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Identification of optimal laxity tests to load individual parts of knee ligaments

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to the applied loads, ligament and contact forces. A reaction moment around the knee flexion axis was included to simulate a fixed knee flexion as typically done during laxity tests. To identify what we will denote the optimal load cases to strain each bundle of the ligaments, we set up the following optimization problem:

$$\max \ x^1, x^2 \ (F^2_i - F^1_i)^2 - \frac{1}{N - 1} \sum_{j=1, j \neq i}^{N} (F^2_j - F^1_j)^2$$ (1)

where $x^1$ and $x^2$ denote two load cases (i.e. each containing the knee flexion angle and the applied force and moment on tibia). $F^2_i$ and $F^2_j$ denote the force in the $k$th ligament bundle under load case $x^1$ and $x^2$, respectively. The first term in the equation specifies the squared difference in the ligament bundle of interest (ith) from which the second term subtracts the average force in all other ligament bundles. $N$ denotes the number of ligament bundles.

To solve this optimization problem, we applied a Monte Carlo sampling approach. First, we applied 104,000 random load cases, containing the knee flexion angle, and tibial forces and moments and recorded the resulting ligament forces. The knee angle was sampled in the interval $[0^\circ:90^\circ]$, and the tibial forces and moments with magnitudes of $[0 \text{ N}: 150 \text{ N}]$ and $[0 \text{ Nm}: 10 \text{ Nm}]$, respectively. The full $0^\circ$ to $360^\circ$ rotation around two axes were sampled for the direction of both the tibial force and moment vectors. Subsequently, we searched through all samples for the load two cases that would result in a maximization of the optimization problem in (1).

### RESULTS AND DISCUSSION

Load cases for all ligaments were found but for the sake of brevity, we only show results for ACL and PCL (Table 1). Fig 2 illustrates the identified load cases for the anteromedial bundle of ACL.

For the anteromedial, anterolateral and posteromedial ACL bundles, the optimal knee angles were between $4.5^\circ$ and $22.1^\circ$ and with a clear anterior and posterior force difference between the two loads for each ligament. The posteromedial bundle of ACL, however, required one load at $7.3^\circ$ and the other at $93.2^\circ$ but still with a clear anterior and posterior load difference. The PCL bundles on the other hand required markedly different load cases both in terms of knee flexion angles, forces and moments.

### CONCLUSIONS

In this study, we identified optimal loads to strain individual ligament bundles. This information can be applied to develop future measurement protocol, ultimately leading to a better assessment of knee ligament properties in vivo.

### REFERENCES


### ACKNOWLEDGEMENTS

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### Table 1: Optimal loads for the different branches (anteromedial (am), anterolateral (al), posteromedial (pm), posterolateral (pl) of ACL and anterior, mid and posterior of PCL). The forces and moments are reported in the tibial ISB coordinate system with standard abbreviations for anterior-posterior (ap), superior-inferior (si) etc.

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Knee flexion [º]</th>
<th>$F_{ap}$ [N]</th>
<th>$F_{si}$ [N]</th>
<th>$F_{ml}$ [N]</th>
<th>$M_{vv}$ [Nm]</th>
<th>$M_{ie}$ [Nm]</th>
<th>$M_{fe}$ [Nm]</th>
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<tr>
<td>ACL am</td>
<td>6.0</td>
<td>-120.0</td>
<td>-44.3</td>
<td>-28.0</td>
<td>-8.4</td>
<td>5.3</td>
<td>-0.6</td>
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<td>ACL al</td>
<td>22.4</td>
<td>95.8</td>
<td>65.0</td>
<td>-92.6</td>
<td>-5.4</td>
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<td>-0.2</td>
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<td>ACL pm</td>
<td>15.6</td>
<td>-128.8</td>
<td>0.9</td>
<td>78.4</td>
<td>0.4</td>
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<td>ACL ap</td>
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<td>-43.8</td>
<td>-2.1</td>
<td>7.6</td>
<td>4.9</td>
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<tr>
<td>ACL pl</td>
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<td>137.9</td>
<td>16.8</td>
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<td>-1.1</td>
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<td>-114.4</td>
<td>-0.3</td>
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<td>PCL a</td>
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<td>16.8</td>
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<td>-1.1</td>
<td>7.4</td>
<td>-4.6</td>
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<td>8.2</td>
<td>-87.2</td>
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<td>PCL p</td>
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<td>-132.2</td>
<td>10.0</td>
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<td>0.5</td>
<td>-1.4</td>
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<td>PCL ap</td>
<td>49.7</td>
<td>-18.5</td>
<td>95.3</td>
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<td>0.8</td>
<td>-0.7</td>
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