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

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1. Background

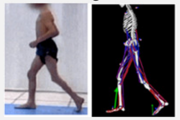
Identifying and quantifying the loads placed on the anatomical tissues that surround the knee is critical for understanding and studying knee pathologies [1, 2]. Experiments cannot detect and identify the causes of abnormal movement, nor can they measure clinically important quantities such as muscle and contact loads. Hence, muscle-actuated dynamic models are becoming a feasible approach for determining how musculoskeletal elements interact to generate movement [2, 3].

2. Motivation

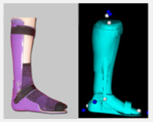
The fundamental research questions that motivate this work are:

i) Why do we care about simulating movement?

Analyze athletic performance



Understand and treat movement disorders



Design medical and orthotic devices

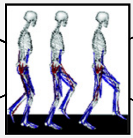
ii) What are the general problems that research teams have to face when they are studying and simulating the human motion?

- Difficulty to reproduce simulation results available in the literature
- Commercial codes are valuable but not extensible
- Cost of commercial software limits use in teaching
- Build your own code is challenging and time-consuming

iii) Why musculoskeletal models are so feasible? What can you do with these models?

Visualize and analyze complex motion patterns

Perform inverse kinematics and inverse dynamics



Estimate forces that are difficult to measure

Identify cause-effect relationships

3. Goal and objectives

The aim of this work is to investigate the potential for using a computational multibody tool to the design of medical devices, *i.e.*, to assess how modeling approaches could complement experiment studies. This work explores the use of OpenSim, as open-source computational tool [3], to study the dynamic response of a musculoskeletal model of a prosthetic knee. A conceptual framework for contact and muscle force modeling is described. The framework entails four tasks, which are listed in the following diagram.

Skeletal Modeling → *Inverse Kinematics* → *Contact Modeling* → *Muscle Modeling*

4. Skeletal Modeling

Fig. 1

The 1st task is the development of the skeletal model. Thus, a knee joint model with a prosthesis is built (see Fig. 1).

7 Markers	10 Rigid Bodies	9 Joints
M1 Thigh_superior	B1 Ground	$J_{(1,2)}$ weld joint
M2 Thigh_lateral	B2 Femur	$J_{(2,3)}$ weld joint
M3 Thigh_inferior	B3 Femoral component	$J_{(2,4)}$ weld joint
M4 Patella	B4 Thigh	$J_{(5,6)}$ weld joint
	B5 Shank	$J_{(6,7)}$ weld joint
M5 Shank_superior	B6 Tibia	$J_{(7,8)}$ weld joint
M6 Shank_lateral	B7 Tibial insert	$J_{(9,10)}$ weld joint
M7 Shank_inferior	B8 Tibial tray	
	B9 Patella	$J_{(3,7)}$ free joint - TF
	B10 Patellar button	$J_{(3,10)}$ free joint - PF

5. Inverse Kinematics

The 2nd step is the inverse kinematics (IK), which is done using experimental marker data acquired in a motion trial, illustrated in Fig. 2. The IK tool analyzes each time step and computes the generalized coordinate values that places the model in a pose compatible with the experimental marker locations for that time step. The weighted least squares problem solved by the IK tool is

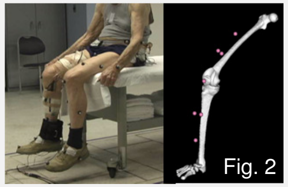


Fig. 2

$$\min_{\mathbf{q}} \left[\sum_{i \in \text{markers}} w_i \left\| \mathbf{x}_i^{exp} - \mathbf{x}_i(\mathbf{q}) \right\|^2 + \sum_{j \in \text{unprescribed coords}} \omega_j \left(q_j^{exp} - q_j \right)^2 \right]$$

$$q_j = q_j^{exp} \text{ for all prescribed coordinates } j$$

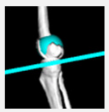
where $\mathbf{q}$ is the vector of generalized coordinates being solved for, $\mathbf{x}_i^{exp}$ is the experimental position of marker i, $\mathbf{x}_i(\mathbf{q})$ is the position of the corresponding marker on the model and q_j^{exp} is the experimental value for coordinate j. At the end of IK, a motion file is generated.

6. Contact Modeling

In the 3rd step, a geometrical definition of the contact surfaces has to be defined as well as an appropriate contact law. In OpenSim, geometries can be modeled as planes or spheres, or by triangular meshes. To model tibiofemoral and patellofemoral contact pairs, three triangular meshes are incorporated into the knee model, corresponding to the femoral, tibial and patellar components.

Contact geometry

Planes or spheres | *Mesh volumes*



In the present work, OpenSim's elastic foundation model is used to compute the intra-joint contact forces. Material properties, namely the stiffness, damping and friction, are assigned to both contact pairs.

7. Muscle Modeling

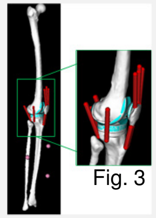


Fig. 3

The 4th step consists of including the muscles and tendons responsible for the desired kinematics. Fourteen musculotendinous actuators are added to the model (see Fig. 3) using an origin, an insertion, and via-points. For each muscle-tendon, several parameters are set: maximum isometric force, optimal fiber length and pennation angle. To estimate muscle activations, OpenSim offers two different methods:*static optimization* (SO) and *computed muscle control* (CMC). SO is an extension to inverse dynamics that resolves the net joint moments into individual muscle forces at each instant in time. In contrast, CMC computes a set of muscle excitation levels that will drive the generalized coordinates of the dynamic model toward the IK trajectory. Since CMC combines SO and forward dynamics (FD) in the same simulation, as Fig. 4 shows, CMC is the method adopted in this study, though its computational cost is higher.

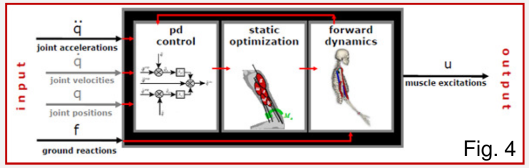


Fig. 4

8. Concluding Remarks

Combining musculoskeletal models with articular contact models is still a challenging problem requiring further research effort. Modeling expertise of existing computational tools require investigation, improvement and validation, which is the main purpose of this work.

Acknowledgements

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