Structural development of cortical bone morphology in the human femoral and tibial diaphyses indicates age- and site-specific biomechanical competence

Zachariah R. Hubbell[1], James H. Gosman[1], Colin N. Shaw[2], Timothy M. Ryan[3,4]

[1]Department of Anthropology, The Ohio State University; [2]McDonald Institute for Archaeological Research, Cambridge University; [3]Department of Anthropology, Pennsylvania State University; [4]Center for Quantitative Imaging, EMS Energy Institute, Pennsylvania State University

BACKGROUND

- Developmental structural differentiation in human long bone morphology is a key element in the variability of adult long bone structure.
- Dimensional scaling methods currently used for determining subadult injury thresholds assume geometric similarity between children and adults.[1]
- Given the unique biomechanical demands of locomotor ontogeny and longitudinal growth, a more nuanced understanding of the developmental timing and spatial variability of long bone morphological characteristics is needed in order to develop accurate child response targets.
- ***HYPOTHESIS:*** Ontogenetic patterns of cross sectional cortical shape change in the human femoral and tibial diaphyses are age- and anatomical site-specific.

MATERIALS

- Human femora (n=46) and tibiae (n=47).
- Ages range from neonatal to 16.5 years.
- Bones obtained from the Norris Farms #36 series, an Oneota Native American skeletal assemblage dating to about A.D. 1300.
- High resolution x-ray CT scans were taken at the Pennsylvania State Center for Quantitative Imaging.
- CT scan resolutions range from 0.013mm to 0.094mm, depending on specimen size (with higher resolutions for smaller bones).

METHODS

- Cortical drift patterns and relative bone envelope modeling activity were assessed across age groups in five locations per bone (at 20, 35, 50, 65, and 80% of total bone length [*Figs. 1 & 2*]) by measuring the distance from the section centroid to the endosteal and periosteal margins in eight cross-sectional sectors using ImageJ (*Figs. 4, 5, & 6*).
- Changes in the periosteal and/or endosteal surfaces and in cortical width were recorded for each of the five diaphyseal slices (per bone).
- Correlation between age and I_{max}/I_{min} ratio was tested at each slice location (*Fig. 3*).

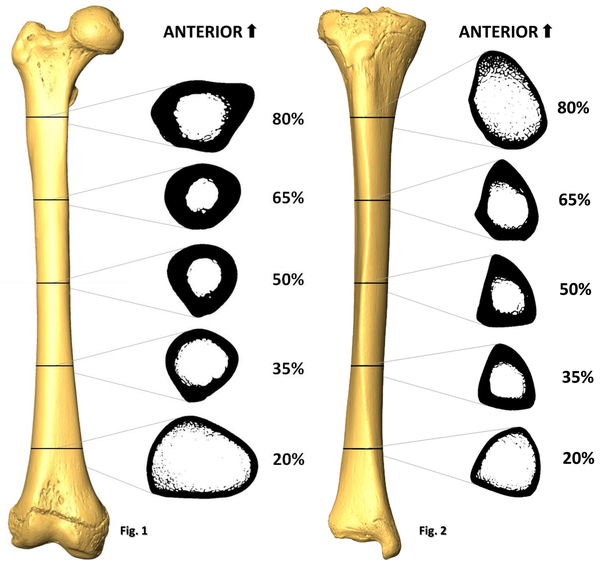


Fig. 1

Fig. 2

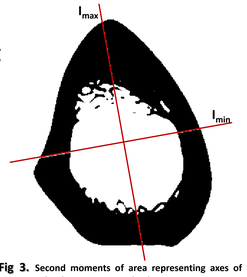


Fig 3. Second moments of area representing axes of maximum (I_{max}) and minimum (I_{min}) bending rigidity. The ratio of these values is an index of shape (1=symmetrical; 0=asymmetrical).

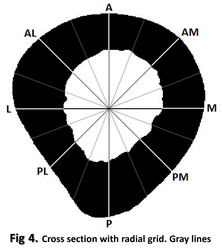


Fig 4. Cross section with radial grid. Gray lines designate 8 sectors. White lines bisect sectors. Letters are directional indicators.

