food preparation. Obsidian points, bone awls, serrated tools, and fish hooks were generally found associated with male burials, indicating that males hunted both coastally and terrestrially (Leventhal, 1993). Charmstones, bird bone whistles, thousands of *Olivella* shell beads, and *Haliotosis* shell pendants are among artifacts inventoried in the assemblage, being especially evident in the Late Phase periods. Leventhal (1993) noted that this could be the result of over representation of the Late Phase Periods or an indication of cultural change. While two possible structures were found during excavation, it is important to note that CA-ALA-329 is not considered to be a village site. From the lack of flake debitage and lack of non-burial associated mortals and pestles in comparison to established village sites, Leventhal (1993) concluded this site was likely not a village site, but a mortuary related ceremonial site for the elite.

Changes in social patterns have also been observed regarding mortuary practices during the warming period. Burials assigned to the Middle Period temporal classification were observed to be flexed and face down, while Late Phase 1 Period burials were observed to generally be face-up and often were found to be adorned with substantial amounts of *Olivella* beads, tools and ceremonial items like charmstones (Leventhal, 1993). Effigy or “banjo pendants” (abalone pendants) associated with burials in the collection indicated individuals may have belonged to the Kuksu religion that has been observed in other archaeological assemblages throughout the region (Leventhal, 1993).

Due to its size, the population of CA-ALA-329 has been studied extensively ranging from studies on health indicators such as anemia (Nechayev 2007), osteoporosis (Atwood, 20008), osteoarthritis (Weiss, 2006) to indications of interpersonal violence (Jurmain et al., 2009), skeletal muscle markers (Weiss, 2007), biological continuity (Weiss, 2018), and even stable isotopic analysis (Bartelink, 2006; Sullivan, 2018). In 2007, Nechayev conducted research on health indicators in the skeletal assemblage. Physiological stresses (e.g. porotic hyperostosis and periostitis) as well as stature and age at death were examined in the entire skeletal collection and revealed no significant difference between the Middle Period and Late Phase 1 Periods. However, the Late Phase 2 period females exhibited higher nutritional stresses evidenced by increased prevalence of porotic hyperostosis (i.e., anemia) compared to males in the Late Phase 2 Period (Nechayev, 2007).

In 2007, Weiss examined muscle markers on humeral bones from the collection to infer sexual division of labor. Weiss's sample included 102 adults consisting of 43 males and 59 females. Weiss examined humeral muscle markers using 28 variables (i.e., sites on the bones) and scored each variable using the categories of robusticity (defined by muscle attachment areas on the humerus) and stress lesions (i.e., pitting of the bone into the cortex). Weiss (2007) found that when controlling for the effects of size and age, muscles associated with throwing had higher scores in males, potentially reflecting hunting or activities associated with violence. Weiss revisited the humeral sample in 2009, and found females were less bilaterally asymmetric in both upper arm bones when compared to males, likely as a result of processing plant foods.

In 2009, Jurmain et al. explored patterns of interpersonal aggression by examining skeletal remains of the collection. The researchers analyzed the skeletons within the SJSU collection (n = 298), the University of California, Berkeley collection (n = 61) and the Stanford University skeletal data of 144 skeletons recorded prior to Ohlone repatriation in 1992. The combination of all three collections and records enabled a sample size of 503. Jurmain et al. (2009) looked at projectile injuries, cranial vault injuries, facial and craniofacial injuries, and forearm injuries with respect to completeness of skeleton. The results indicated that males generally showed higher rates of injury. The researchers also found that young adults were more likely to show evidence of projectile points injuries. It is important to note that a temporal analysis of projectile wounds found that they increased with time, but analysis showed no statistical significance to support the pattern. The researchers also analyzed perimortem bone modification, or trophy taking, and found that evidence of bone trophy taking reduced over time (Jurmain et al., 2009). Though CA-ALA-329 showed high amounts of interpersonal aggression when compared to sites within the region, there has been a much higher prevalence observed in sites within other regions in California (Jurmain et al., 2009). An example of this is the violence observed in a Channel Island (southern California) population in which nearly 20% of the sample (N = 598) showed healed cranial vault fractures (Walker, 1989).

Modern research conducted on the collection has provided insight into landscape mobility and biological distance within the sample. Sullivan (2018) reconstructed diets through stable isotopic analysis on a sample of 20 individuals from the burial collection.

The results infer that female diets were consistent with a matrilocal pattern throughout time in the Middle and Late Phase 1 Periods with a decrease in the Late Phase 2 Period, likely due to overpopulation and stresses imposed by Spanish colonization (Sullivan, 2018). In a study conducted on biological continuity within the collection, Weiss (2018) scored 36 nonmetric skeletal traits in 163 individuals to analyze if biological continuity was present between time periods. The results indicated that the Middle Period and Late Phase 2 Periods represent different populations. Weiss's (2018) research may have broad implications for future studies on the burial collection and the research reflected in this thesis. However, because the Late Phase 2 Period is not represented in this sample, it is reasonable to conclude that the Middle Period and Late Phase 1 Period may not represent two genetically different populations.

METHODS

Samples

Samples used in this study were borrowed from San José State University's collection of CA-ALA-329, currently curated by San José State University's Anthropology Department. The collection is comprised of 284 individuals. Individuals included in the study were chosen based on availability of at least one complete femur in no more than two separate pieces. Initial review of the available burials revealed that more left femora were complete within the collection. When possible, the left femur from each individual was chosen for the study. Individuals who may have potentially had bone pathologies were excluded from the study. Only individuals who could be identified as male or female and had complete age estimation were included. No individuals aged below 18 years were included in this sample to exclude individuals without mature skeletal elements. The collection had been previously sexed and aged using established methods by several academics including Todd(1920), Ubelaker (1978), Lovejoy et al.(1985), Bass (1986), and others (see Leventhal, 1993). Sixty left femora and eighteen right femora were included within the study.

The total potential sample size for this study was 78 individuals. The Middle Period burials were represented by twenty-six individuals including 13 females and 13 males. The Middle Period sample represents the population that lived before the drought. The Late Period Phase 1 individual sample consisted of fifty-two femora from 30 females and 22 males. These individuals comprised the portion of the sample that roughly represents the warming period. Femora were placed in protective bags individually and labeled with burial ID for safe transport to and from San José State University's campus Health Clinic. A complete list of included individuals can be found in Appendix A.

X-rays

X-rays were taken at San José State University's campus Health Clinic using a Quantum Medical Imaging QS-500 machine. San José State's Director of Radiology, Nadia Dhillon, took all of the radiographs analyzed in this thesis. According to Ruff and Hayes (1983), biplanar radiographs have been proven to be an acceptable replacement for CT scanning when analyzing cross-sectional properties. Four femora were placed on each radiograph for efficient use of the clinic's resources. Lead beads were attached to each designated cross-section to allow for later measurement. Each radiograph was first taken in mediolateral view and again in anteroposterior view. When necessary, bean bags were placed at the distal ends of the femora to keep them positioned correctly. The lowest burial number was placed to the left on each radiograph to aide in record keeping. Figures 5 and 6 are example radiographs and include burial femora 6, 20, 23 and 25 in anteroposterior and mediolateral positions. The complete collection of radiographs can be found in Appendix B.

Figure 7. Radiographed femora in mediolateral view.

Figure 8. Radiographed femora in anteroposterior view.

