Slow-adaptive structural changes and fast-adaptive muscle forces act synergistically to reduce bending in the juvenile femur in a computational model.

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Summary

The aim of this study is to investigate the effect of inverse-optimized muscle forces and functional adaption on bending stresses acting on the juvenile femur. Therefore, a finite element model of an eight-year-old boy's femur with physiological boundary conditions under gait load is used. Growth is the epiphyseal plate is given by the Osteogenic Index and periosteal growth using 3rd principal stress as functional stimulus. While optimization of muscles forces results in a maximum reduction of bending forces of 83 %, a relevant proportion of bending leads to functional adaption further reducing bending stresses. We hypothesize that this may represent a transition from an elastic design principle in children to a static one in mature bones.

Introduction

Using finite element analysis and synthesis, both functional adaptation and muscle forces optimized to reduce bending stresses have been shown to achieve lightweight design in mature bone [1]. However, the relevance and interaction of these principles during childhood growth has not been fully investigated.

Methods

We use an established finite element model of an eight-year-old boy's femur [2] with physiological boundary conditions using inertia relief [3] and including muscles and the iliotibial tract in ANSYS Mechanical. First, muscle forces are optimized to reduce bending stresses at the midshaft. Second, epiphyseal growth is modeled using the Osteogenic Index [4] and appositional growth is modeled with 3rd principal stress as functional stimulus in a nonlinear growth function to describe periosteal growth according to Wolff's law during bone development.

Results and Discussion

Inverse-optimized muscle forces reduce bending stresses by 71 % in the frontal plane and 83 % in the sagittal plane compared to muscle forces calculated by multibody simulations alone. Adolescents show a bending minimization due to muscular and ligamentous tension cords just like adults. However, the 3rd principal stress is still highest medially, at approximately 30 MPa. This serves as a functional stimulus and causes an asymmetric increase in bone density and volume (Figure 1). Bone changes in silico are consistent with longitudinal studies in vivo. Combination of both principles results in an axial stress of 15.1 MPa and a bending stress of 3.1 MPa in the sagittal plane, indicating a primary compressive loading of the femoral shaft in children.

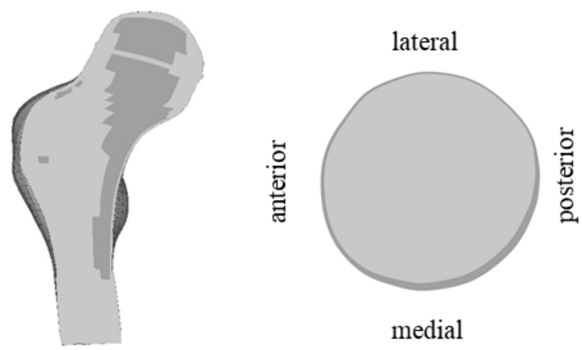

Figure 1: Changes in density in the femoral metaphysis (left) and periosteal growth at midshaft (right). Dark areas indicate bone growth.

As with mature bones, we report that muscle forces can reduce the bending of growing bones. We further hypothesize that the proportion of bending on long bones is age-dependent. This may represent a transition from an elastic design principle in children to a static one in mature bones. Further research should investigate this by simulating a longer period of growth.

Conclusions

While muscles forces and tension cords play a major role in reducing bending stresses in the juvenile femur during gait, functional adaption result in a further decrease of bending during bone growth.

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