Simulation of ACL reconstruction dynamics for optimal rehabilitation planning

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ABSTRACT

This paper presents a framework for simulated evaluation of the biomechanics of the human knee after anterior cruciate ligament (ACL) tear. Following the notion of the Virtual Physiological Human (VPH), a computational model of both the kinematics and dynamics of the human knee is developed that is subsequently simulated for typical motions and activities. The proposed scheme provides a feasibility study on how VPH simulations can be used in a pre-surgical step for optimal planning of several parameters related to the surgical procedure (e.g. physical vs. synthetic reconstruction, positioning, etc.). The effect of the choice of these parameters on the motor behaviour of the knee can be estimated through the proposed simulation scheme, thus leading to a powerful clinical decision support system. Experimental evaluation demonstrates the clinical potential of the proposed framework.

Keywords

Virtual physiological human, Simulation, ACL tear

1. INTRODUCTION

One of the most common injuries in sports is related to the partial or full tear of the anterior mainly, but also of the posterior cruciate ligament. Even if surgical reconstruction practise can be nowadays considered being advanced, it is mainly based on expert judgement and less on objective biomechanical evaluation of the patient's physiology and everyday activities, while patient-specific surgery customization is very rare.

1.1 Related work

Computational modelling of human body parts is lately considered to be an effective method for the study of mechanical behaviour of the knee joint. Single-phase and biphasic analytical models of articular cartilage and their Finite Element (FE) or other simulations were first discussed in their article along with experimental studies by Huiskes and Chao [4]. Hasler et al presented the experimental methods and theoretical models of articular cartilage and consequently the material properties for normal, pathologic, and repaired cartilages were discussed in [3]. Taylor and Miller worked on the macroscopic and microstructural constitutive models of cartilaginous tissues [13].

Weiss et al evaluated models of ligament in one-dimensional and three-dimensional scales especially on the relationship of microstructures and their mechanical behaviour [14]. In another work Provenzano et al examined the non-linear viscoelastic models of ligaments based on the existing experimental data and evaluated their ability to predict the dependency on strain amplitude and frequency [12]. Elias and Cosgarea analyzed different computational aspects of the patellofemoral joint including modelling techniques, for example, patient-specific modelling, and clinical applications [2].

Mackerle published a deep study of articles between 1998 and 2005 and provided an extensive list of publications in different areas of computational biomechanics including knee and hip joints [8]. According to the previous knee joint models can be classified into analytical and computational. Analytical models with different degrees of accuracy have already been published in the literature. These models were used to describe the joint motion and kinematics in 2D or 3D and to predict the loads in tendons, and ligaments [6],[11]. Other models included geometrical non-linearities [9],[10] and often effects of bones.

Although analytical models offered effective approaches to determine knee kinematics, they had limited capacities to describe the stress/strain patterns of cartilages, menisci, and ligaments in 3D configurations. Moreover, the non-linear, anisotropic, and time-dependent response of the soft tissues could not be captured using these approaches. In the majority of joint models, articular cartilages were commonly modelled as single-phase, linear elastic, homogeneous, and isotropic materials with constant stiffness [6],[11]. Concerning simulated replication of knee dynamics only a few approaches have been presented in the past. A complete low-resolution model for disability simulation has been proposed in [5], while OpenSim, an open-source platform for biomechanical simulation, has been introduced in [1].

1.2 Motivation and contribution

Clinical practise in ACL reconstruction is mainly based on expert judgement and less on objective evaluation of the patient's physiology and behavioural profile. Moreover, a predictive decision support system enabling the clinician to predict the result of specific surgical decisions on the motor behaviour of the specific patient, would enable patient-specific customization and optimization of the surgical procedure. The proposed scheme aims to provide a feasibility study on how simulated virtual physiological humans could help towards the aforementioned grand challenge.

The rest of the paper is organized as follows. Section 2 describes some aspects of the computational model of the knee, while Section 3 discusses how it can be simulated in a physics-based manner. Section 4 describes the application scenarios and experiments performed, while Section 5 concludes the paper.

