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A CONCEPTUAL FRAMEWORK FOR CONTACT AND MUSCLE MODELING USING OPENSIM: A PROSTHETIC KNEE CASE STUDY

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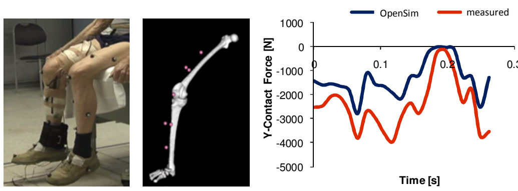
EXTENDED ABSTRACT

The knee joint is comprised of many elements including ligaments, menisci and muscle, which are generally capable of bearing and transferring load during several physical activities. The knee joint has the demanding role of provide movement during locomotion and enable the static stability of the whole body. This human articulation is one of the most requested joints and, as has to withstand high loading forces, it is more susceptible to injuries and diseases such as Osteoarthritis or ligamentous rupture (Machado *et al.*, 2010). In view of that, identifying and quantifying the loads placed on the anatomical tissues that surround the knee joint is critical for understanding and studying realistic knee mechanics, stresses and strains and to assess the true efficacy of any biomechanical intervention (Lin *et al.*, 2010; Machado *et al.*, 2010).
Since the experiments alone cannot detect the sources of abnormal movement and design of treatments is limited because key variables such as muscle forces are generally not measurable accurately without invasive *in-vivo* techniques. Hence, muscle-actuated dynamic models are becoming a feasible approach for determining how the musculoskeletal elements interact to produce movement. These models typically couple a dynamic skeletal model with individual muscle models but rarely include articular contact models due to their high CPU cost and complexity (Seth *et al.*, 2011).
OpenSim is a freely available software, developed using multibody system formulations, that enables the construction of musculoskeletal models, the visualization of their motion, and a set of tools for extracting meaningful information (Seth *et al.*, 2011). Being aware of the capabilities of the OpenSim, the potential of this computational tool is investigated with an application example of a prosthetic knee. As a result, a conceptual framework of contact and muscle modeling using OpenSim is presented here. The aim of the present work is to provide an OpenSim protocol and some practical guidelines of how to build a musculoskeletal model and to analyze contact loads and muscle forces using the same biomechanical model (Lin *et al.*, 2010).
The proposed framework comprises four main tasks. The first task consists of building a biomechanical model as an OpenSim file. In OpenSim a skeleton is comprised of rigid bodies interconnected by joints, which define how a body can move with respect to its parent body. Based on this information, a knee model with a prosthetic device is built. This model is composed by ten rigid bodies, which are connected by nine joints. Seven of them are weld joints and the remaining two are free joints, which correspond to the tibiofemoral and patellofemoral articulations. The mass and inertial properties of each body are set in the model file as well as the corresponding joint location and orientation. The developed multibody model of the prosthetic knee is illustrated in Fig. 1a (Lin *et al.*, 2010).



(a) (b)

Figure 1: (a) Knee joint model. (b) Comparison between the vertical contact forces obtained in OpenSim with the ones measured at the instrumented prosthetic device.

The second step is to perform an inverse kinematics (IK) using the experimental marker data acquired in a motion trial. Thus, firstly the markers have to be included in the knee joint model on its correct position, i.e., in the same location adopted during the motion trial (Fig. 1a). This step may also need a scalling procedure, which can be carried within the OpenSim tools using the Scale Model tool. After editing the marker set, a file containg the marker trajectories is created. Then, the IK tool goes through each time step of motion and computes generalized coordinate values which positions the model in a pose that "best matches" experimental marker and coordinate values for that time step (Seth *et al.*, 2011). At the end of IK, a motion file is generated and stored.

The next task deals with the contact modeling. In this step, a geometrical description of the contact surfaces has to be specified as well as a constitutive contact law to compute the intrajoint contact forces. In OpenSim, the simple geometries can be modeled as flat surfaces or as spheres. In turn, if a more accurate geometry is needed, a triangular mesh should be used. This mesh has to represent a closed manifold and must be stored as .obj file using MeshLab (open-source and extensible software). To model the tibiofemoral and patellofemoral contact, three triangular meshes are introduced in the knee model, which corresponds to the femoral component, the tibial insert and the patellar button. As far as the contact law is concerned, the elastic foundation model (EFM) is selected. The material properties, namely the coefficients of stiffness, damping and friction, are set to both contact pairs. To assess the contact loads, a force report is carried out using as input the motion file previously generated by IK (Lin *et al.*, 2010; Seth *et al.*, 2011). The human subject that performs the motion trial had an instrumented prosthesis, therefore the contact forces obtained in OpenSim were compared to the ones measured experimentally, and the results depict some agreement as illustrated in figure 1-b (Lin *et al.*, 2010).

The fourth and final step of this protocol is to include the principal muscles and tendons responsible for the desired kinematics into the model. Therefore, fourteen musculotendinous actuators are introduced in the model, as illustrates Fig. 2a, using the available model of "Thelen2003Muscle", which is based on the classical Hill-type muscle model. The muscles are placed in the model using an origin point, an insertion point and occasionally via-points. For each muscle element, several muscle properties are stated, such as maximum isometric force, optimal fiber length, tendon slack length, pennation angle, among others. To determine the muscle activations, the OpenSim has two different tools. The simplest one is the Static Optimization (SO), which is an extension to the inverse dynamics that further resolves the net joint moments into individual muscle forces at each instant in time. The other tool is the computed muscle control (CMC) which compute a set of muscle excitation levels that will drive the generalized coordinates of a dynamic model towards a desired kinematic trajectory. Since the CMC combines both SO and forward dynamics (FD) in the same simulation (Fig. 2b), this tool is used in this study, despite it be computationally costly than the SO tool (Seth *et al.*, 2011). Thus, for the desired kinematics presented in Fig. 2b, the muscle excitation levels are estimated and the obtained results are shown in Fig. 2c and 2d.

In short, this work reveals that OpenSim has the potential to be a powerful tool in biomechanical modeling, since it allows the evaluation of the contact loads and, at the same time, it enables the prediction of the muscle excitation levels of a prescribed kinematics.

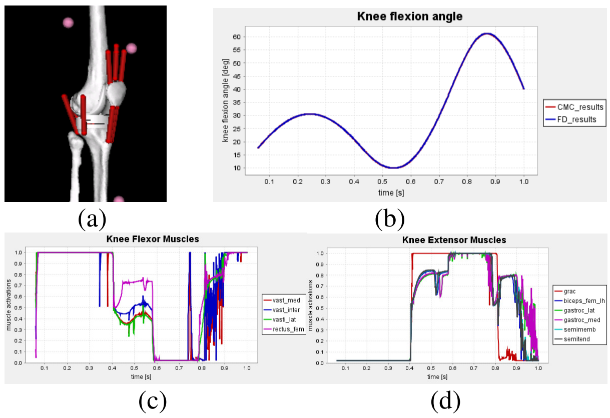


Figure 2: (a) Knee model with muscles. (b) Knee flexion angle resulted from FD and CMC. Normalized muscle excitations obtained from the CMC tool for the knee muscle groups: (c) flexor and (d) externsor muscles.

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