SafeACL: Ligament reconstruction based on subject-specific musculoskeletal and finite element models

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Abstract. This technical report presents the SafeACL project, which focus on the development of a decision support system based on the integration of musculoskeletal computer models with imaging (MRI, X-ray, ultrasound) and motion analysis data (kinematics, kinetics) to simulate the surgery and to improve customization, objectivity, and effectiveness of treatments for ACL reconstruction. The SafeACL system will allow the physician to operate in a virtual environment using an individualized musculoskeletal model that will be able to predict the effect of the surgery. SafeACL is a project co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE, started in July of 2018 (M1) and has a duration of 36 months. The 1st section of this report provides an overview of SafeACL, by describing objectives, the work plan and the implementation phases, the expected results and impact of the project. The current status of the project is described in section 2, while conclusions and future work are included in the last section.

Keywords: sports injuries, decision support system, musculoskeletal modeling and simulation, finite element modeling and analysis, biomechanics.

1 Project Description

1.1 SafeACL Objectives

An anterior cruciate ligament (ACL) tear is a devastating injury to an athlete and unfortunately is one of the most common knee injuries in athletes involved in rapid deceleration moves. Reconstruction of the ACL is commonly performed to restore stability to the knee and allow the patient to return to a healthy and active lifestyle. Revision ACL reconstruction is clinically challenging and associated with worse clinical outcomes than primary reconstructions, and a recent systematic review revealed a 13.7 % overall failure rate. In current clinical practice, the ACL reconstruction plan is selected from a standard menu of options rather than customized to the unique characteristics of

the patient and the treatment selection process is normally based on subjective clinical experience rather than objective prediction of post-treatment function.

The **aim** of SafeACL project, is the development of a decision support system based on the integration of musculoskeletal computer models with imaging (MRI, X-ray, ultrasound) and motion analysis data (kinematics, kinetics) to simulate the surgery and to improve customization, objectivity, and effectiveness of treatments for ACL reconstruction. The SafeACL system will allow the physician to operate in a virtual environment using an individualized musculoskeletal model that will be able to predict the effect of the surgery. The therapist will be able to test a variety of surgical scenarios (bone channel location, initial graft trend, graft fixation methodology, relative movement between the bone canal and graft) before performing the actual surgery. As a result, the customized surgical plan will be fed into a surgical assistant system that will guide the surgeon to reproduce the selected invasive scenario during the actual surgery. With SafeACL, the orthopedic surgeon will be able to predict the outcome of a surgery in an innovative 3D environment (as opposed to two-dimensional images used in clinical practice), thus reducing surgical errors and post-operative complications of the patient. The combination of the software for the pre-design of the operation with the 3D musculoskeletal model will also allow the medical team to predict the post-operatively functionality of the joint during every day and athletic movements. The medical team to present to the patient the operative effect of the surgery to be performed, through the virtual environment in order to strengthen its confidence in the outcome of the surgery.

The SafeACL consortium consists of three research entities:1) Centre for Research and Technology-Hellas, IBO Institute (CERTH /IBO-coordinator, 2) Electrical and Computer Engineering Department, University of Patras (UPAT), 3) School of Health Sciences, University of Thessaly, Faculty of Medicine, and one SME: POLYTECH SA.

1.2 Project Implementation Methodology

The development of the SafeACL medical decision support system will be implemented through a multidisciplinary approach aimed at developing state-of-the-art technology and exploiting the scientific knowledge of all the project partners. During the first work package (**WP1**), the parameters, architecture and interfaces of the SafeACL system will be determined. During the second work package (**WP2**) the validity of the human musculoskeletal models will be tested in dynamic athletic motions beyond walking using OpenSim's musculoskeletal modeling software (www.simtk.org) and experimental motion analysis data in normal participants, using state-of-the-art scientific equipment (kinematics and kinetics, analysis, EMG, DXA, ultrasound etc.). Also, in a later phase, a variety of motion analysis data and clinical images will be received from patients to be submitted to ACL surgery before and after surgery. Typically, the musculoskeletal models used in the literature are based on general parameters and are often parameterized so that the model matches the physical dimensions of each participant. However, this approach lacks credibility, since the personalized characteristics (bone geometry, lever arms, etc.) can differ significantly from the parameterized general model. For this reason, work package 3 (**WP3**) will develop an innovative three-dimensional image analysis technique that allows the extraction of the required parameters from clinical images (MRI, CT, X-ray) for the production of personalized

