Development of an Injury Risk Function for First Metatarsophalangeal Joint Sprains

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Abstract


Introduction: Sprains of the first metatarsophalangeal (1MTP) joint, also known as turf toe, are debilitating athletic injuries. Because 85% of 1MTP sprains result from excessive hallux dorsiflexion, interventions that limit motion to subinjurious levels would greatly benefit athletes. Hallux dorsiflexion range of motion (hdROM) cannot be overly constrained, however, lest athletic performance be compromised. Therefore, the tolerance of the 1MTP joint to excessive dorsiflexion injury must be quantified before appropriate hdROM limitations may be developed. The purpose of this study was to develop a quantitative injury risk function for 1MTP sprains on the basis of hallux dorsiflexion angle. Methods: Twenty cadaveric limbs were tested to both subinjurious and injurious levels of hallux dorsiflexion. Motion capture techniques were used to track six-degree-of-freedom motion of the first proximal phalanx, first metatarsal, and calcaneus. Specimens were examined by physicians posttest to diagnose injury occurrence and ensure clinical relevance of the injuries. Results: A two-parameter Weibull hazard function analysis reveals that a 50% risk of injury occurs at 78° of dorsiflexion from anatomical zero. Conclusion: Methods presented here drove cadaveric 1MTP joints to various degrees of dorsiflexion, resulting in both noninjurious and injurious trials, which were formed into an injury risk function. Key Words: TURF TOE, EXCESSIVE DORSIFLEXION, MOTION CAPTURE, HALLUX

Sprains of the first metatarsophalangeal (1MTP) plantar plate (colloquially called “turf toe”) are common athletic injuries that can severely reduce mobility and diminish performance. For example, 1MTP sprains were the third most common foot/ankle injury of collegiate football players evaluated at the National Football League (NFL) Scouting Combine, and it has been estimated that up to 45% of professional American football players will experience at least one 1MTP sprain during their careers (12,22). In addition to their prevalence, 1MTP sprains also severely inhibit a player’s participation in sporting activities. Coker et al. (5) reported that collegiate football players lost more playing time to 1MTP joint injuries than to ankle injuries, even though ankle injuries occurred over four times more frequently.

The term “turf toe” was initially coined in 1976 for an injury described as a “sprain of the plantar capsule–ligament of the great toe metatarsophalangeal joint” (3). Although 1MTP sprains resulting from mechanisms such as plantarflexion or valgus loading have been reported, excessive hallux dorsiflexion has been identified as the most common injury mechanism. A retrospective survey by Rodeo et al. (22) found that excessive dorsiflexion was responsible for 85% of the turf toe injuries where the cause of injury was known. This result is also consistent with an earlier survey of 66 collegiate athletic trainers in which excessive dorsiflexion was identified as the most common mechanism of 1MTP sprain (5).

Foot orthoses or extended steel shanks are routinely placed in an athlete’s shoe to limit hallux dorsiflexion (19). Although these interventions are typically used to protect those recovering from 1MTP sprains, similar techniques could play a preventative role. Unfortunately, these devices aggressively limit hdROM to such an extent that athlete performance can be compromised. This overconstraint prevents use by uninjured players. Therefore, any countermeasure intended to protect players against 1MTP sprains must prevent injurious hallux dorsiflexion while allowing a maximum hdROM. Performance kinematics of the 1MTP joint in professional football players have previously been described (21); however, the hallux dorsiflexion angle at which injury occurs has not yet been quantified.

Both injurious and subinjurious tests are required to develop an injury risk function if the data are censored (13). Prieskorn et al. (20) authored the only study to date that

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attempted to replicate 1MTP sprain in vitro. However, that study did not record any subinjurious trials, so an injury tolerance cannot be obtained. Therefore, additional study is required to define the relation between 1MTP dorsiflexion and sprain. The objective of this study was to produce 1MTP sprains in cadavers representative of injury patterns routinely seen by physicians (clinically relevant) and, subsequently, to develop an injury risk function based upon 1MTP dorsiflexion angle. Cadaveric limbs were tested by dorsiflexing the hallux to prescribed angles, and motion capture techniques were used to record the six-degree-of-freedom (6DoF) motion of the proximal phalanx relative to the first metatarsal. Posttest necropsies were performed to diagnose gross injury. On the basis of these injury and angle results, survival analysis was used to develop an injury criterion for 1MTP gross sprain due to hallux dorsiflexion.

**METHODS**

Male, cadaveric lower extremities were tested with approval from the University of Virginia Center for Applied Biomechanics Oversight Committee and the University of Virginia Institutional Biosafety Committee. Specimens were fresh-frozen from postmortem subjects and obtained from tissue suppliers accredited by the American Association of Tissue Banks.

