Impact of subject-specific versus generalized gait parameters on simulated meniscus mechanics in the knee

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Disclosures: None

INTRODUCTION: Understanding the mechanical responses of menisci is crucial, given their significant roles in various knee functions such as load distribution, impact absorption, joint steadiness, and lubrication. These biomechanical responses might act as predictive markers for meniscus injuries, degenerative meniscus tears, and knee osteoarthritis. Nevertheless, uncertainties frequently emerge in the knee-specific variables used to formulate finite element (FE) models, specifically the gait parameters implemented in simulations. Personalizing these parameters necessitates elaborate laboratory setups that are often unfeasible in clinical settings. Consequently, in situations where motion capture data is either unavailable or simulations involve a large subject pool, researchers have frequently resorted to non-personalized values from the literature for motion capture-related FE simulation inputs. Yet, the full impact of subject-specific versus generalized gait data on simulated knee mechanics remains elusive. Thus, understanding the significance of this choice in influencing mechanical responses is crucial. Therefore, we investigated how the mechanical behavior of menisci differs in the FE knee joint model using subject-specific and generalized gait data obtained from the literature. By addressing this question, we aim to shed light on the intricate relationship between input data and biomechanical outcomes in knee joint simulations.

METHODS: Knee joint models of three female subjects with knee osteoarthritis (designated as subject 1, subject 2, and subject 3 in the abstract) from our previous investigation [1] were used. Briefly, the subjects performed walking trials at self-selected speed in a motion capture laboratory while wearing reflective markers as per Vicon Plug-in Gait lower body marker set [2]. A subject-specific 12-degree-of-freedom musculoskeletal (MS) model [3] of the knee joint was created using magnetic resonance images and an atlas-based approach [4] (Figure 1A). For each subject, five trials were analyzed and averaged to create representative subject-specific gait inputs (knee moments, knee flexion angle, and total knee joint contact force) for the simulations of the FE model of the knee. For the generalized gait scenario, subject-specific gait data from 15 individuals with knee osteoarthritis [4] walking at a self-selected speed were averaged to create a single set of inputs for the FE model in which the contact force was scaled according to the subject's body mass. A validated atlas-based MS-FE modeling framework [4] was utilized to develop subject-specific knee joint models (Figure 1A). In the FE models, meniscal horn attachments were represented as linear spring bundles, while menisci were characterized using a fibril-reinforced poroelastic material model. Articular cartilage was modeled as a fibril-reinforced poroviscoelastic material. In this study, the FE models of the knee for each subject were separately simulated using subject-specific and generalized gait inputs for the stance phase of gait. The mean of the upper quartile (i.e., the top 25% of the output values of meniscal mechanical responses) of the maximum principal stresses and their relative differences between the subject-specific and generalized gait inputs were analyzed from meniscal surfaces.

RESULTS SECTION: In our investigation, when employing generalized gait, the maximum principal stress was 50-250% higher in the medial meniscus during the loading response for all three subjects as opposed to the results obtained from the FE model utilizing subject-specific gait data (Figure 1B). With generalized gait, the stresses remained consistently elevated throughout most of the stance phase for subjects 1 and 2, whereas subject 3 demonstrated reduced stresses after midstance compared to outcomes of subject-specific gait models. Conversely, in the lateral meniscus, stresses were approximately 50% lower across all subjects during loading response with generalized gait, compared to the stresses observed in simulations using subject-specific gait (Figure 1B).

DISCUSSION: In this study, we have illustrated a substantial disparity in the mediolateral stresses experienced by menisci when employing literature-based generalized gait as opposed to subject-specific gait during the stance phase. This is important since stresses imposed on the meniscal tissue during gait may play a role in the degeneration of the tissue leading to intricate tears [5]. Therefore, for the early identification of possible failure points of menisci, it is imperative to acquire precise stress-related information through computational modeling. Our investigation has highlighted that the selection of gait inputs to FE simulations can affect meniscal stresses significantly, up to 250% at loading response (Figure 1B). Additionally, the stress estimations with subject-specific versus generalized gait show substantial variability between individual subjects.

SIGNIFICANCE: The findings highlight the significant influence of gait parameters on estimating meniscal stresses, underscoring the importance of subject-specificity in computational modeling for early identification of possible overloading-induced meniscus failure.

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ACKNOWLEDGEMENTS: Financial support from the Research Council of Finland (#354916, #332915, #334773 - under the Frame of ERA PerMed), Innovation Fund Denmark (9088-405 00006B - under the frame of ERA PerMed).

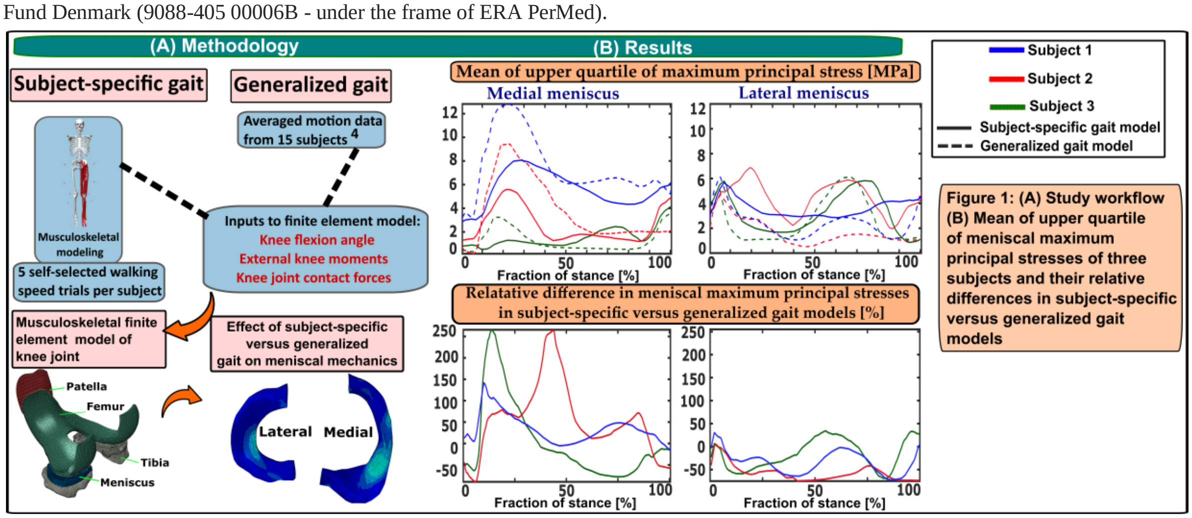

Figure 1: (A) Study workflow (B) Mean of upper quartile of meniscal maximum principal stresses of three subjects and their relative differences in subject-specific versus generalized gait models