THE DEVELOPMENT OF A METHOD TO INDUCE INJURIOUS HYPEREXTENSION OF THE FIRST METATARSOPHALANGEAL JOINT

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INTRODUCTION

Injury to the plantar plate (PP) of the first metatarsalphalangeal joint (1MTP), frequently referred to as turf toe (TT), is one of the more common foot injuries in American football. One review of professional football players found that 45% of the 80 players surveyed had been diagnosed with TT during their career. TT can range in severity. In athletes, it is associated with an average time-loss of 6 days, with a range of 0 to 56 days. First-hand accounts from injured athletes and their trainers indicate that TT most commonly occurs through hallux hyperextension, but no in vitro studies have been performed to verify and quantify this mechanism. This paper describes the development of a test device capable of reproducing clinically relevant TT in cadaver limbs via hyperextension of the 1MTP.

METHODS

Based on the available injury reporting, four key design specifications were established for the test device: 1) generate extension of the 1MTP that exceeds the natural range of motion (viz. 115° from neutral), 2) generate this extension at a nearly constant angular velocity representative of the rates present when injuries occur in the field, 3) maintain the axis of rotation of the proximal phalanx within the head of the first metatarsal, and 4) minimize noise due to vibrations of the system as the loading is applied. A minimum angular velocity of 8.73 rad/s at the 1MTP was targeted based on a concurrent study of athletes’ performance in a range of tasks.

The foot fixture was designed to induce rotation at the metatarsophalangeal joints (Fig 1). This fixture consists of a stationary plate (foot plate) designed to be loaded by the metatarsal heads and a rotating assembly (toe plate) designed to be loaded by the phalanges. Each of the plates was mounted to a six-axis load cell.

Rotation of the toe plate was driven by the interaction of a linear impactor with cables wrapped around a cam mounted to the toe plate. The total angular displacement of the toe plate was controlled by limiting the stroke of the impactor, which was sufficiently massive (91 kg) that its motion could be assumed independent of the characteristics or even the presence of the loaded foot. The toe plate rotated about a fixed axis of rotation nominally passing through the rotation axes of all five proximal phalanges. The angular velocity of the toe plate was varied by changing the initial launch pressure of the linear impactor.

During pre-test preparation, each specimen was amputated immediately distal to the knee and fixed to a positioning tower. Arrays of motion-capture markers were screwed into to the proximal phalanx of the great toe and to the first metatarsal so that 6-degree-of-freedom motion of those structures could be measured. Markers were also mounted to the foot and toe plates. Specimens were dissected after...
testing by orthopedic surgeons familiar with turf toe injuries.

Three cadaver feet have been tested to date. Significant compliance of the foot was observed in the first test. This compliance effectively off-loaded the 1MTP as the toe plate rotated and prevented an injurious level of angular displacement at the 1MTP. To reduce this foot compliance and allow for injurious loading of the 1MTP, a platform was added to limit posterior displacement of the calcaneus and an external fixation system was introduced between the tibia and the first metatarsal to limit midfoot compliance. Both subsequent tests used this modified foot mounting scheme. Data from the first test is not included in this analysis.

RESULTS AND DISCUSSION

The transfer piston traveled at a linear velocity of 1.6 m/s in test 2 and at 1.3 m/s in test 3. In test 2 the angular velocity of the toe plate increased nearly linearly for 0.062 s before reaching a plateau of 20.9 rad/s for a period of 0.051 s (Fig 2). In test 3, which involved a lower launch pressure, the toe plate angular velocity took 0.081 s to reach a plateau of 17.5 rad/s, which was maintained for 0.062 s. The foot fixture rotated through 114º for each test. This rotation occurred over 0.126 s in test 2 and 0.154 s in test 3.

By design, the motion of the first proximal phalanx was not tightly coupled to the motion of the toe plate. Preliminary analysis of the motion capture data indicates that, while the toe plate rotated a total of 114º in all tests, the proximal phalanx of the great toe experienced 101º of rotation during test 2 and 90º during test 3. The loading in test 2 generated a peak 1MTP extension moment of 54.6 Nm, while the loading in test 3 generated 31.4 Nm.

Table 1: Summary of test conditions and observed injuries in tests 2 and 3.

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen Age (yrs)</th>
<th>Angular Rate (rad/s)</th>
<th>Max Fixture Angle (deg)</th>
<th>Max Toe Angle (deg)</th>
<th>Observed Injury*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>69</td>
<td>20.9</td>
<td>114</td>
<td>100</td>
<td>Lateral PP attenuation; medial PP tear; MCL avulsion</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
<td>17.5</td>
<td>114</td>
<td>90</td>
<td>Medial PP tear; MCL avulsion</td>
</tr>
</tbody>
</table>

*PP – plantar plate; MCL – medial collateral ligament

Previous in vitro studies of lower extremity mechanics have included passive tensioning of intrinsic and extrinsic muscular load paths. The pilot experiments reported here did not include this. Maintaining the structural integrity of the plantar aponeurosis was judged by the authors to be the top priority and the risk of damage by attempting to tension the intrinsic foot muscles was considered too high. Future tests may include passive tensioning of intrinsic and extrinsic tendons of the foot since it is possible that this will change the stress state and thus the injury tolerance of the PP.

CONCLUSIONS

A test fixture was designed and built to generate turf toe, or ligamentous 1MTP injury, in vitro. Realistic dynamics of the 1MTP and clinically relevant injuries were produced.

REFERENCES