**Test fixture.** The foot fixture was designed to induce rotation at the metatarsophalangeal joints to drive the phalanges into dorsiflexion (Fig. 1). Previous study has shown that 1MTP instantaneous centers of rotation, although not constant during hallux dorsiflexion, were consistently found within the metatarsal head (23). Thus, applying a fixed center of rotation through the metatarsal head was deemed...
acceptable. Rotation of the toe plate was induced through interaction with a transfer piston driven by a pneumatic linear impactor. Pulleys, mounted to the end of the impactor, caught cables wrapped around a cam on the test fixture and induced toe plate rotation. Varying the launch pressure of the impactor resulted in different toe plate rotation rates. A target angular rate of $800^\circ \text{s}^{-1}$ to $1400^\circ \text{s}^{-1}$ was selected on the basis of previously reported maximum 1MTP dorsiflexion rates in elite athletes (15). Tension was applied through the flexor hallucis longus (FHL) tendon, via a 40-N constant-force spring, to seat the hallux against the toe plate before forced 1MTP dorsiflexion.

The total angular displacement of the toe plate was controlled by limiting the stroke of the impactor transfer piston and arresting the motion of the rotating cams with honeycomb. It was believed that the instant of injury would not be apparent from the collected data (i.e., the data would be censored). Thus, the degree of toe plate rotation was a controlled input parameter. The transfer piston was sufficiently massive (91 kg) such that its motion could be assumed independent of the characteristics or presence of the loaded foot.

**Instrumentation.** The test fixture was instrumented with an angular rate sensor to record induced toe plate rotation (Fig. 1C). A single-axis load cell, in series with the constant-force spring, measured the force through the FHL tendon. Four six-axis load cells captured reactions under the phalanges, metatarsal heads, heel, and tibial test fixture attachment. A two-dimensional, dynamic pressure sensor (TekScan, South Boston, MA) was fixed to the toe plate with adhesive and used to define the percentage of applied force through the toe plate to the hallux. In addition, an eight-camera motion capture system (Vicon, Centennial, CO) was used to record the position of both the test fixture and the specimen during testing. The pressure mat and Vicon system were recorded at 1000 Hz; all other data were sampled at 10,000 Hz.

**Specimen preparation.** During pretest preparation, each specimen was transected immediately distal to the knee. The proximal third of the tibia and that of the fibula were cleaned of soft tissue and potted using FastCast R802 (Goldenwest, Cedar Ridge, CA). Two Steinmann pins were inserted into the first metatarsal, and two additional pins were inserted approximately at the midshaft level of the tibia. All first metatarsals and tibial shaft pins were directed from medial to lateral to prevent interference or injury to the plantar soft tissues of the foot and posterior musculature of the leg. These two sets of pins were connected using an external fixation system (Synthes Corp, West Chester, PA) to limit midfoot and ankle compliance. The FHL tendon and muscle were isolated for the 15 cm immediately proximal to the tarsal tunnel. Gauze was sutured to the tendon/muscle to improve the effectiveness of the tendon clamp. Three arrays of four Vicon markers each were rigidly attached to the specimen and described the 6DoF motion of three bones: the proximal phalanx of the great toe, the calcaneus, and the first metatarsal (via Steinmann pins) (Fig. 2A). Pre- and posttest computed tomography (CT) images recorded the placement of the Vicon markers.

**Test procedure.** Immediately before testing, the potted specimen was secured to the test fixture through an alignment table. The position of the tibia was manually adjusted to ensure that the metatarsal heads did not contact the toe plate and that the first metatarsal head was aligned with the toe plate axis of rotation. A cam cleat (Schaefer Marine, New Bedford, MA) was attached to the gauze-wrapped section of the FHL tendon and connected to the constant-force spring. A pretest data capture confirmed that the specimen was seated on the foot and toe plates and the FHL tendon was loaded to approximately 40 N. All the tests for this study were conducted at room temperature. This was acceptable because ultimate strain has not been shown to be temperature dependent (1,10,25). During testing, the 1MTP joint of each specimen was moved dynamically by rotating the phalanges to a prescribed angle, at a predetermined angular rate. The specimen was then removed from the test fixture and stored for necropsy.

**Injury diagnosis.** Posttest necropsy was conducted on each specimen to diagnose 1MTP sprain. A physician or orthopedic specialist familiar with relevant anatomy conducted each dissection. Injury was classified as any tear in the soft

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**FIGURE 2—A, Motion capture arrays. B, Coordinate systems for the first metatarsal (M1) and proximal phalanx (PP). Zero position found by aligning the x-axes of the two coordinate systems.**
tissue or an avulsion fracture involving the sesamoid complex. Attenuation or stretching of the soft tissue was considered a subjective assessment and, therefore, not classified as injury.