Measurements

Each femur's total biomechanical length was measured to determine cross-section locations. All femora were marked lightly with a pencil at 50% and 80% of the bone's biomechanical length. Following the completion of the biplanar radiographs, cross-sectional measurements were taken using MicroDicom Viewer. Each cross-section was measured to determine lateral inner diameter, medial to lateral outer diameter, anterior to posterior inner diameter, and anterior to posterior outer diameter, in millimeters, for every femora that was able to be measured confidently. Each measurement was taken and recorded twice to calculate intraobserver error rates (Measurement 1 – Measurement 2/ Measurement 1). If a measurement failed to be within 10% of the first measurement, the measurements were re-done until they came within 10%. Measurement data were stored in Microsoft Excel until the data was imported to SPSS 25 for statistical analysis.

Cross-sectional geometry

Geometric formulae to calculate cross-sectional properties has traditionally been borrowed from standard engineering and biomechanical theoretical models. The following formulae presented by Biknevicus and Ruff (1992) and Weiss (2003) were used to calculate cross-sectional data:

- $Ix = \pi / 64 (Tap \times Tml^3 - Map \times Mm^3)$
- $Iy = \pi /64 X (Tml \times Tap^3 - Mml \times Map^3)$
- TA = π X (ML outer diameter X AP outer diameter / 4)
- CA = TA – MA
- J = Iy+ Ix

Note:

Tml = Total mediolateral breadth
Tap = Total anteroposterior breadth
Mml = Medullary mediolateral breadth
Map = Medullary anteroposterior breadth

Results of Ix and Iy were then calculated to ratios to determine in what direction mechanical forces were placed (i.e., anteroposterior or mediolateral), as a result of stress and strain. The sample contained four femora that were not able to be measured at the subtrochanteric region due to bone porosity and degradation that was not visible until seen in the radiographs. An example of this can be seen in burial femora 100 (Figure 9).

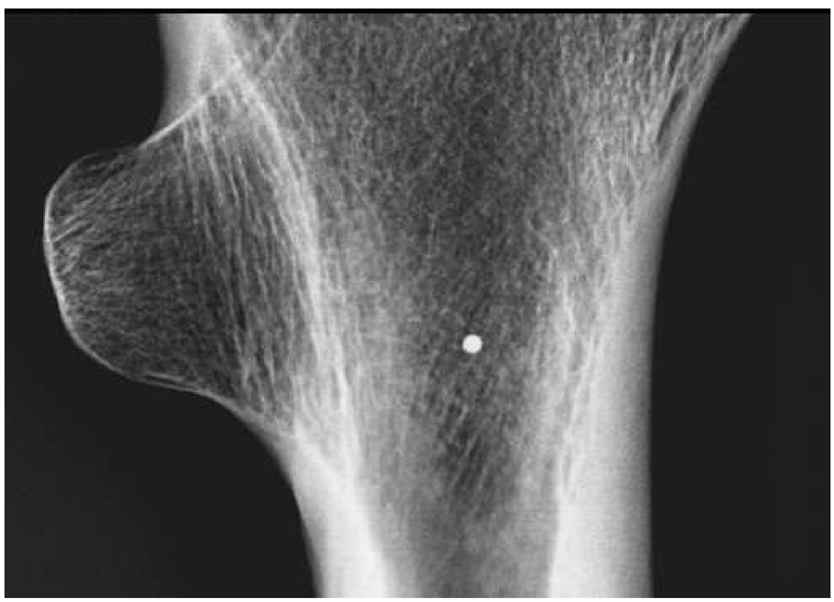

Figure 9. Excluded subtrochanteric cross-section.

The femora that were not able to be included in the ratios at the subtrochanteric region are burials 31, 46, 100, and 158. One femora, burial femur 212, was excluded completely due to improper positioning during radiographing. Burial femora suspected to have been incorrectly placed were included in statistical testing with data set 1, and additional statistical testing was done without the suspected incorrectly placed femora (data set 2) to assess distribution in both data sets. Burial femora suspected to have been placed improperly include 58, 69, 77, 85, 218, 239, 243, and 273.

Statistical analysis

All data were analyzed using SPSS 25. To determine where mechanical stress was highest, the Ix/Iy ratio values reflected either a circular cross-section (i.e., value equal to 1.0), greater anteroposteriorally bending strength (i.e., value greater than 1.0), or mediolaterally (i.e., value less than 1) (Daegling & Grine, 1991; Weiss, 1998). Two data sets were tested for normality using the Shapiro-Wilk test. The first data set included the full sample (data set 1) while the second data set excluded femora that were suspected to have been placed incorrectly while radiographing (data set 2).

To determine potential interaction between sex, time period, and the resultant Ix/Iy values, two-way analysis of variance (ANOVA) tests were run to analyze ratios for data from both 80% and 50% of total femoral length cross-sections. To determine if there were significant differences between sexes in both time periods, one-way ANOVAs were run. Due to the remaining cross-sectional geometric properties not being standardized for body size, dependent variables (DV) CA, TA and J were run separately from Ix/Iy values. Multivariate analysis of variance (MANOVA) was run to analyze CA, TA, and J between sexes and chronologically at both 50% and 80% of total femoral length. To test hypothesis two, one-way ANOVA was run when an interaction was found to determine if sex differences were significant in both time periods for all variables at 50% and 80% of femoral length. Cohen's D was calculated when significant findings were found to determine effect size between males and females in each respective time period; effect size allowed the researcher to determine in which period the sex difference was greater. CA, TA, and J values were not standardized for body size in this study and therefore only Ix/Iy values were used to test hypothesis two to avoid effects of body size between sexes (Weiss, 1998; Ruff 2000). The following data were reported for each analysis where applicable: degrees of freedom (*df*), sum of squares (*SS*), mean of squares (*MS*), Fisher's F ratio (*F*), probability value (*p*), and standard deviation (*SD*).

RESULTS

The Shapiro-Wilk tests of normality showed a normal distribution for all variables except for three variables in the data set that included the entire sample (data set 1) and two variables in the sample that excluded potentially incorrectly positioned femora during radiographing (data set 2). The three variables with nonnormal distributions in data set 1 ($N = 77$) at 80% of femoral length included TA, with skewness of 0.46 (SE = 0.28) and kurtosis of -0.54 (SE = 0.05), J at 80% of femoral length with skewness of 0.907 (SE = 0.28) and kurtosis of 0.903 (SE = 0.55), and J at 50% of femoral length with skewness of 0.90 (SE = 0.28) and kurtosis of 0.90 (SE = 0.55). Two variables at 80% of femoral length in data set two ($N = 69$) were found to have nonnormal distributions; Ix/Iy with a skewness of -0.54 (SE = 0.28) and kurtosis of 1.42 (SE = 0.57) and J with a skewness of -0.42 (SE = 0.28) and a kurtosis of 1.60 (SE = 0.57).

Although TA (80%), J (80%), and J (50%) in data set 1 were found to have nonnormal distributions, the skewness and kurtosis results for the variables were between -1.00 and +1.00, indicating that they did not excessively deviate from a normal distribution (Garson, 2012; Ozmercan, 2015). In addition, parametric tests, such as the ANOVA and MANOVA stand as useful ways to analyze nonnormal data due to their robustness (Rasch & Guidard, 2004). Therefore, all variables were utilized and data set 1 was used for statistical analyses for this study.

The first hypothesis stated that Late Phase 1 Period burial femora would have thinner cortical thickness compared to Middle Period femora in both the subtrochanteric and midshaft regions, especially among males. Results of the two-way ANOVA for Ix/Iy values at the subtrochanteric region revealed a main effect of sex; males had more robust femora than females (Table 1). Additionally, there was an interaction between sex and temporal period in which the male femora decreased in robusticity from the Middle Period to the Late Phase 1 Period and the female femora increased in robusticity from the Middle Period to the Late Phase 1 Period (Table 1; Figure 10).

