AMERICAN ORTHOPAEDIC FOOT & ANKLE SOCIETY

Foot & Ankle International
34(3) 403–408

DOI: 10.1177/1071100712464953
http://fai.sagepub.com

Radiographic Evaluation of Plantar Plate Injury: An In Vitro Biomechanical Study

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Abstract

Background: The term *turf toe* has been generally applied to athletic dorsiflexion injuries of the hallux metatarsophalangeal (MTP) joint. Variations in injury patterns coupled with the complexity of the MTP joint makes the diagnosis of more severe injuries challenging and may lead to a failure in recognition of an unstable joint and a subsequently prolonged recovery. Although the proximal migration of one or both sesamoids has been previously identified with a plantar plate disruption, the current study proposes a quantitative grading system based on dorsiflexion stress radiographs, providing a predictable and reproducible test for evaluating the extent of injury to the first MTP joint.

Methods: Twenty-four nonpaired fresh-frozen foot/ankle specimens with no history or physical evidence of prior injury were used in this study. The specimens were randomly assigned into 4 cutting groups, and the 4 main distal ligaments of the plantar plate were identified and sectioned. Lateral dorsiflexion fluoroscopic stress images were obtained in the intact state and with each subsequent cut. With each image, measurements from the distal margin of the sesamoids to the most proximal margin of the proximal phalanx were taken. Images were obtained at 45 degrees with both a fibrous loop wrapped around the interphalangeal joint and applying 15 N and also with a manual dorsiflexion stress. Statistical testing performed was a repeated-measures analysis of variance with Tukey post hoc to compare measurements between each group to determine if movement of the sesamoid bones relative to the phalanx quantitatively increased with each structure that was cut.

Results: Our results demonstrate a relationship between the number of ligaments injured in the turf toe simulation and an increase in sesamoid phalangeal distance. We found that an increase of 3 mm in the distance from the sesamoids to the proximal phalanx was significant and predictive of a severe injury to the plantar plate.

Conclusion: Injuries producing differences of 3 mm or greater from the intact state have a high likelihood of having sustained injury to at least 3 of the 4 ligaments of the plantar plate complex. This study is the first to establish a quantitative grading scale for evaluating turf toe injuries radiographically based on changes in movement of the sesamoids relative to the intact state.

Clinical Relevance: In assessing a turf toe injury, historically the evaluation has been qualitative, but our study provides quantifiable data for evaluation of the severity of plantar plate injuries, which may provide guidance to physicians for treatment decisions.

Keywords: turf toe, stress fluoroscopy, MTP sprain, plantar plate

Originally described by Ryan et al[11] in 1975, and termed "turf toe" by Bowers and Martin[1] in 1976, injuries involving a sprain of the capsuloligamentous complex of the metatarsophalangeal (MTP) joint of the great toe have become more prevalent over the past 35 years. The interaction of artificial playing surfaces with flexible shoes has been reported to be a major contributing factor to the increasing prevalence of turf toe injuries.[1,5,6] At the college level, the incidence of turf toe injuries per season among athletes has been reported to range from 4.5 to 6.0 injuries per team per year.[2,4] At the professional football level, nearly 50% of 80 National Football League (NFL) players surveyed experienced a turf toe injury during their career.[10]

The term *turf toe* has been generally applied to athletic injuries of the hallux MTP joint, including contusions, sprains, sesamoid disruption or dislocation, or complete disruption of the plantar plate.[5] However, the typical mechanism of turf toe injuries involves the delivery of an axial

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load to a foot, creating a hyperextension injury to the plantar plate complex.[5,7] Although the mechanism of injury is well understood, there is wide variation in the extent of the structural injury, the symptoms and signs, and the time of recovery.[3,5,7,8] This variation, coupled with the complexity of the MTP joint, makes the diagnosis of more severe injuries challenging and may lead to a failure in recognizing an unstable joint and a subsequently prolonged recovery.[3,6,8]

Diagnosis of turf toe injuries requires not only an accurate history but also a thorough physical examination combined with radiographic and occasionally magnetic resonance imaging (MRI) studies.[6,12] Usually, radiographic evidence is used to determine the presence and severity of a turf toe injury. Although a qualitative grading system of turf toe injuries has evolved, quantitative radiographic guidelines for plantar plate tears are lacking.[2,3,5,9] Although the proximal migration of one or both sesamoids has been previously identified with a plantar plate disruption, the current study proposes a quantitative grading system based on dorsiflexion stress radiographs, providing a predictable and reproducible test for evaluating the extent of injury to the first MTP joint.[9]

Therefore, the purpose of this study was to establish quantitative guidelines for the assessment of plantar plate injuries. We hypothesized that we would be able to objectively quantify the amount of increased distance between the proximal phalanx and the sesamoids following injury to the components of a simulated plantar plate injury. These results can assist in the diagnosis of plantar plate tears and their severity by using stress radiographs or fluoroscopy.

