Background

- Use of finite element (FE) analysis to evaluate femur biomechanics in infants and young children is limited by scarcity of CT imaging due to radiation concerns.
- 2D femur radiographs of pediatric femurs are more common and readily available.

Methods

Data set: Imaging from 27 decedents age 10-24 months without bone disease or deformities (Figure 1).

- Each subject had AP (anterior-posterior) 2D radiographs and CT scans of both femurs.
- 3D femur models were previously derived from the CT scans [1]. For each radiograph, a set of femur contour points were identified by 60 points defined based on anatomical landmarks (Figure 2).

Generation of Medullary Canal

- The medullary canal was characterized by elliptical profiles at 3 transverse cross-sections (located in the diaphysis at 25%, 50%, and 75% of femur length). The radii were defined in AP and ML (medial-lateral) directions.
- PLSR was developed predicting the AP and ML radii of the 3 cross sections using the corresponding outer diaphyseal widths from the 2D radiographs and the significant morphometric predictors (age and femur length).
- The overall RMSE for predicting the canal widths was calculated for each femur in the test set.

Comparison of predicted vs CT-derived femur models using FEA:

- Surface geometry for each femur generated using the PLSR was combined with inner medullary canal surface.
- For test femur sets (n=4), compressive loading applied corresponding to subject body weight.
- Compared values and locations of the peak maximum principal stress and strains and peak von Mises stress in the diaphysis.

Results

Generation of Femur Outer Surface: Two methods compared: PLSR and TPS+SSM

1. Method 1: A partial least squares regression (PLSR) was developed to output the point cloud representing the 3D outer surface [2].
   - Predictors considered were the femur contour points (n=60), subject characteristics (e.g., age, height) and key morphometrics obtained from the radiographs (e.g., femur length, trochanter width, and width at the minimum diaphysis [4]).
   - Predictors included/excluded from the model based on variable importance in projection (VIP) score using a cutoff value of 1.

2. Method 2: SSM+TPS utilized a previously developed statistical shape model (SSM) [1] and thin plate spline (TPS) morphing to better conform the approximated SSM-derived shape to that of the radiograph [3].

Comparison of methods: For femurs in the test set (n=4), the CT-derived 3D femur model was compared to the predicted surface geometry to determine:
- The percent difference in volume and surface errors and the mean and max nodal reconstruction errors for each individual femur.
- Root mean square error (RMSE) and $R^2$ for the test set overall.

PLSR resulted in an improved ability to generate the femur outer surface models compared to SSM+TPS.

Table 1. Summary of results for generating 3D surface model. Range of values represents those observed for subjects in the test set (n=4).

<table>
<thead>
<tr>
<th>Method</th>
<th>Overall RMSE (mm)</th>
<th>Mean Nodal Reconstruction Error Range (mm)</th>
<th>Max Nodal Reconstruction Error Range (mm)</th>
<th>Volume Error Range (%</th>
<th>Surface Area Error Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLSR</td>
<td>0.94 ± 1.77</td>
<td>0.84 ± 0.58</td>
<td>2.85 ± 0.59</td>
<td>53-19± 5</td>
<td>2.2-9</td>
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<tr>
<td>SSM+TPS</td>
<td>0.58 ± 0.34</td>
<td>2.48 ± 0.12</td>
<td>4.57 ± 0.75</td>
<td>22.36-12.22</td>
<td>0.02-0.08</td>
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</tbody>
</table>

**SSM = Statistical Shape Model, TPS = Thin-plate spline.**

Comparison of predicted vs CT-derived femur models using FEA:

- Highest errors in the peak stress and strains for femurs with highest RMSE values (Table 2).
- Location of peak stress/strains were similar between the CT-derived model and predicted model all across the whole femur in the test set (Figure 5).

Table 2. The percent difference in the FE results between the CT-derived and predicted femur model and the corresponding RMSE in predicting the shape for femurs in the test set (n=4).

<table>
<thead>
<tr>
<th>Subject Age</th>
<th>Peak Max Principal Stress/Strain</th>
<th>Peak von Mises Stress</th>
<th>Outer Surface RMSE</th>
<th>Medullary Canal RMSE</th>
</tr>
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<tbody>
<tr>
<td>12-14</td>
<td>10.2 ± 6.1</td>
<td>11.3 ± 6.1</td>
<td>0.92 ± 0.95</td>
<td>0.50</td>
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<tr>
<td>15-16</td>
<td>7.86 ± 5.9</td>
<td>6.15 ± 5.9</td>
<td>0.54 ± 0.44</td>
<td>0.65</td>
</tr>
<tr>
<td>17-18</td>
<td>9.96 ± 8.1</td>
<td>7.26 ± 8.1</td>
<td>1.62 ± 1.65</td>
<td>0.48</td>
</tr>
<tr>
<td>19-20</td>
<td>11.26 ± 9.2</td>
<td>9.35 ± 9.2</td>
<td>1.86 ± 1.85</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Discussion

- The PLSR method proved more suitable than SSM+TPS to generate the 3D outer surface model of the femur using 2D imaging.
- PLSR prediction of medullary canal shape allows expansion of previously developed SSM to define a biomechanically relevant medullary canal for healthy femurs.
- Despite the low error metrics in estimating the outer surface, there were high differences in the resulting peak stress and strains. However, the location of the peak FE measures were similar across all femurs in the data set.
- Future work will consider additional types of loading conditions (e.g., bending) to compare the predicted and CT-derived femur models.
- Future work will apply the methodology to generate 3D models for children with abnormal femur morphology.

References