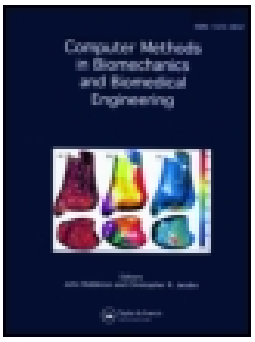

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A custom musculoskeletal model for estimation of medial and lateral tibiofemoral contact forces during tasks with high knee and hip flexions

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ABSTRACT
Most of musculoskeletal models (MSKM) estimate the tibiofemoral joint reaction load at a single point or do not support large lower-limb ranges. This study aimed to adapt a generic MSKM that allows large knee and hip flexions to compute medial and lateral tibiofemoral contact forces (TFCF) during gait and squat tasks. The updated model includes medial and lateral knee compartment geometries that allow computing the vertical TFCF. The updated MSKM does not affect kinematics and kinetics outputs in both of the tasks, and the sum of the medial and lateral TFCF was equivalent to the net TFCF of the original MSKM.

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Musculoskeletal model; tibiofemoral; knee; knee contact forces; squat; gait

Introduction

The inverse dynamic approach has been used to indirectly measure the load on the medial and lateral condyles (Lloyd and Besier 2003); however, this approach still does not take account for muscle forces. Tibiofemoral alignment asymmetry affects the load redistribution on the medial and lateral components, increasing the risks of osteoarthritis (Jackson et al. 2004). Therefore, estimation of knee contact loading in the medial and lateral compartments would provide a beneficial assessment (Manal and Buchanan 2013).

Musculoskeletal models (MSKM) have been efficient to investigate human movement and predict the effect of interventions in a non-invasive fashion (Delp et al. 2007) as well as to estimate muscle forces and joint contact loading (Lerner et al. 2015; Rajagopal et al. 2016; Catelli et al. 2019). In order to account for a better muscle force solution in a young cohort, Rajagopal et al. (2016) used magnetic resonance imaging of young healthy individuals to redefine musculotendon parameters (Figure 1B). This MSKM model was further revised twice when increasing the knee range and updating muscle-tendon units (MTU) force-generating properties and paths (Figure 1C) (Lai et al. (2017), and by controlling the moment arm of hip and knee muscles to enable investigations with high range of motion (Figure 1D) (Catelli et al. 2019).

Still, these MSKMs calculate the knee contact load at a single point in the tibiofemoral joint. Resolving the magnitudes of medial and lateral forces by approximating compartment points of contact is an approach for estimating contact forces (Winby et al. 2009; Kumar et al. 2012; Gerus et al. 2013), which has been already implemented (Lerner et al. 2015) in a preceding MSKM (Delp et al. 1990), that still lacks muscle paths reliability during high lower-limb flexions and has its musculotendon parameters based on cadaveric data (Figure 1A).

Therefore, the purpose of this study was to examine the effect of including the method that computes medial and lateral TFCF to an MSKM that allows large lower-limb joint ranges and test its reliability during gait and deep squatting tasks. We hypothesized that the sum of the medial and lateral vertical components of the TFCF of the updated MSKM should match with the single vertical TFCF of the original MSKM during both tasks, as well as the joint kinematics and kinetics outcomes should not differ between the two models.

Methods

Generic model

The generic MSKM used in this study has 80 lower-limb Hill-type MTU, 37 degrees of freedom, and 17

