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1. Introduction

The knee is one of the most complicated joints in the human body and many biomechanical models with various levels of complexity have been proposed. These models include both the Finite Element (FE) models and the musculoskeletal (MSK) models (Hume et al.; Mo et al.; Rajagopal et al.). The role of muscles in controlling the kinematics of the joint and producing stability during movements is crucial. In the classical musculoskeletal (MSK) modelling technique, the muscles are modelled as 1D structures which facilitates simulating joint kinematics but is not capable of monitoring the stress and strain distribution inside the 3D anatomical structures. More recently, some of the MSK modelling platforms have provided support for multipoint muscles, which are similar to axial muscles, except that they can contain multiple via points and also wrap around obstacles. This allows the associated muscle force directions to vary when the muscle is wrapped around the bone during joint movement.

However, the muscle insertion area and muscle fibre directions in addition to the contacts/sliding between different muscles are not taken into account as long as the muscles are treated as 1D structures. This can be addressed by the use of Finite Element (FE) modelling technique that enables us to model the soft tissues in 3D and capture their individual contribution and joint motion simultaneously in response to a given loading condition. Nevertheless, developing a full 3D FE model of the lower limb can be time consuming and requires a higher computational cost. Thus, depending on the objective of the simulation, the question of which modelling technique can serve the best remains. As a result, the objective of this study is to evaluate the effect of using either of the aforementioned muscle modelling techniques on the extracted tibiofemoral kinematics during knee flexion-extension. The model is developed in ArtiSynth which is a free 3D modelling platform supporting the combined simulation of multibody and finite element models and provides support for both multipoint 1D and 3D active muscles (www.artisynth.org).

2. Methods

2.1 Overview

A biomechanical model of the lower limb of a volunteer subject has been created including the joint constraining ligaments, the hamstring muscle group (biceps femoris, semimembranosus and semitendinosus) and the quadriceps femoris muscle group (rectus femoris, vastus lateralis, vastus medialis and vastus intermedius). The Rectus Femoris muscle is modelled using three different techniques. In the first case, it is modelled using a 1D muscle model defined between the muscle insertions on the patellar and femoral bones while respecting the muscle moment arm. In the second case, it is modelled as a 1D multipoint muscle that has to pass through multiple via points defined based on the 3D geometry of the patient's muscle and it can wrap around the femur bone when it comes to contact with it. In the third case, the muscle is modelled as an active 3D FE model which is in contact with the surrounding passive muscles. The extension of the joint is simulated and the kinematics of the tibiofemoral joint is compared between the three different cases to evaluate the effect of these different techniques on the kinematics.

2.2 Geometry and FE mesh generation

The Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) data obtained from a volunteer subject were used to acquire the desired tissue geometries. Manual segmentation was performed in Amira software to extract the 3D geometry of the bones from the CT images, and the soft tissues including the muscles and the ligaments and tendons insertions from the MRI (elyasi et al.). The Rectus Femoris muscle geometry was then processed and converted to solid 8-node hexahedral elements using a sculpt meshing algorithm.

2.3 Material Properties

The bones and passive muscles were modeled as rigid bodies. All the constraining ligaments including the patellar ligament, the lateral and medial patellar retinaculum ligaments, the collateral and cruciate ligaments and the anterolateral ligament were modeled as 1D spring elements. The hamstring muscle group -

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was modelled as 1D while conserving the muscles' anatomical moment arms. The 3D active muscles consist of an active part using the Blemker constitutive model (Blemker et al.) and a passive part considered to be neo-Hookean hyperelastic (V. et al.). Muscle fibers are distributed along the length of the muscles based on the anatomical descriptions. The quadriceps tendon attached to the 3D rectus Femoris muscle was modeled as multipoint springs being able to wrap around the femur bone.

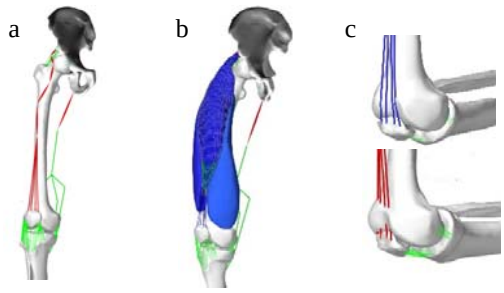

Figure 1. FE model of the thigh with (a) 1D muscles (b) 3D Rectus Femoris muscle (c) Top: 1D quadriceps tendon wrapped around the Femur bone in flexed knee, Bottom: 1D quadriceps tendon without wrapping in flexed knee.

2.4 Boundary conditions and constraints

The femur was fixed in its initial position and the tibia and patella were left unconstrained throughout the simulation. The hamstring muscle group was activated in the first step of the simulation to put the knee in the flexed position. Contact has been defined between the bones and muscle components, having frictionless tangential behavior and hard normal behavior.

3. Results and discussion

The anterior/posterior and superior/inferior movement of the tibial mass centre with respect to the fixed coordinate system defined on the femur (Azmy et al.) is demonstrated in Figure 2. The flexion range of the knee model starts at 25 degrees of flexion and continues to 90 degrees of flexion. The tibial mass centre continues to move posteriorly and speriorly as the knee undergoes flexion. By comparing the results of the model with 3D Rectus Femoris muscle with the models having 1D muscles with and without wrapping it is clear that the kinematic results of the 1D muscle model with wrapping is closer to the results of the 3D muscle model in both the anteroposterior and superior/inferior degrees of freedom. In conclusion, the results of this study suggest that using the multipoint 1D muscles that can wrap around the bony tissues can result into closer kinematic outcomes to the 3D muscle models.

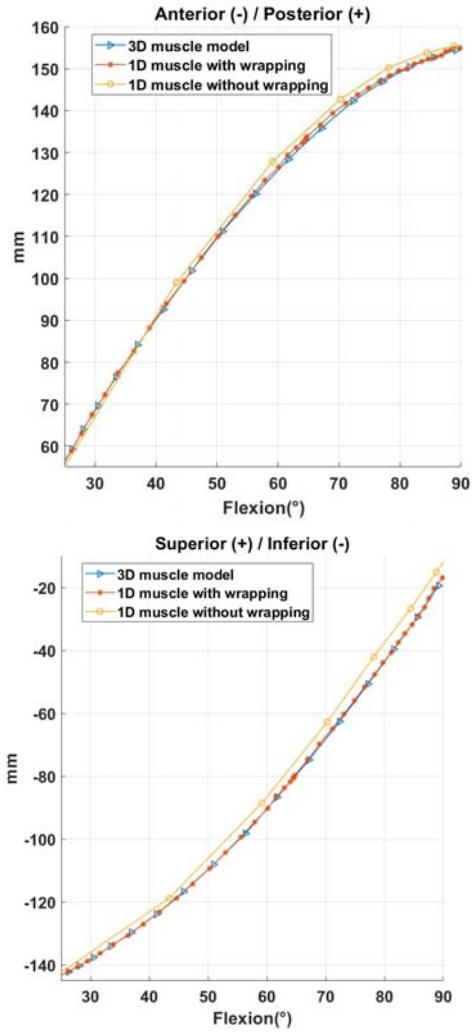

Figure 2. Extracted knee kinematics

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