Etiology and Biomechanics of First Metatarsophalangeal Joint Sprains (turf toe) in Athletes

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ABSTRACT: Sprains of the first metatarsophalangeal (MTP) joint, referred to colloquially as “turf toe,” are a debilitating sports injury because the hallux is pivotal to an athlete’s ability to accelerate and cut. Severe sprains may require weeks to full recovery, and injuries requiring surgery may prevent an athlete from full athletic participation for months. Whereas the diagnosis and treatment of turf toe are well documented in the literature, less is known about the biomechanics of this joint and the mechanical properties of the structures that compose it. Nevertheless, this information is vital to those, such as equipment designers, who attempt to develop athletic footwear and surfaces intended to reduce the likelihood of injury. To that end, this review summarizes the literature on the anatomy of the first MTP joint, on biomechanical studies of the first MTP joint, and on the incidence, mechanisms, and treatment of turf toe. Furthermore, gaps in the literature are identified and opportunities for future research are discussed. Only through a thorough synthesis of the anatomic, biomechanical, and clinical knowledge regarding first MTP joint sprains can appropriate countermeasures be designed to reduce the prevalence and severity of these injuries.

KEYWORDS: first metatarsophalangeal joint sprain; turf toe; sports; biomechanics

I. INTRODUCTION

The first metatarsophalangeal (MTP) joint plays a pivotal role in an athlete’s ability to run and cut. The big toe carries more than double the load of the other toes and the peak plantar pressures occur beneath the first MTP joint for important athletic activities including running, jumping, and cutting.\textsuperscript{1-4} Given its important mechanical role, any injury to the big toe can severely limit an athlete’s performance. For example, Coker et al.\textsuperscript{5} reported that injuries to the first MTP joint resulted in more time loss for collegiate American football players than ankle injuries, despite the fact that ankle injuries occurred more than four times more frequently.

A number of different hallucal injuries occur in athletics, including sesamoid and first metatarsal fractures, first MTP joint dislocations, and ligamentous injuries. This review focuses specifically on one such injury: sprains of the first MTP joint, more commonly referred to as “turf toe.”

The term “turf toe” was coined by Bowers and Martin\textsuperscript{6} for an injury they described as a “sprain of the plantar capsule-ligament of the great toe metatarsophalangeal joint.” That usage has since expanded to encompass many injuries to the first MTP joint. McCormick and Anderson\textsuperscript{7} emphasized the lack of specificity in the usage of the term, saying that turf toe may represent the full range of injury from ligament strain to frank dislocation of the first MTP joint. Prieskorn et al.\textsuperscript{8} claimed that any idiopathic peri-hallucal plantar pain may be termed turf toe. For clarity, when used throughout this review, the term “turf toe” will be limited to include only first MTP sprains.

Although a number of excellent turf toe reviews
are available in the literature, they have been intended exclusively for clinicians and surgeons. Consequently, the focus of existing reviews is on the diagnosis and treatment of these injuries (i.e., what happens post-injury). Much less attention has been given to the biomechanical studies of the first MTP joint or its components. This singular focus is unfortunate because numerous stakeholders have an interest in the biomechanics of turf toe. Athletic shoe and surface manufacturers, biomechanists, governing bodies for sport, and the athletes themselves are all motivated to reduce the incidence and severity of these injuries.

 Achieving the goal of injury reduction, however, requires information about what happens before and during an injury event. For example, epidemiological data are needed to identify those athletes most likely to suffer a turf toe injury and the conditions under which it is more likely to occur. Quantitative injury-risk criteria are needed by athletic equipment manufacturers to better guide product development. Finally, kinetic and kinematic data for the first MTP joint, and the material properties of its components, are needed to create and validate computer models of the hallux. These models can then be used to better understand the mechanics of turf toe injuries and to simulate the reduction in injury risk achieved by various prophylactic measures. To date, no reviews have synthesized the diverse body of literature relevant to turf toe.

The goal of the current work is to provide a comprehensive overview of both the clinical and biomechanical literature relevant to first MTP sprains. This review is divided into four sections. First, the relevant anatomy of the first MTP joint is reviewed. Geometric and mechanical properties for the anatomic structures are also summarized, where available. Then, the biomechanics of the first MTP joint are discussed, with particular focus given to relevant cadaveric studies. Turf toe injuries are then described in detail, including the incidence and severity of turf toe, the hypothesized mechanisms of injury, as well as clinical diagnosis.
and assessment. Finally, the gaps in the literature are discussed and opportunities for future work are identified.

II. ANATOMY OF THE FIRST MTP JOINT

Although turf toe is a ligament injury, a number of important bony, cartilaginous, ligamentous, and muscular/tendinous structures contribute to the overall biomechanics of the first metatarsophalangeal (MTP) joint (Figure 1). The anatomic descriptions of these structures are reviewed according to these four categories. Experimental data characterizing the mechanical behavior of individual components, where such data exist, are given to serve as a reference for computational modeling efforts.

A. Bones

The first MTP joint is comprised of four bony structures: the first metatarsal, the first proximal phalanx, and the medial and lateral sesamoids. The first metatarsal is remarkable for its size, with an average cross-sectional area at midshaft \((72.4 \pm 15.9 \text{ mm}^2)\) that is almost twice the size of the other metatarsals.\(^{17}\) The first metatarsal is also the shortest \((62.0 \pm 4.3 \text{ mm in length})\) of the metatarsals.\(^{17}\) The proximal phalanx of the hallux has an average mid-shaft cross-sectional area of \(46.4 \pm 9.7 \text{ mm}^2\) and a length of \(28.6 \pm 2.8 \text{ mm}\).