TABLE 1. Two-way ANOVA results for Ix/Iy at 80% of femoral length

Source	*df*	*SS*	*MS*	*F*	*p*
Time Period	1	0.14	0.14	2.27	0.136
Sex	1	0.39	0.39	6.17	0.015
Time Period and Sex	1	1.31	1.31	10.65	0.002
Error	69	4.40	0.06		
Total	73				

$p \leq 0.05$

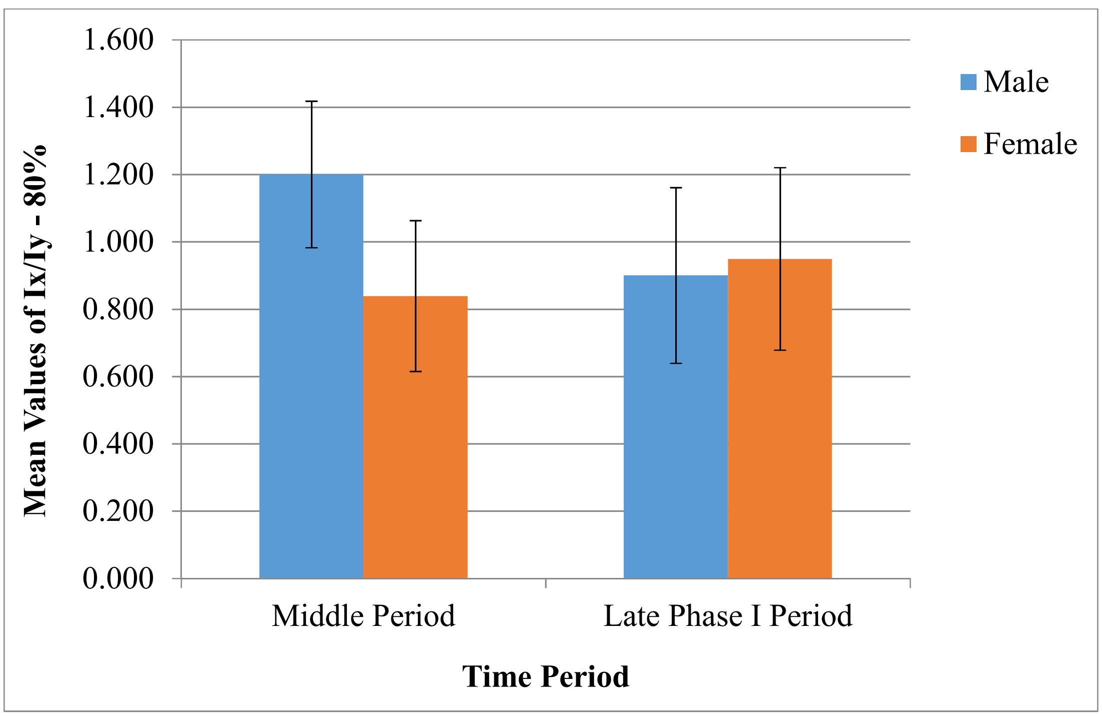

Figure 10. Ix/Iy interaction for time period by sex at 80% of femoral length. Bars show means and error bars show standard deviations.

Given the interaction found, one-way ANOVAs were run to test statistical significance between Middle Period males and Late Phase 1 Period males, and again for Middle Period females and Late Phase 1 Period females (Table 2). The results of the one-way ANOVAs revealed the differences between males at the subtrochanteric region were statistically significant. These results partially support the first hypothesis; Middle Period males are significantly more robust anteroposteriorly when compared to Late Phase 1 Period males (Table 2).

TABLE 2. One-way ANOVA results for Ix/Iy at 80% of femoral length

Sex	Source	*df*	*SS*	*MS*	*F*	*p*
Males	Between Groups	1	0.69	0.69	11.59	0.002
	Within Groups	30	1.79	0.06		
	Total	31	2.48			
Females	Between Groups	1	0.10	0.10	1.54	0.221
	Within Groups	39	2.60	0.06		
	Total	40	2.71			

$p \leq 0.05$

Results of the two-way ANOVA for Ix/Iy values at midshaft revealed a main effect of sex; males had more robust femora than females (Table 3). Additionally, there was an interaction between sex and temporal period in which the male femora increased in robusticity from the Middle Period to the Late Phase 1 Period and the female femora decreased in robusticity from the Middle Period to the Late Phase 1 Period (Table 3; Figure 11).

TABLE 3. Two-way ANOVA results for Ix/Iy at 50% of femoral length

Source	*df*	*SS*	*MS*	*F*	*p*
Time Period	1	0.01	0.01	0.85	0.359
Sex	1	0.09	0.09	5.93	0.017
Time Period and Sex	1	0.27	0.27	16.50	0.001
Error	73	1.20	0.16		
Total	77	1.72			

$p \leq 0.05$

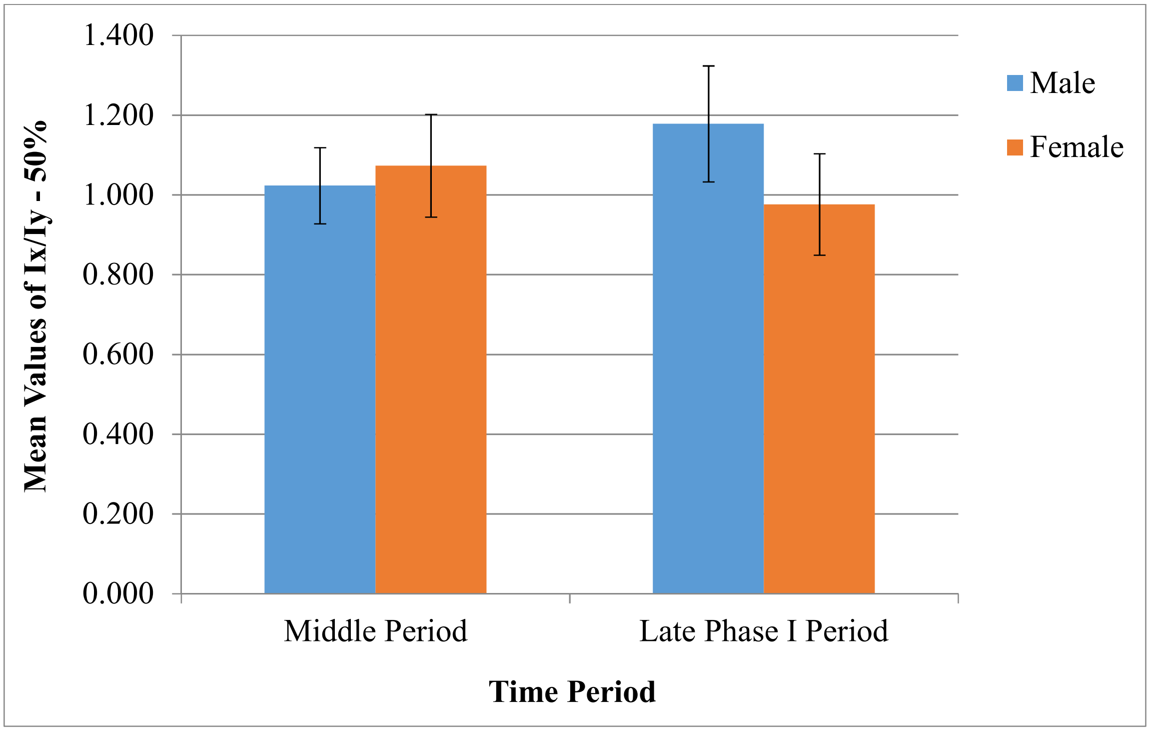

Figure 11. Ix/Iy interaction for time period by sex at 50% of femoral length. Bars show means and error bars show standard deviations.

