ANGLE OF TWIST AFFECTS STRESS VALUES AND DISTRIBUTIONS IN HUMAN ANTERIOR CRUCIATE LIGAMENTS A 3D FINITE ELEMENT ANALYSIS

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INTRODUCTION

The knee is one of the most frequently injured joints in the body. Studies estimate that 1.6 to 1.9 million patients in the US, most between the age of 15 and 44 years, see a physician for a knee sprain each year [1]. Among those who sustain an acute traumatic hemoarthrosis to the knee, the anterior cruciate ligament (ACL) is partially or completely torn more than 70% of the time [2].

Experimental studies of ACL mechanics are technically difficult, costly, and prone to error. The emerging field of computational biomechanics (finite element (FE) method) offers a new set of tools for studies of solid and fluid biomechanics that can provide information that would otherwise be difficult or impossible to obtain from experiments [3,4].

OBJECTIVES

The ultimate goals of this study are to understand ACL mechanics so that reconstructed and/or synthetic ACLs can be adapted to fulfill normal mechanics more effectively, and to improve the clinical diagnosis and treatment of ACL injuries.

METHODS

A mathematical Finite Element model for the human ACL was developed that takes into account some of the complex characteristics of the ACL such as; correct three-dimensional anatomic geometry, helical fibre reinforcement with correct fibre alignment (angle of twist), and a gradual change in the material properties (ligament to bone) near the insertion sites. The model is shown in (Figure 1). Accurate anatomical dimensions needed for the model were collected from fresh cadavers using a custom-made accurate caliper. PATRAN V.5 and ABAQUS V.6.1 are the two commercial FE packages used for data processing and analysis.

The boundary conditions applied were flexion of the tibial insertion with the femoral insertion constrained to move as one surface. 1-mm posterior displacement and 10º internal flexion were applied to the centre of the femoral insertion (Figure 1).

The ligament was given anisotropic material properties with an elastic modulus of 100MPa in the direction of fibres (direction 2). Models were analysed with different angles of twist starting from zero (straight fibres) and ending with 45º. Both linear and nonlinear geometry approaches were tried on the analysis.

Peak values of the maximum principal stress were chosen to compare the results for the different angles of twist and for the linear/nonlinear geometry effect.

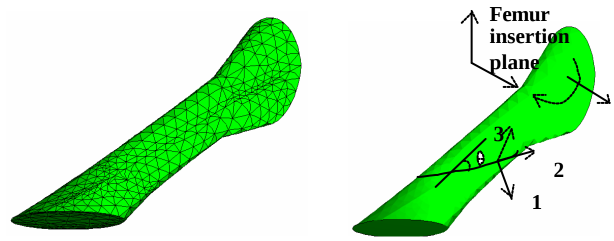

Figure 1: Geometry and meshing scheme of Finite Element Model of the human ACL (θ= angle of twist).

RESULTS

Principal stresses (strains) in the fibres of the ligament can be obtained for different cases of external loading and/or relative deformations of the tibia and the femur. An example is shown in (Figures 2, 3 and 4) for linear and nonlinear geometry analysis.

Stresses and strains varied with the angle of twist of the fibres (Figure 5).

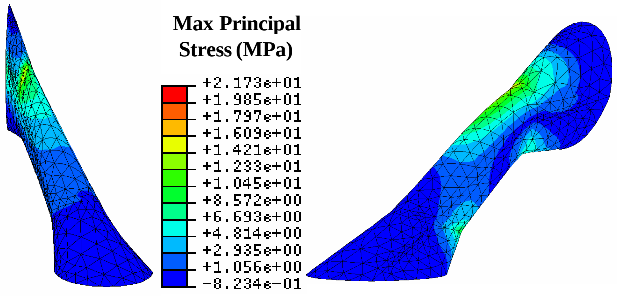

Figure 2: Anterior (left) and medial (right) view of the deformed shape of the ACL showing maximum principal stress with straight fibres (linear geometry analysis)