The motion of the first MTP joint can be roughly approximated as a two-dimensional cam that allows dorsiflexion and plantarflexion and slight abduction and adduction (up to 15° range of motion).\(^{18}\) Anatomic variation, as described by Manning and Levy\(^{19}\) and Coughlin\(^{20}\), can lead to a joint that is either more spherical or more flattened in shape. In general, the relatively shallow convexity of the articular surface of the proximal phalanx provides little stability to the joint. Both Bowman\(^{21}\) and Coker et al.\(^{5}\) have suggested that the more flattened joints may be at higher risk of athletic injury. It is not clear, however, how frequently this variation occurs, and a mechanism by which injury potential increases is not universally accepted.\(^{22}\)

There are two sesamoids inferior to the head of the first metatarsal. They are typically referred to as medial and lateral, but they are also known as the tibial and fibular sesamoids. Karadaglis and Grace,\(^{23}\) based on their review of 1032 radiographs, describe the sesamoids as typically equal in size, disk shaped, convex on the plantar side, and concave on the dorsal side. One or both sesamoids can occur as two pieces (bipartite sesamoid) either congenitally or as a result of trauma.\(^{24}\) Tripartite and quadripartite sesamoids have also been observed\(^{23}\), but they are much less common. Karadaglis and Grace\(^{23}\) also note a higher incidence of multi-partite sesamoids medially \((16.5\%)\) than laterally \((2.5\%)\). Whether congenital or traumatic, a diastasis can be created between the segments of multi-partite sesamoids that does not respond to conservative treatment. Surgical excision of one or more portions of the sesamoid is required in such cases.\(^{24}\)

The sesamoids are functionally linked to the proximal phalanx of the big toe, and displace relative to the metatarsal head during flexion and extension. Three distinct functions of the sesamoids have been proposed (e.g., Richardson\(^{25}\)); they are thought to provide mechanical advantage to the muscles and tendons, to serve as shock absorbers, and to protect the flexor hallucis longus (FHL) tendon. The mechanical advantage results from the sesamoids’ role in displacing the line of action of the tendons of flexor hallucis longus and brevis (FHB) away from the metatarsal head, thus increasing their moment arms. Cadaveric studies by Aper et al.,\(^{26,27}\) confirm that progressive resection of the sesamoids decreases the effective moment arm of both tendons.

B. Cartilage

While the MTP joint provides a degree of sliding, rolling, and compression under physiologic ranges of motion, localized joint compression can occur when normal ranges of dorsiflexion are exceeded. For more severe turf toe injuries, the associated injuries of articular cartilage damage and subchondral bone bruises may be present. A cadaveric study by Ahn et al.\(^{28}\) reported the contact distribution in the MTP joint as a function of dorsiflexion for six
cadaveric specimens. Consistent with the cam-like description of the joint, the area of contact on the metatarsal translated dorsally with the increasing angle of dorsiflexion as the base of the proximal phalanx moved around the metatarsal head. The contact area on the base of the first proximal phalanx did not move as much and remained on the plantar portion of the articular surface.

The thickness of the cartilage layer on the head of the first metatarsal has been examined in detail by Muehleman and Kuettner.\textsuperscript{29} Regional heterogeneity was observed, with the cartilage being thickest (1.3 mm) at the apex of the head, and thinnest (0.8 mm) along the superior edge; similar thicknesses have been measured by others.\textsuperscript{30} Athanasiou et al.\textsuperscript{30} also measured the indentation modulus at several locations within the MTP joint and reported average modulus values of between 0.63 and 1.34 MPa.

The role of cartilage in the biomechanics of a first MTP sprain is unknown. Nevertheless, cartilage damage is frequently observed in severe injuries\textsuperscript{7} and this damage has been hypothesized to be responsible for the reduction in hallux range of motion observed following injury.\textsuperscript{31} Chondral damage has been linked to the development of hallux valgus in the general population,\textsuperscript{32} so similar damage may explain the fact that hallux valgus is a common sequela of first MTP sprains. The mechanical behavior and failure tolerance of the first MTP joint cartilage are important considerations when attempting to reduce injury severity and improve functional outcomes.

C. Ligaments

Given the shallowness of the articular surface of the proximal phalanx, stability of the first MTP joint is provided primarily by the capsuloligamentous-sesamoid complex. Because of the integration of multiple ligaments into a single complex, it is difficult to clearly identify individual structures; a diversity of nomenclatures results. We have adopted the terminology of Sarrafian.\textsuperscript{33} Four ligaments involved in the first MTP joint have been described in detail by Sarrafian.\textsuperscript{33} The two sesamoids are connected by the intersesamoid ligament, and each sesamoid is attached separately to the proximal phalanx by a medial or lateral sesamophalangeal ligament. The sesamophalangeal ligaments are also connected to one another by a transverse ligament band. Medial and lateral metatarsosesamoid ligaments (which are also called suspensory ligaments) originate on the metatarsal head and insert on the corresponding sesamoid. Both of these structures attach proximally to the sesamoids and glide on the metatarsal head during flexion and extension.\textsuperscript{34}

The mechanical behavior of these four ligaments has not been reported in the literature. This lack of attention undoubtedly reflects the technical challenges both with testing such small ligaments and with isolating them from the capsuloligamentous-sesamoid complex.

