A Computational Framework to Guide Neuromuscular Rehabilitation Protocols Following ACL Reconstruction

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INTRODUCTION

The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments in the knee, with approximately 100,000 injuries occurring annually in the United States [1]. Due to the increased risk for secondary damage to the meniscus and cartilage associated with ACL deficiency, surgical reconstruction (ACL-R) using either a hamstrings tendon (HT) or patellar tendon (PT) autograft is indicated for many patients [2]. Traditional neuromuscular rehabilitation training protocols have been used to restore range of motion and muscle strength in these patients [2]. However, one of the prevailing long-term outcomes associated with ACL-R is the development of anterior knee pain (AKP), which may be influenced by increased or abnormal post-surgical contact stresses in the patellofemoral (PF) joint [3]. Thus we argue that, given the surgically mediated changes to the joint structures, rehabilitation protocols targeting normal muscle activation patterns may be suboptimal in restoring normal contact stress distributions. Accordingly, in this study, we sought to use a finite element model of the knee joint to identify the neuro-mechanical interplay between graft properties, muscle activation patterns, and PF stresses during a functional dynamic task. In this context, we will explore whether changes in rehabilitation training protocols can recover these stresses to their pre-injury values.

METHODS

An anatomically accurate, three-dimensional finite element (FE) model of the knee joint was created from magnetic resonance images (MRI) of a male subject. The final model consisted of four bones, all relevant ligaments, articular cartilage, menisci, and muscle attachment sites as shown in *Figure 1*.

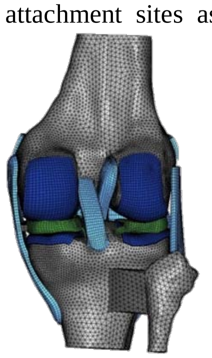

Figure 1 FE model.

The FE mesh was created in HyperMesh (Altair Engineering, Troy, MI) with all soft tissues and ligaments modeled with continuum-based brick elements. The bones were rigidly constrained and modeled using shell elements for computational efficiency.

The mesh was imported into Abaqus (Simulia, Providence, RI) to solve the FE problem. Interacting surfaces were defined to simulate frictionless contact between neighboring soft tissues (e.g. between the femoral cartilage and the superior aspect of the meniscus). Boundary conditions were applied to fix the femur in space. Muscle actions during the load acceptance phase of gait [4] were represented as distributed surface tractions or concentrated forces/moments as appropriate.

The mechanical properties of the ligaments were represented with a hyperelastic material law. Due to the large range of material values reported in the literature, simulations were carried out using a Monte Carlo framework, representing these material uncertainties in all ligaments. The first series of simulations assumed that the ACL had the properties of the native ligament; the next two series were performed to represent an ACL-R using either a PT or HT graft. The contact stress distributions on the PF articular cartilage surfaces were then compared over the range of simulations.

To simulate altered rehabilitation training protocols, loading conditions were modified in the ACL-R groups to recreate the predicted stress distribution ranges observed with the native ACL. Muscle forces were varied such that they remained within physiological constraints for the task.

RESULTS

Preliminary results have shown that the model is able to accurately simulate the kinematics of the functional task. Additionally, *Figure 2* shows the predicted stress distribution pattern on the cartilage of the patella, comparing the native ACL (*a*) to the PT graft (*b*). As highlighted in the figure, the contact stress magnitude is greater with the PT graft. Simulations using HT graft properties are currently in progress.

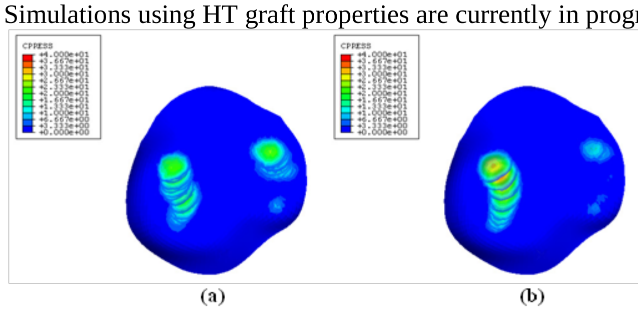

Figure 2 Contact stress distribution on the articular cartilage of the patella with the native ACL (**a**) and a PT graft (**b**).

Simulations representing changes to muscle activation patterns attributable to altered rehabilitation protocols are currently under way. We anticipate that the maximum stress values in the ACL-R groups will decrease with these changes.

DISCUSSION

Further analysis will allow us to determine whether the stress patterns can be significantly altered through changes to the muscular inputs. While the preliminary results are promising, the current study does have some limitations. Because the model only represented the geometry of one patient, the results may not be fully generalizable. Furthermore, surgical parameters such as graft size, shape, and attachment sites were not considered. While we argue that muscle training could lead to pre-injury stress distribution patterns, the effects on the biomechanics of neighboring joints are unknown. As such, many factors need to be considered further before this research can be applied clinically.

REFERENCES

[1] Gulick & Yoder. *J Sports Sci Med*, 2002; [2] Andersson et al. *Arthroscopy*, 2009; [3] Hsieh et al. *Am J Sports Med*, 1998; [4] Besier et al. *J Biomech*, 2009.

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