musculoskeletal models. Work package 4 (**WP4**) will develop personalized musculoskeletal and finite element models based on the results of EU2 and EU3 and will examine their ability to predict the functional outcome of subjects. Then, a software for the interactive connection between the models and the surgeon physician will be developed in work package 5 (**WP5**) using virtual reality algorithms and three-dimensional imaging techniques. The surgeon will be able to parameterize each patient's musculoskeletal model by simulating the intervention plan. In WP5, the surgical effect of surgical intervention on the patient's kinetic and kinematic model during daily and athletic activities will be assessed using individualized musculoskeletal models including the adjustments made to the knee joint after surgery. Predictions of the patient's postoperative functioning are purely mathematical and therefore not usable by surgeons. For this reason, an easy-to-use graphical environment will be created in work package 6 (**WP6**) to allow the orthopedic surgeon to interpret the results of surgical simulations. A graphical navigation environment will be developed that will allow the attending physician to extract the optimal surgical scenario from the SafeACL system and enter it into a surgical assistant system where the surgeon will be able to reproduce the selected invasive scenario during the actual surgery. Finally, a detailed feasibility study, work package 7 (**WP7**), will be developed by a specialized subcontractor for the new system, focusing on its optimal commercial exploitation and business models of exploitation.

1.3 Expected Results

The SafeACL project will make a significant contribution to improving the quality of health services associated with musculoskeletal injuries. The SafeACL system will allow the physician to operate in a virtual environment using an individualized musculoskeletal model that will be able to predict the surgical effect of the surgery. In this way, the therapist will be able to test a variety of surgical scenarios (bone channel location, initial graft tendon, graft fixation methodology, relative movement between bone channel and graft) in a pre-surgical and simulated environment. After evaluating its validity, the developed system can be used by orthopedic clinics to offer quality and personalized health services at a competitive cost. The productivity of orthopedic surgeons will be improved significantly as well as the results of surgical procedures without postoperative relapses. The personalized surgical procedure followed by the SafeACL system will help to restore the patient's functional capacity over a shorter period of time. Immediate effects include cost reduction in the healthcare system and faster returning to the production process for the patient. Benefits of SafeACL for the main user groups and stakeholders are:

- *For Physicians*: simulation of surgery in a virtual environment; selection of the best procedure for the surgery, for each patient; assisted surgery.
- *For Patients:* personalized surgery, quicker restoration of ACL function, better quality of life, reduced chance of failure of the surgery operation.
- *For the Research community*: development of innovative personalized musculoskeletal models, development of interactive virtual surgical environment.
- *For the National Health System*: improvement of the services and products provided, reduction of hospitalization and rehabilitation costs.

2 Current Status and Achievements

In this section, we will present the progress of the modeling and simulation pipeline for planning the ACL reconstruction. One of the project goals is to create subject-specific knee models that can be used to model the different surgical options and simulate their outcome. A necessary step is to create detailed and accurate models of the knee. After the model is created from experimental measurements, the user of the system can select between different ACL reconstruction options, such as single/double bundle, tunneling method, graft material properties, and adapt the initial model representing the individual's anatomy. Different boundary conditions are applied to the model so that one can examine the stress distribution of the ACL for different movements such as walking, pivot, running, jumping, etc. The final goal is to determine the optimal surgical parameters for the specific subject. This can be achieved by creating multiple models by sampling the parameter space, simulating their behavior and selecting the one that satisfies the performance criteria defined by the surgeon. The process starts with the creation of the model from MRI. As outlined in Figure 1, MRI are segmented automatically, then the 3D surfaces are reconstructed and finally the volumetric meshes are created. Experimental kinematics and ground reaction force measurements are used in conjunction with a musculoskeletal model (OpenSim) to extract boundary conditions for the finite element analysis using inverse dynamics methods. This methodology is employed to determine the boundary conditions for walking, running, pivoting, sit-to-stand and other benchmark activities. Finally, a detailed finite element analysis is performed to determine the loading conditions of the soft tissues and determine the injury risk factors.

