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A musculoskeletal model customized for squatting task

Danilo S. Catelli[a,b], Mariska Wesseling[c], Ilse Jonkers[c] and Mario Lamontagne[a,d]

[a]School of Human Kinetics, University of Ottawa, Ottawa, Canada; [b]CAPES Foundation, Ministry of Education of Brazil, Brasilia, Brazil; [c]Department of Human Movement Sciences, KU Leuven, Leuven, Belgium; [d]Department of Mechanical Engineering, University of Ottawa, Ottawa, Canada

ABSTRACT

Most musculoskeletal models (MSKM) are designed to evaluate gait and running, which have limited range of motion (ROM). The purpose of this study was to examine the effect of wrapping surfaces (WS) at the knee and hip joints in a MSKM, on the muscle moment arms (MA) and activations during squatting. The MSKM was then customized by changing parameters of the original WS and by implementing additional WS. The WS prevent muscles from crossing into the bones, providing realistic muscle MA for large ROM. The modified MSKM is suitable for analysis up to 138° hip and 145° knee flexions.

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KEYWORDS
Musculoskeletal model; squatting; hip; knee; wrapping surfaces

Introduction

Musculoskeletal models (MSKM) provide a non-invasive mechanism to investigate human movement and predict the effect of interventions on different tasks (Delp et al. 2007). Most of the lower limb MSKM (Delp et al. 1990; Arnold et al. 2010; Rajagopal et al. 2016) are designed for tasks with limited range of motion (ROM) such as walking and running, and consequently less extreme muscle lengths and moment arms (MA) compared to higher flexion tasks, such as a deep squat. The ability to simulate larger ROM tasks is of utmost importance for sports movements (e.g. sprinting block start, race-walk, long jump take-off) (Lai et al. 2017).

A recent study (Lai et al. 2017) adapted the knee muscle paths of the Rajagopal model (Rajagopal et al. 2016), based on cadaver and MRI data, and modified the muscle-tendon properties of eleven muscles, to allow knee flexion up to 140° for pedalling simulations. To better predict muscle and hip contact forces for tasks requiring large ROM at the hip and knee, the MSK model needs reliable and physiological muscle-tendon properties as well as muscle paths. To avoid muscles paths crossing the bones, the appropriate MA lengths are essential. To our knowledge, the muscle geometry in extreme hip flexion positions is not well established, as only Németh and Ohlsén (1985) have reported in-vivo hip muscles MA length during high hip flexion. Thus, the purpose of this study was to examine the effect of including wrapping surfaces (WS) at the knee and hip joints in a MSKM on the muscle MA and muscle activations during deep squatting.

Methods

The generic MSKM (Rajagopal et al. 2016) consists of 37 degrees of freedom, 80 lower-limb Hill-type muscle-tendon units (MTU), 40 lower-body WS and 17 torque actuators driving the upper body (OpenSim^{TM} 3.3, Stanford University, Stanford, USA) (Delp et al. 2007). The lower extremity muscle architecture was defined by combining cadaver and in-vivo MRI muscular data (Rajagopal et al. 2016), and recently updated to allow muscle-driven simulations of higher knee flexion tasks (Lai et al. 2017).

This model was further adjusted by altering the WS parameters through visual assessment of a subject during a deep squatting. Modifications were done respecting the anatomical shape of the muscles, preventing bone crossing and respecting muscle MA reported by Németh and Ohlsén (1985), and the model was then used to simulate walking and deep squat.

Modifications to the model

To allow simulation-based studies of deep squatting involving high hip and knee flexions, we increased

CONTACT Mario Lamontagne mlamon@uottawa.ca Faculty of Health Sciences, School of Human Kinetics, University of Ottawa, 200 Lees Avenue (E 020), Ottawa, ON, K1N 6N5, Canada

Supplemental data for this article can be accessed here.