**Motion capture methods.** To analyze motion capture information, the CT scan of each foot was segmented into three structures, including images of the associated reflective markers: the calcaneus, the first metatarsal, and the proximal phalanx of the hallux (Mimics software; Materialise, Leuven, Belgium). Coordinate systems were defined relative to the first metatarsal and to the proximal phalanx. The x-axis of the first metatarsal connected the centers of the proximal and distal joint surfaces of the bone. The first metatarsal y-axis was parallel to a line connecting the most plantar points of the sesamoid bones. The z-axis was orthogonal. The origin was the center of the base of the first plantar points of the sesamoid bones. The characteristic of predicting zero probability of injury at zero stimuli (13).

The location of each motion tracking marker array (η) was determined within the defined coordinate system on the bone (β) using a transformation matrix (T):

$$\beta_y = T_{x} \eta_y$$  \hspace{1cm} [1]

These transformations were computed using Magics software (Materialise). Each bone’s 6DoF motion was calculated in OpenSim (version 2.4) (http://opensim.stanford.edu) using a mathematically consistent coordinate transform. Joint motion was defined as the hallux coordinate system relative to the first metatarsal coordinate system. A zero angle (θ⁰) was defined as the alignment of the x-axis of the hallux coordinate system with the x-axis of the metatarsal coordinate system (Fig. 2B). Absolute maximum hallux dorsiflexion angle was taken as a change from this zero position (θmaxhmax). The maximum change in hallux dorsiflexion angle (∆θmaxhmax) was calculated as the difference between the maximum angle and the angle at the start of the test (t = 0).

**Exclusion criteria and data analysis.** Exclusion criteria included incorrect placement of Vicon markers, misalignment of a specimen before testing, or absence of pretest FHL loading. Each test was examined for conditions that would necessitate removal from the final data set. After finalizing the data set, a binary logistic regression was performed to measure association with injury outcome (14). Along with specimen age and rotation rate, three measures of hallux dorsiflexion angle were evaluated: previously defined $θ_{\text{halmax}}$ and $θ_{\text{halmax}}$ as well as hallux dorsiflexion as measured by toe plate rotation ($θ_{\text{tp}}$). The concordance, as represented by the Goodman–Kruskal gamma, indicated the predictive ability of each variable.

A survival analysis was then performed on the variable with the greatest association with injury. Survival analysis, originally created for use with time-to-death medical studies, is a statistical tool by which censored data may be formed into injury risk functions relating a quantifiable parameter to the probability of injury (9). Because a continuous injury risk function was desired, a parameterized form was used. Specifically, a two-parameter Weibull distribution was used to fit a hazard function, with 95% confidence intervals, to the final data set. This distribution was chosen because of its characteristic of predicting zero probability of injury at zero stimuli (13).

**RESULTS**

Twenty specimens, 10 right and 10 left, were tested at varying degrees of hallux dorsiflexion (Table 1). Specimen age ranged from 18 to 69 yr old, with an average age of 46.5 yr and SD of 16.3 yr. Clinically representative IMTP sprains were found in 11 of the 20 specimens. In the remaining nine specimens, no tearing of the sesamophalangeal ligament was noted during posttest necropsy. In all 20 specimens, posttest CT revealed no injury at the external fixation pin–bone interface or at motion capture array attachment. Fifteen specimens were included in the final analysis. Four specimens were excluded because of issues with motion capture marker or camera placement; the fifth specimen was rejected because of an absence of FHL loading at the start of the test.

The typical injury was a partial thickness tear of the sesamophalangeal ligament just distal to the medial sesamoid