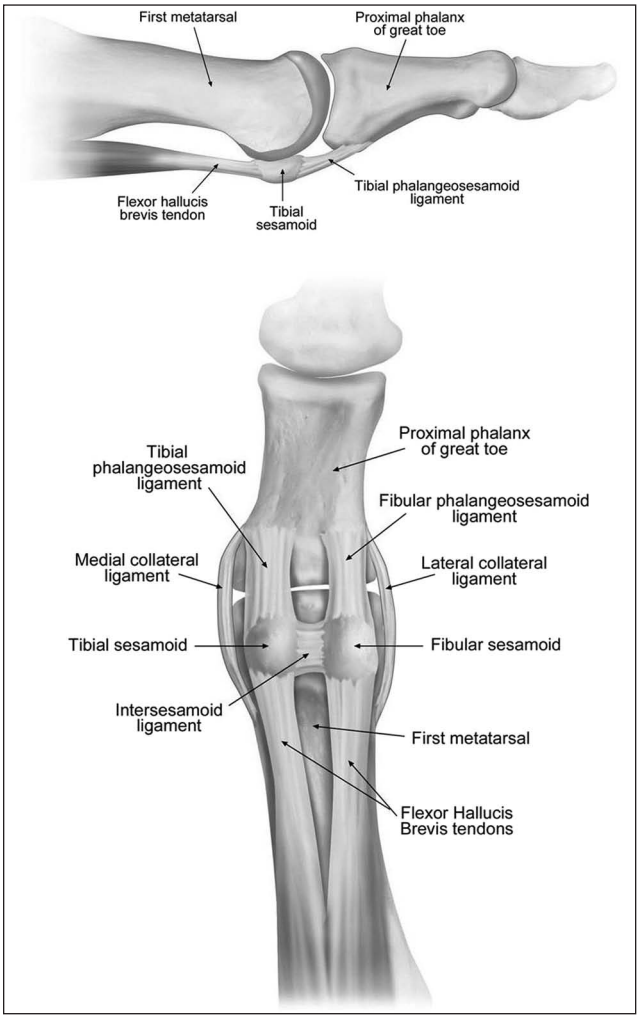

Figure 1. Illustration (lateral and plantar views) of the anatomy of the plantar plate of the first metatarsophalangeal joint.

Methods

Specimen Preparation

Twenty-four nonpaired fresh-frozen foot/ankle specimens with no history or physical evidence of prior injury were used in this study. The specimens were from 10 males and 14 females whose average age was 58.4 (range, 29-69 years). The specimens were kept at −20°C and thawed at room temperature prior to testing. Each specimen underwent fluoroscopic stress testing prior to plantar plate release, after each partial release, and following full plantar plate sectioning. In each case, the plantar plate was exposed in a similar manner. A standard "J" incision was made with the proximal limb extending along the medial border of the foot. The distal limb extended from medial to lateral along the plantar crease of the great toe. The 4 main distal ligaments of the plantar plate were identified, including the medial collateral ligament, the tibial phalangeal sesamoid ligament, the fibular phalangeal sesamoid ligament, and the lateral collateral ligament (Figure 1). The plantar plate ligamentous complex was then released in sequential fashion (Figure 2). The feet were randomized into 4 groups of 6 specimens. Each group had a separate sectioning order of the 4 ligaments with fluoroscopic stress imaging taken after each structure was sectioned.

For the first group, structures were sectioned from medial to lateral starting with the medial collateral ligament, then tibial phalangeal seseamoid ligament, fibular phalangeal sesamoid ligament, and ending with the lateral collateral ligament. The second group reversed this sectioning order. The third group began initially by cutting the tibial phalangeal sesamoid ligament followed by the fibular sesamoid, lateral collateral, and medial collateral ligaments. The fourth group released the fibular sesamoid, tibial phalangeal, medial collateral, and lateral collateral ligaments in respective order (Table 1). Each anatomic dissection and plantar plate release was performed by a fellowship-trained orthopaedic foot and ankle surgeon (NEW).