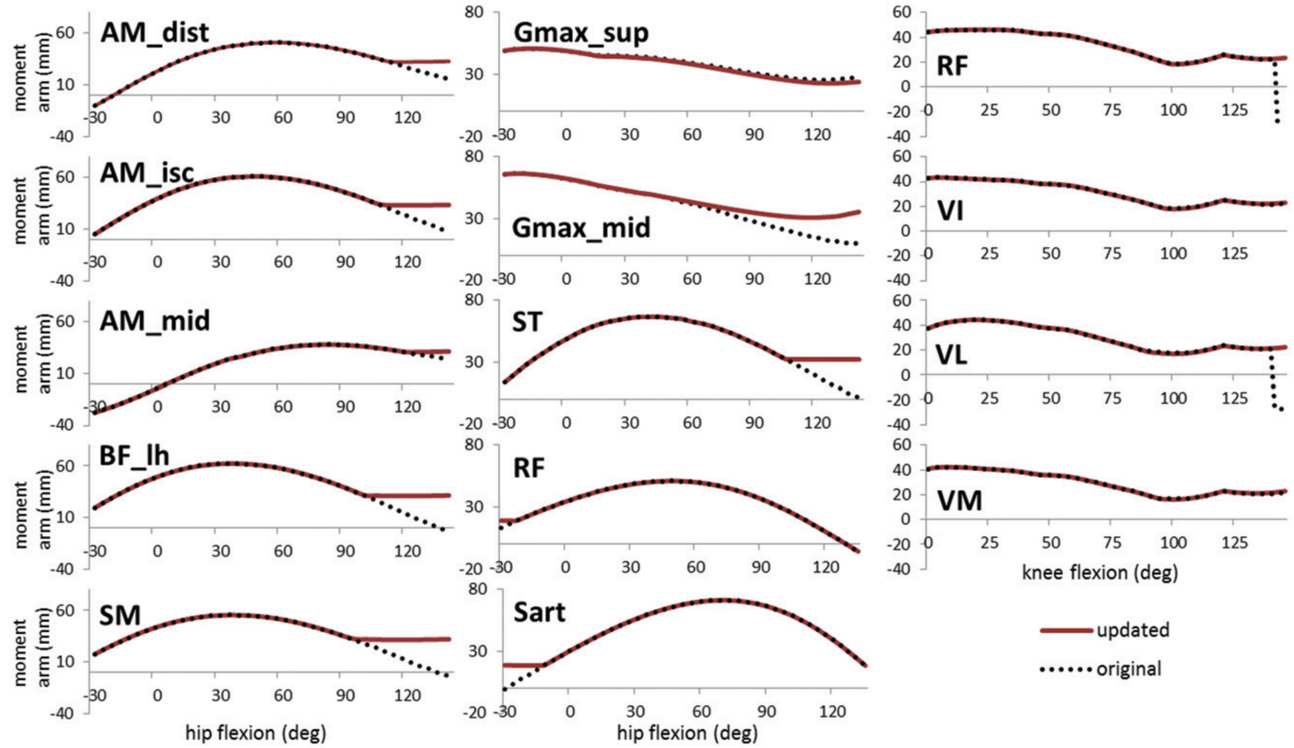

Figure 1. Muscle MA between the original (black dotted) and updated models (red) for hip and knee sagittal movement. The fourteen MTU include the three portions of the *adductor magnus* (distal: AM_dist, ischial: AM_isc, middle: AM_mid), *biceps femoris* long head (BF_lh), *semimembranosus* (SM), two portions of the *gluteus maximus* (superior: Gmax_sup, middle: Gmax_mid), semitendinosus (ST), *rectus femoris* (RF), *sartorius* (Sart), *vastus intermedius* (VI), *vastus lateralis* (VL) and *vastus medialis* (VM).

maximal hip flexion from 120° to 138° and maximal knee flexion from 140° to 145°. Four WS of six MTU (superior and middle portions of the *gluteus maximus, rectus femoris, vastus intermedius, vastus medialis* and *vastus lateralis*) were updated. Two additional WS were implemented in order to prevent nine MTU (distal, ischial and middle portions of the *adductor magnus, biceps femoris* long head, *semimembranosus, semitendinosus*, and anterior, medial and posterior portions of the *gluteus medius*) from crossing the femur and/or pelvis in deep hip and knee flexion angles (supplemental Table 1). A third additional WS was implemented at the head of the femur to prevent the *rectus femoris* and the *sartorius* muscles to cross the bone during hip extension. Cylindrical WS were used, except for the WS for the middle portion of the gluteus maximus, where an ellipsoidal surface was used instead.