The intersesamoid ligament, adductor hallucis, flexor hallucis brevis, and abductor hallucis attach to a structure known as the plantar plate.\textsuperscript{34} Best described as a thickening of the joint capsule, a plantar plate is found beneath the head of each metatarsal.\textsuperscript{33} The plates are connected to one another by transverse metatarsal ligaments that act to prevent splaying of the forefoot during loading. With specific regard to the anatomy of the first MTP joint, the plantar plate serves to anchor the sesamoids to each other and to the base of the proximal phalanx.\textsuperscript{33} Deformation (i.e., ripping, swelling or attenuation) of the plantar plate, along with the collateral capsular ligaments, is often implicated in first MTP sprains.\textsuperscript{5,7,34,35} In addition to the ligaments and tendons already discussed, the plantar plate also serves as an attachment point for the plantar aponeurosis. More generally, the plantar plate of the foot is said to be formed by the combination of the plantar aponeurosis and plantar capsule, with the structures already discussed forming the plantar capsule.\textsuperscript{36}

Much attention has been given in the literature to the important role of the plantar aponeurosis in gait and foot biomechanics. This structure, sometimes also called the “plantar fascia,” is a
longitudinally arranged bundle of dense fibrous connective tissue investing the central plantar muscles, which arises from the calcaneus and joins with the enclosure of the flexor tendons to insert on the proximal phalanx of each digit. In supporting the longitudinal arch, the plantar aponeurosis has also been shown to be a key contributor to Hick’s windlass mechanism, which explains how the arch of the foot is elevated as the plantar aponeurosis wraps around the heads of the metatarsals during toe extension. Because of this characteristic, the plantar aponeurosis has been described as a critical energy-storing mechanism of the foot.

Limited material testing of the plantar aponeurosis has been performed. The study by Kitaoka et al. found that the plantar aponeurosis is relatively strain rate-insensitive for loading rates of 11 to 1100 N/s, with an average stiffness of approximately 210 N/mm. Unfortunately, the average age of the feet tested was 75 years (range: 56–81), a problem shared by most cadaveric studies. How these properties may differ in a younger, athletic population is unknown.

D. Muscles and tendons

There are six main muscles and their tendons that are structurally relevant to the first MTP joint: the flexor hallucis longus (FHL) and brevis (FHB), the extensor hallucis longus (EHL) and brevis (EHB), and the abductor (ABH) and adductor hallucis (ADH) muscles (Figure 1). Very little mechanical characterization of the tendons has been performed, despite their use as an allograft material for reconstructive surgery. As a result, this section focuses exclusively on the origins, insertions, and actions of these muscles.

The tendons of three muscles (FHB, ADH, ABH) blend with the ligaments of the first MTP joint to form the capsuloligamentous complex. The FHB originates from the plantar surfaces of the cuboid and the lateral cuneiform, and it divides into medial and lateral sections before inserting at the base of the proximal phalanx of the hallux. The sesamoids bones are embedded in the medial and lateral tendons of the FHB. The ABH originates from the medial process of the calcaneal tuberosity, travels the medial side of the foot, and inserts with the medial tendon of the FHB on the proximal-medial head of the proximal phalanx of the hallux. The ADH consists of two heads that insert on the lateral side of the base of the proximal phalanx. The oblique portion of the muscle originates from the bases of the second, third, and fourth metatarsals, while the transverse portion originates from the heads of the third, fourth, and fifth metatarsis. The actions of these three intrinsic muscles are expected to influence the stress state in the capsuloligamentous complex of the first MTP joint, and they undoubtedly play a role in ligamentous injuries associated with that joint.

The FHL muscle originates in the lower two-thirds of the posterior surface of the fibula, and the tendon descends on the medial side of the talus and calcaneus, then wraps around to the plantar side of foot to insert at the base of the distal phalanx of the hallux. The FHL tendon passes between, and planter to, the sesamoids. Aper et al. have argued that the FHL is the primary flexor, and this muscle has been shown in simulated gait studies to be responsible for increasing the contact area at the toes and the forces borne by the phalanges, thereby decreasing the load on the first metatarsal head.

Finally, there are two extensor muscles. The EHL originates from the lateral anterior side of the fibula, descends in a tendon, crosses over the medial side of the foot, and inserts on the base of the distal phalanx. The EHB originates from the calcaneus with the extensor digitorum brevis, crosses dorsally to the first metatarsal, and inserts on the proximal phalanx.

Automotive crash research has shown that muscle loads at the moment of impact can influence the nature of the injury. While those studies are concerned with lower extremity fractures, it is expected that ligamentous injuries have similar sensitivity to muscle loads. This is particularly true of the three muscles whose tendons insert into the capsuloligamentous complex. The magnitude and pattern of muscle loading in an athlete prior to sus-
obtaining a first MTP sprain are currently unknown.

III. BIOMECHANICS OF THE FIRST MTP JOINT

This section reviews biomechanical studies related to the kinetics and kinematics of the first MTP joint. In particular, attention is given to the range of motion, the instantaneous centers of motion, and the kinematics of the first MTP joint.

A. Range of motion

Reported ranges of motion (ROM) of the first MTP joint vary substantially due to differences in experimental methods and wide individual variation. Based on a review of the literature, external manipulation of the big toe generates a total passive ROM of roughly 110°, which is the sum of approximately 75° of dorsiflexion and 35° of plantarflexion (Table 1). The active range of motion (i.e., that which can be achieved through active muscle tensing) is much less.

