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Long-term biomechanical adaptation in a biologically-reconstructed femur after Ewing sarcoma

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Introduction and Objectives: Biological reconstruction of the femur using massive bone allograft (MBA) is a worldwide solution for limb-salvage surgery after bone sarcoma. Because of the risk of MBA mechanical failure and size limitations of vascularised fibula autografts (VFA), a combination of VFA placed inside a MBA represents an original solution. [1] However, the remodelling and long-term survival of the reconstruction are not consistent,[2] and there is limited knowledge about functional outcomes after surgery based on quantitative data. Our aim is to study the long-term biomechanical adaptation in a paediatric oncology case of biologically reconstructed femur, by analyzing: (i) musculoskeletal forces and muscle compensation strategies in different motor tasks through image-based musculoskeletal modeling; (ii) mechanical stress in the reconstruction during the motor tasks through finite element analysis, also including potential revision surgery scenarios.

Methods: The patient (male, 8 years old) underwent a biological reconstruction of the proximal right femur, and was then continuously disease free. CT scans of the lower limbs were acquired post-operatively and during follow-ups at every 6 months for routine controls. The evolution of bone morphology and density was quantitatively evaluated. After 7 years, the patient underwent gait analysis (walking, chair rise/sit, stair ascent/descent, squat) and CT scanning after being instrumented with the same reflective marker setup.[3] A 9-body segment, 12 degree-of-freedom articulated 3D linkage actuated by 85 musculotendon actuators was created from these images (Figure) using a previously developed framework[4], and a typical inverse dynamics and static optimization approach was then applied to calculate muscle and joint contact forces during each motor task. Subject-specific finite element models of both femurs were built using a validated procedure.[5] The subject-specific muscle and joint contact forces were applied as loading conditions onto the corresponding nodes, and physiologically-oriented constraints were used.[6] Plate and screws safety was tested in terms of von Mises stresses against fatigue limit. Bone principal strains and strain energy density were computed to assess risk of fracture[5] and remodeling stimulus,[7] respectively. In the operated femur, the finite element analyses were repeated simulating different screw-removal configurations to reduce the expected stress-shielding.

Results: Overall, joint contact forces were larger in the contralateral limb during all motor tasks, except for walking. Knee and ankle loads were markedly higher (up to 3 body-weight difference), particularly in double-support tasks (chair rise/sit and squat). Muscle compensation strategies showed large forces of the vasti and gastrocnemius muscles of the contralateral limb, while gluteii and biarticular hip muscle forces of the operated leg were marked. Plate and screws stresses were below critical values for titanium alloy fatigue in all motor tasks. While maximum strains were not critical in both femurs (safety factor of 3 or above) in the non-demanding motor tasks, the average strains in the operated femur were lower than in the intact contralateral. A marked regional variation in strains and strain energy density was observed within the allograft: normal levels in medial compartment, extremely low values in anterior and posterior compartments. Despite the allograft thinning already observed during follow-up, the mechanical condition in the anterior and posterior compartments appears compatible with a further bone resorption. When simulating different patterns of proximal screws removal, we found that their complete removal would be needed to restore a more physiological bone strain configuration.

Conclusion: This study presents a successful integration of subject-specific musculoskeletal modeling and finite element analysis of a long-term biomechanical reconstruction after Ewing sarcoma. The predicted musculoskeletal forces and muscle compensation strategies can provide advice for rehabilitation therapy in specific clinical scenarios. The results from finite element analysis allow interpretation of the complex bone remodeling mechanism, and seems not to imply a high risk for the remaining screws and plate, nor for bone in the medial compartment, but suggests caution in the postoperative phase due to reduced bone thickness and density in the lateral compartment.

References:

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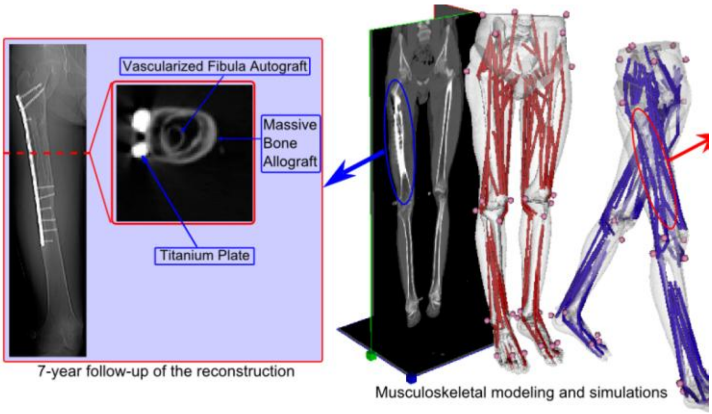

Figure 1. *Workflow of subject-specific musculoskeletal modeling and simulations of the motor tasks and finite element analysis of the femurs*