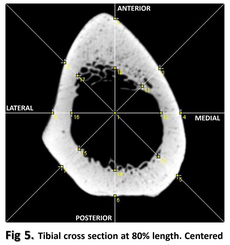


Fig 5. Tibial cross section at 80% length. Centered radial grid intersects cortical surfaces in 16 locations (twice per sector). Age = 16.5 yrs.

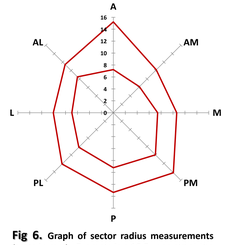
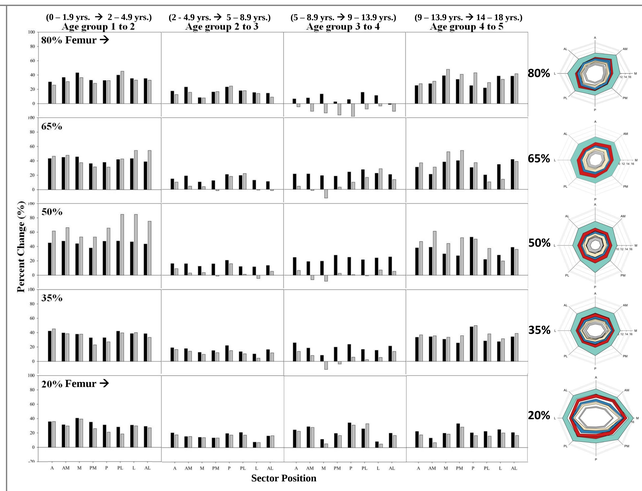
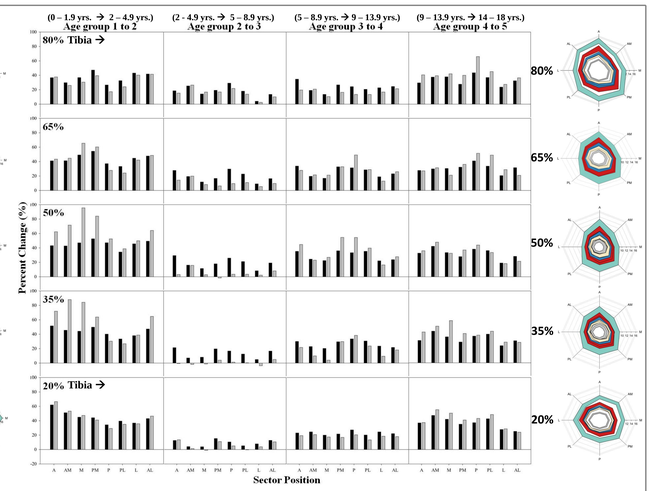


Fig 6. Graph of sector radius measurements (scale in mm). Example is a 16.5 year-old at the 80% tibia slice.





Figs 9 & 10 (above). Percent change (with age) in mean cross-sectional radius in each sector for femora (left) and tibiae (right). Black bars = periosteal change; grey bars = endosteal change. Radial graphs show mean cross-sectional radii for all age groups, plotted separately for each slice location.

RESULTS

- Cortical shape changes are most strongly associated with age in the distal (20% total bone length) and proximal (80% total bone length) regions of the *femoral* diaphysis, and in the proximal regions (65% and 80% total bone length) of the *tibia* (Pearson correlation results in *Tables 1 & 2*).
- This indicates that these anatomical locations may be more sensitive to developmental mechanical load shifts than the midshaft (50% length).
- Age-specific mean I_{max}/I_{min} values at 5 shaft locations are shown in *Figs. 7 & 8*.
- Bone surface changes are highly age- and site-specific, with accelerated periods of change identified in the early childhood and pre-pubertal stages of development (*Figs. 9 & 10*).