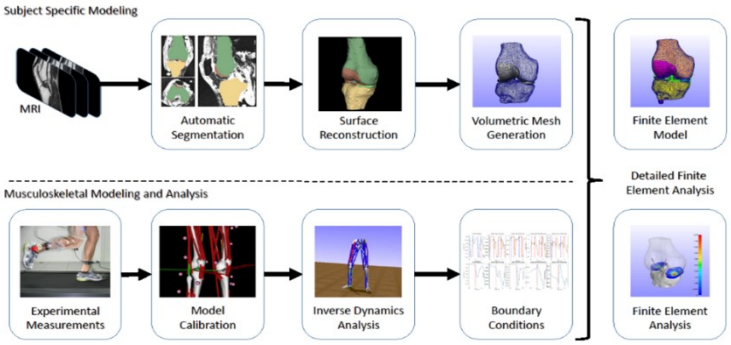

Fig. 1. Overview of modeling and simulation pipeline for creating subject-specific detailed models of the knee that are used for finite element analysis of complex movements.

Figure 2a left depicts the result of the ACL reconstruction modeling. In this case, the footprints of the ACL are marked on the femur and tibia, whereas the tunneling positions and diameters are left as free parameters. The artificial ligament is modeled with two bundles that wrap around each other, having material properties of a patella tendon. Figure 2b presents the maximum shear stress at the first pick of the gait stance

phase. This preliminary result merely demonstrates the possibility of this pipeline as a pre-surgical decision support system.

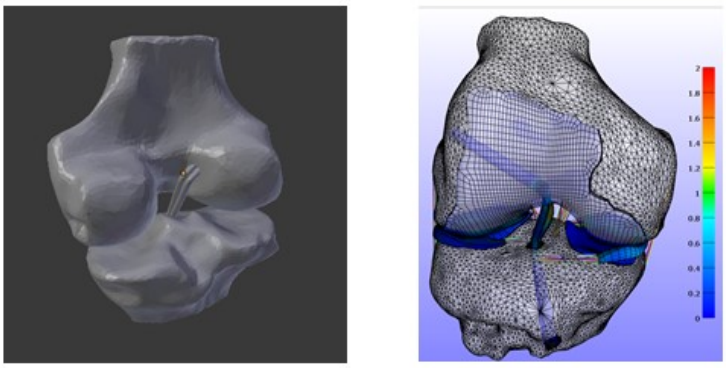

Fig. 2. (a) Modeling of ACL reconstruction options and (b) finite element analysis

3 Conclusions and Future Work

The goal of the SafeACL is to create a framework that can guide the surgeon in evaluating the optimal ACL reconstruction strategy based on individual's anatomy and detailed computational models of the knee complex in a simulated manner. The pipeline presented in the previous section is currently semi-automated, meaning that one can create and simulate a new model relatively easy. This is very important, because such tools must be applied on large cohorts and they must be used by users that do not have much expertise in image processing, modeling and simulation. The definition of the finite element model has been constantly improved towards validation, improvement of material properties and inclusion of other modeling components, such as patella, tendons and muscles that are very important for stabilizing the knee joint. There are different ACL reconstruction options available and it is very important that they are properly modeled without compromising the slightest accuracy and realism. Although, only the modeling and simulation aspects of the project were presented here, the model editing and visualization utilities as well as the intuitive presentation of simulation results that were developed are essential parts of the whole system.

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