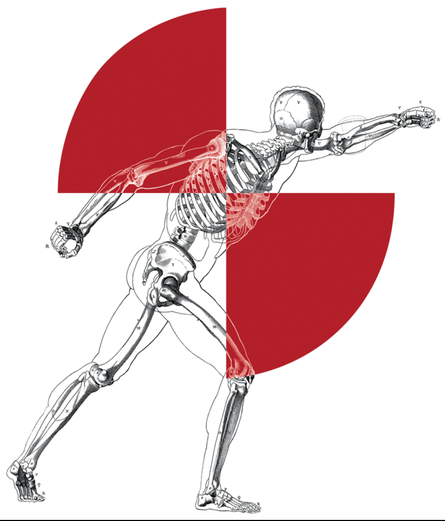

Quantifying Variation in Human Cortical Thickness in the Tibia: Implications for Fracture Risk

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INTRODUCTION

- A computed tomography (CT) scanner is a prevalent clinical instrument providing images that can be used to assess bone quality[1]. Cortical thickness (Ct.Th) has been established as an important predictor of bone strength across the skeleton; however, data are lacking in the variation present both along the diaphysis of the tibia and within a cross-section of the tibial cortex[2,3].
- Quantifying bone quality across various skeletal elements is important in understanding fracture risk, namely for the purpose of creating a more biofidelic finite element (FE) human body model[4,5,6]. Considering the commonality of tibiae injuries in automotive crash scenarios, especially pedestrian impacts, it is of interest to investigate tibial variation to improve the accuracy of injury prediction[7].
- It is also commonly assumed by commercially available computer analysis software programs that an averaged Ct.Th value sufficiently represents the amount of bone present in the entirety of a cross-section.
- **Therefore, the purpose of this study is twofold:**
  - **To quantify the variation in Ct.Th between segment sites of the tibia**
  - **To quantify the variation of Ct.Th within a cross-section**

MATERIALS AND METHODS

- Sixty left tibiae were obtained from 30 male (63.6 ± 10.0 years) and 30 female (63.4 ± 15.8 years) post-mortem human subjects (PMHS) ranging from 45 to 89 years of age.
- Tibiae were scanned on a Philips Ingenuity 64-slice CT at 0.671mm slice thickness. Acquisition parameters were consistent, resulting in an in-plane resolution of 0.335mm.
- CT images were imported into commercially validated SkyScan (Bruker) software for segmentation into 38%, 50%, and 66% segment sites relative to the distal articular surface (Fig. 1). Average Ct.Th values were automatically quantified per segment site.
- An ANOVA was performed using SkyScan Ct.Th values to investigate variation in average (around the cross-section) Ct.Th between segment sites of the tibia.

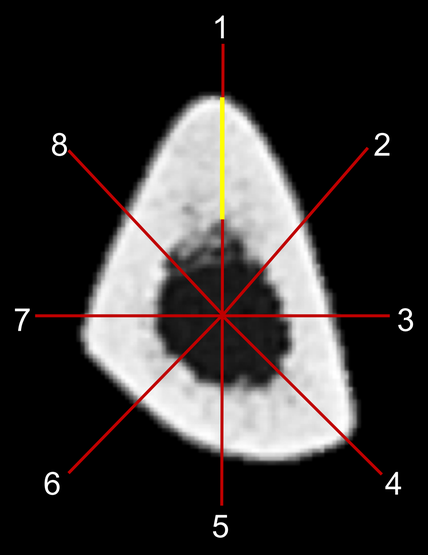

Figure 2. Eight equidistant points, depicted by the red lines, where Ct.Th was manually measured. The yellow line represents Ct.Th measured from periosteum to endosteum.

