Defining Patterns in Human Bone Microstructure Through the Application of Geographic Information Systems (GIS) Software

David C Rose, Timothy P Gocha, Amanda M Agnew, Sam D Stout
The Ohio State University, Department of Anthropology

Introduction

Geographic information system (GIS) software is typically used for mapping projects, however it has other constructive applications for physical anthropologists. The objective of this study was to evaluate and quantify the heterogeneity of bone microstructure distribution over an entire cross section of bone using ArcGIS v 9.3. This was performed while evaluating signs of remodeling in a right first metatarsal compared to bending axes and areas where modes of strain are known.

Two hypotheses were explored. The first hypothesis tested was to evaluate the predicted distribution of osteon morphotypes, as defined by Skedros *et al*. (2009). The second hypothesis tested was that remodeling present would be higher in areas of maximum compression and tension. It was expected that the axis of maximum bending resistance would be situated to counteract the primary direction of applied force and remodeling evidence would be higher near this axis.

Materials and Methods

The metatarsal sample was embedded and thin sectioned according to standard histological procedures. Overlapping photographs were obtained at 100x magnification with a Spot Insight QE digital camera under polarized light. The resulting 120 images were then photomerged using Adobe Photoshop® CS2 (Figure 1). This image was then imported into ArcMap and converted to scale. Cross-sectional geometric measurements were obtained with the MomentMacro plugin for ImageJ software. The resultant JPEG image, featuring I_{max} and I_{min}, was also imported into ArcMap.

New feature classes, or map layers, were then created in ArcGIS to represent the second moments of area (SMA), and remodeling points (Figure 1). Creating line feature classes for the axes allowed measurement of the distance between each identified remodeling point and the given axis. A total of 270 points were defined by manual annotation of remodeling evidence, such as secondary osteons and resorptive bays. Of these, 203 were assigned a morphotype score between zero and five. Measurement tools within ArcMap were used to determine the area and perimeter of each remodeling point, while osteon circularity was manually calculated. Each of the characteristics were added to an attribute field for the given remodeling point. Separate map layers were created for each of these characteristics, in order to facilitate further analyses within ArcGIS.

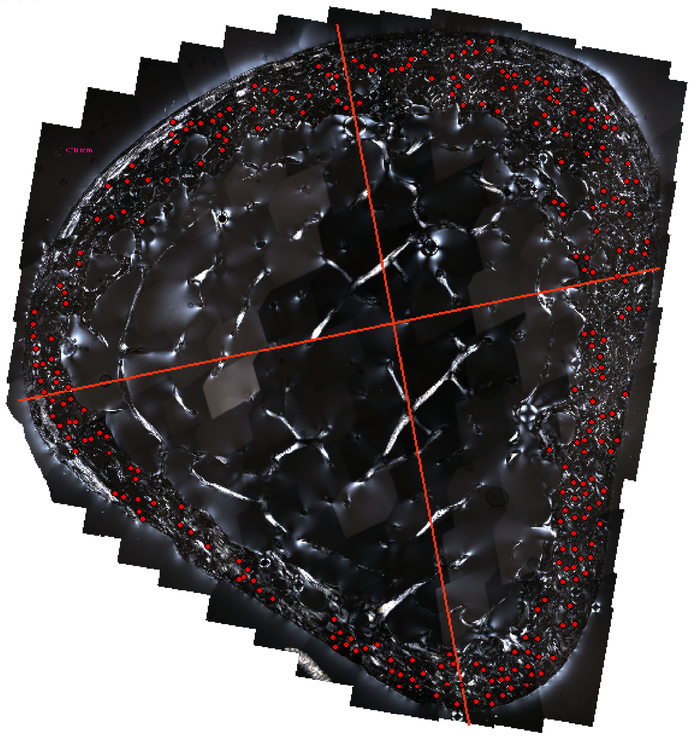

Figure 1. Complete cross section of a right first metatarsal, digitally merged from 120 separate images. I_{max} and I_{min} bending axes, as well as remodeling points (osteons) are identified. The image is oriented so that the dorsal surface is at the bottom and the medial surface is to the left.