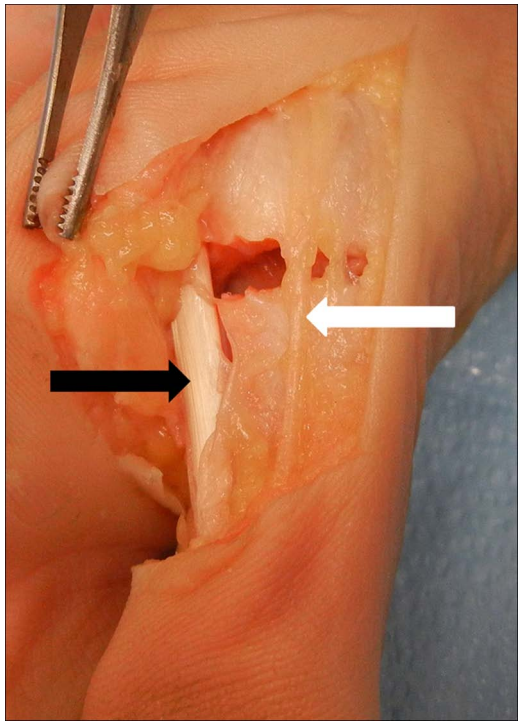

Figure 2. Specimen after all 4 plantar plate ligaments have been sectioned. White arrow indicates plantar medial cutaneous nerve. Dark arrow indicates flexor hallucis longus tendon.

Figure 3. Technique demonstrating standardized instrumented dorsiflexion stress test with fabric strap and tensiometer.

Table 1. Specimen Cutting Sequence

Sequential Cutting Groups	
Group	Cutting Sequence
A	Intact → MCL → tibial phalangeosesamoid ligament → fibular phalangeosesamoid ligament → LCL
B	Intact → LCL → fibular phalangeosesamoid ligament → tibial phalangeosesamoid ligament → MCL
C	Intact → tibial phalangeosesamoid ligament → fibular phalangeosesamoid ligament → LCL → MCL
D	Intact → fibular phalangeosesamoid ligament → tibial phalangeosesamoid ligament → MCL → LCL

Abbreviations: LCL, lateral collateral ligament; MCL, medial collateral ligament.

Radiography

Radiography was performed using fluoroscopic imaging. The foot was placed in a custom-made radiolucent foot holder that facilitated reproducible positioning of the foot. Lateral views were taken with the ankle in neutral position. The feet were secured in the radiolucent foot holder to allow for true lateral views to be obtained after each partial sectioning was performed. Three lateral images were obtained with each cut performed. An initial, nonstressed lateral image was obtained with the great toe in the resting position. A second image was obtained with the orthopaedic surgeon applying a dorsiflexion stress test at 45 degrees of first MTP joint dorsiflexion, while a third test was applied using a fabric strap around the great toe distal to the interphalangeal joint and dorsally stressed using a handheld digital force gauge (Model GTX; Quantrol, Fairmont, MN) to pull 15 Newtons (N) of force.

We standardized this dorsiflexion stress test to ensure that the scale was developed such that it could be used by other clinicians. This test was performed by looping a fabric strap around the great toe, distal to the interphalangeal joint, and tensioning using the handheld force gauge to pull 15 N at a 45-degree angle (Figure 3). To validate use of this technique for quantitative diagnosis of turf toe injury, it was compared directly with a manual dorsiflexion stress test performed by an orthopaedic surgeon. Therefore, each dorsiflexion stress test performed during this study was accompanied by this standardized instrumented stress test.

Measurements

For each lateral image obtained, the distance from the distal margin of the sesamoid to the most proximal plantar margin

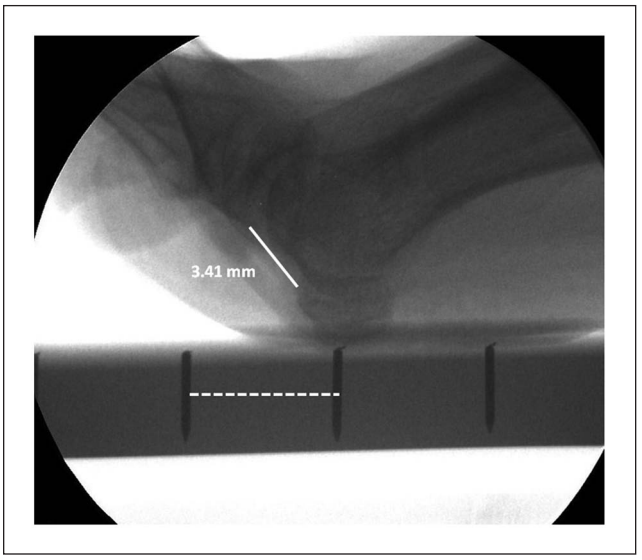

Figure 4. Fluoroscopic image taken after sectioning of 3 plantar plate ligaments under manual stress. Measurement is in millimeters after calibration using radio-opaque markers in the calibration grid (dashed line).

of the proximal phalanx was measured. Each measurement was obtained independently by 2 of the authors, (NEW and CAZ), using a digital picture archiving and communication system (PACS; Stryker, Kalamazoo, MI). A scale was created on the radiolucent foot holder by placing radiopaque markers at precisely measured intervals, allowing calibration of each measurement in the digital PACS (Figure 4).