**TABLE 1. Tested specimens included in final data set.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cadaver ID</th>
<th>Foot Aspect (Left/Right)</th>
<th>Age (yr)</th>
<th>$θ_{\text{hal}}$ (°)</th>
<th>$θ_{\text{halmax}}$ (°)</th>
<th>$\Delta θ_{\text{halmax}}$ (°)</th>
<th>Toe Plate Rotation Rate (° s⁻¹)</th>
<th>Injury (Yes/No)</th>
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<tr>
<td>1</td>
<td>400</td>
<td>R</td>
<td>53</td>
<td>72</td>
<td>91</td>
<td>38</td>
<td>1300</td>
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<tr>
<td>2</td>
<td>411</td>
<td>L</td>
<td>60</td>
<td>74</td>
<td>89</td>
<td>51</td>
<td>900</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
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<td>R</td>
<td>69</td>
<td>75</td>
<td>83</td>
<td>58</td>
<td>1125</td>
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<tr>
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<td>486</td>
<td>L</td>
<td>59</td>
<td>90</td>
<td>92</td>
<td>74</td>
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<td>R</td>
<td>53</td>
<td>87</td>
<td>72</td>
<td>57</td>
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<td>Y</td>
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<td>487</td>
<td>L</td>
<td>27</td>
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<td>72</td>
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<tr>
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<td>R</td>
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<td>72</td>
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<td>R</td>
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<td>R</td>
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<tr>
<td>14</td>
<td>496</td>
<td>L</td>
<td>31</td>
<td>60</td>
<td>67</td>
<td>37</td>
<td>950</td>
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<tr>
<td>15</td>
<td>496</td>
<td>R</td>
<td>31</td>
<td>68</td>
<td>79</td>
<td>31</td>
<td>1000</td>
<td>Y</td>
</tr>
</tbody>
</table>
FIGURE 3—Plantar view of 1MTP joint (right foot) showing the bones, ligaments, and major muscles of the 1MTP joint. Injury was noted as a tear in the sesamophalangeal ligament distal to the sesamoid (reprinted from Frimenko et al. (8) with permission from Begell House, Inc).

TABLE 2. Evaluation of variables for 1MTP sprains by excessive hallux dorsiflexion (n = 15).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Age (yr)</th>
<th>( \theta_{\text{h}} ) (°)</th>
<th>( O_{\text{max}}^{\text{hallux}} ) (°)</th>
<th>( \Delta O_{\text{max}}^{\text{hallux}} ) (°)</th>
<th>Toe Plate Rotation Rate (° s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>0.14</td>
<td>0.5</td>
<td>0.5</td>
<td>0.61</td>
<td>0.08</td>
</tr>
<tr>
<td>Percentage concordance</td>
<td>51.8</td>
<td>75.0</td>
<td>75.0</td>
<td>80.4</td>
<td>46.4</td>
</tr>
<tr>
<td>Percentage discordance</td>
<td>39.3</td>
<td>25.0</td>
<td>25.0</td>
<td>19.6</td>
<td>39.3</td>
</tr>
<tr>
<td>Ties</td>
<td>8.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14.3</td>
</tr>
</tbody>
</table>
that age scaling would significantly affect the risk curve; however, because approximately half of our specimens were near or over the 55-yr age threshold, there is a possibility that failure strain could be altered with tissue age. Because turf toe injuries predominantly occur in the athletic population, future studies should examine possible limitations based upon age of the sample group.

The longitudinal arch height of a specimen may also be a confounding variable to 1MTP sprain through excessive hallux dorsiflexion. The arch height and other anatomical specifics of an individual foot influence the initial stress state of the plantar plate and the manner in which stress builds within it under force during 1MTP dorsiflexion. Furthermore, muscle tensing, lividity, and other aspects of living humans generate internal loads and therefore stresses within the orthopedic structures of the foot. A cadaver model cannot replicate all of these loads. Although efforts were made to control some of the internal loads (e.g., through applied tension through the FHL and fixing the load in the Achilles tendon by constraining the position of the calcaneus), the degree to which this represented the in vivo situation is unknown but likely to influence the relation between 1MTP dorsiflexion angle and injury. The role of internal load paths is a complex topic for future research, including the use of computational models and more complex experimental methods possibly involving less constraint on anatomical structures and joints (e.g., Wei et al. (24) and Lievers and Kent (16)).

Establishing a correlation between 1MTP dorsiflexion and injury risk is the first step toward creating effective countermeasures to prevent turf toe. This study focused exclusively on injury through excessive hallux dorsiflexion, because this is the dominant injury mechanism; however, 1MTP sprain may occur through plantarflexion and varus/valgus mechanisms as well. Future work should consider these mechanisms and their implication to 1MTP sprain.

CONCLUSION

This study developed an injury risk curve that describes the probability of 1MTP sprain through hallux dorsiflexion. The results presented herein were developed from in vitro tests of cadaveric limbs within both the injurious and sub-injurious regimens. A 50% risk of injury was established at 78° of dorsiflexion. Through the compilation of injury risk and performance hrDOM data, a design space will be described within which effective, useable equipment may be created to protect athletes from turf toe injuries.

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All authors have no professional relationship with companies or manufacturers that will benefit from the results of the present study.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES


FIGURE 4—Injury risk curves for 1MTP sprain from excessive hallux dorsiflexion. The thin lines represent 95% confidence intervals, and the circles are $\Theta_{\text{max}}$ for each specimen.