One-way ANOVAs were run to test statistical significance at the femoral midshaft for Ix/Iy between males in both periods and again between females in both periods. Both male and female values were found to be statistically significant (Table 4).

TABLE 4. One-way ANOVA results for Ix/Iy at 50% of femoral length

Sex	Source	*df*	*SS*	*MS*	*F*	*p*
Males	Between Groups	1	0.19	0.19	11.60	0.002
	Within Groups	32	0.53	0.01		
	Total	33	0.72			
Females	Between Groups	1	0.08	0.08	5.28	0.027
	Within Groups	41	0.67	0.16		
	Total	42	0.75			

$p \leq 0.05$

Descriptive statistics for CA, TA, and J at 80% of femoral length are displayed in Table 5. Males had greater J values at 80% of femoral length than did females (Tables 6).

TABLE 5. Means and standard deviations for CA, TA, and J at 80% of femoral length

				Cortical Bone (mm)	
DV	Time Period	Sex	*N*	*M*	*SD*
CA	Middle	Female	12	3.59	4.43
		Male	13	5.00	4.68
	Late Phase 1	Female	29	3.70	4.61
		Male	19	4.54	3.76
TA	Middle	Female	12	8.06	2.72
		Male	13	10.20	3.86
	Late Phase 1	Female	29	7.98	3.27
		Male	19	8.02	4.11
J	Middle	Female	12	1681.19	507.19
		Male	13	2125.33	669.99
	Late Phase 1	Female	29	1657.33	320.04
		Male	19	1858.14	554.06

TABLE 6. Two-way MANOVA results for CA, TA, and J at 80% of femoral length

Source	DV	*df*	*SS*	*MS*	*F*	*p*
Time Period	CA	1	0.49	0.49	0.02	0.873
	TA	1	20.63	20.63	1.64	0.204
	J	1	343909.86	343909.86	1.44	0.233
Sex	CA	1	20.33	20.33	1.05	0.308
	TA	1	19.19	19.19	1.52	0.220
	J	1	1684827.27	1684827.27	7.08	0.010
Time Period and Sex	CA	1	1.31	1.31	0.06	0.795
	TA	1	17.78	17.78	1.41	0.238
	J	1	240609.96	240609.96	1.01	0.318
Error	CA	69	1331.90	19.30		
	TA	69	866.31	12.55		
	J	69	16412475.54	237861.96		
Total	CA	73	2601.49			
	TA	73	6078.20			
	J	73	254343280.0			

$p \leq 0.05$

The results of the MANOVA for CA, TA, and J at the midshaft region revealed main effects of temporal period and sex on J; both Late Phase 1 Period males and Late Phase 1 Period females femora had lower J values compared to Middle Period males and Middle Period females (Tables 7 and 8). Additionally, there was a main effect of sex on TA; males had higher TA values than did females (Table 8; Figures 12). There were also interactions on CA and TA; in both instances, female femora decreased in robusticity from the Middle Period to Late Phase 1 Period and male femora increased from the Middle Period to the Late Phase 1 Period (Table 8; Figures 12 and 13).

TABLE 7. Means and standard deviations for J at 50% of femoral length

			Cortical Bone (mm)		
DV	Time Period	Sex	*N*	*M*	*SD*
J (50%)	Middle	Female	12	1681.19	507.19
		Male	13	2125.33	669.99
	Late Phase 1	Female	29	1657.33	320.04
		Male	19	1858.14	554.06

TABLE 8. Two-way ANOVA results for CA, TA, and J at 50% of femoral length

Source	DV	*df*	*SS*	*MS*	*F*	*p*
Time Period	CA	1	8.69	8.69	0.33	0.567
	TA	1	1.74	1.74	0.04	0.839
	J	1	399168.11	399168.11	5.97	0.017
Sex	CA	1	30.19	30.19	1.14	0.287
	TA	1	548.65	548.65	13.05	0.001
	J	1	1929622.45	1929622.45	28.87	0.001
Time Period and Sex	CA	1	274.72	274.72	10.45	0.002
	TA	1	215.74	215.74	5.13	0.026
	J	1	109395.54	109395.54	1.63	0.205
Error	CA	73	1918.16	26.27		
	TA	73	3086.61	42.03		
	J	73	4878150.14	66823.97		
Total	CA	77	2319.21			
	TA	77	4173.13			
	J	77	7683296.60			

$p \leq 0.05$

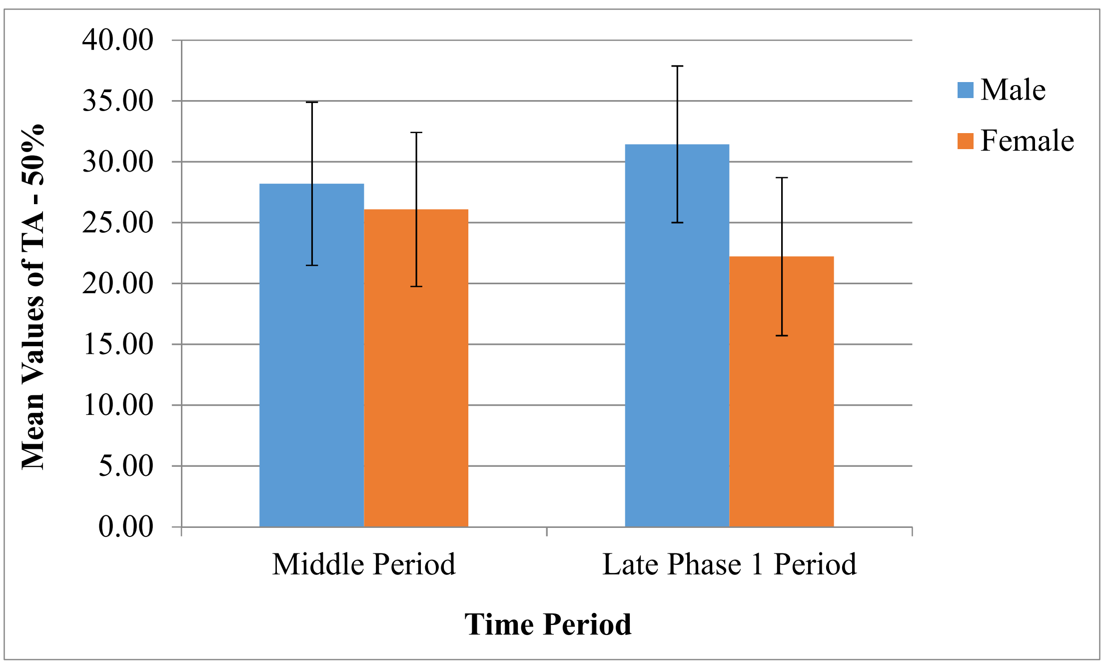

Figure 12. TA interaction for time period by sex at 50% of femoral length. Bars show means and error bars show standard deviations.

