Do osteon morphotypes identified in the mid-diaphysis of human femurs indicate the same torsional load history as chimpanzees?

Bailey A G Colohan

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Do osteon morphotypes identified in the mid-diaphysis of human femurs indicate the same torsional load history as chimpanzees?

by

Bailey A. G. Colohan

Submitted in partial fulfillment of the requirements for the degree of Master of Arts (Anthropology), Hunter College The City University of New York

2018

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INTRODUCTION

Histological research in recent years has looked to morphological traits of osteons to recognize numerous biological characteristics of the larger bone and/or organism. For example, osteon area, circularity, size, and shape have all been examined to determine human from nonhuman bone, sex, age, and pathologies (Mulhern & Ubelaker, 2012; Guatelli-Steinberg & Huffman 2012; Schultz 2012). Recent research has also turned to examining osteon morphotypes to determine if load-bearing on these microscopic structures changes their individual formation and affects their birefringence patterns. Martin et al. (1996) were the first researchers to set forth a method considering the mechanical variation taking place across secondary osteons in their examination of equine third metacarpals. Their 6-point osteon morphotype scoring (MTS) scheme examines the birefringence patterns of osteons viewed under circularly polarized light (CPL) with the birefringence or brightness patterns being associated with lamellar collagen orientation, and brightness patterns corresponding to different effects of habitual load-bearing. “These range from ‘hoop’ osteons, containing a bright peripheral ring of highly oblique-to-transverse collagen fibers, to ‘distributed’ osteons, with highly oblique-to-transverse collagen patterns distributed across the entire osteon wall” (Skedros, 2011).

Skedros et al. (2009) modified the Martin et al. (1996) osteon scoring scheme (M-6-MTS) to better fit the loading patterns present in portions of bone experiencing compression or tension. “Osteon morphotypes with relatively greater amounts of transverse collagen (bright birefringence) distributed in the osteon wall represent adaptation for prevalent compression, whereas osteon morphotypes with more longitudinal collagen (dark) represent adaptation for prevalent tension” (Skedros et al. 2004, 2006, 2007). These compression and tension osteons correspond to collagen fiber orientation (CFO) which reliably indicates habitual load-bearing
effects. The presence and orientation of CFO is what creates the birefringence patterns that are evident in the different osteon morphotypes (Skedros, 2012). Skedros et al. (2006) examined equine third metacarpals implying that the variations of osteon morphotypes yield the differences observed in CFO that “strongly influenced energy absorption in strain-mode specific testing”. Bigley et al. (2006) also described the mechanical properties of individual osteons as they relate to their surrounding matrix histomorphology using the third metacarpal of an adult horse. He described 4 osteon morphotypes that corresponded with variations in CFO and their analysis suggested an association between the amount of oblique-to-transverse collagen fibers and mechanical properties.

Skedros et al. (2009) found that osteons which appeared to have alternating rings within the osteon and a bright hoop outside of them were being scored by Martin and coworkers in a way that skewed the osteon score counts towards dark or tension adapted osteons as they counted all these osteons with a score of “0”. In Skedros and coworkers’ modified scheme, these “hybrid” osteons are scored as a “5” on their 6-point scale of 0-5, which indicates them as being compression adapted osteons. In a study on chimpanzee femora, Skedros et al. (2011) investigated the eight known methods of osteon morphotype scoring to determine which scoring scheme most closely correlated CFO (Table 1). As aforementioned, M-6-MTS and Skedros et al.’s (2009) S-6-MTS place osteons with alternating bright rings in a score of “0” or “4/5” respectively, but closely follow the same scoring categories dark=0, weak incomplete hoop=1, weak hoop=2, incomplete hoop=3, hoop=4, and bright/distributed=5 (Skedros 2009, 2011, 2013). Skedros et al. (2011) created the 12A-MTS and 12-MTS schemes to better identify the “hybrid” osteons or “osteons with variable amounts of alternating birefringent patterns and peripheral hoops that did not correspond … to any of the [S-6-MTS].” 12A-MTS places more
emphasis on the bright ring on the outside of the osteon while 12B-MTS places more emphasis on alternating patterns of rings within the osteon. Skedros et al. (2011) included the 3-MTSa and 4-MTSb for their simplicity and ease of use. The 3-MTSa sorts osteons as “0” = dark and hooped, “1” = alternating, and “2” = bright, while the 4-MTSa sorts osteons as “0” = dark, “1” = hooped, “2” = alternating, and “3” = bright. Skedros et al. (2011) also provided a slight modification to these 2 scoring schemes by including a score of 0.5 and 1.5 for hybrid osteons in 3-MTSb and 4-MTSb respectively.

