Evaluation of Correlations between Equivalent CT Density and Elastic Properties of Human Lower Limb Cortical Bones

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Introduction

The majority of occupant lower extremity (LEX) injuries in automotive crashes occur in the knee-thigh-hip (KTH) complex. While many Finite Element (FE) models have been developed to assess KTH injury mechanisms, their bone models were usually defined as homogeneous. Models that account for heterogeneous nature of bone are crucial for better predicting mechanical and injury responses. Recently, correlations between Computed Tomography (CT) scan data and cortical bone material properties were established. To figure out the best correlation for the LEX cortical bones, this study evaluated the consistency of reported correlations with respect to the experimental force-displacement data.

Background

- **Most of the current FE cortical bone models have homogeneous material properties (E, σ_{max} etc.).**
- **However, cortical bone stiffness varies in different sites.**
  - Femur head: ~ 1 GPa[1]
  - Femur neck: ~ 10 GPa[7]
  - Femur shaft: ~ 15 GPa[3],[5]

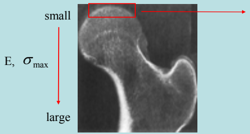

Figure 1: Typical CT image of human proximal femur

Figure 2: Typical meridional section of spongy subchondral bone[1]

- **Many correlations of equivalent CT density ~ cortical bone material properties were established[1],[2],[4],[6],[8],[9], but their accuracy was not verified by independent studies.**

Methods

Reconstruct coupon geometry from μCT data

Mesh coupon FE models (six samples)

Convergence study to decide coupon mesh density

- 0.1mm, 0.2 mm, 0.4 mm and 0.8 mm coupon models
- Uniaxial coupon tension simulation and force-displacement curve comparison

Calculate averaged Hounsfield (HU) values for each element of the coupon models using μCT data

Assign equivalent density and elastic modulus based on six different literature correlations for each coupon sample

Run Quasi-static coupon tension simulation

- Input: Aramis displacement time history
- Output: Coupon section force time history

Data analysis

- Compare force-displacement curves between simulation and test data
- Calculate SE values for each correlation

- Coupon geometry reconstruction done using Mimics 13.0 (Materialise, Belgium)
- HU calculation for coupon FE models done using in-house MATLAB 2009 program (MathWorks, MA)
- Experimental coupon displacement time history extracted using Aramis 6.2.0 (GOM mbH, Germany)
- Coupon tension simulation done using LS-DYNA 971 R4 (LSTC, CA)

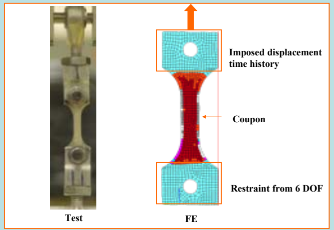

Figure 3: Coupon quasi-static tension test setup[10]

Table 1: Literature correlations between equivalent density and elastic modulus

Name of Study	Site	Type of Bone	Density Type	Density Range	E (ρ) (GPa)	Test Condition	Strain Rate (min^{-1})
Lotz et al.[7] (1991)	Femoral metaphysis	Cortical	ρ_{app}	1.20-1.845^{RFG}	$E= -13.43+14.261\rho$	3 point bending	0.05
Snyder et al.[8] (1991)	Tibial diaphysis	Cortical	ρ_{app}	1.748-1.952	$E= 3.891\rho^{2.39}$	3 point bending	0.001
Keller[6] (1994)	Femur	Cortical & Trabecular	ρ_{ash}	0.092-1.221	$E= 10.5\rho^{2.29}$	Platen	0.01
Carter et al.[2] (1977)	Femoral mid-diaphysis	Cortical	ρ_{app}	All	$E= 2.875\rho^{3}$	Tension	0.01
Wirtz et al.[9] (2000)	Average (femoral	Cortical	ρ_{app}	$\rho_1 < 0.95$ $\rho_2 > 0.95$	$E_1 = 1.904\rho^{1.64}$ $E_2 = 2.065\rho^{3.09}$	N/A	0.01
Duchemin et al.[4] (2007)	Femoral mid-diaphysis	Cortical	ρ_{HA}	All ρ	$E = 0.012\rho + 0.26$	Tension	0.04