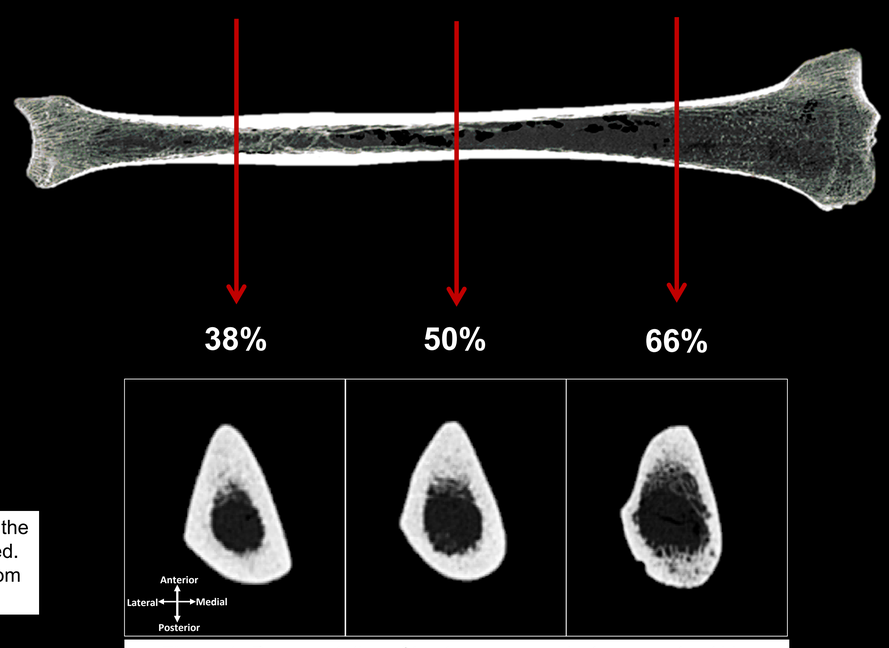

Figure 1. Representation of the three segment sites along the tibial diaphysis and their respective cross-sections. Anatomical orientation consistently maintained for all analyses.

- OsiriX MD (v.8.0.1) was used to similarly segment tibiae for ImageJ (NIH) analysis. Manual measurements of Ct.Th were performed at 8 equidistant vectors across each tibiae cross-section in ImageJ (Fig. 2).
- Within the cross-section of each segment, manual Ct.Th measurements were compared using two ANOVAs: first, to compare the Ct.Th at the 8 equidistant vectors for each segment site individually; and secondly, to compare individual matched vectors between the three segment sites.

RESULTS

- Ct.Th was averaged across the entire cross-section per segment site, and significant differences were found between both 38% and 50% compared to 66% ($p<0.01$); however, no differences existed between 38% and 50% ($p>0.87$) (Fig. 3).

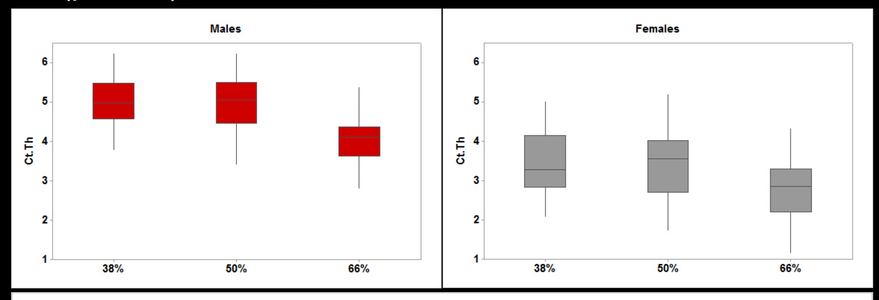

Figure 3. Males and females had significantly larger average Ct.Th values at 38% and 50% compared to 66% sites ($p<0.01$). Independent samples t-test indicate male Ct.Th is larger than females at all segment sites ($p<0.05$).

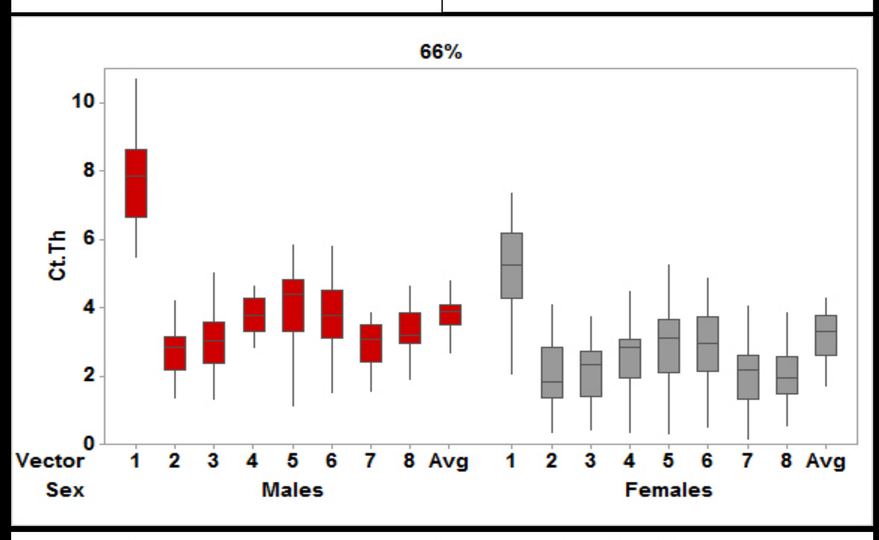

Figure 4. Boxplot depicting differences in Ct.Th per vector at the 66% segment site for males and females.