2. KNEE MODEL PROPERTIES

The main biomechanical roles of the knee joint complex are first to allow locomotion with (a) minimum energy requirements from the muscles and (b) stability, accommodating for different terrains and second to transmit, absorb and redistribute forces caused during the activities of daily life.

During rotation in knee joint flexion extension is up to 160 deg of flexion (up to -5 deg flexion-hyperextension), varus-valgus is up to 6-8 deg in extension and internal-external rotation is up to 25-30 deg in flexion. Additionally during translation anterior-posterior is up to 5-10 mm, compression up to 2-5 mm and medio-lateral is up to 1-2 mm. The knee joint kinematics in the sagittal plane during gait can be summarized in: a) Extension: contact is located centrally. b) Early flexion: posterior rolling; contact continuously moves posteriorly and c) Deep flexion: femoral sliding; contact is located posteriorly; the unlocking of the ACL prevents further femoral roll back.

Since the development of a highly detailed biomechanical model of the knee was out of the scope of this paper, a multiresolutional model has been developed, emphasizing on aspects that are important for ACL tear reconstruction and rehabilitation.

The major physical element for the proposed model is the joint and in particular the knee joint. Movable human joints are divided into four main categories, according to their degrees of freedom (DOF) [7], namely uniaxial, biaxial, poliaxial and plane joints. Even, if a perfectly accurate model would require a plane joint with a purely physics based simulation approach, in the proposed framework and in order to make the simulation tractable a biaxial joint is considered. Moreover, customization of the model is possible with respect to muscle activation and contraction dynamics, subject specific customization (weight, height), ACL positioning and dynamics parameters, e.g. stiffness, damping, tear threshold.

3. SIMULATION

The backbone of the proposed framework is the simulation engine. It aims to predict, for specific actions, the muscle activation necessary for their execution and the resulting ligament forces.

3.1 Simulation engine

Figure 1 illustrates an overview of the proposed system. It is mainly comprised of two independent entities, namely the "simulation" and "visual analytics" block. The simulation block consists of the inverse kinematics and the inverse dynamics modules, while supported by the action management module.

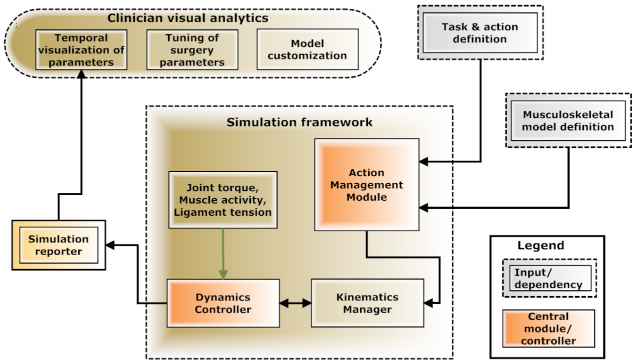


Figure 1: Overview of the proposed framework

Inverse kinematics (IK) calculate the rotations necessary to achieve a desired end effector's position and orientation. IK is the inverse problem of forward kinematics, which calculate the position of a body and its end effector after applying a series of joint rotations. The IK input parameters are the desired end effector's position and orientation and the output is a series of joint angles.

Based on a motion sequence defined through the IK procedure, inverse dynamics estimate the appropriate joint torques that are subsequently related to muscle forces, necessary to preform the specific motions.

The clinician can access the system through the visual analytics module that allows for model customization, tuning of critical parameters and visualization of the simulation results. Moreover, it should be emphasized that the simulation platform requires a formal definition of the musculoskeletal model to be simulated and a description of the action to be executed. These two requirements can be edited and customized by the visual analytics block that inherently serves as a clinical decision support system.

In the context of this work the authors emphasized on the musculoskeletal modelling and simulation part, while the simulation results are visually displayed. A full implementation of the visual analytics block is left as future work. Finally, it should be mentioned that the proposed simulation framework is based on the OpenSim platform [1].

