INTRA-SUBJECT VARIABILITY OF FEMORAL GROWTH SIMULATIONS BASED ON PERSONALIZED FINITE ELEMENT MODELS

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Introduction

Mechanobiological bone growth predictions have a huge potential for improving clinical decision-making in children with bony deformities. A typical workflow to predict bone growth is based on a combination of musculoskeletal (MSK) and finite element (FE) simulations. The FE model usually requires hex elements aligned with the growth plate. Creating such a model is very time-consuming and therefore previous studies [1-3] only included small sample sizes (n<3), which limited the generalization of the research findings. The proposed mechanobiological model to predict bone growth is based on the osteogenic index (OI), which is determined by the octahedral shear stress and the hydrostatic stress. The twofold aim of the current study was i) to identify intrasubject variability of the OI and ii) to analyze how material properties and MSK loadings affect the OI.

Methods

We collected and analyzed three-dimensional motion capture data and magnetic resonance images (MRI) of eight typically developing children. MRI of each femur was segmented using 3D Slicer and used to calculate the subject-specific neck-shaft angle and anteversion angle. Two models were used for the MSK simulations:

1. we used the torsion tool [4] to create personalized models based on the measured angles from the MRI and subsequently scaled each model to the anthropometry of each participant [5].
2. the generic "gait2392" model was scaled by the identical scale setup file.

Joint kinematics, muscle and joint contact forces were calculated using OpenSim [6]. We developed a semi-automated workflow using Coreform Cubit, MeshLab, STAPLE toolbox and MATLAB to create FE models with subject-specific hex meshes from the segmented femurs. The FE models, including muscle forces and hip joint contact forces from the OpenSim simulations, were used to calculate the OI [1–3] in FEBio. Two FE models were used with Youngs' modulus of 1, 10, 10 and 0.1, 2, 5 GPa for growth plate, proximal and distal trabecular bone, respectively. The OI was then plotted as heatmaps and the shape and distribution of these images were compared within participants (left versus right femur) using OpenCV's template matching and histogram comparison. Additionally, the magnitude (mean and range) of the OI was compared between the left and right growth plate.

Results

The range of the magnitude of the OI between left and right side differed up to 0.074 while the mean OI values were quite similar with a maximum difference of 0.038 (Figure 1). Altering material properties of the FE model mainly changed the distribution of the OI (0.056±0.035 vs 0.089±0.06). Changes in MSK loading only had a minor effect on the OI (Figure 1, blue bars).

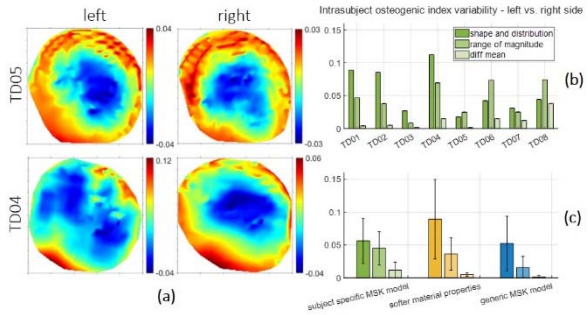

Figure 1: (a) heatmap plots of the OI of the left and right femur of 2 children; (b) intrasubject variability of OI; (c) OI variability for the baseline FE model and models with different material properties and MSK loadings.

Discussion

Previous research showed that a simplified growth plate leads to different OI magnitude and distribution when compared to a subject-specific growth plate [2]. Our work based on personalized FE models further highlights that the OI is similar between the left and right femur in most typically developing children.

Using a generic-scaled instead of a subject-specific MSK model mainly changed the magnitude and not the direction of the hip joint contact forces. Therefore, the general loading environment barely changed, leading to similar OI distributions between the generic-scaled and subject-specific MSK models.

Only half of the simulations converged when lowering the values of the Youngs' modulus in the FE model. Considering that little is known about the material properties of pediatric femurs, FE simulations based on subject-specific geometry and loading might help us to narrow down material properties to a realistic range.

In conclusion, we developed a workflow to create personalized FE models with a hex mesh based on MRI images in a rapid way and quantified the intra-subject variability of the OI. We hope our workflow and reference simulations will enable peers to conduct mechanobiological growth studies with larger sample sizes and enhance our understanding of femoral growth.

References

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