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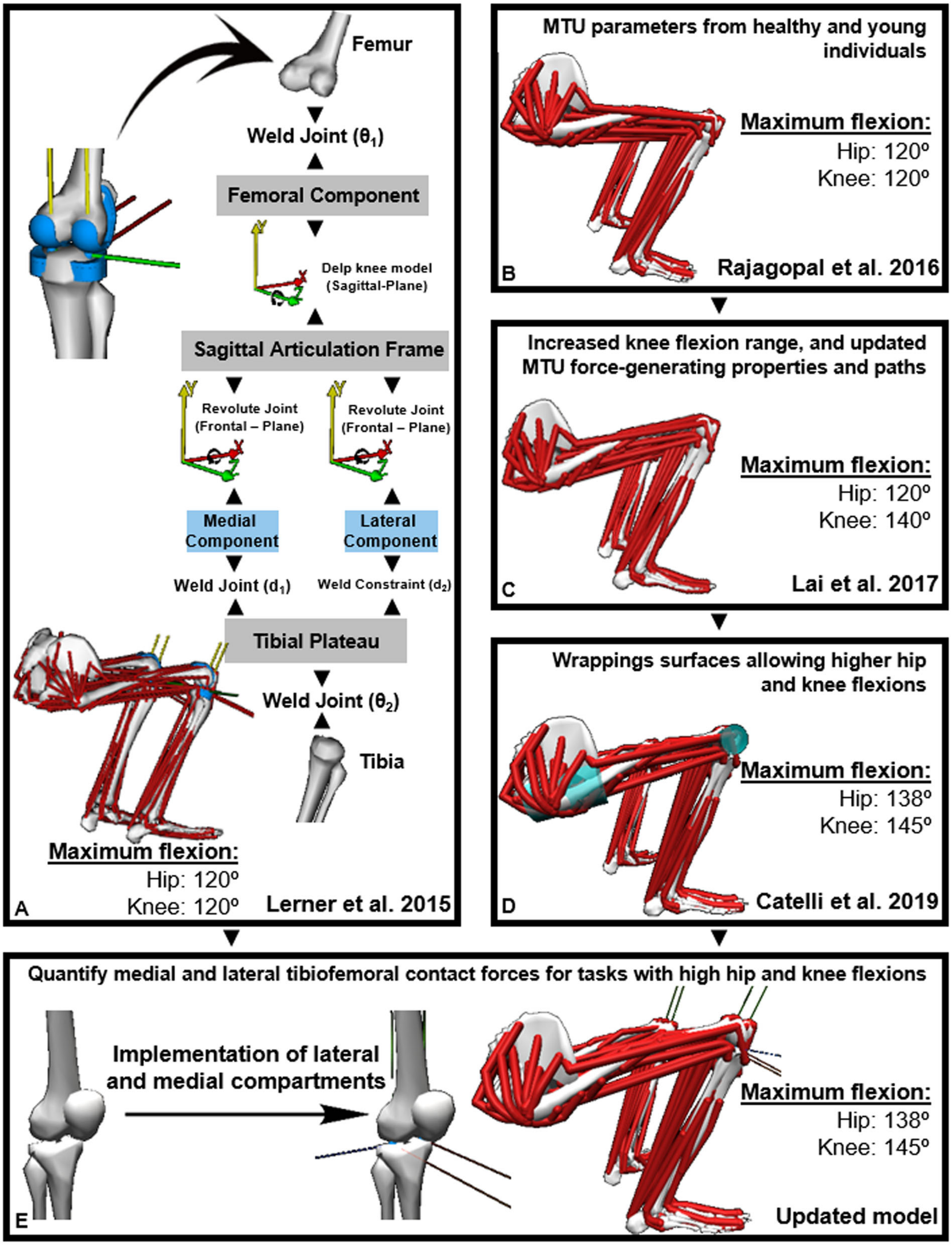

Figure 1. The schematic musculoskeletal models (MSKM) that have been used in lower limb research and the implementation in the updated model. (**A**) Allows quantifying medial and lateral tibiofemoral contact forces. (**B**) Implemented musculotendon unit (MTU) parameters based on healthy and young individuals. (**C**) Increased knee range of motion and updated knee MTU parameters and path. (**D**) Controlled hip MTU moment arms to allow higher hip and knee flexion. The updated model (**E**) implemented the medial and lateral tibiofemoral contact forces strategy in an MSKM based in young and healthy MTU parameters and that allows a high range of motion of the hip and knee.

torque actuators driving the upper body (Rajagopal et al. 2016). The MTU parameters were based on the combination of MRI cadaver and in-vivo data (Rajagopal et al. 2016), had its knee paths and some force-generating properties updated (Lai et al. 2017), and had some addition wrapping surface implemented at the knee and hip joints to control the MTU moment arms during deep squatting task (Catelli et al. 2019). The analyses were all processed in OpenSim^{TM} 3.3 (Stanford University, Stanford, USA) (Delp et al. 2007).