Skedros et al. (2011) found the modified 6-point scheme (S-6-MTS) created from Martin et al.’s (1996) scoring system most closely matched the tension and compression data of CFO, which corresponds to strain experienced by the bone. S-6-MTS appeared to perform more strongly in this attribute than the 3- and 4-point schemes and had better intra- and interobserver reliability that the 12-point schemes. Unless the direct identification of hybrid or alternating osteons is necessary, S-6-MTS is the best option when attempting to distinguish tension and compression in osteons (Skedros et al. 2011). S-6-MTS has been used to study equine calcanei and long bones, as well as chimpanzees and other species for habitual load-bearing and strain. This MTS has also been compared to other forms of osteon morphotypes and measurement systems that are thought to correlate with mechanical properties of bone. Skedros et al. (2013) compared their modified MTS to osteon diameter to determine if both correlate closely with CFO and habitual compression and tension in the femora of humans and chimpanzees, the radii of horse and sheep, and the calcanei of horse and deer. It was found that while osteon diameter can sometimes be associated with load-bearing properties of a bone, it is inconsistent, especially when compared to osteon morphotypes. Using the results of these rigorous analyses investigating
the relationship between MTS and habitual load-bearing, this study will employ the Skedros and coworkers’ modified 6-point scoring system (S-6-MTS).

*Mechanical Properties and Morphology of the Human Femur*

This study will examine the midshaft diaphysis of the human femur and the type of habitual load-bearing that its osteons endure in comparison to chimpanzee femora. Aiello and Dean (2002) noted that the estimated load axis of ape femora is straight down from the femoral head to the bicondylar plane and does not intersect with the axis of the femur. The assessment of this axis is that it crosses the femoral shaft axis in humans from medial to lateral at the femoral midshaft (Walmsley, 1933). There is also a point of minimum shaft breadth found in humans but not in apes where the femoral shaft is noticeably narrower in the region of the femur where the load-bearing axis crosses the femoral axis at the midpoint of the shaft (Kennedy, 1983 in Aiello & Dean, 2002). Aiello and Dean (2002) also argue that the lateral cortices of the human femoral midshaft are also thicker than the medial due to the weight transmission from medial to lateral at this point in the diaphysis (Kennedy, 1983).

When looking at the femur, this type of load-bearing appears to show simple weight transfer from medial to lateral along the femoral shaft, indicating more compression occurring on the lateral cortices than the medial, but there are more complex load-bearing mechanisms and forces affecting the femur than this simple description of compression and tension. Skedros (2012) points out that the load-bearing model described by Aiello and Dean (2002) is not present when osteons and microstructure are viewed at points where torsion takes place. While MTS can differentiate areas of habitual simple bending in bone, such as areas found in the human tibia, areas with more complex load-bearing where shearing and torsion are the predominant forces on a bone, do not show regional variation in osteon morphotypes. There are four load-complexity
categories that range from the least complex (bending) to the most complex (torsion combined with bending at compression) and “[these] categories are based on typical ranges of neutral axis [N.A.] rotation; where the [N.A.] rotates the most there is prevalent/predominant torsion” (Skedros, 2012). “These four load-complexity categories are based on typical ranges of [N.A.] rotation” and include low complexity (N.A. <10˚ rotation), intermediate A (N.A. 10˚ -20˚), intermediate B (N.A. 20˚-40˚), and high (N.A. >40˚) (Skedros, 2012). It is at the midpoint of the femoral diaphysis where the neutral axis rotates the most, and where shearing and torsion are present as the predominant forces.

