WRAPPING SURFACES TO CONTROL MOMENT ARM LENGTHS DURING A SQUAT TASK

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Simulation of high flexion tasks such as squatting is hindered through invalid moment length estimation when using generic musculoskeletal (MSK) models. The purpose of this study was to examine the effect of wrapping surface (WS) at the knee and hip joints on the muscle moment arms calculated using a MSK model during squatting tasks. A generic full body model was modified by (1) increasing knee and hip flexion range of motion (ROM), (2) adjusting translation and size parameters of two WS, and (3) implementing three additional WS. Muscle moment-arm lengths were calculated in OpenSim using motion capture data. The WS prevent muscles to cross into the bones, and the moment arm length of several hip extensors reach a plateau after 85º of hip flexion. The use of the modified MSK that includes additional WS is suited for the analysis of high flexion tasks.

KEY WORDS: musculoskeletal modelling, squatting, simulation.

INTRODUCTION: Musculoskeletal models provide a non-invasive mechanism to investigate human movement and predict the effect of interventions on different types of tasks (Delp et al., 2007). Most of the lower limb MSK models (Arnold et al., 2010; Delp et al., 1990; Rajagopal et al., 2016) are designed to evaluate gait and running tasks, which have limited ROM, and consequently reduced muscle lengths and moment arms compared to higher flexion tasks such as a deep squat. The ability to analyse high flexion tasks is of utmost importance when generating simulations of sports movements, which may require larger joints ROM compared to motions more commonly analysed in clinical settings.
Rajagopal et al (2016) combined cadaver-based and MRI muscular data to define the model's architecture. However, to our knowledge, the muscular architecture description during extreme flexion of hip and knee is not well established, and a limited number of researchers provide information about muscle-tendon structure during these types of tasks (Earp et al., 2010; Earp et al., 2011). The challenge is to have reliable and physiological muscle paths in musculoskeletal models, without crossing bones, as this would provide erroneous moment arm lengths and further impact on simulations, for example when studying muscle forces. Thus, the purpose of this study was to examine the effect of WS at the knee and hip joints in a modified musculoskeletal (MSK) model on the muscle moment arms during squatting tasks.

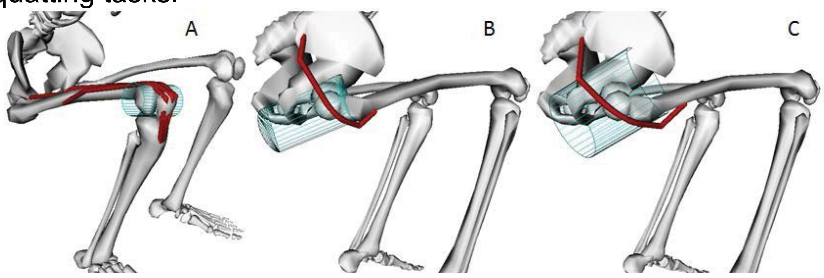
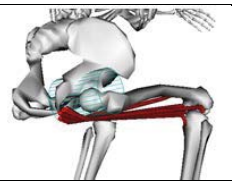
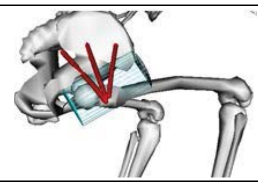


Figure 1: WS modified in the model in order to avoid bone crossing (A) of the *quadriceps* muscles, (B) of the superior and (C) of the middle portions of the *gluteus maximus*.

METHODS: The selected generic MSK model was the recently developed full-body musculoskeletal model with 37 degrees of freedom, 80 lower-limb Hill-type muscle-tendon units, 40 lower-body WS and 17 ideal torque actuators driving the upper body (Rajagopal el al, 2016) to be used in the open-source musculoskeletal simulation software, OpenSim 3.3 (Stanford University, Stanford, USA) (Delp et al., 2007). This model can successfully