A variety of different techniques for measuring hallux ROM have been employed in the literature. Studies on living patients are typical performed using goniometers or three-dimensional position tracking systems. Radiographic imaging measurements have also been performed using either living volunteers or cadaveric limbs. Unfortunately, the measured ROM has been shown to be dependent, not only on the technique itself but also on whether the patient is bearing weight on the foot being measured. Care must be taken when comparing ROM values from different studies.

Various factors can reduce the total ROM at the first MTP. For example, Shereff et al. have shown that total ROM is lower in those with hallux valgus (47°) or hallux rigidus (69°) when compared with normal controls (111°). Artificial reductions in ROM have also been achieved by the addition of inserts under the first metatarsal head and under the heel. Conversely, foot orthoses have been shown to increase ROM in patients with functional hallux limitus. Taken together, these diverse results underscore the fact that the “range of motion” at the first MTP, even for a single individual, is a dynamic value. This multi-factorial dependence must be considered when performing tests involving the first MTP.

It has been hypothesized that athletes with less big toe ROM would be more prone to first MTP sprains. A study by Eggert found no statistically significant difference in pre-injury ROM for a group of football players who did eventually sustain an MTP sprain, when compared with an age and position-matched uninjured control group. But while there is no evidence to suggest reduced ROM predisposes a player to injury, ROM has been shown to be reduced following injury. Eggert reported that the dorsiflexion ROM of 37 players who had previously sustained first MTP sprains was significantly lower than the ROM of 37 never-injured controls (p<0.0001). A similar reduction in ROM following injury has also been reported by Brophy et al. Interestingly, Eggert found no effect of injury on plantarflexion ROM (p<0.20) and hypothesized that the mechanism

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**TABLE 1: Passive range of motion (ROM) of the first MTP joint**

<table>
<thead>
<tr>
<th>Study</th>
<th>Plantar flexion</th>
<th>Dorsiflexion</th>
<th>Total range of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joseph</td>
<td>-</td>
<td>73°</td>
<td>-</td>
</tr>
<tr>
<td>Shereff et al.</td>
<td>34°</td>
<td>76°</td>
<td>111°</td>
</tr>
<tr>
<td>Buell et al.</td>
<td>17°</td>
<td>82°</td>
<td>99°</td>
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<tr>
<td>Eggert</td>
<td>36°</td>
<td>82°</td>
<td>109°</td>
</tr>
<tr>
<td>Nawoczenski et al.</td>
<td>37°</td>
<td>57°</td>
<td>94°</td>
</tr>
</tbody>
</table>
of injury may explain this observation. Although injury mechanisms were not determined for this study population, it is known that 85% of first MTP sprains occur during hyperextension.\textsuperscript{60} Therefore, Eggert speculated that reduced plantarflexion ROM may only be observed in athletes who had sustained plantarflexion injuries. Mechanism-dependent changes in toe function warrant further investigation.

As might be expected, Eggert\textsuperscript{31} found that a prior injury did increase the likelihood of subsequent injury; more than 40% of the injured players studied reported a previous injury. Surprisingly, the second injury was 70% more likely to occur in the opposite foot. Biomechanical compensation to protect the injured foot may place the other foot at greater risk.

B. Instantaneous centers of rotation

Shereff et al.\textsuperscript{54} studied the kinematics of the first MTP and sesamoid metatarsal articulations through the entire range of motion. Using radiographic analysis of below-knee amputations, they evaluated the centers of rotation (COR) for normal feet and determined that the COR were located within the metatarsal heads during flexion and extension. Similar results were found for the instantaneous centers of rotation for the sesamoids in the sagittal plane. Minimal translation of the proximal phalanx on the metatarsal head in the transverse plane was observed during motion in the sagittal plane.

The studies describing the ROM and COR of the first MTP joint have shown that the kinematics and kinetics change significantly when the anatomical structures of the joint are abnormal (e.g., Nevin,\textsuperscript{18} Shereff et al.,\textsuperscript{54} Perez et al.\textsuperscript{61}). For cadaveric studies, this suggests that an initial screening of the specimens be performed to exclude specimens with hallux valgus or hallux rigidis. In addition, preparation of cadaveric samples for testing to determine injury criteria must avoid altering the natural mechanics of the foot and the first MTP joint, especially if an angle-based injury criterion is considered.

While understanding the normal biomechanics of the first MTP joint is useful for ensuring representative behavior during \textit{in vitro} cadaver studies, it must also be recognized that the above describes only non-injurious motion. The kinematics of the first MTP during injury may deviate dramatically from this pattern. Alterations to the center of rotation may prove to be a useful criterion of injury and should be considered.

C. First MTP kinematics

Prieskorn et al.\textsuperscript{8} performed the only known cadaver tests of the first MTP joint kinematics in hyperextension. The interphalangeal joints of five fresh-frozen cadavers were pinned, and the foot was mounted to the test fixture via three Schantz pins in the first metatarsal, third cuneiform, and navicular bone. The test fixture included a flywheel attached via a cable to a linear materials testing machine such that motion of the actuator generated rotation of the flywheel and a shelf on the flywheel loaded the plantar aspect of the great toe. The axis of the flywheel was nominally positioned at the center of the first MTP joint. The specimens were dorsiflexed through an angle change of 110° at an average rate of 489°/sec, which the authors cite as the rate of dorsiflexion observed during the single-limb stance of a normal running cycle. Three distinct injury patterns were generated: capsule rupture proximal to the sesamoids, plantar plate rupture distal to the sesamoids, and rupture of the medial capsule, with associated lateral motion of the sesamoids around the head of the metatarsal. One of the cases with distal plantar plate rupture also sustained a fracture of the lateral sesamoid. While this study did employ instrumentation to measure the applied force and the degree of dorsiflexion, the data are only partially reported, including one force-vs.-angle cross-plot. Unfortunately, insufficient information is reported to allow the applied force to be translated to a joint moment.