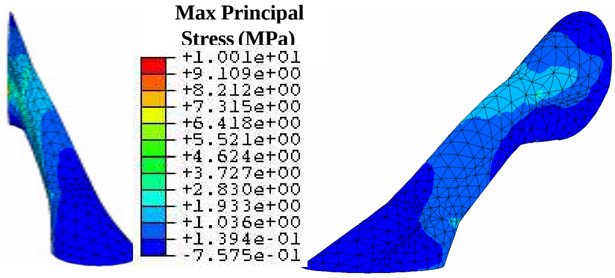

Figure 3: Anterior (left) and medial (right) view of the deformed shape of the ACL showing maximum principal stress with fibres at q=45º (linear geometry analysis)

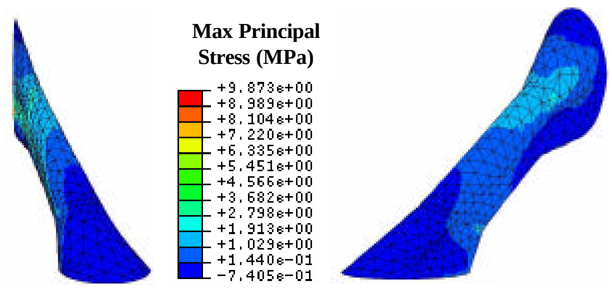

Figure 4: Anterior (left) and medial (right) view of the undeformed shape of the ACL showing maximum principal stress with fibres at q=45º (nonlinear geometry analysis)

DISCUSSION

The largest stresses and strains were observed in the anterior regions near the femoral insertion (Figure 2) similar to the results of Hirokawa et al [3].

By twisting the fibres with 45º (the normal angle of twist for human ACL), the overall stresses in the ligament reduced by approximately 55% compared to the case of straight fibres (Figure 3).

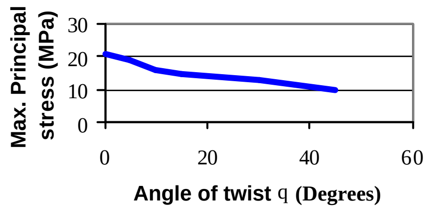

Figure 5: Relation between angle of twist and maximum principal stress obtained

The nonlinear geometric approach appeared to have only a marginal effect on the values and distribution of principal stresses (Figure 4). The reason could be the small deformation values used in the analysis. The nonlinear geometry would be expected to have a more noticeable effect if larger deformations were specified.

The results presented in Figure 5 suggest that twisting a harvested graft (ligament substitute) when inserting into the knee with an angle larger than 10º will help to minimize the stresses in the new graft.

Future studies will include expanding the model to account for other important characteristics of the ACL such as: hyperelastic stress-strain relationships, fibre recruitment, fibre reorientation within the matrix, the role of water during ligament function (poroelastic model), and time dependent characteristics such as creep and stress relaxation. Since creep is one of the important viscoelastic characteristics of ligament, modeling and prediction of creep using artificial neural networks (ANN) will be investigated.
Continuing study will also include experimental testing of animal and cadaver knees for the purposes of improving the mathematical model and data validation.

SUMMARY

A Finite Element model for the human ACL has been developed that considered most of its complex characteristics. The model is able to predict stresses and strains within the ligament caused by different cases of loading/deformations. The model presents a new perspective for gaining a better understanding of the details of ACL function, injury mechanisms and the mechanical needs of reconstruction.

The results of the model might be able to help the surgeon with the correct positioning and installation of the ACL graft (tunnel location, graft length, amount of twist required, etc.). The results may also help to define optimum material properties and/or fibre orientation for better performance of artificial ligaments.

REFERENCES

1. Butler, D.L., 1989, “Anterior cruciate ligament: its normal response and replacement”, Journal of Orthopaedic Research, Vol. 7, pp. 910-921.
2. DeHaven, K., 1980, “Diagnosis of acute knee injuries with hemarthrosis”, American journal of sports medicine, Vol. 8, pp. 9-14.
3. Hirokawa, S., and Tsuruno, R., 2000, “3D deformation and stress distribution in an analytical/computational model of the ACL”, Journal of Biomechanics, Vol. 33, pp. 1069-1077.
4. Yamamoto, K., and Hirokawa, S., 1998, “Measurement/ analysis of deformation and strain distribution of the anterior cruciate ligament in the human knee”, Medical engineering and physics, Vol. 20, pp. 161-168.