Motion capture

Subject-specific simulations of squatting were done by tracking experimental data from a healthy male participant (42.5 years, 89.2kg, 186 cm). The motion capture system included 10 infrared cameras at 200 Hz (MX-13, Vicon, Oxford, UK). For the deep squat, the participant stood with each foot on a force platform (1000 Hz, Bertec Corporation, Columbus, USA), feet hip-width apart, and was instructed to squat as low as possible without lifting his feet from the floor. Electromyography (EMG) activity of 8 lower limb muscles was monitored (FreeEMG 300, BTS, Padua, Italy). The squat cycle was analyzed from standing to the deepest squat (0–50%) and back to standing position (50–100%). The markers trajectories (Mantovani and Lamontagne 2017) were labelled and filtered in Nexus 2.5 (Vicon, Oxford, UK) and imported into OpenSim (Mantoan et al. 2015). The anterior and posterior superior iliac-spine, and lateral and medial epicondyles markers were placed according to identification through a CT scan (GE Healthcare, Mississauga, Canada). EMG data were normalized to their peak activation during a maximum voluntary isometric contraction.

Model evaluation

Simulations were performed for the original (Lai et al. 2017) and updated MSKM. The MSKM were first scaled based on a static pose. Joint kinematics and the net joint moments for each degree of freedom were computed

