ON THE FATIGUE LIFE OF THE ANTERIOR CRUCIATE LIGAMENT DURING SIMULATED PIVOT LANDINGS

David B. Lipps, Edward M. Wojtys and James A. Ashton-Miller

University of Michigan, Ann Arbor, MI, USA
email: dlipps@umich.edu, web: http://me-engin.umich.edu/brl

INTRODUCTION

Passive collagenous structures such as rabbit medial collateral ligament exhibit fatigue behavior under cyclic loading: the larger the magnitude of repetitive loading, the fewer the number of loading cycles until failure [1]. A knowledge gap exists as to whether the human ACL might also exhibit fatigue behavior under cyclic loading. If so, this would help explain why an ACL rupture can occur during a common athletic maneuver that has been performed hundreds, if not thousands, of times before without injury. In addition, since smaller ACL cross-sectional area (CSA) and greater lateral tibial slope (LTS) increase peak ACL strain during simulated jump landings [2], might these morphological factors affect ACL fatigue life by increasing peak ACL strain? To find out, we tested the null hypotheses that landing force, gender, CSA, or LTS will not affect the number of cycles to ACL failure during repeated simulated pivot landings.

METHODS

Ten pairs of human lower extremities (5 females) from donors of similar age, height and weight (53(7) years, 174(9) cm and 69(9) Kg) with no visual scars or deformities were harvested and dissected, leaving the ligamentous knee structures intact along with the muscle tendons of the quadriceps, medial and lateral hamstrings, and medial and lateral gastrocnemius. Prior to testing, all knees underwent 3-Tesla T2-weighted MR imaging (Phillips scanner, 3D-PE sequence, field of view: 330 mm, slice thickness: 0.7 mm); the ACL CSA and LTS were measured using established methods in OsiriX (v3.9, open source) [2].

Using a published testing apparatus [2], the matched pairs of knees were tested under repetitive simulated pivot landings until ACL failure was achieved, with one knee having been randomized to a three-times body-weight (3*BW) pivot landing and the paired knee to a 4*BW pivot landing. The simulated quadriceps, hamstrings, and gastrocnemius muscles were pre-tensioned to place the knee in 20 degrees flexion prior to each trial. The knees underwent 5 non-pivot trials (compression + knee flexion) to adjust the height and mass of the drop weight on the apparatus in order to achieve the impulsive 3*BW or 4*BW simulated landing force. After the fifth trial, an impulsive 32(7) Nm internal tibial torque was added to place the ACL under large peak strain [2]. Cumulative peak relative strain of the anteromedial bundle (‘AM’) of the ACL was monitored (@ distal 1/3 location) with a DVRT (Microstrain Inc, Burlington, VT) from the first rotation trial. Tibiofemoral kinematics were measured at 400 Hz using optoelectronic marker triads on the proximal tibia and distal femur (Optotrak Certus, NDI, Waterloo, ON) to measure relative and absolute changes in tibiofemoral 3-D translations and rotations. The 3-D forces and moments applied to the knee joint were monitored at 2 kHz with paired 6-axis AMTI load cells on the distal femur and proximal tibia.

The testing protocol concluded when (a) the ligament had clearly failed, (b) a 3-mm increase in the absolute anterior tibial translation had occurred, or (c) a minimum of 60 trials were performed. The ACL was visually inspected for signs of tearing on the AM as well as the posterolateral (PL) bundles. A Cox regression model with shared frailty was performed in Stata (v12) to predict the number of cycles to ACL failure, with gender, simulated landing force, ACL cross-sectional area, and lateral tibial slope as covariates, and p < 0.05 being significant. For the purposes of the analysis, the ACL was considered to have failed if a complete or partial tear or an avulsion occurred, or absolute anterior tibial translation increased by 3 mm.
RESULTS AND DISCUSSION

The null hypotheses were rejected: a greater landing force and a smaller ACL cross-sectional area are significantly associated with a reduced number of cycles to ACL failure (Table 1). Thirteen of 20 knees failed during testing. There was one complete tear, six tears of the PL bundle (one combined with AM tear), two tibial avulsions, and four greater than 3 mm increases in anterior tibial translation with visible elongation of the PL bundle (Fig. 1). No knees showed visual signs of MCL damage. Relative to the first rotation trial, there was a mean (SD) increase of 4.0(2.2) mm anterior tibial translation and 3.3(1.1)° internal tibial rotation in the 13 failed knees. Peak AM-ACL cumulative relative strain averaged 16% by the failure cycle.

Figure 1: Scatterplot of simulated landing force vs. number of loading cycles. Legend: circle – failed, square – intact; black – male, grey – female; T – complete tear; P – partial tear; A – avulsion; E – >3mm anterior tibial translation; D – did not fail.

Table 1: Cox regression results for 20 knees with shared frailty term (theta) to control for matched pairs. Abbreviations: CSA – cross-sectional area; LTS: lateral tibial slope.

<table>
<thead>
<tr>
<th></th>
<th>Hazard Ratio</th>
<th>95% CI</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Force</td>
<td>6.77</td>
<td>1.03-44.4</td>
<td><strong>0.04</strong></td>
</tr>
<tr>
<td>Gender</td>
<td>2.29</td>
<td>0.25-21.1</td>
<td>0.46</td>
</tr>
<tr>
<td>ACL CSA</td>
<td>0.89</td>
<td>0.79-0.99</td>
<td><strong>0.03</strong></td>
</tr>
<tr>
<td>LTS</td>
<td>0.88</td>
<td>0.64-1.21</td>
<td>0.43</td>
</tr>
<tr>
<td>Theta</td>
<td>1.22</td>
<td></td>
<td>0.06</td>
</tr>
</tbody>
</table>

Wald X² = 9.64; p = 0.047

Partial tears of the PL bundle, as well as tibial avulsions, have previously been reported in quasi-static torsional failures without muscle forces [3]. A 3-mm increase in anterior tibial translation was used because it has been found arthroscopically in 85% of complete ACL tears [4]. Four knees reached a 3-mm increase with no macroscopic tearing despite visible elongation of the PL bundle; it is likely that these knees underwent intra-substance damage and histology will be used to examine this. The tears and elongation of the PL bundle shown in this study supports the PL bundle’s role in providing torsional stability of the knee. While only 10% of symptomatic ACL tears are reported as ‘partial’ tears [5], our results suggest that many PL tears may go undetected because an intact AM bundle continues to provide resistance to anterior tibial translation [6].

Limitations include the possibility that one or both DVRT barbs might have initiated failure in the AM bundle. But, since only one knee had a partial AM tear occurring distal to the DVRT, and because the majority of ACLs sustained a PL tear, this is unlikely to have significantly influenced the results.

CONCLUSIONS

This is the first evidence that the human ACL demonstrates fatigue failure. Greater landing force and smaller ACL CSA significantly reduced the number of cycles to ACL failure under repetitive 3-4*BW simulated pivot landings.

REFERENCES


ACKNOWLEDGEMENTS

Funding: PHS grant R01 AR054821. Assistance: Dr. Catherine Brandon, Suzan Lowe, Dr. Youkeun Oh, Mélanie Beaulieu, and Jessica Deneweth.