Results

Directional distribution analysis was performed on each of the characteristics. This tool creates polygons that are situated to demonstrate spatial distribution trends. The resulting polygon encompasses 68%, or one standard deviation, of the analyzed remodeling points. Directional distribution analysis of morphotypes with a score of four was not possible due to their low frequency. The resulting analysis of morphotype scores was of interest because it shows a clear dorsoplantar trend for morphotype scores from highest to lowest respectively (Figure 2). This pattern fits an expected pattern of morphotype score distribution based on the known mode of strain (i.e., compression in the dorsal cortex and tension in the plantar cortex during gait).

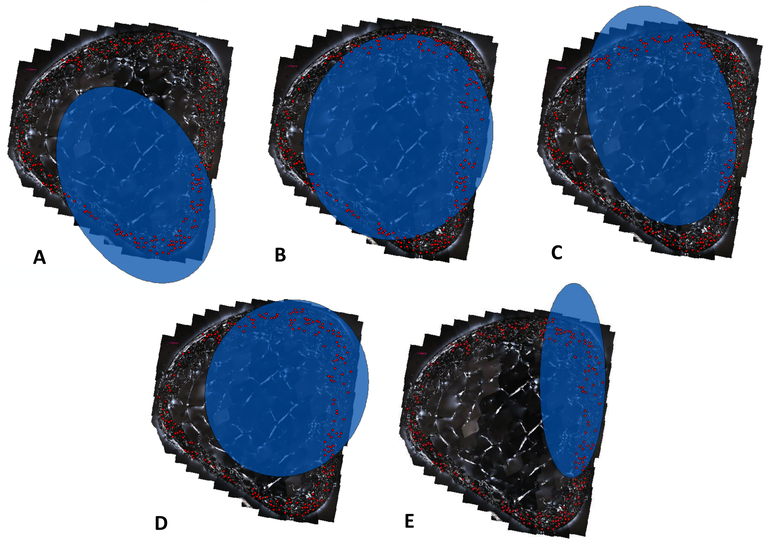

Figure 2. Directional distribution analysis of remodeling points based on morphotype scores. A = 0, B = 1, C = 2, D = 3, E = 5.

The near tool in the spatial analyst toolset was used to calculate the closest distances between features. This tool was used in an effort to view the relationship of remodeling points to the bending axes. This tool allowed for the calculation of the distance of each remodeling point in comparison to an assigned bending axis. The calculation was performed for both I_{max} and I_{min}. The results demonstrated that 54.1% of the remodeling points were closer to I_{max} than I_{min}.

The hot spot analysis tool calculates the Getis-Ord Gi statistic (Getis and Ord, 1992; Ord and Getis, 1995) for each point and demonstrates where high or low valued features cluster. Clusters are located by the identification of high or low valued points that are surrounded by points with similar values. The results of the hotspot analysis show that hotspots of osteons with larger areas exist within the dorsal, plantar, and lateral regions of the cortex and that hotspots of osteons with lower areas exist in the dorsal and medial cortices. The morphotype score hotspot analysis shows that osteons with higher scores exist in the dorsal cortex and lower scores cluster in the plantar cortex (Figure 3).

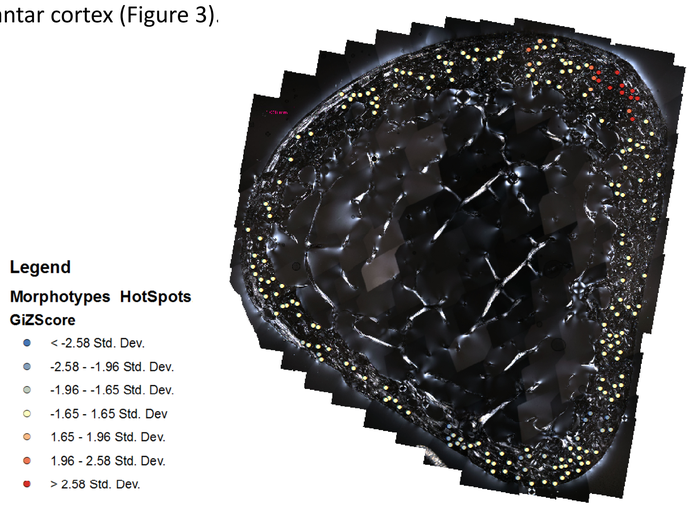

Figure 3. Morphotype Hotspot Analysis

The Cluster and outlier analysis tool examines each of the points and assigns a Z-score and p-value. High Z-scores indicate a cluster, whereas low scores indicate outliers. This analysis demonstrates that similar morphotypes cluster together throughout the cortex (Figure 4).