Due to these complex load histories that take place on bone, and the fact that bone is biological matter that that does not always follow strict rules of structural engineering, cross sectional shape and cortical thickness are not reliable indicators of interpreting load history, or, at least, do not tell the whole story when evaluating the load-bearing functions of a bone (Skedros, 2012). While Aiello and Dean (2002) may view the presence of thicker lateral cortices at the midshaft of the human femur as indicative of the presence of more weight distributed towards the lateral than medial sections of bone, Skedros (2012), Lieberman et al. (2004), Demes (2007), and Ruff et al. (2006) have all shown that using these cross-sectional interpretations of bending are unreliable. The unreliability of cortical thickness in determining load-bearing history can also be seen in sheep and deer calcanei as well as horse and sheep radii (Skedros 2012).

Since it has been demonstrated that relying on cortical thickness or cross-sectional bone shape is inaccurate in interpreting load history, it leaves tools such as CFO and MTS to evaluate the simple or complex forces that are acting on bone. If cortical thickness alone were considered, it should be expected that there would be habitual bending from medial to lateral at the femoral midpoint, but as previously mentioned, the forces exerted at the midshaft of the
femur are more complex than simple bending. There is, in fact a reduction of medial to lateral bending at the femoral mid-diaphysis and a greater degree of variability of the strain distribution (Cristofolini et al. 1996; Oh and Harris 1978). Due to the complex forces surrounding the mid-diaphysis and the degree of torsion that is present in this area of the bone, there are no regional (anterior, posterior, medial, lateral) differences when viewing CFO patterns. Because of this, there should be no regional differences of MTS in cross-sectional regions from the midshaft of the femur.

Chimpanzee vs. Human Cross-Sections

Among chimpanzee femora, Skedros et al. (2011) showed that in “the torsion loaded mid-diaphysis section (i.e. where broad shifts occur in the neutral axis) there were, as expected, no significant regional differences in CFO/WMGL [or] … S-6-MTS” while Martin et al.’s (1996) MTS (M-6-MTS) showed prominent differences between the lateral and posterior cortices. Since the S-6-MTS has previously been noted to correlate more closely with CFO patterns that denote habitual loading, this will be the method employed in the present study. While center of gravity and load axis in relation to femoral shaft axis are different in chimpanzees and humans (Kennedy, 1983 in Aiello & Dean, 2002), human femora, like chimpanzee femora, experience torsion at the midshaft. Thus, it is hypothesized here that when cross-sectional slides from the mid-diaphysis of the human femur are scored and analyzed using the S-6-MTS, they will also present no significant degree of variation between the 4 regions (anterior, posterior, medial, lateral) of the bone’s cortices.

MATERIALS AND METHODS

Osteon slide images were sampled from the Kerley collection at the National Museum of Health and Medicine in Silver Spring, MD. 16 unstained human femoral midshaft slides were
curated by staff with additional information on individuals provided. Sex, age, and known pathology were included in slide data (Table 2). Of these 16, the slides of 3 females and 7 males were chosen due to quality and preservation of the slide or age. After imaging, one male was excluded from the study due to the bone cross section being milled too thin, resulting in osteons not appearing clearly. After this individual was removed, the final total of sampled individuals was 9. Of these 9, four had known pathologies. All individuals sampled were adults ranging from ages 34 to 76.

Images were captured using the software program Image Pro Plus. Slides were viewed for imaging on a Nikon Eclipse E800 at 4X magnification while using an Olympus polarizing filter lens to provide greater contrast. The preselected slides were individually handled and marked using a slide safe pen for imaging sections. These sections correlate with anterior, posterior, medial, and lateral quadrants of the cross-section. 1709 total images were recorded from the femoral cross-section slides. These images were sorted into their respective quadrants for each individual, and 2 slide images were chosen from each quadrant. Images of osteons were selected based on distinct, clear views and images that were from mid-cortical bone region of each quadrant. A total of 8 images were scored for each individual. These images were converted into PDFs for scoring purposes.

