Development of a Statistical Shape Model of the Infant Femur

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Background

- Due to scarcity of pediatric bone, little is known about fracture potential of pediatric femurs
- Statistical shape models provide a means of generating representative bone models when other methods are not possible

Objective

- Develop a statistical shape model of the infant femur
  - Anthropometric features are inputs to a predictive model
  - Predictive model could then be used to generate representative femur models of different ages

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Methods

- CT scans of 42 infant decedents were obtained (Fig 1)

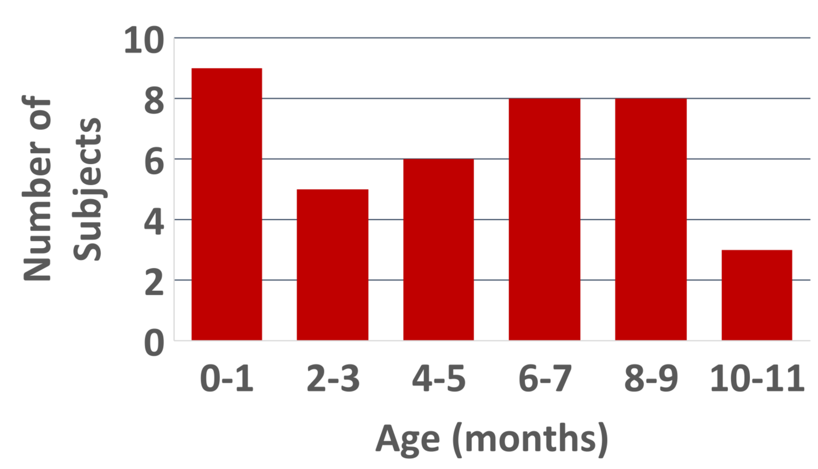

Figure 1. Distribution of decedent ages.

- Left femur was segmented from each scan
- 29 anatomical landmarks were manually identified (Fig 2)

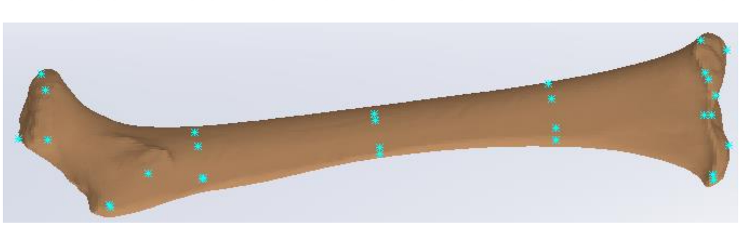

Figure 2. Representation of select anatomical landmarks (blue) identified.

- Mesh Morphing: Creating femur models with a similar mesh
  - Baseline model developed: Composed of triangular elements with 9864 nodes
  - RBFmorph (Monte Compatri, Rome – Italy) used to morph the baseline to the remaining femurs
    - Anatomical landmarks used as initial alignment between baseline and target femur
    - Software optimizes use of radial basis functions to complete the morphing process
- All femur models were aligned to the baseline using Procrustes analysis
- Principal component analysis (PCA) conducted in MATLAB
  - Hoteling T^2 ($\alpha = 0.05$) was used to identify outliers
  - 3 femurs were identified and excluded from further analysis
- 6 femur models were reserved to evaluate the model's accuracy:
  - 1 from each 2-month interval
- A PCA was conducted on the training set's (n=33) morphed meshed models
- Partial least squares regression used to develop a predictive model
  - Anthropometric features (age, height, body mass index, and weight) used to predict principal component scores
- Evaluated model accuracy for the test set: R^2, root mean square error, nodal reconstruction error and the error normalized to femur length