Subsequently, knee geometry adaptations were implemented to allow the quantification of medial and lateral TFCF, according to a previous generic MSKM (Lerner et al. (2015). This MSKM used tibial and femoral components to resolve the differences between medial and lateral TFCF, configured the frontal-plane alignment of the knee joint and also shared all loads transmitted between the femur and tibia, resolving them as the medial and lateral contact forces (Lerner et al. 2015).

Modification to the model

The updated MSKM knee joint included a femoral component acting directly to the sagittal articulation frame, with two revolute joints connecting the parent (*sagittal articulation frame*) and to the child (*medial and lateral compartments*). Also, one weld joint (d_1 - *medial*) and one weld constraint (d_2 - *lateral*) connects the medial and lateral components to the tibial plateau that, in turn, is connected to the tibia through another weld joint (θ_2) - Figure 1A. (Supplement Figure 1). The two revolute joints, connecting the sagittal articulation frame to the medial and lateral tibiofemoral compartments, share the load transmitted between the femur and tibia and resolve them as medial and lateral contact forces (Lerner et al. 2015).

Motion capture

Gait and deep squat modelling were performed by tracking experimental data from a healthy male participant (35.0 years, 78.2 kg, and 176 cm). The three-dimensional motion capture system included 10 infrared cameras at 200 Hz (MX-13, Vicon, Oxford, UK), that tracked 45 full-body marker trajectories (Mantovani and Lamontagne 2017), and two force plates (1000 Hz, Bertec, Columbus, USA).

For the gait task, the analyses were performed during the stance phase (i.e., foot-strike to foot-off). For the deep squat task, the participant stood with each foot on a force plate with feet hip-width apart and was instructed to squat as low as possible. The squat cycle was defined from standing to the deepest squat and back to the standing position. The markers trajectories were labelled and along with the ground reaction forces, were filtered in Nexus 2.5 (Vicon, Oxford, UK) and imported into OpenSim.

Data analysis and model evaluation

The simulations of both tasks were performed using the original (Catelli et al. 2019) and updated MSKM. Both MSKM were scaled based on a static pose, the joint angles and the net joint moments were computed using the inverse kinematics and the inverse dynamics tools, respectively. Muscle activations were calculated using static optimization while minimizing the sum of squared muscle activations. The joint reaction forces were computed using resultant forces and moments acting on each articulating joint from all muscle forces and also the internal and external load applied to the model. The medial and lateral TFCF were calculated using OpenSim's *JointReaction* analyses. The knee contact impulse was calculated based on the integral of the vertical TFCF in both MSKM to compare the net TFCF of the two models.

Results

Minimal differences in kinematics (max difference: 1.8° in the sagittal plane for the ankle joint) and kinetics (max difference: 0.42 N.mm in the frontal plane for the hip joint) were found between the two models during the gait or the squat tasks (Supplement Table 1). Muscle forces of both models were also similar, with the highest difference between models found for the muscle *semimembranosus* (0.04 BW) and *rectus femoris* (0.02 BW) for gait and squat, respectively (Supplement Table 2).

The two revolute joints inserted on medial and lateral condyles actuated on the frontal plane connecting the medial and lateral components to the sagittal articulation frame enabled the vertical medial and lateral TFCF quantification. The sum of the medial and lateral vertical components of the updated MSKM nearly matched the vertical component of the original MSKM, with the highest difference of 0.07 BW for gait and 0.04 BW for squat.