Overall, 2798 osteons were scored using Skedros’s 6-point osteon morphotype scoring (MTS) system (Skedros et al. 2009). Only identifiable secondary osteons were scored, given that primary osteons are “un-remodeled” bone that have not been changed due to strain or load-bearing (Skedros et al. 2009). Secondary osteons were selected using criteria provided by Martin et al. (1996) and employed by Skedros et al. (2009, 2011, 2013), and the categories were as follows: 1) presence of a scalloped cement line, 2) absence of a Volkmann's canal connection, 3)
reasonably circular or ellipsoid shape, and 4) refilling complete or nearly so. Drifting osteons were also identified and eliminated from any collected scores. The key for scoring osteons along this 6-point scale was provided by Dr. John Skedros and is the same key used for scoring in previous studies. These scoring categories are dark=0, weak incomplete hoop=1, weak hoop=2, incomplete hoop=3, hoop=4, and distributed=5 (Skedros 2009, 2011, 2013). For each osteon score on the key, a color was designated to identify these types of osteons (Figure 1). Adobe Acrobat Reader DC was used to score each osteon based on birefringence pattern by marking it with a color dot that corresponds with the one of the 6 osteon morphotype scores on the key (Figure 2). All osteons were scored by the same person on the same computer. After all osteons were scored, colored dots were counted and recorded for each score.

**STATISTICAL ANALYSIS**

A Kruskal-Wallis test was performed between all pairs of quadrants for each osteon score. Means for all quadrants for each osteon score were calculated and then run through a Kruskal-Wallis test to compare all osteon scores across all quadrants. A Kruskal-Wallis Test was also performed across the means of quadrants for each individual. One individual who showed a significant degree of variation between quadrants was removed and new means were calculated for a Kruskal-Wallis test between all quadrants for the remaining 8 individuals. The removed individual, 951566, showed significant difference between the anterior vs. medial and lateral vs. medial quadrants with p-values of 0.0247 and 0.02891 respectively. All statistical analysis was performed in PAST 3.x (Hammer et al. 2001).

**RESULTS**

For the comparison between paired quadrants for each osteon score, there were no significant differences found between any of the individual score counts (Table 3). A p-value
approaching significance (0.061) was found when the counts of osteons scored as a “5” were compared between the posterior and lateral regions of bone. This score still does not satisfy the 95% confidence level required for this study, and all the other paired tests were nowhere near the significance threshold, meaning that there were no discernable differences between the regions. This p-value approaching significance between the posterior and lateral regions osteons scored as a “5” or “bright” osteons may be due to the relatively low counts found in posterior regions and the higher counts found in the lateral region. Mean and median for both can be found in Table 4. A large degree of overlap is also seen between osteon counts of quadrants in Figures 3-8.

The analysis of quadrants for each individual showed that there was no significant difference between regions except for individual 951566, who exhibited a significant p-value of 0.039 between all quadrants (Table 5). The only known pathology/cause of death for this male individual was a gunshot wound (GSW) and may or may not have had any effects on mobility and strain associate with tension and compression in the femur. Both with the individual included and removed, there is no statistical significance between the quadrants across the means of osteon counts (Table 6). A graph (Figure 9) of the means for all quadrants with all individuals included shows similar counts for osteon score across regions.

**DISCUSSION**

The statistical analyses performed on the data in this study indicates that there are no real differences in the MTS of osteons between the four regions of the human femur in these samples. The results match what was expected in the hypothesis, which noted that there should be no differences in the regional osteons in the mid-diaphysis of the femur based on the complex load history it experiences (Skedros 2009, 2012, 2012). When considering Skedros et al.’s (2011) study, this homogenous distribution of differing MTS scores across all quadrants in humans
matches the femoral mid-diaphysis in chimpanzees. Both experience a complex load history associated with combined torsion, compression, and bending at the midpoint.

It is important to draw this comparison for many reasons, first and foremost being that even though *Homo sapiens* and *Pan paniscus* have differing locomotor behaviors, the forces that act upon this point in the femur are similar in that they share the same load history factors, and this is evident in the microstructure of the bone. Using distinctions such as cortical bone thickness to indicate bending at the femoral midshaft (Aiello and Dean, 2002) is a misclassification of the load history this section of bone endures and while cortical bone thickness may sometimes indicate load history, it is not a reliable indicator (Skedros, 2012).

The type of secondary osteon remodeling that is observed at the mid-diaphysis of both humans and chimpanzees is indicative of the very complex load-bearing that takes place there. Certain osteon morphotypes can be categorized or associated with tension or compression in bone. This habitual strain puts pressure on bone that would remodel in response to the mainly shearing force that is present in torsion (Skedros, 2011, 2012). In these high strain areas it is important for bone to prevent microdamage that it might incur, so in response, it appears that bone adapts best to mitigate microcracks in these locations by creating certain osteon morphotypes that deal with the habitual strain appropriately; therefore, in areas where complex loading is occurring, multiple morphotypes of osteons would be expected (Skedros, 2012). This is seen in both the chimpanzee data from Skedros et al.’s (2011) study and the human data from the present study. It corresponds to the expected load history of prevalent/predominant torsion that takes place in the mid-diaphysis of the femur.