1	Imax/Imin vs Age (FEMUR)				
Slice	20%	35%	50%	65%	80%
r	-0.665	-0.358	0.038	0.599	0.365
p-value	<0.001	<0.01	NS	<0.001	<0.01

2	Imax/Imin vs Age (TIBIA)				
Slice	20%	35%	50%	65%	80%
r	-0.417	0.792	0.825	0.880	0.859
p-value	<0.01	<0.001	<0.001	<0.001	<0.001

Tables 1 & 2. Pearson correlation results for I_{max}/I_{min} and age in the femur (left table) and in the tibia (right table) at each of the five slice locations per bone. Red significance values indicate significant p-values after Bonferonni correction (corrected p=0.005).

Fig. 7

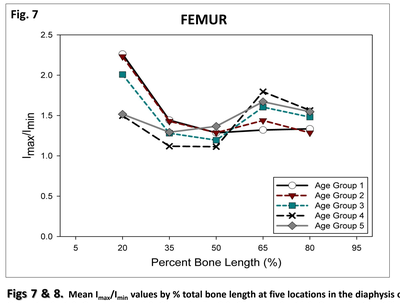
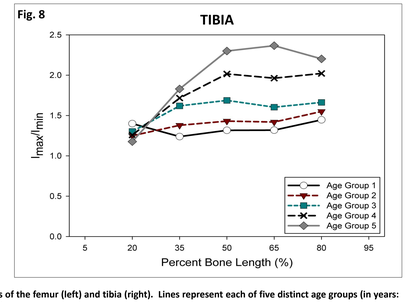


Fig. 8



Figs 7 & 8. Mean I_{max}/I_{min} values by % total bone length at five locations in the diaphysis of the femur (left) and tibia (right). Lines represent each of five distinct age groups (in years: Group 1 = 0 - 1.9; Group 2 = 2 – 4.9; Group 3 = 5 – 8.9; Group 4 = 9 – 13.9; Group 5 = 14 – 18).

DISCUSSION

- Sensitivity of morphological adaptation to locomotor forces is heterogeneous throughout the diaphysis of the tibia and femur.
- Significant age-related differences in cortical morphology indicate a major limitation of current geometric scaling techniques.[2, 3, 4]
- According to previous studies, diaphyseal fractures in the subadult *tibia* occur most frequently in the distal third of the shaft, followed by the middle third, with the fewest occurring proximally[5]; diaphyseal fractures of the subadult *femur* occur most frequently in the midshaft, followed by the distal region.[6]
- Most common fracture sites correspond to smallest I_{max} values found in this study, indicating that the femur and tibia tend to fracture at sites of least bending rigidity.

CONCLUSIONS

- Structural response to mechanical use is age- and site-specific in the femur & tibia.
- Nuances of developmental timing and spatial variability of long bone morphology can contribute to refinement of geometric scaling techniques for child injury biomechanics research.
- Future research should combine age- and site-specific morphometrics with experimentally-derived subadult injury threshold data.

REFERENCES

1. J. Ash, Y. Abdelilah, J. Crandall, D. Parent, C. Sherwood, D. Kallieris. 2005. Comparison of Anthropomorphic Test Dummies with a Pediatric Cadaver Restrained by a Three-point Belt in Frontal Sled Tests. Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles.
2. R.H. Eppinger, J.H. Marcus, R.M. Morgan. 1984. Development of Dummy and Injury Index for NHTSA's Thoracic Side-Impact Protection Research Program. Society for Automotive Engineers, Technical Paper.
3. H.J. Mertz. 1984. A Procedure for Normalizing Impact Response Data. Society for Automotive Engineers, Technical Paper.
4. H.J. Mertz, P. Prasad, A.L. Irwin. 1997. Injury Risk Curves for Children and Adults in Frontal and Rear Collisions. Society for Automotive Engineers, Technical Paper.
5. E.S. Hart, B. Luther, B.E. Grottkau. 2006. Broken Bones: Common Pediatric Lower Extremity Fractures – Part III. Orthopaedic Nursing 25(6):390-407.
6. R. Schwend, C. Werth, A. Johnston. 2000. Femur Shaft Fractures in Toddlers and Young Children: Rarely from Child Abuse. J Ped Ortho 20(4):475-481.

ACKNOWLEDGMENTS

This research was supported by NSF grant BCS-1028904 (JHG, TMR)

The authors thank Amanda Agnew and Laura Boucher for their helpful comments and suggestions.