3.2 Parameterization and customization

The table below describes the allowable parameterization of the knee model. "ACL positioning" refers to the positioning of the artificial ACL, usually tendon, on the bone that is considered as a critical parameter for surgical ACL reconstruction. The "Dynamics parameters" differ if a physical or synthetic transplant is considered. "Model customization" and "Muscle parameters" relate actually to a rough personalization of the subject, while the "Actions" parameter reflects the potential activities that can be simulated.

Parameter type	Variable
ACL positioning	Tendon position coordinates
Dynamics parameters	Stifness, Damping, Tear
Model customization	Weight, Height
Actions	Activities to simulate
Muscle parameters	Activation dynamics

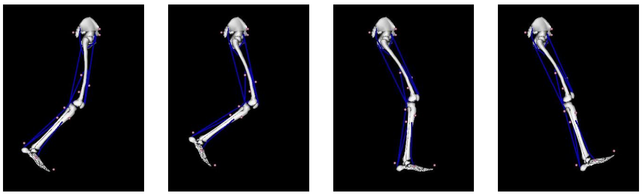
Table 1: Parameters and the corresponding computational variables that can be tuned by the clinician so as to drive the simulation

It should be emphasized that the values of these parameters reflect different strategies in ACL tear rehabilitation. The ultimate functionality of the proposed framework is to allow the clinician to fine tune these parameters and proceed to a personalized rehabilitation plan, based on the patients physical and behavioural profile.

4. APPLICATION AND EXPERIMENTS

The clinical potential of the proposed framework has been investigated in the context of ACL surgical reconstruction. In particular, the framework aims to provide decision support with respect to several rehabilitation parameters, like surgical reconstruction or not, artificial ligament surgical positioning, etc. Of critical importance is the estimation of ligament and muscle loads in performing specific actions with respect to the rehabilitation strategy adopted.

The behavioural result of each choice is demonstrated in muscle and ligament forces, while performing a leg "swing" action. Figure 2 illustrates screenshots of the latter.



(a) (b) (c) (d)

Figure 2: Key-frames of the swing activity

Figure 3 illustrates the comparison between 6 indicative performed experiments regarding the exerted forces on the posterior cruciate ligament (PCL) over time for the "swing" action. The paremeterization of the experimental models lies to the mass scaling and the positioning of the anterior cruciate ligament (ACL).

For the performed experiments, the Computed Muscle Controls (CMC) and Inverse Dynamics tools where incorporated [1]. The CMC tool computes muscle excitation levels at specified time intervals, that will drive the generalized coordinates (e.g., joint angles) of a dynamic musculoskeletal model towards a desired kinematic trajectory. CMC does this by using a combination of proportional-derivative (PD) control and static optimization. The inverse dynamics tool uses the CMC generated motion of the model to solve the equations of motion for the unknown generalized forces.