Results

- Three principal components (PC) were required to have the mean nodal reconstruction error be less than 1mm for all of the training set.
- Representation of the mean shape and the first PC coefficients can be found in Fig 4
- 1st PC explained 98.05% of the variance of the training set
  - Only PC with scores linearly related to anthropometrics (Fig 3)
  - Coefficients were dominated by changes in the longitudinal direction
  - 0-1 and 9-11 month old cases most heavily contributed to this component
- 2nd PC explained 0.45% of variance
  - Results in shifts in the anterior-posterior and medial-lateral directions for the proximal and distal metaphyses
- 3rd PC explained 0.27% of variance
  - Results in mostly anterior-posterior shifts for the proximal metaphyses
- 1st PC was found to be significant ($\alpha = 0.05$) in the PLS regression with age/height as predictors
- Accuracy of model for the test set
  - R2= 0.53 and RMSE of 5.9mm
- Mean and max nodal reconstruction errors were 0.77-6.59mm and 2.33-10.40mm, respectively
- Reconstruction errors were found to be greatest at the metaphyses (Fig 5)
  - Difficulty in reconstructing the varying degrees of rotation of the femoral head
- Greatest reconstruction errors (Fig 6) associated with cases (7 and 10 month olds) whose shape deviated differently from the mean shape compared to similarly aged femurs in the training set
  - Both were the only models with mean nodal reconstruction error greater than 2mm