During the gait task, the medial condyle showed a larger contact force (peak = 2.60 BW) in comparison to lateral one (peak = 0.69 BW; Figure 2A). This difference can also be inferred on the compass graph

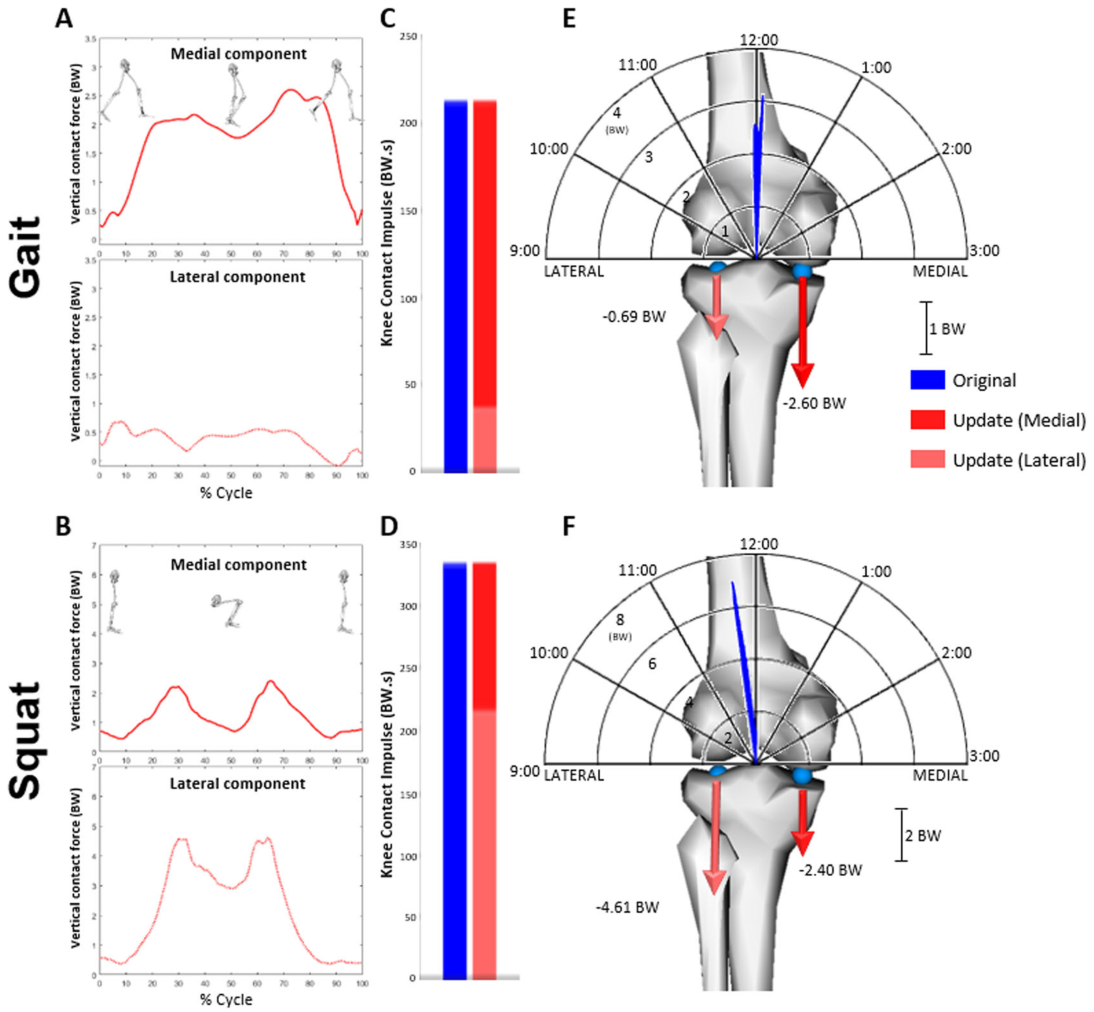

Figure 2. Tibiofemoral contact forces (TFCF) during the gait (top) and squat (bottom) cycles for the original (blue) and updated (red) musculoskeletal model. The graphs on the left column represent the medial (top) and lateral (bottom) components reaction forces during the gait (**A**) and squat (**B**) cycles for the updated model. The graphs in the middle show the joint contact impulse calculated by the integral of TFCF from de original and updated models during the gait (**C**) and squat (**D**). The dark and light red columns represent the medial and lateral components, respectively. Lastly, the graphs on the right column show the body weight (BW) normalized TFCF resultant during the gait (**E**) squat (**F**) cycle, reported with the compass graph (posterior view). The blue lines show the magnitude (radar graph) and direction to the tibial plateau obtained from the original model. The red arrows represent the inverse of the peak TFCF of the lateral (light red) and medial (dark red) components obtained from the updated model.

generated from the original MSKM, where its peak points towards the medial direction, corroborating with the descriptive medial and lateral results of the updated MSKM (Figure 2E).