Since osteon morphotypes are distributed in a similar array in the cross-section, “the mid-diaphyseal human femur is a good choice for the analysis of potential relationships between
osteonal characteristics and general mechanical-related parameters” (Skedros, 2012). Body weight is a parameter that could be examined here since it would not be confounded with any other habitual forms of strain (such as bending or compression) that might affect how osteons are identified and studied (Skedros, 2012). This opens the possibility of studying multiple factors in humans as they relate to body weight across current and past populations. What cannot be examined are the effects of habitual bipedalism on this region of the bone. Since both chimpanzees and humans share the same type of strain and load-bearing history that creates torsion with shearing force at the mid-diaphysis, it cannot be used as an indicator to show differences in locomotor abilities of quadrupedalism vs. bipedalism. Because of this factor, caution should be used when examining other osteon features and aspects (osteon circularity, area, size, or density) when examining the femoral midshaft for locomotor indicators.

Because of the lack of any prominent osteon morphotype emerging from the femoral midpoint cross-section, other areas such as the proximal femur, observed by Skedros et al. (2013) and tibial midshaft demonstrate simpler load histories more clearly. The proximal femur and femoral neck have both been examined for their load-bearing history in both humans and chimpanzees (Skedros, 2009, 2011, 2013) and have shown to correspond closely with CFO that indicates the compression and tension apparent in the lateral and medial quadrants of the bone. The tibial midshaft also shows similar bending and compression areas as the proximal femur and “is typically in the intermediate B load-complexity category where bending produces these quasi-habitual…regions” (Skedros, 2012). These areas of bone could be analyzed for locomotor patterns across species since these sections experience strain such as bending which shows clear compression and tension on osteon morphotypes. A point of interest that might be considered in future research is the distal femur of both humans and chimpanzees. It is expected that humans
might show more compression on the lateral cortices of the femur than chimpanzees due to the angled nature of the femur in *Homo sapiens*. Another point of interest might lie in the femoral condyles, where the larger, lateral condyle is presumed to have more strain placed upon it. Any future research would benefit from employing CFO analysis along with S-6-MTS, to ensure that the strain mode and load history of bone are being interpreted correctly in osteon morphotype studies.

*Study Limitations*

Even though the results of this study align with what is expected of an area of bone that experiences torsion and shearing forces, there is still room for error in the data collection and implementation. The slides that were examined and imaged for this study were not well-preserved as needed and many presented difficulties in viewing due to glue, bubbles in slides, or tape. These slides were also not as uniformly milled as in Skedros et al.’s (2009, 2011, 2013) slides that were prepared specifically for each study. Additionally, a large portion of individuals sampled for this study had various pathologies in their lifetimes ranging from sarcomas to fractures. I am also not trained extensively in identifying osteon morphotypes and was the sole scorer of the materials collected from the Kerley collection. In future studies, oversight from a more senior trained scorer would help in scoring osteons that prove difficult to assign to an exact score. To ensure no scoring bias, it would be prudent to replicate the interobserver error study that Skedros et al. (2009, 2011, 2013) performed so that all scorers are reliably scoring osteons in a similar fashion. Any future studies would benefit from a larger sample size than the 9 individuals that this study was limited to.

*Future Research*

Using S-6-MTS to score osteon morphotypes is a valid research method when analyzing
load history in bones. The current study adds to previous research (Martin et al. 1996; Skedros et al. 2006, 2009, 2011, 2013; Bigley et al. 2006; Beraudi et al. 2009) and evidence that osteon morphotypes correspond to bending, torsion and the various other complex load histories of these combined forms of strain which are enacted on bone. Skedros et al.’s (2011) research suggests that S-6-MTS is the best available method for describing compression and tension in cortical bone when addressing osteon morphology. This form of research could be more widely used to compare the areas of bone across different species with different locomotor behaviors.