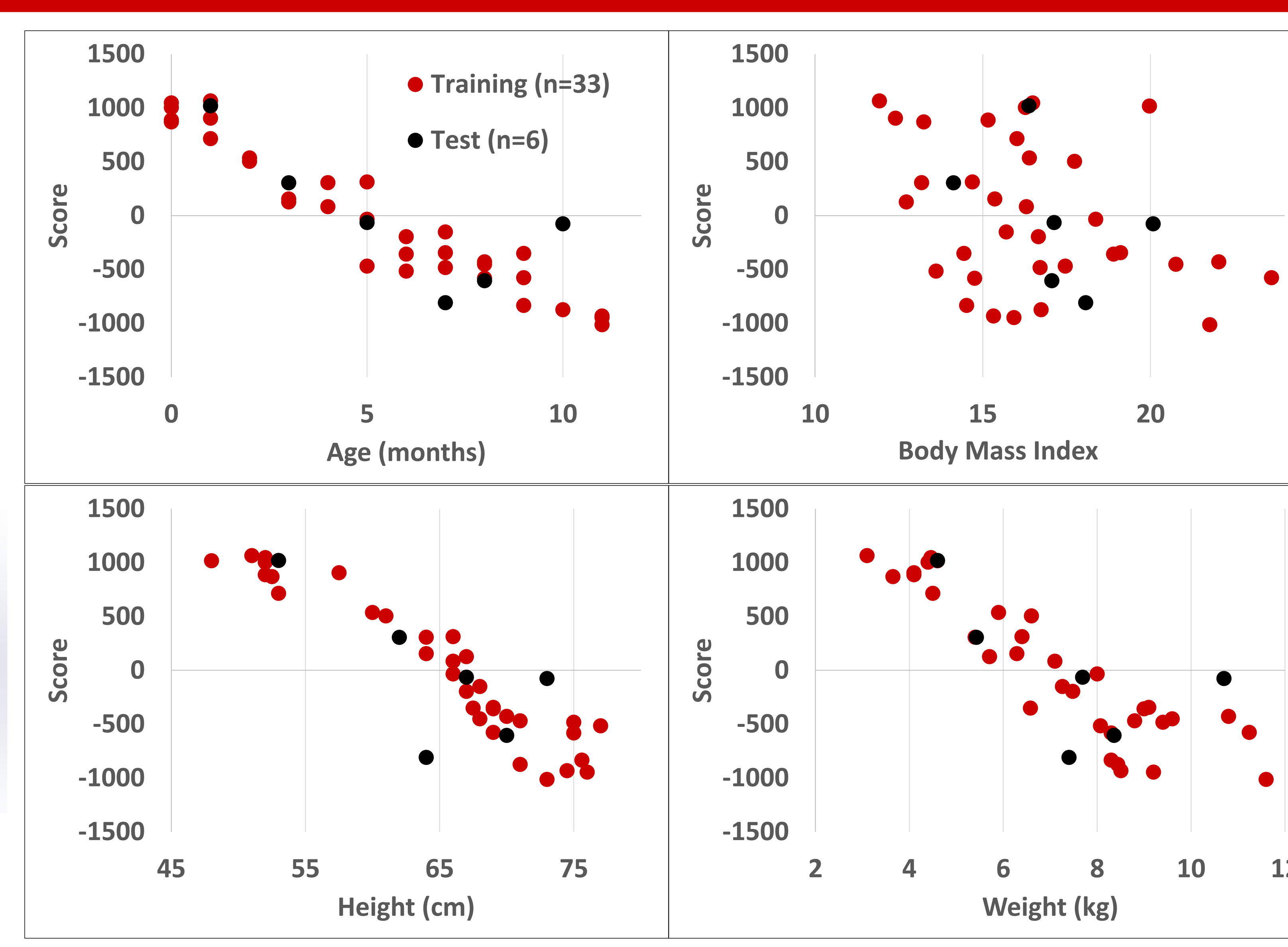

Figure 3. First PC score versus the age, body mass index, height, and weight of each included case. The training (red) and test (black) sets are displayed.

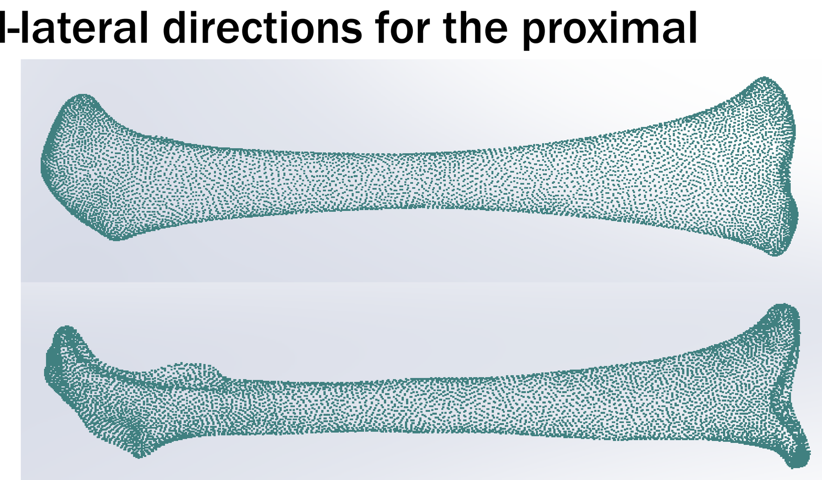

Figure 4. The mean shape (top) of the training set and the weighting of the 1st PC (bottom). Anterior view.

Figure 6. Nodal reconstruction errors normalized with respect to femur length for the test set (n=6).

