FINITE ELEMENT ANALYSIS OF THE KNEE:
DEVELOPMENT OF A FAILURE LOCUS FOR THE ANTERIOR CRUCIATE LIGAMENT


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INTRODUCTION

A full or partial tear of the anterior cruciate ligament (ACL) is a common and painful injury that has been estimated to occur approximately 250,000 times annually in the U.S. [1]. Articular cartilage and meniscal injuries are also associated with ACL injuries [2]. ACL injuries can often lead to degenerative osteoarthritis of the articular cartilage [2]. An epidemiology study of athletic injuries by Majewski et al. [3] determined that out of 19,530 sports injuries, 20% were ACL injuries and 8% were medial collateral ligament (MCL) injuries.

Many research studies and theories offer explanations of the ACL injury mechanism. Several of these studies have observed and concluded that ACL injury occurs when the athlete lands with the knee close to full extension, in valgus, and the tibia in internal rotation [4,5,6,7], see figure 1A. These studies make the assumption that an ACL injury occurs only in certain combinations of loading. Despite ACL injury prevention strategies developed from previous research, the rate of injury occurrence has not changed [8].

In this study, a finite element analysis (FEA) program was used to simulate the resultant forces in the ACL under a variety of loading conditions. Using previous research as a basis for ACL failure during injury [9,10], a failure locus of the ACL was developed. The purpose for the development of this locus is to show the multitude of loading combinations that cause ACL disruption.

MODEL DEVELOPMENT

A three-dimensional model of the left knee was created by lofting point clouds from sagittal view magnetic resonance images (MRI), see Figure 1B. The subject modeled was a healthy male, age 23, weighing 725N, measuring 173cm tall. The MRI data was obtained at the Weymouth MRI Center located in Weymouth, MA. The images used to create the knee model were obtained in 2 mm sagittal increments at 256 x 256 pixel resolution.

Figure 1 – A) Knee moments are applied about the anterior-posterior axis, external rotation of the femur is shown. B) 3-D model of the knee created from MRI undergoing external rotation of the femur (with respect to tibia)

The knee model was assembled and meshed in the FEA program ABAQUS/CAE v6.8. The bones were defined as rigid and the cartilage as isotropic/elastic with properties defined in previous studies [12]. Loads were applied in a four step explicit analysis. First, body weight was applied along the vertical axis of the tibia via the femur. Second, the knee was flexed to 25°. Third, the femur was rotated about the vertical axis of the tibia (internally or externally) to represent a closed chain reaction. Finally, a varus/valgus moment was applied to the model about the anterior-posterior axis.

Resultant tensile forces in the MCL and ACL were recorded with respect to time. The failure criterion used to define ACL disruption was identified as 2160±157N, defined by Woo et al. [9] in a cadaveric
examination. Likewise, the failure criterion established for the MCL was to be 1153N, defined by cadaveric studies performed by Robinson et al. [13]. If at any point during the simulation, the MCL reached its disruption criterion, its stiffness was halved—which was intended to simulate a partial tear of the MCL during injury. The varus/valgus moment and femoral rotation angle associated with the MCL tear were recorded onto a failure locus. When the ACL exceeded the failure criterion established above, the varus/valgus moment and femoral rotation angle associated with the disruption were recorded onto a failure locus. This was performed for each of the 18 analyses.

RESULTS AND DISCUSSION

Figure 2 shows the failure locus of ACL and MCL with the femur in internal or external rotation with respect to tibia and varus/valgus moments. In valgus scenarios, MCL failure occurs prior to complete ACL disruption. The data also shows a higher potential for ACL injury during higher degrees of femoral rotation. In varus, from 24 to 36 degrees of external rotation there is a 19% decrease in the moment required to tear the ACL. In varus, from 24 to 36 degrees external rotation, there is a 32% decrease.

Figure 2: Femoral rotation angle versus ACL failure moment.

Table 1: Specific ACL Failure Values

<table>
<thead>
<tr>
<th>Femoral Rotation Angle</th>
<th>Failure Moment (Nm)</th>
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<tbody>
<tr>
<td>External</td>
<td></td>
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<tr>
<td>1</td>
<td>120.7</td>
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<tr>
<td>5</td>
<td>112.1</td>
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<tr>
<td>12</td>
<td>117.6</td>
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<td>134.6</td>
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<tr>
<td>5</td>
<td>154.4</td>
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<tr>
<td>12</td>
<td>171.4</td>
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Figure 3 shows the maximum Von Mises stress in the cartilage of the tibial plateau at each ACL failure point. In varus there is an average maximum Von Mises stress of 23.8MPa. In varus there is an average maximum Von Mises stress of 13.0MPa. This shows that a valgus moment produces considerably more stress than a varus moment.

Von Mises Stress on Tibial Cartilage at Time of ACL Failure

Figure 3: Von Mises stress on tibial plateau cartilage at time of ACL injury

CONCLUSION

The simulation showed that the average maximum Von Mises stress on the tibial cartilage during varus loading was 70% higher than the average stress during varus loading, see Figure 4. Therefore, an ACL injury that results from a valgus orientation is more detrimental to the articular cartilage when compared to a varus orientation.

Figure 4: Von Mises Stress on lateral tibial cartilage, valgus orientation; Posterolateral view

The study also revealed that at 25º of knee flexion, an MCL injury will always be associated with an ACL tear with the knee in valgus. Therefore, MCL tears will be more prevalent than ACL tears in valgus knee orientations. The ACL, also, exhibited the tendency to tear more readily at higher degrees of external/internal femoral rotation. However, valgus and varus moment proved to be the prevailing mechanism of injury.

The results of these simulations can be used in clinical applications. In sports where ACL injuries are prevalent, training programs can be adapted to avoid the potential for potentially harmful knee orientations.

Further development of the simulation model will include failure analysis of the individual ligament bundles. This will aid practitioners in identifying more precise mechanisms of injury to ligaments and cartilage within the knee joint.

REFERENCES