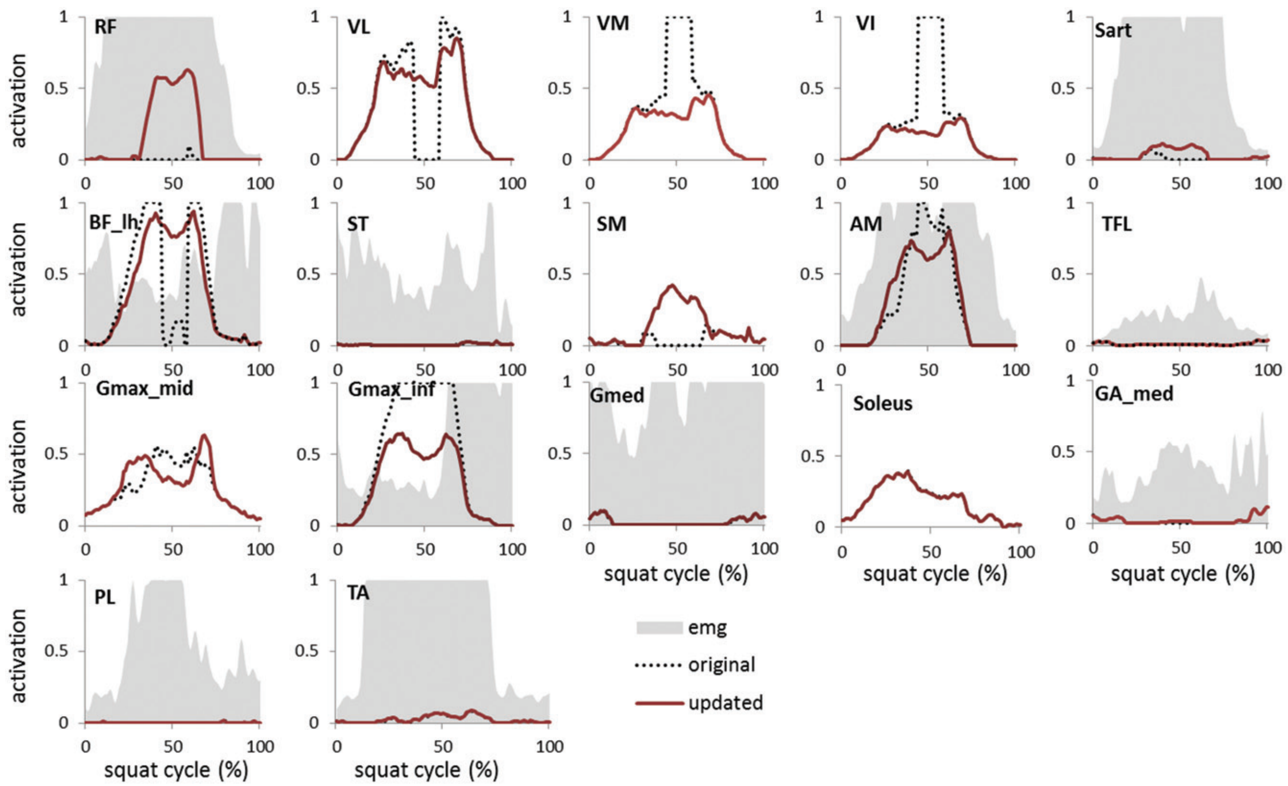

Figure 2. Muscle activation patterns predicted from the original (black dotted) and updated (red) models, compared with measured EMG activity (shaded regions) for fifteen MTU during the squat task: *rectus femoris* (RF), vastius lateralis (VL), *vastus medialis* (VM), *vastus intermedius* (VI), *sartorius* (Sart), *biceps femoris* long head (BF_lh), *semitendinosus* (ST), *semimembranosus* (SM), the proximal portion of the *adductor magnus* (AM), *tensor fascia latea* (TFL), the middle portion of the *gluteus maximus* (Gmax_mid), the inferior portion of the *gluteus maximus* (Gmax_inf), the anterior portion of the *gluteus medium* (Gmed), *soleus*, *medial gastrocnemius* (GA_med), *peroneus longus* (PL) and *tibialis anterior* (TA).

using the inverse kinematics and inverse dynamics tools. Muscle activations were calculated using static optimization while minimizing the sum of squared muscle activations. The MA lengths of the *quadriceps, hamstrings, glutei* and *adductor magnus*, as well as lower limb muscle activations during squat, were compared between the original and modified MSKM.

Results

No differences in kinematics were observed between the two models. Visual inspection of the muscle paths shows that the WS prevented all hip and knee muscles from crossing the bony structures during the squatting task (Supplemental figure 3). Joint angles achieved maximally 120.2° hip flexion, 13.7° hip abduction, 19.6° hip external rotation and 142.2° knee flexion.

Modifying the two knee WS (KnExt_at_fem, KnExtVL_at_fem) increased the MA of the *rectus femoris* and *vastus lateralis* for knee flexion angles larger than 141°. The changes in the WS (Gmax2_at_pelvis) corrected the middle portion of the *gluteus maximus* MA after 50° of hip flexion, resulting in a 25 mm increase at maximum hip flexion. The additional posterior WS (Post_at_pelvis) affected the MA of the *adductor magnus*, *biceps femoris*, *semimembranosus*, and *semitendinosus* from 96° of hip flexion onwards, increasing the hip MA up to 30 mm. The WS (Flex_at_femhead) at the femoral head affected the *sartorius* and the *rectus femoris* only after 13° and 24° of hip extension, respectively (Figure 1).

Muscle activation patterns predicted by the updated model avoided activations dropping to zero or maxing out when the model was in extreme hip and knee flexions (Figure 2). Measured EMG had higher activity than predicted models activations.

Discussion

In this study, a newly developed model (Rajagopal et al. 2016; Lai et al. 2017) was customized to allow extreme hip and knee flexion angles. The results show that the updated model avoids very small muscle MA while performing a high ROM task. Mostly cylindrical WS were used, as it improves simulation speed in comparison to ellipsoidal WS (Rajagopal et al. 2016).

An ellipsoidal WS in the middle *gluteus maximus* was necessary, as during a deep squat task, the hip also abducts and internally rotates, making the positioning of a simpler cylindrical WS very challenging.

A qualitative analysis of the modified MSKM showed no muscles crossing the pelvis, femur or tibia, in contrast to the original model. The MA lengths reported in this study are within the range described in the literature (Németh and Ohlsén 1985) – supplemental figure 4 – although the deep squat requires larger hip flexion ROM than the reported studies. MTU that show incorrect MA in deep hip flexion may cause an instantaneous drop in generated activation in an overall muscle group (e.g. VL, BF_lh, SM, Figure 2).

Our proposed updates extend the model's functional range of motion, making it more applicable to biomechanical studies of movements involving high hip and knee flexions. Still, individual examination when scaling the model is highly recommended, since pelvic geometry may change and affect the location of the WS with respect to the muscle paths. This model is available from SimTK.org (https://simtk.org/projects/high-hip-flex).

Disclosure statement

No potential conflict of interest was reported by the authors.

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ORCID

Danilo S. Catelli http://orcid.org/0000-0002-8546-0836
Mariska Wesseling http://orcid.org/0000-0002-3347-2130
Ilse Jonkers http://orcid.org/0000-0001-7611-3747
Mario Lamontagne http://orcid.org/0000-0001-5635-7162

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