- Significant differences in Ct.Th were observed between vectors within each cross-section ($p<0.05$) at all segment sites. Figure 4 depicts relationships at 66% only.
- For both sexes, post-hoc tests found the anterior (vector 1) Ct.Th significantly larger than all other vectors at all segment sites.
- In males only, at 38%, the postero-lateral (vector 6) was significantly larger than antero-medial (vector 2), medial (vector 3), lateral (vector 7) and antero-lateral (vector 8) ($p<0.03$). 50% demonstrated the fewest differences (vector 6 > 7 and 8). 66% demonstrated the largest amount of variation between vectors (Fig. 4).

Vector	Sex	38% Mean±SD (mm)	50% Mean±SD (mm)	66% Mean±SD (mm)	F	p
1	Male	8.99±1.61	10.37±1.91	7.83±1.39	18.06	**<0.001**
	Female*	5.96±1.79	6.77±2.06	5.04±1.74	6.01	**0.003**
2	Male*	4.02±0.91	3.84±0.88	2.82±0.83	16.56	**<0.001**
	Female*	2.87±0.96	2.66±1.07	2.07±1.08	4.42	**0.015**
3	Male*	4.11±0.77	4.07±1.10	3.01±0.79	14.39	**<0.001**
	Female	2.58±0.93	2.80±0.98	2.21±0.85	2.80	0.066
4	Male*	4.71±1.09	4.47±0.96	3.82±0.91	6.42	**0.002**
	Female	3.35±1.35	2.95±1.20	2.67±1.01	2.43	0.093
5	Male	4.61±0.66	4.63±0.73	4.21±1.16	2.19	0.118
	Female	3.21±1.10	3.17±1.21	2.94±1.46	0.406	0.667
6	Male*	5.28±1.25	4.75±0.96	3.86±1.05	12.86	**<0.001**
	Female	3.53±1.45	3.33±1.33	2.85±1.19	2.10	0.129
7	Male*	3.87±0.98	3.74±1.01	3.04±1.05	6.35	**0.003**
	Female*	2.77±0.93	2.62±1.24	2.00±0.95	3.92	**0.023**
8	Male	4.39±0.69	3.82±0.89	3.32±0.68	14.90	**<0.001**
	Female*	2.88±0.98	2.82±1.03	2.02±0.96	6.09	**0.003**

Table 1. Results from the ANOVAs comparing a single vector between the segment sites (38%, 50%, 66%). * indicate significantly smaller 66% compared to 38% and 50% using Bonferroni post-hoc tests.

- There were significant differences found between segment sites at the same vector ($p<0.02$) except at the posterior location (vector 5) in males, and vectors 3-6 in females (Table 1).
- Generally, Ct.Th values significantly decreased at 66% compared to 38% and 50% in both sexes for select vectors (Table 1). 38% and 50% Ct.Th were not significantly different with the exception of vectors 1 and 8 in males only ($p<0.04$).

DISCUSSION AND CONCLUSIONS

- Results indicate a significant amount of Ct.Th variation both along the tibia and within each cross-section at varying segment sites, therefore, Ct.Th variation should be accounted for when creating biofidelic finite element models.
- Considering previous studies have mentioned both the importance of FE modeling in biomechanical studies and the impact of Ct.Th on such models, it is important to quantify Ct.Th variation[4].
  - While an average Ct.Th value qualitatively appears to be representative of Ct.Th at different points around the cross-section, more work must be done to quantify differences between individual vectors and average Ct.Th.
- While a deficit in Ct.Th has been linked to increased fracture risk, it has not been investigated if Ct.Th variation has an effect on fracture propagation[7].
- 88.9% of tibial shaft fractures are located in the middle or distal part of the shaft, which implies there may be more factors than Ct.Th affecting fracture risk considering Ct.Th increases as total bone size decreases moving distally[8].

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