Statistics. Statistical analysis was performed with the use of Predictive Analytics Software (PASW) Statistics Version 18 (SPSS, Inc, an IBM Company, Chicago, IL). Significance between cuts was determined using a repeated-measures analysis of variance (ANOVA). For ANOVAs that demonstrated significance, a post hoc Tukey's HSD (honestly significant difference) test was conducted to assess the location of the mean between statistically significant groups. Correlations between observer measurements and between the surgeon and standardized measurements were determined using intraclass correlations (ICCs). Significance was defined at $P < .05$.

Intraobserver Repeatability and Interobserver Reproducibility

Intraobserver repeatability was measured by having 2 examiners measure the distance from the distal most portion of the sesamoid to the plantar most proximal aspect of the proximal phalanx of the great toe for both tests. Interobserver reproducibility was measured by having examiners with different levels of training independently measure the dorsiflexion stress radiographs for each great toe. The observers were a fellowship-trained orthopaedic surgeon and a research intern.

Table 2. Dorsiflexion Stress Test: Surgeon Applied and Standardized Instrumented Dorsiflexion Stress Test

	Dorsiflexion Stress Test (n = 24 Specimens)			
	Cut 1	Cut 2	Cut 3	Cut 4
Surgeon	0.08	1.20	3.04[a]	6.96[a]
Instrument	0.68	1.53	3.37[a]	7.89[a]

The results are reported in changes in millimeters relative to the intact state and averaged across all 24 specimens. Significant values are compared with the intact state.
[a]Statistically significant at $P \leq .05$.

Results

The results are summarized in Table 2 for both the manually applied stress test and the instrumented stress test. The results are reported in changes in millimeters relative to the intact state and averaged across all 24 specimens. Significant values are compared with the intact state.

Twenty-four specimens underwent sectioning of the 4 plantar plate ligaments as described earlier. There was no difference between the 4 groups in comparing similar cuts. Each successive cut across the 4 groups was similar when compared with the intact state, resulting in no differences between the patterns of injuries investigated.

There was no significant difference between the results for both the surgeon testing and the instrumented testing. For the first 2 cuts, there was no significant difference between the manual and instrumented states versus the intact state. The third and fourth cuts, however, resulted in a significant change relative to the intact state. The surgeon group had a change of 3.0 mm and 7.0 mm ($P \leq .05$). The instrumented testing resulted in an average increase of 3.4 mm and 7.9 mm relative to the intact state ($P \leq .05$).

Intraobserver and Interobserver Analysis

The intraobserver intraclass correlation between the 2 test groups for each observer was 0.95. The interobserver intraclass correlations for radiographic measurements of the phalangeal sesamoid distances for standardized instrumented testing and surgeon stress testing were 0.88 and 0.94, respectively.

Discussion

Our study is the first to establish a quantitative measurement that surgeons can use to determine the severity of an athlete's turf toe injury. We found that an increase of 3 mm

in the distance from the sesamoids to the proximal phalanx was significant and predictive of a severe injury to the plantar plate. When compared with the intact state, which, in the case of an injured athlete, would be the unaffected, contralateral side, a 3-mm increase in the space from the sesamoid to the base of the proximal phalanx represented injury to at least 3 of the 4 ligaments of the plantar plate. In addition, we found no difference in pathological joint excursion when only 1 or 2 structures in the capsuloligamentous complex of the first MTP joint were sectioned.

In our analysis, each of the 4 groups was compared with each other, with each cut being compared with not only the other groups but also the intact state. In comparing the 4 different groups, we found no difference between the states, no matter what the pattern of injury was. There was no difference between the individual cuts for each group when compared with the intact state. The first ligament cut, regardless of which ligament, resulted in no difference across the 4 groups. This applied to all 4 initial ligament cuts. As a result, the specific pattern of injury was not significant in determining the severity of the injury. Because of this, we examined all 24 specimens as a single entity.