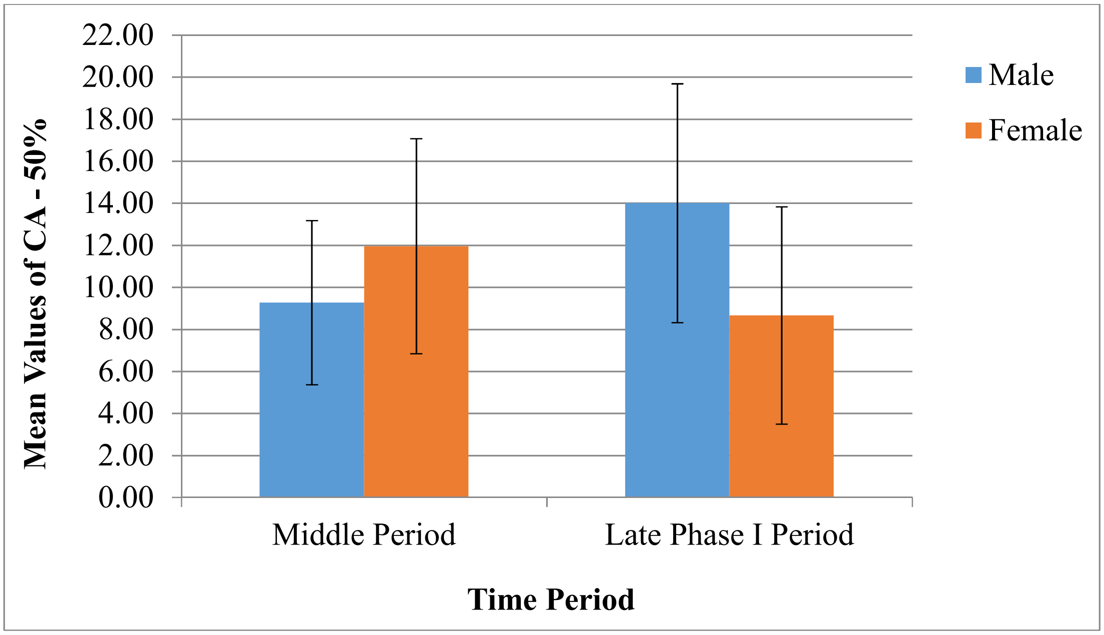

Figure 13. CA interaction for time period by sex at 50% of femoral length. Bars show means and error bars show standard deviations.

One-way ANOVA results revealed that compared to Middle Period males, Late Phase 1 Period male results achieved statistical significance for higher CA (Table 9).

TABLE 9. One-way ANOVA results for CA and TA at 50% of femoral length

DV	Sex	Source	*df*	*SS*	*MS*	*F*	*p*
CA	Males	Between Groups	1	179.66	179.66	6.93	0.013
		Within Groups	32	828.62	25.89		
		Total	33	1008.29			
	Females	Between Groups	1	98.84	98.84	3.71	0.061
		Within Groups	41	1089.54	26.57		
		Total	42	1188.38			
TA	Males	Between Groups	1	84.21	84.21	1.97	0.170
		Within Groups	32	1367.34	42.730		
		Total	33	1451.55			
	Females	Between Groups	1	136.45	136.45	3.28	0.077
		Within Groups	41	1701.26	41.49		
		Total	42	1837.72			

$p \leq 0.05$

The second hypothesis stated Middle Period femora Ix/Iy values would show greater sex differences than Late Phase 1 Period femora. One-way ANOVAs revealed that

Middle Period males were more robust than Middle Period females at 80% of femoral length (Table 10). The result of Cohen's D determined there was a large effect size between the sexes (d = 1.634). Late Phase 1 Period one-way ANOVAs revealed that the differences between males and females at 80% of femoral length were not statistically significant (Table 10).

TABLE 10. One-way ANOVA for Ix/Iy by time period and sex at 80% of femoral length

Time Period	Source	*df*	*SS*	*MS*	*F*	*p*
Middle	Between Groups	1	0.81	0.81	16.70	0.001
	Within Groups	23	1.12	0.04		
	Total	24	1.91			
Late Phase 1	Between Groups	1	0.02	0.02	0.38	0.538
	Within Groups	46	3.28	0.71		
	Total	47	3.31			

$p \leq 0.05$

One-way ANOVA results for Ix/Iy at 50% of femoral length between sexes within each period revealed Middle Period males were not found to be more robust than Middle Period females (Table 11). Late Phase 1 Period males were found to be more robust than females (Table 11). A Cohen's D calculation determined that the effect size was large (d = 1.478). The effect size on sex differences are only slightly greater in the Middle Period (d = 1.634; nonoverlap = 73.1%) than in the Late Phase 1 Period (d = 1.478; nonoverlap = 70.7%), and both effect sizes are large.

TABLE 11. One-way ANOVA for Ix/Iy by time period and sex at 50% of femoral length

Time Period	Source	*df*	*SS*	*MS*	*F*	*p*
Middle	Between Groups	1	0.01	0.01	1.29	0.267
	Within Groups	24	0.30	0.01		
	Total	25	0.32			
Late Phase 1	Between Groups	1	0.50	0.50	27.67	0.001
	Within Groups	49	0.89	0.01		
	Total	50	1.39			

$p \leq 0.05$

DISCUSSION

The results of the statistical analyses indicate that the first hypothesis must be rejected; Late Phase 1 Period femora were not less robust when compared to Middle Period femora in both the subtrochanteric and midshaft regions. A general temporal and sex related pattern has emerged from the findings of this study. Males were found to generally be more robust than females in both time periods. At the subtrochanteric region, a temporal decrease in anteroposterior robusticity was found in males from the Middle Period to the Late Phase 1 Period. At the midshaft region, a temporal increase in anteroposterior robusticity, torsional strength, and compressive strength was found in males from the Middle Period to the Late Phase 1 period. Conversely, a decrease was found in female anteroposterior robusticity in the midshaft with an increase in torsional strength from the Middle Period to the Late Phase 1 Period. These patterns suggest a shift in mobility patterns between the sexes over time.

The indication of a shift in mobility patterns over time may be explained by environmental and cultural factors relating to subsistence patterns. One environmental factor established to cause bone remodeling is mechanical load bearing through dynamic activity (Heinonen et al., 1995; Frost, 1997; Mosley & Lanyon, 1998; Turner, 1998; Andreoli et al., 2001). The results indicate that Late Phase 1 males were likely engaging in activities that placed biomechanical force on femoral muscles more so than the rest of the sample. In a study of knee and hip kinetics during stairclimbing, Costigan, Deluzio & Wyss (2002) found that stairclimbing produced greater force compared to walking. It is reasonable to assume that the results found for Late Phase 1 Period males at midshaft indicate greater mobility compared to the rest of the sample. It is possible that males in the Late Phase 1 Period were traveling, hunting and trading more during the warming period. This may be an indication that the warming period placed resource stress on the population and required traveling further distances rather than relying heavily on marine resources. Males traveling further and carrying heavy loads may be a reason that Late Phase 1 Period males were found to be more robust at the midshaft region.

The results of this study indicate that females became less mobile over time. In Sullivan's (2018) stable isotopic research, it was found that females during the Middle and Late Phase 1 period showed little difference in isotopic signatures between the two periods, which was consistent with eating local foods. The results of Sullivan's (2018) research indicated that while mobility decreased the diets of females remained the same. It is possible that this indicates females had to travel less during the warming period to retain resources like tulle and other plants (Margolin 1978) that contributed to making subsistence related items (i.e., baskets for cooking and carrying babies). It is also possible that as populations grew, distant resources, such as acorns, may have been in occupied landscapes and thus became a material to trade rather than gather. However, Sullivan's (2018) research included only three females from the Middle Period and only four from the Late Phase 1 Period. More research on stable isotopic analysis and cross-sectional data could help to provide further insight into Sullivan's (2018) findings.