generate muscle-driven simulations for walking and running trials and has its lower extremity muscle architecture defined by combining cadaver-based and MRI muscular data.
A modified MSK model was defined based on the modified generic model by adjusting the parameters of three cylindrical WS and creating two new ones in order to avoid the muscles to cross the bones during extreme hip and knee flexions. These modifications were done through visual assessment of the model in the deepest squat position, respecting the anatomical shape of the muscles and preventing bone crossing. The radius of the surface over the patella was increased by 0.5 cm, from 2.5 cm to 3 cm (Figure 1A). The surface over the superior portion of the *gluteus maximus* muscle had its body rotated in the z direction from 0 to 0.5 rad (Figure 1B). The WS over the middle portion of the *gluteus maximus* muscle had its radius increased from 4 cm to 6 cm, and its length increased from 10 cm to 15 cm; also its body translation was adjusted in the mediolateral (x), anteroposterior (y) and superoinferior (z) directions (from -8.0 cm, -8.3 cm, 6.8 cm to -6.6 cm, -7.7 cm, 7.0 cm respectively) – Figure1C. In addition, two new cylindrical WS associated to the pelvis were created in the model (Table 1), which affects primarily the moment arm of the hip extensor muscles, but also hip adductors and abductors.
The motion capture system included 10 infrared cameras (MX-13, Vicon, Oxford, UK) and marker trajectories were captured at 200Hz. Three-dimensional marker trajectories were collected, labelled and filtered with a zero-lag fourth order Butterworth filter (6Hz) in Nexus 1.8 (Vicon, Oxford, UK).
A healthy control male subject (78.2 kg, 1.76 m) was instructed to perform a static trial, followed by a sequence of five deep squats, with his feet hip width apart pointing forward, and with his arms up to the shoulder level. Only the second trial was used in this study. Both the original and adapted models were scaled based on the 51 marker positions (Mantovani & Lamontagne, 2016) and inverse kinematics was performed in OpenSim.
The moment arm lengths of the *quadriceps*, *gluteus maximus*, *gluteus medius*, *adductor magnus*, *biceps femoris*, *semimembranosus* and *semitendinosus* were compared between original and modified MSK models, as well as a qualitative description of the muscle paths outputs according to each WS.

Table 1
Additional WS Associated to the Pelvis

WS Name		Post_at_pelvis_r	Gmed_at_pelvis_r
Associated Muscles		*Adductor magnus* (distal) *Adductor magnus* (ischial) *Adductor magnus* (middle) *Biceps femoris* long head *Semimembranosus* *Semitendinosus*	*Gluteus medius* (anterior) *Gluteus medius* (middle) *Gluteus medius* (posterior)
Size (m)	radius	0.045	0.04
	length	0.12	0.15
Body Rotation (rad) Respect to the pelvis	x	-0.1	-1
	y	0	0.6
	z	0	0.7
Translation (m) Respect to the pelvis	x	-0.06	-0.03
	y	-0.07	-0.055
	z	0.068	0.1
Illustration			

RESULTS: A visual inspection of the muscle paths (Figure 2) shows that the modified WS along with the new ones implemented in the generic model, avoid all the hip and knee muscles to cross bony structures during the squatting task. The 0.05 m increase at patellar wrapping radius avoided the quadriceps to cross the patella avoiding its moment arm reduction. Both WS for the superior and middle portions of the gluteus maximus prevented them to cross the great trochanter and the femoral neck respectively. The new posterior wrap (Post) prevented adductors, long head of the *biceps femoris*, *semimembranosus* and *semitendinosus* of crossing the head of the femur. The wrap for the *gluteus medius*, prevented the anterior and middle portions of the muscle to cross the ilium, while the posterior portion still demonstrated a superficial bone contact.

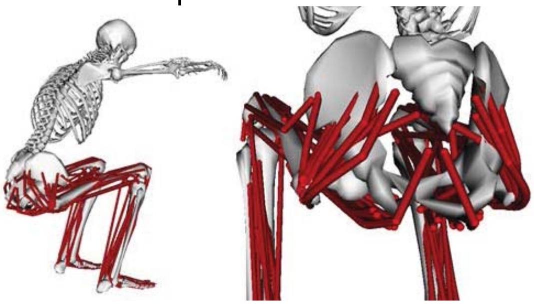


Figure 2: Lower limb muscular paths in the modified musculoskeletal model.

Kinematics did not differ between both models: after inverse kinematics, peak hip flexion was 113º and peak knee flexion was 124º. Modifying the patellar WS increased the moment arm length of all four portions of the *quadriceps* for knee flexion angles exceeding 80º (Figures 3a, 3d, 3g). The changes in the WS for the superior portion of the *gluteus maximus* (1) did not affect its moment arm length, on the other hand, the changes for the middle portion (*gluteus maximus* 2) have created an effect that prevents the reduction of the moment arm length after 20º of hip flexion, representing a 2.5 cm difference between the models at their maximum hip flexion (Figures 3b, 3e, 3h). The additional WS for the *gluteus medius* (Gmed) affected its moment arm length as a function of hip flexion, reducing the slope of the curves, and reaching an overall reduction of 2 cm in the hip flexion/extension moment arm at maximum hip flexion (Figure 3h). The additional posterior WS (Post) affected the moment arm length of the *adductor magnus*, *biceps femoris*, *semi membranosus* and *semitendinosus*, avoiding very small moment arm lengths for all associated muscles by creating a plateau of -3.6 cm from 85º to 100º hip flexion onwards (Figure 3c, 3f, 3i).