Other cadaveric investigations of first MTP joint mobility have been performed,\textsuperscript{28,61,62} but none has examined the loads or deformations needed to cause ligament failure. By investigating the properties (e.g., stress responses to strain) of the struc-
atures within the first MTP, injury tolerances may be determined for a variety of loading conditions, including those involving superimposed forces sustained under different athletic activities. Thus far, the literature does not contain specific, quantifiable data associated with injury. Both the mechanism of injury and the tolerance of joint structures need investigation before injury prevention can be addressed.

IV. SPRAINS OF THE FIRST MTP JOINT

This section summarizes the incidence and severity of turf toe, the mechanisms of injury, and existing statistical correlations with various physiologic and situational factors. Some clinically relevant information is also provided related to the diagnosis, classification, and prevention of turf toe injuries.

A. Epidemiology

First MTP joint sprains are most frequently associated with American football, both due to the initial description by Bowers and Martin and because they have been studied most thoroughly in the context of that sport. A survey of the literature reveals that turf toe injuries have been reported in many different sports (Table 2); however, the often expansive use of the term “turf toe” makes it unclear whether the same injury is being identified in each case. As noted by Prieskorn et al., “turf toe” is often used as an umbrella term that encompasses any discomfort of the hallux regardless of whether this pain results from nerve damage, tendonitis, stress fractures, or some other cause. This lax terminology could confound inter-study comparisons.

Four studies, performed at three American universities, suggest that the rate of first MTP sprains among college football players is between four and six injuries per team per season. At the professional level, Rodeo et al. found that 45% of 80 players surveyed had suffered such an injury at some point during their career, and Brophy et al. reported that 30% of 44 athletes on a single professional football team had a history of first MTP sprains. Unfortunately, the limited nature of the published data prevents meaningful comparisons with the rate of other foot injuries in men’s football. No information about the rate of first MTP sprains in other sports exists in the open literature.

The colloquial nature of the term “turf toe” belies the potentially severe consequences of these injuries. Ligamentous damage in the first MTP joint can significantly affect a player’s ability to perform or even participate in athletics. A study conducted at the University of Arkansas found that football players sustained 74 ankle injuries over a 3-year period and that these injuries resulted in 152 missed practices and 6 missed games. By comparison, just 18 first MTP sprains resulted in 92 missed practices and 7 missed games over the same time period. Clanton et al. reported an average time-loss of 6 days with a range of 0 to 56 days for collegiate football players. Indeed, serious cases may take weeks before the athlete can return, and those requiring surgery may take 6 to 12 months for full recovery. In rare cases, first MTP injuries are career ending.

The time-loss with a first MTP injury is not only a function of the severity of the injury itself but also of the athlete’s sport or position. In football, for example, McCormick and Anderson

| TABLE 2: Literature describing the first metatarsophalangeal sprains by sport |
|-------------------------|------------------|
| Sport                  | References       |
| Basketball             | 5,69,83          |
| Dance                  | 84               |
| Football (American)    | 5,6,24,31,34,52,60,63,67, 70,74,85 |
| Gymnastics             | 75,83,86         |
| Rugby                  | 87.88            |
| Running/track          | 70,89            |
| Skimboarding           | 90               |
| Soccer                 | 19,35,83,91      |
| Tae Kwan Do            | 92               |
| Volleyball             | 68,83            |
remark that a cornerback will likely require longer recovery time than a lineman because of the increased demands for push-off and cutting; however, this observation has yet to be validated using epidemiological methods.

A variety of sequelae of first MTP sprains have been described in the literature. One consistent observation is reduced range of motion in the first MTP joint following injury.\textsuperscript{31,52,60} In addition, hallux limitus, hallux rigidus, hallux valgus, calcification of the ligaments, metatarsalgia, and arthritic changes have all been reported post-injury.\textsuperscript{10,63,66}

\section*{B. Injury mechanisms}

Three mechanisms of injury are generally associated with the term “turf toe”: hyperextension (hyperdorsiflexion), hyperflexion, and valgus/varus loading (Figure 2). Although injuries to the plantar plate complex have been described due to automotive and industrial accidents,\textsuperscript{67} only sports-related mechanisms are considered here.

Bowers and Martin\textsuperscript{6} first introduced the concept of turf toe as a great toe hyperextension injury. They proposed a mechanism where an external force, such as that produced by a falling player, is applied to the leg of a player whose forefoot was fixed on the ground, thereby driving the player’s MTP joint into hyperextension.\textsuperscript{6} While the method of identifying the role of hyperextension in first MTP injury was not detailed, it is presumed that through their interactions with players and athletic trainers, Bowers and Martin would have considerable anecdotal evidence. In a retrospective survey involving 80 active, professional football players and their trainers, Rodeo et al.\textsuperscript{60} found that, among the 45% of players who had suffered a turf toe injury, 85% of them had reported hyperextension to the first MTP joint as the injury mechanism. An earlier survey of 66 collegiate athletic trainers also identified hyperextension as the most frequent mechanism.\textsuperscript{5}
While the literature published since the original description by Bowers and Martin\(^6\) has confirmed the prominence of the hyperextension mechanism, first MTP sprains have been shown to occur without an externally applied force. In sports such as soccer, which generally involve less contact than football, partial tears of the first MTP plantar capsule have reportedly resulted from forced hyperextension during cutting and push-off maneuvers.\(^8,19\) The absence of an external force must also be assumed in the other individual or non-contact sports (e.g., running and gymnastics) where turf toe injuries have been reported (Table 2). Whereas the literature does not provide a distribution of turf toe injury by player activity at the time of injury, it is reasonable to assume that the forced-dorsiflexion manner of hyperextension of the first MTP may also occur in football during activities such as push-off from a 3-point stance.\(^31\)