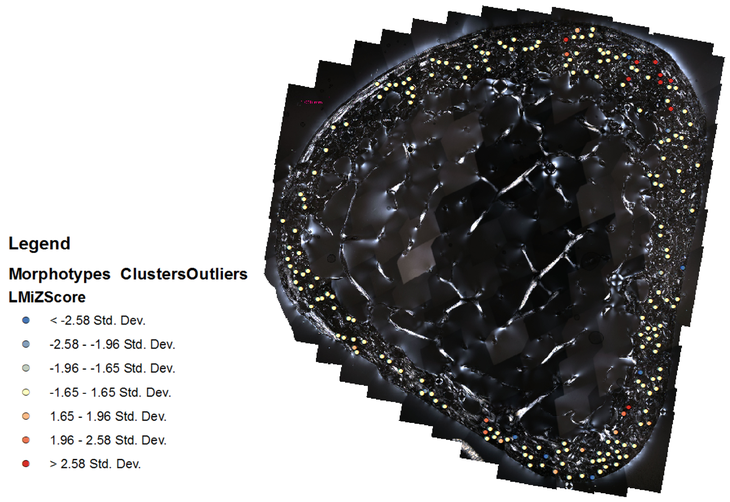

Figure 4. Results of Morphotype Clusters and Outliers Analysis (Anselin Local Morans I)

Discussion

The use of GIS software for the study of bone histology offers a novel opportunity to analyze the distribution of one or more features while considering complicating factors such as load history. This finally allows for the examination of characteristics of single osteons while considering their impact, or role, at the macroscopic level. Assuming collagen fiber orientation and mode of strain have a functional relationship, this research seems to have immediate promise in helping to unravel load history of bone. This method also offers an interesting opportunity to analyze the relationship between microdamage in relation to known modes of strain and in relation to osteocyte apoptosis. Eventually, it may be useful for broader evaluation of the skeleton to help map the "burden" of damage (Martin, 1993) present in skeletal elements or mapping remodeling paths on a larger scale traveling through bone.

The applications for this method in skeletal biology are two-fold. This method allows for in-depth evaluation of an entire cross-section from any bone, which may be utilized in further research to identify appropriate sampling locations for histological techniques. Furthermore, use of GIS software offers an alternative method for marking remodeling points, useful in age-at-death estimations. Multiple layers of points can be turned on and off in a single image, allowing direct comparison between observers in a format that is suitable for indefinite digital storage. These strengths of using GIS software in examinations of histomorphometry may be used to address concerns of intra- and inter-observer variability that have been reported (Lynnerup *et al.*, 1998).

Conclusions

This study demonstrated that spatial analysis can be performed on full cross-sections of bone with geographic information systems software. This type of analysis has the potential to be a new and exciting approach to study skeletal variation and represents the arrival of a new scale for the evaluation of variability of histomorphology. It also provides new means for incorporating histomorphometric research into other areas of skeletal research, such as biomechanics or cross-sectional geometry studies.

Acknowledgments: Presentation partially funded by the Daniel Hughes Memorial Fund, Department of Anthropology, The Ohio State University

References: Getis A, Ord, J. 1992. The Analysis of Spatial Association by Use of Distance Statistics. Geographical Analysis. 24:189-206. Lynnerup N, Thomsen JL, Frohlich B. 1998. Intra- and inter-observer variation in histological criteria used in age at death determination based on femoral cortical bone. Forensic Science International. 91:219-230. Ord, JK, Getis, A. 1995. "Local Spatial Autocorrelation Statistics: Distributional Issues and an Application." Geographical Analysis. 27: 286-306. Martin RB. 1993. Aging and strength of bone as a structural material. Calcified Tissue International. 53(Suppl 1):S34-S40. Skedros JG, Mendenhall SD, Kiser CJ, Winet H. 2009. Interpreting cortical bone adaptation and load history by quantifying osteon morphotypes in circularly polarized light images. Bone. 44:392-403.