Deformation Toolbox for Morphology Modifications for Femur Finite Element Analysis to Aid Surgical Planning

Alireza Yahyaiee Bavil[1], Emmanuel Eghan-Acquah[1], Laura E Diamond[1], Rod Barrett[1], Chris Carty[1], Azadeh Nasseri[1], Martina Barzan[1], David G Lloyd[1], David J Saxby[1], Stefanie Feih[1]
[1]Griffith Centre of Biomedical and Rehabilitation Engineering (GCORE), Griffith University, Australia
Presenting Author Email: alireza.yahyaieebavil@griffithuni.edu.au

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INTRODUCTION: Finite element analysis (FEA) of isolated femurs is commonly performed in orthopaedic research to predict stresses and strains, bone remodelling, and implant performance. The FEA can further serve as a surgical planning tool, aiding the prediction of required surgical corrections to restore femur mechanics. Several open-source toolboxes exist that can deform generic models to approximate a patient's femoral pathology, such as anteversion (AVA) or neck shaft angle (NSA) [1,2]. However, these toolboxes are constrained to generating models intended for musculoskeletal (MSK) analyses. In our current research, we present a MATLAB-based deformation toolbox designed for FEA of the human femur. This toolbox accepts finite element input file format (.inp) and applies gradual controlled torsion to targeted regions to obtain desired AVA and/or NSA.

METHODS: Three-dimensional (3D) finite element models were created from computed tomography (CT) imaging of the right lower leg of a male participant (aged=12 years, height=1.72 m, mass=93.4 kg, NSA=133˚, AVA=13˚). Participant-specific material properties were assigned to the model based on material mapping equations [3]. The 3D joint angles, external joint moments, and muscle parameters estimated from the participant's gait data were combined with electromyography (EMG) data [4] to estimate joint contact forces and muscle forces. Values of NSA=115˚ (*coxa vara*), NSA=150˚ (*coxa valga*), AVA=-10˚ (retroversion), and AVA=45˚ (anteversion)) were tested (Figure 1a). The femur deformation toolbox achieved targeted deformations by first parsing the information from .inp file and identifying node locations from an intact template model. Subsequently, the femur anatomical axis was calculated and aligned with the global vertical. For AVA modification, the toolbox fits 3D lines to nodes located in the mid-diaphyseal region. Two reference planes are then fitted onto the ends of the selected diaphyseal region. The intended torsion angle is thereafter gradually applied to nodes between these two planes. This adjustment extends to proximal femoral nodes and their positions are updated accordingly (Figure 1b). The toolbox estimates the neck-shaft axis via a 3D line fitting algorithm to achieve the desired NSA modification. Two parallel datum planes, perpendicular to the neck-shaft axis, are positioned at the base of the femoral neck and the junction of the femoral head and neck, respectively. Gradual transformations are applied to nodes between these planes until the desired deformation is achieved (Figure 1b). The toolbox maintains the original input file format and produces an output retaining the same format. The toolbox preserves mesh quality, muscle attachment points, and designated locations for applying joint forces.

RESULTS: Notably, all deformations were executed quickly, typically in less than 15 seconds. Desired NSA and AVA were achieved with a mean error of ±2°. Subsequent FEA conducted on extreme NSA and AVA models yielded anticipated differences in stress and strain distributions (Figure 2) throughout the stance phase of gait. Morphological deformations were primarily confined to the femoral neck region (Figure 1c).

DISCUSSION: The MATLAB-based deformation toolbox enables an innovative approach to modifying femoral geometry for FEA, offering valuable implications for orthopaedic research and surgical planning. By swiftly adjusting AVA and NSA with minimal error, this tool demonstrates the potential for enhancing clinical decision-making in scenarios involving bone geometry modifications. Observed stress and strain from deformed bones highlights the toolbox's relevance for identifying critical areas of impact during gait cycles. Further validation with clinical cases is needed to clarify its utility.

SIGNIFICANCE/CLINICAL RELEVANCE: This fast and user-friendly toolbox can be used for predictive purposes in the surgical planning of osteotomies to investigate changes in stresses and strains due to morphologic changes in bone anatomy.

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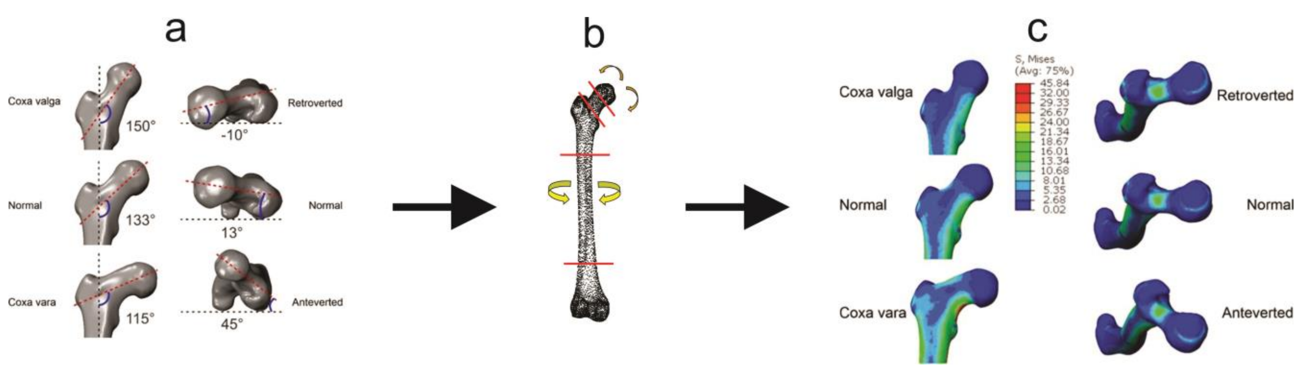

Fig 1. (a) Extreme neck-shaft and anteversion angles were created using the femur deformation toolbox. (b) The FEA input files are read by the toolbox and target NSA and/or AVA is achieved through a sequence of curve fitting and node translations and rotations processes (c) Peak von Mises stress distributions generated from the FEA outputs of the toolbox highlight the changes in stresses with femur geometry modifications.