During the deep squat, a larger force was found in the lateral knee component (peak = 4.61 BW) in comparison with the medial (peak = 2.40 BW), which also corroborates with the compass plotting, where the peak contact force is directed to the lateral compartment of the knee (Figure 2B and 2D). Also, the integral of the vertical TFCF curve of the original MSKM matched with the sum of the areas of the medial and lateral components from the updated MSKM in both gait and squat tasks (Figure 2E and 2F).

Discussion

The purpose of this study was to update an MSKM that was recently customized to allow high knee and hip flexions (Catelli et al. 2019) to quantify the TFCF in the medial and lateral condyles. The results demonstrated that the updated MSKM successfully quantified the medial and lateral force components for gait and squat tasks without compromising kinematic, kinetic or muscle force analysis. Equally to the original MSKM, the updated MSKM also allows maximum knee and hip flexions of 145° and 138°, respectively.

The updated model showed higher TFCF in the medial component during gait and higher TFCF in the lateral component during squat, which could be inferred by the compass plots showing the TFCF directions. These results provide an important contribution toward understanding the joint load on the knee joint during gait and squat tasks, that can also be helpful in clinical cases (e.g., knee osteoarthritis patients).

The similarity between the kinematics, kinetics and muscle forces confirms that the muscles and joints geometries were not affected by the changes performed on the updated MSKM. The sum of both medial/lateral condyles vertical load matched with the vertical component quantified on the original MSKM, as well as the sum of the medial/lateral joint contact impulse matched the single joint contact impulse of the original MSKM. The larger medial contact force found during gait is likely a consequence of a medial deviation on the transversal axis during gait (Zhao et al. 2007). Differently, the larger lateral contact force during squatting can be associated with the tibiofemoral orientation during the extreme knee flexion occurring during the task (i.e., deep squat), as the orientation between the femur (*parent*) and the tibia (*child*) on the original MSKM undergoes an internal rotation while the knee flexion increases. Therefore, it is plausible that the larger knee flexion increases the forces in the medial contact, once the tibiofemoral alignment affects the knee joint load distribution (Lerner et al. 2015).

In musculoskeletal modeling, sensitivity and validation have always been a concern. Lund et al. (2012) and Hicks et al. (2015) have demonstrated that well developed MSKM could have a strong sensitivity whereas Fregly et al. (2012) and Kinney et al. (2013) have made strong effort to validate estimated knee loading MSKM simulation against in vivo knee load data. The original model for this study (Rajagopal et al. 2016) presented the validation with the inclusion of successful simulations of walking and running, that showed a qualitative agreement of the simulated muscle activity with experimental electromyography data. Considering that joint contact forces estimation is sensitive to both the joint kinematic definition and the distribution of muscle forces crossing the joint in that motion (DeMers et al. 2014; Hicks et al. 2015), the comparability between these models assures that the joint contact forces of the updated one are reliable. Furthermore, the outputs of both medial and lateral knee contact forces estimated form this updated model during gait are well aligned with the ones provided by the Grand Challenge competition to predict in vivo knee loading (Fregly et al. 2012; Kinney et al. 2013), providing same load ranges and time-series patterns. Future work is still necessary to validate both of these components in healthy and young individuals.

This updated model brings an important contribution toward understanding the medial and lateral knee loading compartments during movements involving high hip and knee flexions. Still, individual examination after scaling the model is strongly recommended, since the distance between the condyle is scaling dependent. This model is available from SimTK.org (https://simtk.org/projects/knee-contact), and we encourage others to make refinements and share them with the researchers of the computational modeling area.

Disclosure statement

No potential conflict of interest was reported by the authors.

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