Results

- **Convergence study**
  - Force-displacement curves of the four different mesh-density coupon models were quite identical in the elastic regions
  - 0.4 mm was chosen as the element size, considering the computational time cost and quality of geometry representation
- **Comparison of quasi-static force-displacement curves of coupon FE models to test data**
  - Six coupon samples • Six equivalent CT density to elastic modulus literature relationships for each coupon FE sample

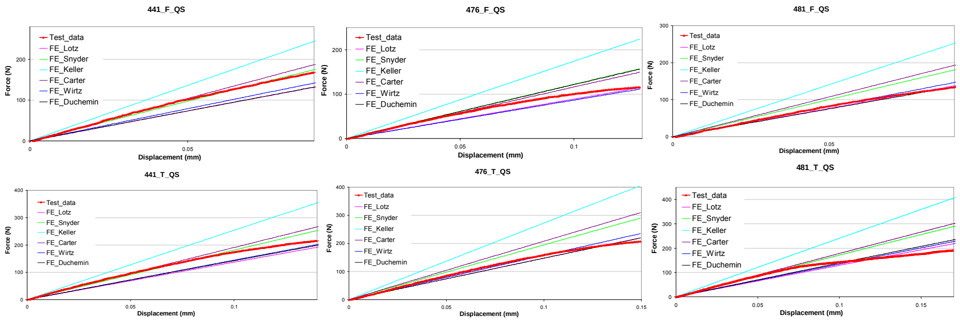

Figure 4: Comparison of force-displacement responses up to failure between test and FE data (F: femur; T: tibia; QS: quasi-static)

- **Square Error (SE) calculation**
  - Compare only elastic regions of force-displacement curves

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n-1}}$$

- x and y are test and simulation data
- n is the sample number

Table 2: SE calculation of literature correlations to the test data

Name of Study	Correlation SE values for each sample						Averaged
	441_F	441_T	476_F	476_T	481_F	481_T	
Lotz et al.[7]	20.0	23.0	9.8	9.0	3.7	16.9	**13.7**
Snyder et al.[8]	3.4	3.1	4.1	15.6	24.8	2.1	**8.9**
Keller[6]	24.6	32.5	25.4	55.7	67.7	31.7	**39.6**
Carter et al.[2]	2.6	3.4	1.8	22.3	32.2	4.7	**11.2**
Wirtz et al.[9]	16.0	19.6	10.7	4.0	5.3	14.6	**11.7**
Duchemin et al.[4]	19.8	20.6	3.9	9.2	4.6	12.8	**11.8**

- **Axial displacement contour comparison of coupon 476_T**

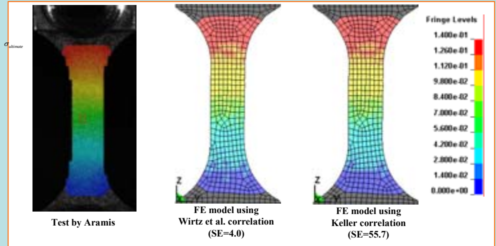

Figure 5: Comparison of axial displacement contours (coupon 476_T)

Discussion

- Force response of FE models:
  - The models using Lotz et al., Wirtz et al. and Duchemin et al. correlations were similar to each other and softer among all.
  - The model using Keller correlation was the stiffest.
  - The models using Snyder et al. and Carter et al. correlations were similar and their stiffness were in the middle among all.
- Force response of the FE model using Snyder et al. correlation was the closest to test data (smallest averaged SE value).
- All six correlations produced similar displacement contours, indicating their quasi-proportional relationships in the cortical density range.
- While the density ~ elastic moduli correlations were defined only in the elastic region, they can not be applied to the plastic region preceding bone fracture.
- The tibia has a larger $\sigma_{ultimate}$ than the femur.

Conclusions

- **The FE models using six different CT equivalent density ~ elastic modulus correlations showed different stiffness responses.**
- **The FE model using Snyder et al. correlation showed the closest match to the test data.**

Future Work

- **Propose a more accurate density ~ modulus correlation utilizing optimization techniques from this study.**
- **Investigate the possibility of establishing a relationship between density and parameters of the plastic region, which may include the bone fracture parameters (e.g. yield strain / stress) as well.**

References

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