Physical examination and radiographic imaging play an important role in the diagnosis of injuries to the first MTP joint. To our knowledge, no quantitative data have been established that correlate with the severity of the injury. Previously, the examination of athletes with turf toe injuries established a qualitative evaluation of the injury based on clinical signs and symptoms.[3,5] This system established 3 grades of severity of the injury based on physical examination findings. In their articles, the authors reported that some grade 2 and all grade 3 injuries warrant further radiographic imaging to assess the extent of the injury. In these studies and others, stress testing was suggested to be used as a primary tool to rule out plantar plate instability.[3,5,7,8] This qualitative measurement does not provide any further insight for the physician as to the extent of the injury unless gross instability is present. To date, manual dorsiflexion stress testing of the first MTP joint has attempted to demonstrate instability in the joint or a comparative difference in the position of the sesamoid position without any quantification of the difference relative to the structures injured.

On the other hand, when the sesamoid is visualized to move with the base of the proximal phalanx as the great toe is dorsiflexed, the severity of the injury and its subsequent treatment becomes more challenging. The dorsiflexion stress test under fluoroscopy or with stress radiography is an adjunctive test in this situation, but questions arise with this diagnostic tool. Many of these questions, including how much change is seen with injuries to different structures of the plantar plate or what measureable change correlates with a severe injury, have not been answered.

Our data indicate that when there is no movement of the sesamoids with the proximal phalanx as the great toe is dorsiflexed, all 4 components of the plantar plate are injured. Furthermore, when there is an increase in the distance of the sesamoid to the base of the proximal phalanx of at least 3 mm with dorsiflexion stress, our study indicates a statistical likelihood of a 3-ligament injury. Regardless of the cutting order, if 3 ligaments were cut, at least 2 of those included both the tibial and fibular phalangeal sesamoid ligaments. These are the ligaments that envelop the sesamoids, providing the sagittal plane stability of the first MTP joint. Therefore, a more significant injury is present that could potentially affect the long-term stability of the first MTP joint.

The importance of recognizing the extent of the injury not only plays an important role in the immediate treatment of the athlete but can help avoid long-term sequelae associated with failure to recognize more severe injuries. Such long-term sequelae include hallux rigidus, hallux valgus, hallux cock-up deformity, and failure to regain push-off strength.[2,7] Although surgical repair of turf toe injuries is uncommon, it is important to identify when the injury to an athlete is severe enough to warrant surgical stabilization through primary repair of the torn ligaments. Although our study does not provide an algorithm for treatment decisions, it does identify the more serious, higher grade injuries that warrant consideration of surgical repair of the ligaments while avoiding further expensive workup in those patients with less severe injuries. Based on past experience, discussion with experts in this area, and extrapolation from standard of care for other major joints, it is our recommendation that injuries involving 3 of the 4 ligaments in this area should be repaired surgically in athletes. In the situation where surgery is not an acceptable alternative, immobilization in plantarflexion at the first MTP joint for 4 to 6 weeks is the next best treatment.

Our study does have limitations. The cadaveric specimens were from an older age group, which could potentially affect the overall movement of the sesamoids due to decreasing movement in the joint that can occur with age. A second limitation of the study is that the sectioning protocols attempted to replicate naturally occurring turf toe injuries. Although 4 different cutting protocols were randomly chosen, it is difficult to perform all combinations of sectioning, which could potentially affect excursion of the sesamoids. A final limitation is the 45-degree dorsiflexion test that was performed for the standardized instrumented testing. This degree of motion could potentially be difficult to obtain in the posttraumatic scenario because of pain, hematoma, and soft tissue swelling. However, our results demonstrate that when a value of 3 mm is seen, one should be aware of the possibility of a complete plantar palate injury. In the face of an acute injury when suspicions are present, one may wish to reexamine the patient at a later date, examine the patient under local or digital block anesthesia, or obtain an MRI scan.

Conclusions

This study is the first to establish a quantitative measurement indicating the severity of injury to the plantar plate of the first MTP joint. A 3-mm change in movement of the sesamoids relative to the uninjured or intact side on a lateral radiograph is highly predictive of a severe turf toe injury involving at least 3 of the 4 plantar ligaments in this cadaver model.

Acknowledgments

The authors thank Kyle Jansson for his expertise in mechanical engineering.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Supported by a grant from the American Orthopaedic Foot & Ankle Society with funding from the Orthopaedic Foot & Ankle Outreach & Education Fund (OEF) and the Orthopaedic Research and Education Foundation (OREF). The Steadman Philippon Research Institute is a 501(c)(3) nonprofit institution supported financially by private donations and corporate support from the following entities: Smith & Nephew Endoscopy, Arthrex, Siemens Medical Solutions USA, OrthoRehab, ConMed Linvatec, Össur Americas, Small Bone Innovations, and Opedix. One or more of the authors are paid/unpaid consultants for Arthrex.

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