The results also revealed that both populations were less robust in the anteroposterior plane in the subtrochanteric regions, except for Middle Period males. This finding may be explained by subsistence related activities involving habitual squatting. The vastus lateralis and vastus medialis muscles attach to both medial and lateral sides of the proximal femora and produce approximately 50% greater force output compared the rectus femoris, which attaches to the anterior femora while engaging in a squatting activity (Schoenfeld, 2010). In addition, the hamstring and quadriceps are both engaged in squatting activity, which may explain the mediolateral robustness seen in Middle Period females and Late Phase 1 Period femora. Squatting facets located on the talus and tibia have been observed and studied on several prehistoric populations (Prasada Roa, 1966; Satinoff, 1969; Dlamini, 2005). It is possible that the results found within this study indicate a cultural pattern of squatting. However, it is not known to what extent the skeletal collection and sample within this study have these facets, nor is it clear that these facets are genetic or a result of habitual posture (Satinoff, 1969).

Results indicating Middle Period males were significantly more robust anteroposteriorly at the subtrochanteric region compared to Late Phase 1 Period males may also be explained, in part, by differing activity patterns. The pectineus muscle attaches to the subtrochanteric region of the femur posteriorly and works in concert with hip abductor muscles. This muscle is activated mostly by hip abduction and external rotation of the legs (Giphart, Stull, Laprade, Wahoff & Phillipon, 2012). One activity that involves hip abduction and external hip rotation is climbing (Mermier, Janot, Parker & Swan, 2000). Climbing may have been a method used to gather resources from trees or rock faces, such as cliffs. There is potential that the robustness found in the AP subtrochanteric region in Middle Period males may also be a result of squatting (with hips widely apart). However, muscles that attach to the proximal femur are also highly activated by activities like running, jumping, and weight training (Mayoux, Leyge, Roux & Revel, 1999).

The second hypothesis was rejected. Middle Period males were more robust than Middle Period females at the subtrochanteric region while Late Phase 1 Period males were more robust compared to Late Phase 1 Period females at the midshaft region. In both instances a large effect size was found. Two findings within this study, although not significant, found that females were more robust than males; Middle Period females were more robust than Middle Period males at the midshaft region and Late Phase 1 Period females were more robust than Late Phase 1 Period males at the subtrochanteric region. These results coupled with the results regarding male robusticity in different femoral regions across time may indicate that while sexual division of labor remained the same, labor may have been defined by different activities across the two time periods. There is a possibility that subsistence patterns shifted from males dominating local subsistence labor and females traveling to gather resources to males travelling farther for resources (indicated by robust midshafts) while females took over local activity patterns (indicated by robust subtrochanteric regions).

In Weiss's (2018) study on biological continuity, Weiss proposed that the burial population assigned to the Middle Period and Late Period Phase 2 Period should be considered two different populations based on observable skeletal traits. Though this thesis does not include burial samples from the Late Phase 2 Period, biological discontinuity between the Middle Period and Late Phase 1 Period must be considered for this study. It is possible the differences found within this study are a result of bone mass and skeletal development due to differing ethnicities and genetics (Pollitzer &Anderson, 1989). However, it is important to note that appearance of discrete traits may also be a result of nongenetic (i.e., environmental) factors (Armelagos, Carlson & Van Gerven, 1982).

Wolff's Law stated that bone remodeling takes place as a result of strain where stress is placed on the bone (Frost, 2001). The findings of this study indicate differences in bone remodeling as a result of stress and strain taking place in different areas of the femora. These results could be due to different activity patterns between the two time periods. However, the findings do not indicate that the people of the Late Phase 1 Period were less mobile during a period of known warming and sex differences were not greater during the warming period either. Further research with comparable temporal samples may help to elucidate the findings within this study.

Limitations and implications for further research

There are limitations to the research reflected in this thesis. The resultant data calculated for CA, TA and J were not standardized for body size. Studies show that body weight has an impact on mechanical loading and therefore results of geometric properties of the femur need to be standardized to control for effects on bone morphology (Ruff, 2000). Sexual dimorphism could have been explored further in this study had the CA, TA, and J values been standardized for body size due to females generally being smaller compared to males. Further cross-sectional research done on mobility in the sample should consider controlling for body size.

Another limitation that is important to note is sample size. The entire collection housed at San José State is nearly 300 individuals; this study represents a little over one fourth of the complete sample. In addition, the Middle Period femora sample represented in this study are relatively small (n = 26) when compared to the Late Phase 1 Period (n = 51). Sample size is a recurrent issue that bioarchaeological researchers face when trying to answer questions about past populations. Additional research should focus on burial populations throughout the region to see if the patterns observed in this study can be found in similar populations.

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APPENDICES

Appendix A

List of Burials

BURIAL	CHRONOLOGY	SEX	AGE L	AGE U	SIDE	LENGTH	50%	80%
6	Late	female	21	30	L	383	191.5	76.6
20	Late	female	19	24	L	425	212.5	85
23	Late	male	30	40	L	442	221	88.4
25	Late	female	35	44	L	407	203.5	81.4
26	Late	female	35	45	L	414	207	82.8
31	Late	male	27	35	L	422	211	84.4
36	Late	male	35	44	L	452	226	90.4
46	Middle	female	35	99	R	412	206	82.4
51	Late	female	39	44	L	408	204	81.6
52	Late	female	40	99	R	384	192	76.8
54	Late	female	35	44	L	410	205	82
56	Late	male	21	35	R	463	231.5	92.6
58	Late	male	25	35	R	451	225.5	90.2
69	Late	male	25	34	R	434	217	86.8
71	Late	male	31	40	L	410	205	82
77	Late	female	21	30	L	409	204.5	81.8
78	Late	male	35	44	L	439	219.5	87.8
85	Late	male	35	99	R	430	215	86
86	Late	female	35	99	R	404	202	80.8
87	Late	female	19	21	L	456	228	91.2
88	Late	female	41	50	L	422	211	84.4
92	Middle	female	20	24	L	409	204.5	81.8
93	Late	female	39	44	L	384	192	76.8
94	Late	male	21	30	L	413	206.5	82.6
96	Late	female	35	45	L	412	206	82.4
97	Late	male	35	50	L	439	219.5	87.8
99	Middle	male	35	44	L	428	214	85.6
100	Late	male	41	50	L	432	216	86.4
103	Middle	male	31	40	L	430	215	86
104	Middle	female	35	44	L	399	199.5	79.8
105	Late	male	25	99	L	414	207	82.8
106	Middle	male	31	40	R	440	220	88
108	Middle	female	31	40	L	424	212	84.8
109	Middle	male	27	35	L	443	221.5	88.6
110	Late	male	30	35	R	476	238	95.2
111	Middle	female	31	40	L	412	206	82.4