First MTP sprains have also been reported to occur by hyperplantarflexion. In the survey of football players and their trainers conducted by Rodeo et al.,\(^60\) hyperflexion was the second most common injury mechanism (12%). While not infrequent in football, the plantarflexion mechanism of first MTP injury is more common in beach volleyball, where it has been dubbed “sand toe.”\(^68\) By referring to the injury as “hyperplantarflexion,” it may be inferred that the dorsal aspect of the first MTP joint is injured; however, no information has been provided in the literature denoting differences in the anatomical locations between hyperflexion and hyperextension injuries.

The third mechanism of first MTP joint strain is a valgus or varus force. The survey by Rodeo et al.\(^60\) reported that 4% of turf toe cases in football result from a valgus force,\(^60\) and this mechanism is also described in case studies of other sports. Fabeck et al.\(^35\) report the case of a soccer player who, during an attempt to kick the ball, was struck on the medial aspect of his forefoot by an opposing player. A rupture of the medial collateral ligament of the great toe lead the authors to surmise that the primary mechanism in this case was a valgus force through the first MTP joint caused by an external load acting perpendicular to the long axis of the hallux. Whereas the football-related studies of Coker et al.\(^5\) and Rodeo et al.\(^60\) did not attribute any injuries to a varus loading mechanism, Mulis and Miller\(^69\) hypothesized that this mechanism produced a rupture of the lateral structures of the first MTP joint in a basketball player who simultaneously pivoted and externally rotated his foot.

Regardless of the exact mechanism, a first MTP joint injury is typically treated in the literature as an acute traumatic event. This is certainly a reasonable assumption in cases where a fall, or contact from another player, subjects the hallux to loads and motions that exceed those required for normal athletic performance. However, injuries have also been observed during seemingly routine sports-related activities\(^69\) and some patients presenting with first MTP pain have no recollection of a distinct injury event.\(^70\) These cases suggest that, in addition to acute trauma, some injuries may also be caused by the accumulation of repetitive, subcatastrophic damage.

After reviewing the available literature, it is clear that the loading environments that generate MTP injuries in the field are complex, with the potential for multiple forces and moments producing motions in multiple planes.\(^9\) Unfortunately, relatively few studies provide specific information on the precise location of injury to the first MTP capsuloligamentous complex that would enable a retrospective analysis of the primary loading mechanisms from a biomechanical perspective. In addition to lacking information on the precise rotations of the MTP joint during injury events, the role of superimposed joint compression on MTP joint kinematics and injury remains unknown. Small flecks of bone have been identified from diagnostic radiographs of first MTP injuries. These may be avulsed fragments, but Clanton et al.\(^63\) hypothesize that they may be osteochondral fragments produced by compression.

In summary, a key aspect of the literature describing mechanisms of first MTP joint sprains is its anecdotal, retrospective, and qualitative nature. Mechanisms have historically been identified through surveys of athletic trainers and, to a lesser degree, the injured athletes themselves. The litera-
ture is lacking any assessment of the validity of these determinations based on either direct or indirect physical evidence. Even if the general descriptions are accurate, they are not sufficiently specific or quantitative to enable the development of a robust injury criterion and associated risk function.

C. Correlation of injury to physiology and situational factors

Since the term “turf toe” was first coined, first MTP sprains have been linked to situational factors that reportedly predispose the player to greater injury risk, including extrinsic factors (e.g., footwear, synthetic surfaces) and intrinsic factors (e.g., a player’s weight, position). For many of these factors, their correlation with associated risk of turf toe is unclear due to contradictory findings within the literature.

Since hyperextension of the first MTP is widely considered to be the primary mechanism of injury in football, flexibility in the forefoot region of a player’s footwear is considered a contributory factor. Bowers and Martin evaluated the flexibility of the soles of three different shoe types: a seven-posted natural turf shoe and two different twenty-cleated artificial turf shoes. The anterior portion of the two turf shoes was shown to be significantly more flexible than that of the conventional natural turf shoe ($p \leq 0.002$). Because the Bowers and Martin study was conducted nearly 35 years ago, it is unclear how the design differences between modern athletic shoes and those of the 1970’s would influence their findings. Rodeo et al. attempted to study the role of footwear, but they did not find a statistical difference in the shoes worn by injured and uninjured players; however, in her study of 119 college football players, Eggert (1990) concluded that shoes with a stiffened forefoot region were associated with a lower risk of injury than an unmodified shoe.

Artificial playing surfaces have also been associated with first MTP injury, as implied by the very term “turf toe.” Rodeo et al. studied the role of playing surface in their retrospective survey of active professional football players who had sustained MTP sprains. There was no significant difference in injury rates between groups of players who had natural turf on their home fields and those who had artificial turf, but 83% (24 of 29) of the players who could identify the type of playing surface on which they were injured reported that they were injured on artificial turf.