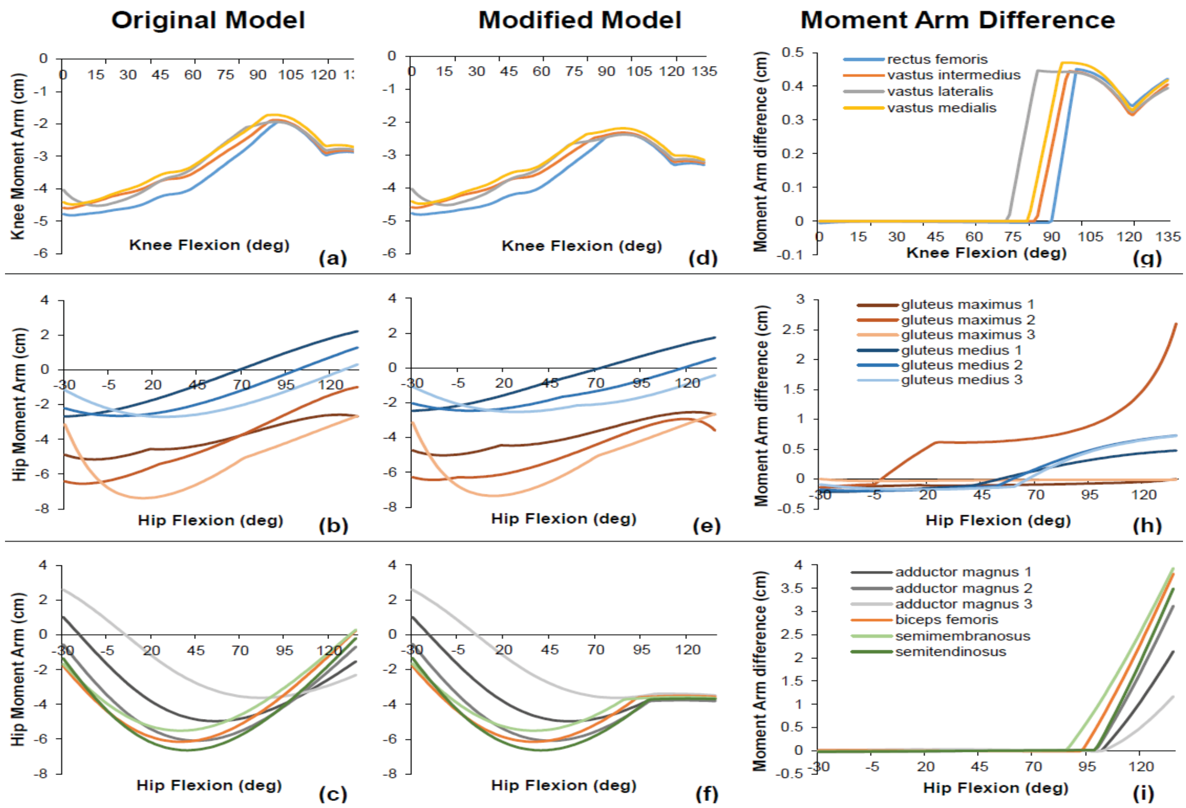


Figure 3: Moment arm length as function of the knee and hip flexion angles calculated by the original (a, b, c) and modified (d, e, f) MSK models, and their difference (g, h, i) for the

quadriceps, **the three portions of *gluteus maximus*, *gluteus medius* and *adductor magnus*, the *biceps femoris* (long head), the *semimembranosus* and the *semitendinosus* muscles.**

DISCUSSION: The reliability of muscle paths plays an important role in muscle-driven models; however, model reliability is dependent of the specific kinematics of the analysed task. This study relies on a newly developed model (Rajagopal et al., 2016) that based its properties in cadaveric and in-vivo data to redefine the muscles paths in a simple way without changing any other muscular parameters. The results show that the original model needs to be adapted in order to perform higher ROM tasks. Cylindrical surfaces were kept for the existing and the new WS as it improves simulation speed in comparison to ellipsoidal WS (Rajagopal et al., 2016). A qualitative analysis of its modified version solved most of the problems of muscles crossing the bones at the hip and knee joints; however the WS of the posterior portion of the *gluteus medius* must be re-evaluated in order to prevent the muscles from penetrating the bone. Perhaps a dedicated wrapping for that portion may improve its path. The moment arm length reported in this study had similar range to previous researches (Arnold et al., 2000; Delp et al., 1999 and Scheys et al., 2008); however, the squat task had a greater hip flexion ROM than the reported studies.

CONCLUSION: This study shows that musculoskeletal gait models are not suitable to evaluate higher levels of hip and knee flexions without specific adaptations of included wrapping tasks. The addition of new WS was needed to prevent muscles to cross the pelvic and femoral bones, resulting in invalid moment arm estimation. However, further testing with a larger database of more participants and different motions with large ROM is vital to further refine the WS to allow analysis of deep squat and other sportive dynamic tasks.

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