In vivo assessments analyzed during controlled ambulation in birds, sheep, and other various mammals have shown that predominant bending and torsion are the most representative load histories found in bone diaphyses, with most other load regimes on the continuum between the two (de Margerie et al. 2005; Lanyon & Bourn 1979; Lieberman et al. 2003). In vivo data also supports that in many appendicular long bone diaphyses, bending is the most conserved load regime (Rubin and Lanyon 1984) and accounts for most of the longitudinal strains during peak loading at the time of controlled activity (Biewener & Bertram 1993; Biewener et al. 1986). Given that MTS is most useful when identifying compression and tension that is present in load histories such as bending, it can be applied most easily to long bones and diaphyses for future research. Identifying the types of osteon morphotypes in load-bearing bones could indicate the habitual strain that occurs in more simply loaded areas. These load patterns have the potential of detecting locomotion behaviors as they might be seen across non-human primates. There are several areas that could be explored based on locomotion patterns or lack thereof, such as the proximal humerus (Scherf et al. 2013), carpals or wrist bones (Schilling et al. 2014), or the tarsals and metatarsals of the foot, specifically the calcaneus (Nowak et al. 2010). These are just
a few examples where osteon morphotyping might indicate the effects of locomotion that humans and nonhuman primates experience.

Osteon MTS could also be used to explore habitual load-bearing in the bones of archaic humans and the fossil record. There have been previous studies of osteons in Neanderthals and ancient humans (Pfeiffer and Zehr, 1996; Sawada et al., 2004; Streeter et al., 2010) that compared both osteon size and remodeling rates between the two species. As mentioned previously, though, osteon size is not a reliable correlate to habitual load-bearing which would affect remodeling (Skedros, 2012). Unfortunately, collecting samples of cross-sections from bone most likely involves destruction of the specimen in some manner. When rare fossils are at risk of being destroyed through research, certain studies on these materials do not seem feasible. As technology progresses however, there are ways to analyze cortical bone through non-destructive techniques. Micro-CT scanning is a method that more and more researchers are employing to provide a means for 3D analysis of cortical bone. This allows for greater view of histological structures and reveals the structure of osteons as they appear in complete structures, and not just their cross-sections (Cooper et al. 2012). As micro-CT scans progress in their ability to pick up more and more details of these bone cells, a scoring system such as S-6-MTS might be applied or modified to fit these new capabilities. This would allow for analysis of fossil specimens where histological traits have been preserved.

CONCLUSION

Skedros and coworkers’ modified osteon morphotype scoring system can be used to identify load-bearing history and strain in bones. Certain identifiable osteons are associated with forms of load-bearing history and correlate to the forces of tension and compression. This study shows that, like in Skedros et al. (2011) study on the chimpanzee femoral midshaft, humans do
not show any significant difference in the quadrants of the mid-diaphysis when S-6-MTS is used as a method to score and quantify osteon morphotypes. This finding goes along with the complex load history that is experienced at this point in the femur, where torsion and shearing forces are present. This appearance of evenly distributed osteons across the femoral mid-diaphysis allows for this cross-sectional region of the bone to be examined for other mechanical influences, such as those of body weight. Other segments of femur can be examined in future studies using S-6-MTS to identify osteons that are associated with compression and tension adaptation in areas of the bone that are more simply loaded and experience load histories like that of bending. Future research could examine locomotor patterns across species and investigate the fossil record using nondestructive methods.
Figure 1: Osteon scoring key created and provided by Dr. John Skedros (Skedros et al. 2009, 2011, 2013). Osteons were color coded for ease of scoring on PDFs.
Figure 2: Example of marked osteons with colors that correlate to scores on osteon scoring key. 0=Orange, 1=Yellow, 2=Dark Blue, 3=Purple, 4=Green, 5=Light Blue
Figure 3: Box and Jitter plot of osteon MTS “0” with one sigma standard deviation
Figure 4: Box and Jitter plot of osteon MTS “1” with one sigma standard deviation
Figure 5: Box and Jitter plot of osteon MTS “2” with one sigma standard deviation
Osteon Counts of MTS “3”