Despite this association, there is no consensus as to what attributes of turf, if any, are responsible for injury. The constant evolution of artificial turf technology also makes characterization and comparison difficult. Nevertheless, more recent studies have found very little difference in the overall injury rates between grass and turf, although some injury-specific differences have been detected. To date, there are no comprehensive epidemiological data to show any effect of playing surface on an athlete’s likelihood of suffering a first MTP sprain.

The associations of some player-specific characteristics with injury risk have been investigated. Rodeo et al. report that player age and number of years spent playing professional football were significantly correlated to incidence of turf toe ($p < 0.01$), but player height, weight, and height-to-weight ratio were not. Although Rodeo et al. found that 60% of offensive players had sustained first MTP injury versus just 32% of defensive players, the difference was not statistically significant. Eggert also failed to observe a position-dependence for turf toe injuries in collegiate football players.

Anatomic factors may also increase an individual’s likelihood of suffering a first MTP joint sprain. In particular, the risk of turf toe injury is reportedly related to the ankle range of motion (ROM). Rodeo et al. found that mean ankle dorsiflexion ROM was higher ($p < 0.05$) in the uninjured, contralateral limb of players who had sustained a first MTP injury (13.3°) versus players who had never had a first MTP injury (7.9°). The reason for this association is not clear, and we caution against an overly broad interpretation of that finding.

D. Diagnosis of Injury

Although it is an ambiguous clinical term, it has
been noted that turf toe is typically not associated with any marked fractures. Therefore, any assessment leading to a diagnosis of turf toe injury should begin with observation of the hallux MTP joint. Indications such as ecchymosis or swelling, as well as decreased range of motion (as compared to the uninjured foot), factor into the diagnosis of a turf toe injury. These activities should be followed by a radiographic evaluation, though it is noted that most often an injured plantar plate is not directly diagnosed radiographically. However, by comparing weight-bearing x-rays of the injured and contralateral feet, the clinician may observe proximal migration of the sesamoids indicating a severe disruption of the plantar plate (Figure 3). In addition, radiographs will occasionally show flecks of bone around the first MTP joint, which may indicate either capsuloligamentous avulsions from tension or osteochondral fragments produced by a compression injury.

More recent publications indicate that the diagnosis of turf toe may be assisted by high-resolution magnetic resonance imaging (MRI). Tewes et al. present a case study involving a 24-year-old professional football player who presented with pain consistent with injury to the first MTP. In this case study, the authors compare two sets of magnetic resonance (MR) images: one set from the uninjured great toe and one set from the injured hallux. Disruption of the plantar plate can be clearly identified. Similar success is reported by other authors with an amateur soccer player and with a 17-year-old gymnast. These and other studies confirm that MRI is beneficial in diagnosing and assessing the extent of first MTP injury.

**FIGURE 3**: Bilateral weight-bearing radiographs of a professional football player with a severe tear of the plantar plate complex in the right first MTP joint. Note the proximal migration of the sesamoids (white arrowhead).
E. Classification and treatment of injury

Upon diagnosis of a turf toe injury, the immediate treatment is a course of rest, ice, compression, and elevation (RICE) to reduce swelling. The longer-term intervention and treatment, however, are dependent on the extent of injury. Clanton et al. developed a three-level gradation system for classifying turf toe injuries that was later updated by McCormick and Anderson (Table 3).

Grade 1 injuries are treated through a course of stretching the capsuloligamentous complex. Stabilization through use of a walking boot or short leg cast is suggested for Grade 2 and 3 injuries. While surgery is not precisely linked to the grade of injury, only the most extreme cases require surgery. McCormick and Anderson list nine criteria for surgical intervention with surgery suggested for any obvious injury that presents on a radiograph, although most turf toe injuries do not fall within this category. Sesamoid fractures are addressed as an injury separate from first MTP sprain. However in cases where sesamoid fracture is listed as a concomitant injury for first MTP sprain, surgical treatment is usually recommended.

F. Injury rehabilitation and prevention

Because the vast majority of first MTP sprains are caused through hyperextension, the focus of injury rehabilitation and prevention has been to limit this movement of the joint. Unfortunately, preventative measures are usually only taken following an injury in order to prevent aggravation or re-injury of the first MTP joint.

Limiting movement may initially be attempted through taping, but shoes with stiffer soles have also been recommended. Current footwear may be modified with a rocker sole and an extended steel shank placed between the layers of the shoe sole to increase rigidity. A final option is to add custom-made orthotics to the athlete’s shoe. Whereas these methods entail different approaches and varying degrees of intervention and intrusiveness, they collectively attempt to achieve the same goal: limiting the motion of the first MTP joint.

V. DISCUSSION AND RESEARCH OPPORTUNITIES

Whereas there have been a few studies on the injury mechanisms and mechanics of the first MTP, the majority of the relevant literature focuses on what happens post-injury. There is a large body of work on how to diagnose, treat, surgically repair, and rehabilitate a patient who has suffered a turf toe injury. This information is critical to phy-

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<th>Grade</th>
<th>Objective Findings</th>
<th>Activity Level</th>
<th>Pathology</th>
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<tr>
<td>1</td>
<td>Plantar or medial localized tenderness with minimal, if any, swelling and no ecchymosis</td>
<td>Players continue to participate in sports with pain</td>
<td>Stretching of the capsuloligamentous complex</td>
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<tr>
<td>2</td>
<td>Sprains have diffuse tenderness with mild to moderate swelling and ecchymosis. Pain and usually some restriction in range of motion</td>
<td>Time loss 3-14 days. Moderate pain and mild limp with weight bearing</td>
<td>Capsuloligamentous complex is partially torn, but there is no articular injury</td>
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<tr>
<td>3</td>
<td>Severe tenderness to palpation, which, although diffuse, is minimal dorsally. Considerable swelling and ecchymosis is combined with marked restriction in joint motion</td>
<td>Athletes may miss 3 to 6 weeks.</td>
<td>Tear of capsuloligamentous complex. Possible associated injuries include medial/lateral injury, sesamoid fracture and bipartite diastasis, articular cartilage and subchondral bone bruise.</td>
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sicians and trainers, as it allows injured athletes to return to competition as quickly and safely as possible. Nevertheless, there are a number of areas where additional research is needed to further work aimed at reducing both the frequency and severity of first MTP sprains. Five areas for future work are described below and are summarized in Table 4.

