Assessment of Contemporary Boundary Conditions for Finite Element Analysis for Isolated Femurs

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INTRODUCTION: Finite element analysis (FEA) is a mechanical analysis method enabling the study of localized tissue mechanics. Various boundary conditions have been proposed in the literature for FEA of the isolated femur [1-2], but most commonly by distal constraint in all degrees of freedom (DoF) thereby allowing unrestricted movement of the proximal femur (fixed knee method). Other studies have used isostatic constraint, whereby knee joint center is fixed in all three translational DoF, fixed centrally for anterior-posterior and medial-lateral DoF, and lateral epicondyle fixed in anterior-posterior DoF [2]. Critically, isostatic imposes non-physiological constraints on the femur head, which may result in spurious simulated mechanics. The effect of these diverse boundary conditions on FEA simulations of bone mechanics remains ambiguous due to the lack of comprehensive study. Inertia relief (IR) method has been shown to produce accurate numerical solutions based on static force equilibrium without the need for additional displacement constraints and is considered the best-practice approach for an isolated system [3]. However, the IR method is not readily available in most FEA software and may lack support for multi-component models. In this study, we undertake a comprehensive comparison of the fixed knee and isostatic methods on FEA simulated femoral mechanics (i.e., head deflections (FHD) and peak Von Mises stresses (PVMS)). These femur mechanics were benchmarked against the gold standard IR method. We then introduce a novel "biomechanical" constraint that demonstrates comparable performance to the IR method, but also is supported across FEA software and can be used in multi-component simulations.

METHODS: A validated neuromusculoskeletal (NMSK) pipeline was used to estimate joint contact forces and muscle forces at the thigh segments. Briefly, three-dimensional (3D) joint angles and moments, as well as muscle dynamics, were estimated using subject-specific gait data and combined with electromyography (EMG) [4] to estimate joint contact forces and muscle forces. A 3D model of the right femur of the participant (male: 1.72m, 93.4 kg) was constructed from computed tomography (CT) images of the lower limb, meshed with linear tetrahedral elements, and assigned material properties based on greyscale values [5]. Joint contact forces and muscle forces derived from the NMSK model were applied to the respective surfaces on the femur model. Four FEA models were created to test different boundary conditions: IR (Figure 1ai), fixed knee (Figure 1aii), isostatic (Figure 1aiii), and biomechanical (Figure 1aiv). For the biomechanical method, a connector was defined between femur head center and knee center. The hip contact force was applied through a defined connector, thereby allowing the femur head to translate and rotate without the imposition of artificial constraint. The knee joint center was fixed in all translational DoFs. The most lateral region of the greater trochanter was constrained in medial-lateral and anterior-posterior DoFs as well as rotations around the superior-inferior axis to simulate passive constraints due to thigh soft tissues. Each boundary condition was compared with IR for FDH (mm) and PVMS (MPa) using normalized root mean squared error (nRMSE) and coefficient of determination (R^2).

RESULTS: The fixed knee method had the lowest FHD agreement with IR (R^2=0.89, nRMSE=20.8), whereas the biomechanical method had the best agreement (R^2=0.97, nRMSE=0.17) throughout the stance phase of gait (Figure 1b). Maximum PVMS was highest in the fixed knee (~136 MPa) and had a moderate agreement (R^2=0.46, nRMSE=1.23) with IR. Similarly, isostatic over-predicted PVMS (~83 MPa) and showed moderate agreement (R^2=0.5, nRMSE=0.6) with IR. The biomechanical method had the best agreement with IR (R^2=0.92, nRMSE=0.13) among all boundary conditions tested (Figure 1c).

DISCUSSION: Commonly used boundary conditions for FEA of isolated femurs either overestimate (fixed knee) or underestimate (isostatic) FHD and overestimate PVMS. The biomechanical method, which imparts physiological loading and constraints, yielded more physiological bone mechanics throughout the complete stance phase of gait compared to other constraints tested. We recommend the biomechanical method be employed for the FEA of the isolated femur to achieve more physiological mechanics.

SIGNIFICANCE/CLINICAL RELEVANCE: Simulated mechanics for isolated femurs are highly sensitive to the choice of boundary conditions in FEA. Thus, the selection of appropriate boundary conditions and constraints is crucial to achieve credible simulation outcomes. Physiological boundary conditions should be selected for critical analysis involving implant design and surgical planning processes, else spurious simulations may place humans and assets at risk when products are deployed.

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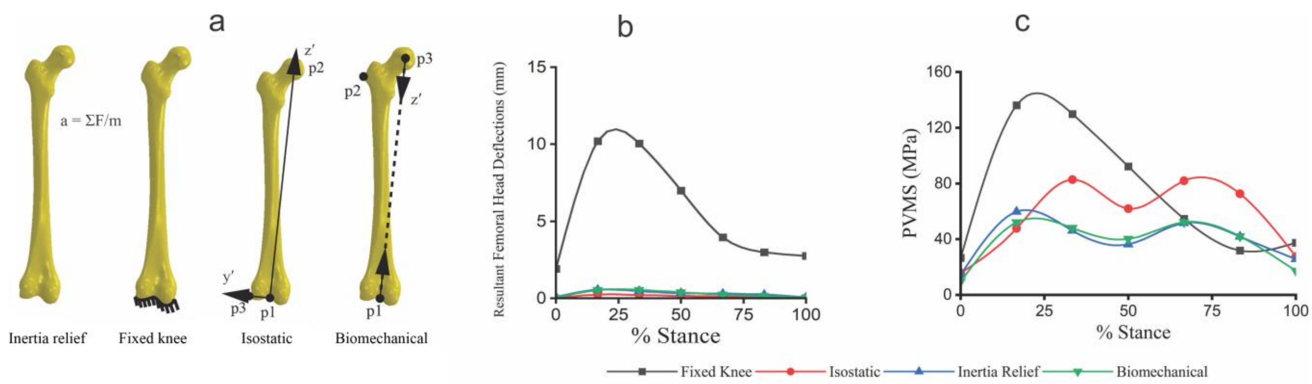

Figure 1. (a) Four boundary conditions applied to right femur throughout stance phase of gait: (i) inertia relief, (ii) fixed knee, (iii) isostatic, and (iv) biomechanical. (b) Fixed knee method over-predicted FHD while isostatic under-predicted FHD. Biomechanical method resulted in best agreement with IR (R^2=0.97, nRMSE=0.17). (c) Fixed knee and isostatic methods over-predicted PVMS, whereas biomechanical method showed best agreement with IR (R^2=0.92, nRMSE=0.13).