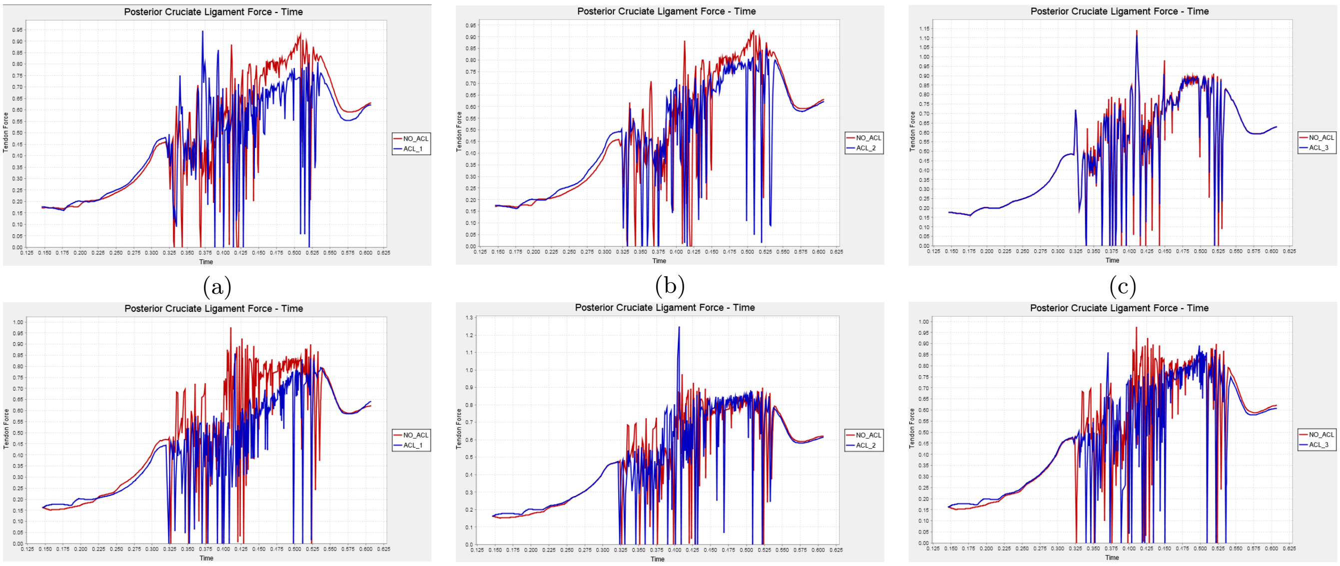
Regarding the mass parameterization of the musculoskeletal model, two different instances were chosen; an initial form of the model and a second version of an increased mass by 20%. In each scenario, four different ACL positioning states where chosen; the absence of the ACL and presence of the ACL in three different positions. The location of the ACL refers to its contact point on the tibia, moving it in a relatively two dimensional plane, forming an equilateral triangle.

Each diagram represents the comparison of the exerted forces on the PCL, between the absence of the ACL scenario and the three simulated positioning states, on each one of the two mass scaled models. For the baseline weighted model, "type 2" positioning seems optimal in terms of the force applied on the PCL, while for the weight scaled model the optimal positioning choice is of "type 1". The relative differentiation of the exerted forces on the PCL is prominent, providing a decision support framework for the planning of the ACL surgical reconstruction.

5. DISCUSSION AND CONCLUSIONS

The aim of this work is to provide a feasibility study on the use of virtual physiological human (VPH) knee models for optimal rehabilitation and reconstruction planning of ACL tear. A computational model of both the kinematics and dynamics of the human knee is developed that is subsequently simulated for custom motions and activities. The proposed scheme provides a feasibility study on how VPH simulations can be used in a pre-surgical step for optimal planning of several parameters related to the surgical procedure. The effect of the choice of these parameters on the motor behaviour of the knee can be estimated through the proposed simulation scheme, thus leading to a powerful clinical decision support system.

Even if the potential use of such a framework is evident, there are several issues that still need to be considered. Even if, by definition, the proposed scheme aims to provide relative evaluations of different rehabilitation treatment strategies as mentioned in Section 4 a clinical validation of the simulation results is still necessary. Moreover, it is still important to allow interaction of the existing knee models with soft tissues like the menisci that is also a major direction for future work.



(a) (b) (c)

(d) (e) (f)

Figure 3: Exerted forces on the posterior cruciate ligament (PCL) over time for the swing action. In each diagram the red curve corresponds to the baseline, where no ACL is present. The blue curve corresponds to the reconstruction in different positioning (”type 1”, “type 2”, “type 3”) for the specific the mass scaled model. In the top row the diagrams correspond to the baseline model and the bottom row to the mass scaled (120%) model.

6. ACKNOWLEDGEMENTS

This work is partially funded by the EC FP7 project NoTremor: Virtual, Physiological and Computational Neuromuscular Models for the Predictive Treatment of Parkinson's Disease, Grant Agreement No. 610391.

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