Figure 6: Box and Jitter plot of osteon MTS “3” with one sigma standard deviation
Figure 7: Box and Jitter plot of osteon MTS “4” with one sigma standard deviation
Figure 8: Box and Jitter plot of osteon MTS “5” with one sigma standard deviation
Graph of Means of Osteon Counts for All Quadrants

Figure 9: Graph of Means of counts for all 6 MTS for all quadrants
<table>
<thead>
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<th>Method</th>
<th>Name</th>
<th>Scale Range</th>
<th># of available scores</th>
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<td>3-MTSa</td>
<td>0-2</td>
<td>3</td>
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<tr>
<td>Bigley et al. (2006)</td>
<td>4-MTSa</td>
<td>0-3</td>
<td>4</td>
</tr>
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<td>3-MTSb</td>
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<td>4</td>
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<td>Skedros et al (2011)</td>
<td>12B-MTS</td>
<td>0-11</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1: Eight Osteon Scoring Methods explored by Skedros et al. (2011). Scale Range refers to the range of numbers available in scoring osteons in each method. # of available scores is the total number of scores that are available to choose from in each method. 3-MTSb and 4-MTSb have 1 more available score than their names denote due to the addition of 0.5 and 1.5 respectively to their scoring schemes.
<table>
<thead>
<tr>
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<th>ELEMENT</th>
<th>AGE</th>
<th>SEX</th>
<th>PATHOLOGY/CoD</th>
<th>NOTES</th>
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<td>940302</td>
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<td>41</td>
<td>F</td>
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<td>946206</td>
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<td>F</td>
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<td>Femur</td>
<td>76</td>
<td>F</td>
<td>Arteriosclerosis</td>
<td></td>
</tr>
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<td>48</td>
<td>M</td>
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<tr>
<td>772323</td>
<td>Femur</td>
<td>34</td>
<td>M</td>
<td>Osteogenic sarcoma</td>
<td>Tumor of tibia</td>
</tr>
<tr>
<td>936786</td>
<td>Femur</td>
<td>49</td>
<td>M</td>
<td>Metastatic carcinoma</td>
<td>Proximal fracture</td>
</tr>
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<td>Femur</td>
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<td>M</td>
<td>GSW</td>
<td></td>
</tr>
<tr>
<td>956150</td>
<td>Femur</td>
<td>63</td>
<td>M</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>965887</td>
<td>Femur</td>
<td>42</td>
<td>M</td>
<td>Arteriosclerosis</td>
<td></td>
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</tbody>
</table>

Table 2: Individuals Sampled from Kerley Collection
Table 3, a-f: Pairwise p-values determined from the Kruskal-Wallis test performed for each osteon score across all quadrants.
Table 4, a-b: Mean and Median for MTS score of “5” for both Lateral (a) and Posterior (b) Quadrants

<table>
<thead>
<tr>
<th></th>
<th>MTS “5” Lateral</th>
<th>MTS “5” Posterior</th>
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</thead>
<tbody>
<tr>
<td>Median</td>
<td>11.50 MEDIAN</td>
<td>7.50 MEDIAN</td>
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<tr>
<td>Mean</td>
<td>10.94</td>
<td>7.83</td>
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### Table 5: P-values of all individuals across quadrants.

<table>
<thead>
<tr>
<th>Individual</th>
<th>p-value</th>
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<tbody>
<tr>
<td>662836</td>
<td>0.592</td>
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<tr>
<td>772323</td>
<td>0.602</td>
</tr>
<tr>
<td>940302</td>
<td>0.183</td>
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<tr>
<td>946206</td>
<td>0.760</td>
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<tr>
<td>950605</td>
<td>0.611</td>
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<tr>
<td><strong>951566</strong></td>
<td><strong>0.039</strong></td>
</tr>
<tr>
<td>956150</td>
<td>0.704</td>
</tr>
<tr>
<td>965887</td>
<td>0.373</td>
</tr>
<tr>
<td>936786</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Individual 951566 (highlighted) shows a p-value which indicates significant variation between regions.
Table 6: Kruskal-Wallis test p-values: performed on all individuals and with outlier removed across all quadrants

<table>
<thead>
<tr>
<th># of Individuals</th>
<th>p-value</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>0.7935</td>
</tr>
<tr>
<td>8</td>
<td>0.7516</td>
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</tbody>
</table>
REFERENCES