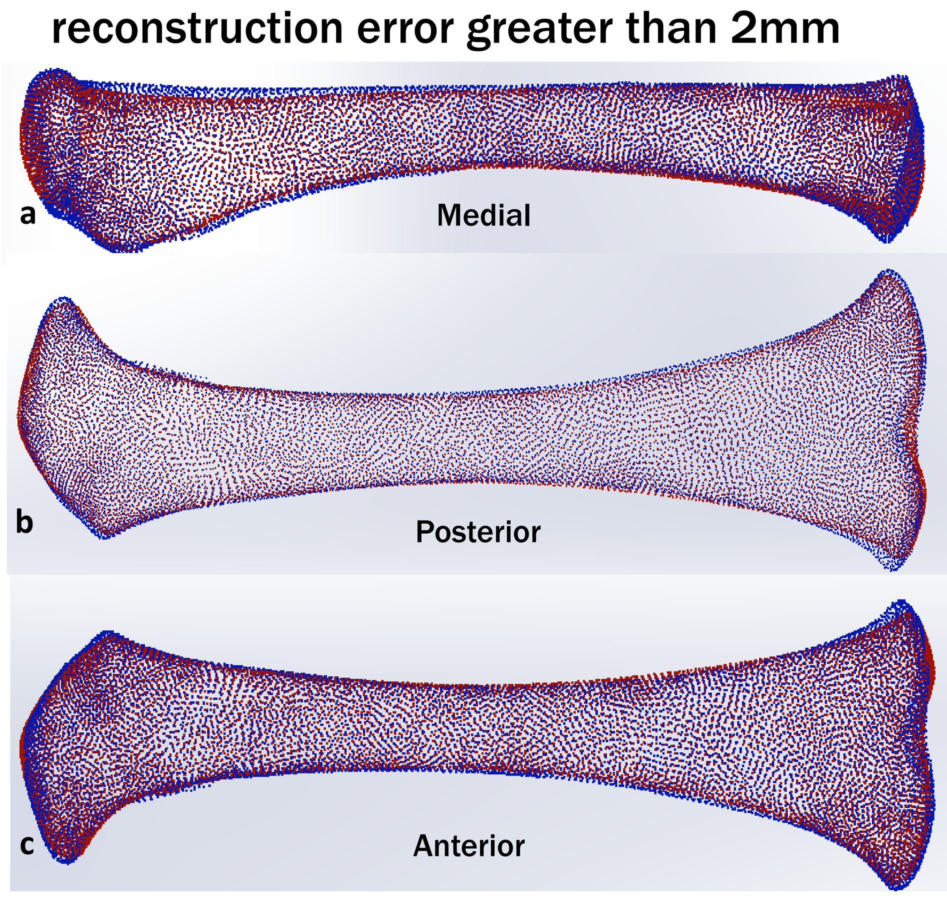

Figure 5. The original (blue) and reconstructed with 1 principal component (red) five month old femur. Medial (a), posterior (b), and anterior (c) views are displayed.

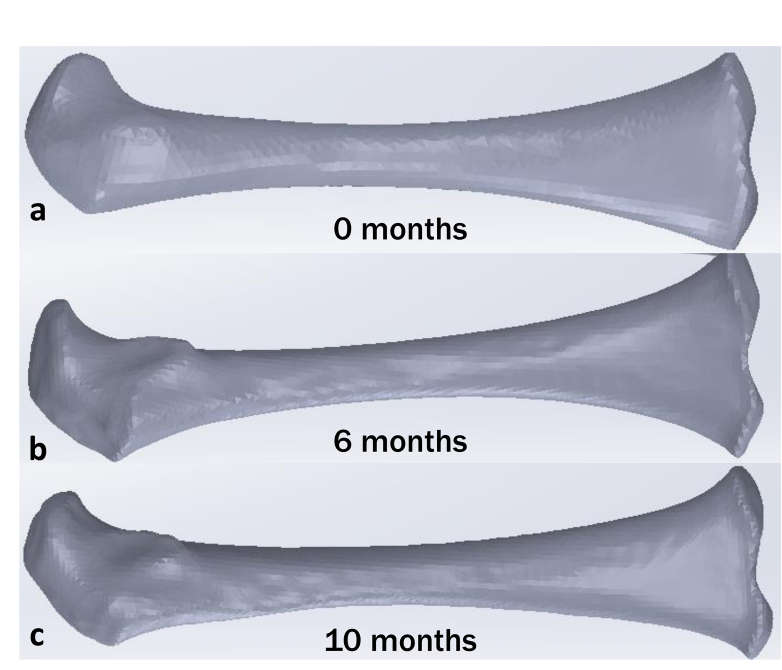

Figure 7. Representative femur shapes of 0 (a), 6 (b), and 10 (c) month old femurs with femur lengths of 83, 120, and 109 mm, respectively. Posterior view.

Discussion

- Compared to adult femur statistical shape models (Klein, 2015):
  - Ours captured more of the variance with fewer PCs
  - Our model had a lower R^2 (0.53 vs 0.79)
- Differences are likely due to greater variation of morphology in developing infants compared to adults
  - Greater variation of the degree of femoral anteversion
  - Varying growth rates and development of features (Fig 7)
- Limitations
  - Both PCA and partial least squares regression are linear methods
  - Only evaluated the surface model
- Future Work:
  - Improve model's predictive ability
  - Expanding age range up to 35 months where an additional 57 CTs are available for inclusion

Conclusion

- A statistical shape model of the infant femur was developed
- Newly generated femur models can be used in finite element analysis to study biomechanics and fracture potential