113	Middle	female	18	21	L	429	214.5	85.8
122	Late	female	39	44	L	428	214	85.6
125	Late	male	25	40	L	436	218	87.2
129	Late	female	35	99	L	386	193	77.2
132	Late	female	31	40	L	416	208	83.2
143	Middle	female	25	30	L	405	202.5	81
149	Late	female	25	98	L	383	191.5	76.6
158	Late	female	25	39	R	404	202	80.8
163	Late	female	39	50	L	405	202.5	81
167	Late	female	30	40	L	437	218.5	87.4
186	Late	male	30	39	R	470	235	94
188	Late	female	41	50	R	400	200	80
194	Late	female	35	45	L	400	200	80
209	Late	female	18	22	R	411	205.5	82.2
211	Late	female	21	30	R	381	190.5	76.2
212	Late	male	31	99	L	420	210	84
213	Late	male	39	50	L	434	217	86.8
216	Late	male	39	50	R	467	233.5	93.4
217	Late	female	39	44	R	400	200	80
218	Middle	male	41	50	L	444	222	88.8
219	Late	female	19	30	L	420	210	84
223	Late	male	20	25	L	444	222	88.8
225	Middle	male	35	45	L	465	232.5	93
229	Middle	male	31	45	L	463	231.5	92.6
231	Middle	female	20	30	L	435	217.5	87
239	Late	male	18	25	R	472	236	94.4
242	Middle	male	35	44	L	447	223.5	89.4
243	Middle	male	35	44	L	443	221.5	88.6
244	Middle	male	39	44	L	440	220	88
245	Middle	male	31	40	L	431	215.5	86.2
251	Middle	female	25	35	L	411	205.5	82.2
254	Late	female	40	99	L	430	215	86
256	Late	male	30	40	L	462	231	92.4
257	Middle	female	20	30	L	422	211	84.4
260	Middle	male	21	25	L	452	226	90.4
261	Middle	female	21	35	L	406	203	81.2
266	Middle	female	39	44	R	419	209.5	83.8

269	Middle	female	30	45	L	411	205.5	82.2
273	Middle	male	20	31	L	470	235	94
279	Late	female	30	99	L	435	217.5	87
280	Late	female	31	40	L	421	210.5	84.2
284	Late	female	30	99	L	419	209.5	83.8

Notes:

1. LENGTH is total biomechanical length of the femur.
2. 50% and 80% are cross-sectional points on each femora.

Appendix B

Radiographs

ML – (left to right) 6 -20-23-25

AP – (left to right) 6-20-23-25

ML – (left to right) 26-31-36-46

AP – (left to right) 26-31-36-46

ML – (left to right) 51-52-54-56

AP – (left to right) 51-52-54-56

ML – (left to right) 58- 69-71-77

AP – (left to right) 58-69-71-77

ML – (left to right) 78-85-86-87

AP – (left to right) 78-85-86-87

ML – (left to right) 88-92-93-94

AP – (left to right) 88-92-93-94

ML – (left to right) 96-97-99-100

AP – (left to right) 96-97-99-100

ML – (left to right) 103-104-105-106

AP – (left to right) 103-104-105-106

ML – (left to right) 108-109-110-111

AP – (left to right) 108-109-110-111

ML – (left to right) 113-122-125-129

AP – (left to right) 113-122-125-129

ML – (left to right) 132-143-149-158

AP – (left to right) 132-143-149-158

ML – (left to right) 163-167-186-188

AP – (left to right) 163-167-186-188

ML – (left to right) 194-209-211-212

AP – (left to right) 194-209-211-212

ML – (left to right) 213-216-217-218

AP – (left to right) 213-216-217-218

ML – (left to right) 219-223-225-229

AP – (left to right) 219-223-225-229

ML – (left to right) 231-339-242-243

AP – (left to right) 231-239-242-243

ML – (left to right) 244-245-251-254

AP – (left to right) 244-245-251-254

ML – (left to right) 256-257-260-261

AP – (left to right) 256-257-260-261

ML – (left to right) 266-269-273-279

AP – (left to right) 266-269-273-279

ML – (left to right) 280-284

AP – (left to right) 280-284

Appendix C

Data

ID_ORIG	CHRONOL	SEX	AGE L	AGE U	Side	TOTAL BIOMECH l	TA (80%)	CA (80%)	J (80%)	Iml/Iap (80%)	%CA (80%)	TA (50%)	CA (50%)	J (50%)	Iml/Iap (50%)	%C (50%)
6	Late	female	21	30	L	383	4.37	-1.36	1477.99	1.08	-0.31	28.90	14.36	1019.02	1.03	0.50
20	Late	female	19	24	L	425	5.91	-5.79	1557.85	0.72	-0.98	24.34	4.73	1266.06	0.88	0.19
23	Late	male	30	40	L	442	3.30	-6.54	1264.06	0.48	-1.98	43.02	27.35	1452.63	1.27	0.64
25	Late	female	35	44	L	407	4.68	-10.48	1693.72	1.13	-2.24	17.17	6.98	1476.83	0.92	0.41
26	Late	female	35	45	L	414	12.93	-4.31	1282.15	0.58	-0.33	32.19	18.33	1090.59	0.87	0.57
31	Late	male	27	35	L	422	0.00	0.00	0.00	0.00	0.00	28.62	10.18	1570.64	1.18	0.36
36	Late	male	35	44	L	452	7.77	-2.30	1751.46	1.03	-0.30	28.75	10.50	1660.59	1.10	0.37
46	Middle	female	35	99	R	412	8.35	-7.23	2068.57	0.70	-0.87	12.73	0.33	1096.76	1.01	0.03
51	Late	female	39	44	L	408	8.82	0.39	1632.99	0.65	0.04	23.90	10.78	1508.78	0.97	0.45
52	Late	female	40	99	R	384	9.30	3.33	2480.38	0.97	0.36	12.97	-1.27	1296.32	0.94	-0.10
54	Late	female	35	44	L	410	4.78	-3.01	1249.82	0.82	-0.63	15.36	3.98	1127.17	0.94	0.26
56	Late	male	21	35	R	463	4.78	-2.76	1282.55	0.85	-0.58	22.61	15.37	1299.05	1.24	0.68
58	Late	male	25	35	R	451	5.28	-9.73	2308.59	1.07	-1.85	33.34	10.98	2123.04	1.19	0.33
69	Late	male	25	34	R	434	11.16	1.82	1809.62	0.67	0.16	34.83	15.22	1967.91	1.28	0.44
71	Late	male	31	40	L	410	11.26	-7.81	1540.24	0.44	-0.69	30.22	8.84	1961.29	1.03	0.29
77	Late	female	21	30	L	409	6.84	-8.49	1674.66	1.47	-1.24	22.49	6.46	1036.61	1.17	0.29
78	Late	male	35	44	L	439	5.19	0.43	1073.58	0.89	0.08	20.07	4.10	1252.66	1.14	0.20
85	Late	male	35	99	R	430	13.37	-1.49	3041.50	1.10	-0.11	27.64	9.31	1835.16	1.17	0.34
86	Late	female	35	99	R	404	6.00	-3.65	1151.56	0.91	-0.61	18.24	4.02	1120.12	0.96	0.22
87	Late	female	19	21	L	456	14.50	4.31	1271.80	0.97	0.30	24.49	12.09	1013.49	1.22	0.49
88	Late	female	41	50	L	422	14.40	-1.32	1656.75	0.63	-0.09	31.02	-3.08	1608.27	0.75	-0.10
92	Middle	female	20	24	L	409	3.36	-6.23	1182.99	0.71	-1.85	27.31	6.26	946.25	0.92	0.23
93	Late	female	39	44	L	384	9.33	-2.32	1602.84	0.91	-0.25	30.99	12.66	1989.47	1.26	0.41
94	Late	male	21	30	L	413	5.92	-5.78	1702.38	0.85	-0.98	32.48	8.73	1592.75	0.88	0.27
96	Late	female	35	45	L	412	5.39	-4.26	1412.33	0.86	-0.79	20.67	7.27	945.74	1.04	0.35
97	Late	male	35	50	L	439	11.21	-7.41	2180.74	0.67	-0.66	38.84	19.02	1949.94	1.13	0.49
99	Middle	male	35	44	L	428	2.33	-9.49	2404.98	1.21	-4.07	25.15	8.83	1361.36	0.84	0.35
100	Late	male	41	50	L	432	0.00	0.00	0.00	0.00	0.00	33.69	11.59	1751.85	1.06	0.34
103	Middle	male	31	40	L	430	6.94	-7.73	1856.56	1.09	-1.11	30.14	12.02	1284.64	0.95	0.40
104	Middle	female	35	44	L	399	9.43	-5.90	1582.30	0.67	-0.63	26.18	13.10	1406.62	0.96	0.50
105	Late	male	25	99	L	414	3.14	-2.41	1500.71	1.02	-0.77	35.07	13.09	2089.82	1.37	0.37
106	Middle	male	31	40	R	440	13.16	2.41	1785.96	0.95	0.18	30.83	8.13	1640.26	1.10	0.26
108	Middle	female	31	40	L	424	6.99	-5.19	1409.75	0.73	-0.74	34.44	18.34	1281.96	1.03	0.53
109	Middle	male	27	35	L	443	13.48	-0.17	1901.81	1.43	-0.01	17.44	2.36	1321.80	1.14	0.14
110	Late	male	30	35	R	476	12.53	0.30	1674.27	0.57	0.02	31.35	13.51	1495.60	0.99	0.43
111	Middle	female	31	40	L	412	10.19	0.17	1790.78	0.79	0.02	19.42	7.89	1024.19	1.19	0.41
113	Middle	female	18	21	L	429	8.12	-0.05	1291.04	0.66	-0.01	30.90	12.91	1027.68	1.03	0.42
122	Late	female	39	44	L	428	8.27	-1.42	1271.69	0.70	-0.17	28.25	17.23	1202.21	0.91	0.61
125	Late	male	25	40	L	436	6.06	-8.73	1511.03	0.82	-1.44	48.33	28.07	1891.29	1.53	0.58
129	Late	female	35	99	L	386	6.35	1.55	1982.40	1.22	0.24	11.89	4.04	1259.72	0.77	0.34
132	Late	female	31	40	L	416	7.41	-10.70	1970.05	0.66	-1.44	22.57	11.42	1168.21	0.99	0.51
143	Middle	female	25	30	L	405	4.33	-3.17	1229.65	0.67	-0.73	24.24	9.32	1160.14	1.33	0.38
149	Late	female	25	98	L	383	5.80	1.43	1499.06	0.94	0.25	24.77	12.39	1259.15	1.03	0.50
158	Late	female	25	39	R	404	0.00	0.00	0.00	0.00	0.00	26.54	4.10	1137.49	0.82	0.15
163	Late	female	39	50	L	405	4.71	-7.85	1855.29	0.85	-1.67	25.88	14.59	1383.52	0.98	0.56
167	Late	female	30	40	L	437	4.91	-8.25	1213.05	0.79	-1.68	14.09	6.46	914.21	0.94	0.46
186	Late	male	30	39	R	470	7.72	-6.02	1399.98	0.81	-0.78	28.98	13.57	1500.65	1.06	0.47
188	Late	female	41	50	R	400	4.73	-1.77	1721.78	0.97	-0.37	17.32	6.86	1748.54	1.16	0.40
194	Late	female	35	45	L	400	6.54	-3.17	1496.73	0.64	-0.48	22.13	9.73	1183.23	0.87	0.44
209	Late	female	18	22	R	411	11.26	-17.11	1994.78	1.07	-1.52	34.22	15.35	1382.29	1.10	0.45
211	Late	female	21	30	R	381	12.80	-6.71	1938.64	0.91	-0.52	31.92	12.34	1507.72	1.00	0.39
212	Late	male	31	99	L	420	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
213	Late	male	39	50	L	434	6.31	-4.23	2045.40	0.92	-0.67	32.83	17.44	1854.49	1.39	0.53
216	Late	male	39	50	R	467	2.74	-7.00	1742.57	1.12	-2.56	27.32	14.91	1201.86	1.24	0.55
217	Late	female	39	44	R	400	7.77	-2.63	1611.53	0.72	-0.34	16.96	9.67	1265.62	1.01	0.57
218	Middle	male	41	50	L	444	11.16	-13.57	2016.61	1.30	-1.22	33.94	12.35	1501.55	1.18	0.36
219	Late	female	19	30	L	420	11.64	-3.87	2182.30	1.43	-0.33	22.32	8.52	1214.64	1.08	0.38
223	Late	male	20	25	L	444	18.09	0.20	2976.84	1.33	0.01	25.47	12.87	1725.30	1.09	0.51
225	Middle	male	35	45	L	465	9.79	-7.97	2230.13	1.30	-0.81	22.63	7.17	1146.37	0.94	0.32
229	Middle	male	31	45	L	463	13.68	-6.33	2782.74	1.23	-0.46	31.46	14.53	1544.82	1.14	0.46
231	Middle	female	20	30	L	435	7.55	-10.06	1900.04	0.56	-1.33	33.37	20.18	1563.83	1.23	0.60
239	Late	male	18	25	R	472	5.91	-11.08	2045.29	1.40	-1.88	27.39	12.66	1443.25	1.18	0.46
242	Middle	male	35	44	L	447	16.15	-6.76	811.29	1.64	-0.42	40.87	14.68	1454.75	0.98	0.36
243	Middle	male	35	44	L	443	12.13	-0.04	3452.59	1.36	0.00	25.80	11.88	2195.50	1.05	0.46
244	Middle	male	39	44	L	440	9.93	-1.84	2631.54	1.01	-0.18	30.42	11.69	1623.82	0.99	0.38
245	Middle	male	31	40	L	431	5.39	-8.54	2032.18	0.80	-1.58	33.34	7.03	1444.35	1.02	0.21
251	Middle	female	25	35	L	411	13.63	-0.27	1756.42	1.24	-0.02	32.24	14.32	1152.03	1.00	0.44
254	Late	female	40	99	L	430	9.68	-5.65	1804.40	1.58	-0.58	19.45	13.11	974.25	1.09	0.67
256	Late	male	30	40	L	462	10.84	-5.71	2453.97	1.07	-0.53	29.40	16.80	1494.96	1.22	0.57
257	Middle	female	20	30	L	422	8.04	-7.61	1164.90	0.90	-0.95	25.57	12.78	790.92	1.05	0.50
260	Middle	male	21	25	L	452	11.54	-4.80	2468.86	1.18	-0.42	27.85	5.47	1275.00	1.00	0.20
261	Middle	female	21	35	L	406	7.29	-8.54	2704.42	0.88	-1.17	28.48	13.62	1362.86	0.90	0.48
266	Middle	female	39	44	R	419	7.37	5.14	1610.27	1.06	0.70	18.20	12.56	1261.53	1.18	0.69
269	Middle	female	30	45	L	411	10.52	-1.43	2551.72	1.22	-0.14	26.03	13.85	1297.79	1.13	0.53
273	Middle	male	20	31	L	470	7.01	-0.17	1262.29	1.12	-0.02	16.76	4.44	911.77	0.96	0.26
279	Late	female	30	99	L	435	12.97	1.94	2110.08	1.20	0.15	13.31	7.39	1078.90	0.83	0.56
280	Late	female	31	40	L	421	4.05	-1.81	1755.20	0.80	-0.45	19.89	7.49	1432.81	0.86	0.38
284	Late	female	30	99	L	419	5.55	-4.45	1510.93	1.38	-0.80	12.00	1.74	1052.28	0.90	0.14