A. Epidemiologic data

There is a great need for more information on the precise mechanisms and conditions of injury. Improved epidemiological data could provide further insight into the factors that contribute to first MTP sprains. While limited statistics exist for collegiate and professional football, there is scant information from other sports. Insufficient epidemiologic data are also preventing any assessment of the incidence and severity of turf toe relative to other athletic foot injuries.

Beyond just reporting the injuries themselves, it would be useful to link the details surrounding their occurrence and their severity with suspected or potential contributing factors. Although correlation does not indicate causality, the presence of robust statistical patterns in the data could confirm or disprove existing theories and illuminate additional relationships that need to be further investigated. Because some data already exist for football, epidemiological data would also help us understand whether the rate of injury has changed with improvements in artificial turf and athletic shoe technology over the last two decades.

B. Experimental models

A suite of experimental tests is also needed that can replicate first MTP sprains. Because our limited epidemiological knowledge suggests that hypertonse-related injuries are most prominent, this particular mechanism needs to be initially investigated. Current experimental apparatuses used to investigate first MTP joint mobility might be suitable for the large range of motion needed to cause hyperextension. Whereas the kinematics of the joint may be replicated with these fixtures, very little is known about the muscle and joint forces in the toes during athletic tasks; superimposing representative internal and external forces on the toes will require information from additional experiments and modeling. Nevertheless, experimental tests would provide objective and quantitative descriptions of the mechanisms and kinematics of injury. A suitable injury criterion could subsequently be developed to provide design guidelines for athletic shoe and surface manufacturers.

C. Countermeasures

An improved biomechanical understanding of first MTP sprains would allow for the development of countermeasures to prevent injury. These coun-

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<th>Area</th>
<th>Description</th>
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<tr>
<td>Epidemiologic data</td>
<td>Expand data beyond single teams in men’s football and to additional sports. Link injuries with potential contributing factors.</td>
</tr>
<tr>
<td>Experimental models</td>
<td>Develop an experimental test that replicates first MTP sprains. Study superposition of joint and muscle forces on injury.</td>
</tr>
<tr>
<td>Countermeasures</td>
<td>Engineer footwear that limits hallux ROM to subinjurious levels.</td>
</tr>
<tr>
<td>Numerical models</td>
<td>Develop experimentally validated FEM models of first MTP joint. Evaluate the effectiveness of potential countermeasures.</td>
</tr>
<tr>
<td>Component data</td>
<td>Characterize the failure behavior of the first MTP ligaments. Quantify ligament differences in elderly cadaver and young athletic populations.</td>
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termeasures may take the form of alterations to athletic footwear, to athletic surfaces, or even to the rules governing certain sports. For example, athletic shoes could be designed to limit hallux dorsiflexion to subinjurious levels. The interaction of shoes and artificial surfaces could be engineered such that traction would be lost once some maximum forefoot torsion was achieved. This behavior could reduce the valgus and varus forms of first MTP sprains while also providing protection to athletes’ knees and ankles. Finally, governing bodies for sport could mandate biomechanically based equipment standards to maximize safety while ensuring that all players are performing under consistent restrictions.

Any proposed changes must be examined carefully, however, to understand how other areas may be affected. For example, for factors such as footwear, it is clear that a simultaneous evaluation of protection versus performance must be performed.

D. Numerical models

Numerical models provide a convenient and reproducible method to combine the epidemiological data, biomechanical studies, and in vitro data. Finite element method (FEM) models of the foot can be created to replicate these experimental observations. Once properly validated, such a model could be used to systematically investigate various factors that may contribute to a first MTP joint sprain such as footwear design, shoe playing surface interactions, and variations in foot anatomy. This sensitivity analysis may also be extended to examine more severe first MTP injuries such as dorsal dislocations.80–82 Finally, the FEM models can be used to evaluate the effectiveness of potential methods of injury prevention by quantifying their influence on first MTP response at the tissue level (i.e., stresses and strains within the capsuloligamentous structures, articular cartilage, and periarticular regions).

E. Biomechanical component data

Whereas the advantages of an FEM model are clear, the creation and validation of accurate models requires detailed information about the geometry and material properties of various anatomic structures beyond what currently exists in the literature. For example, no studies are available on the mechanical or failure properties of the ligaments of the first MTP joint. A thorough evaluation of the data needed for modeling, relative to the limited information that has been published, can provide a roadmap for future biomechanical studies.

Moreover, even where data exist, there are significant discrepancies between the experimental and target populations. Cadaveric data are typically obtained using adults with an average age in the 60s or 70s. The athletes who suffer turf toe injuries are not only significantly younger but also more active than this experimental population. Determining and accounting for the effects of age and conditioning, to accurately model young athletes, will be an important consideration to ensure the validity of any computational models.

VI. CONCLUSION

Sprains of the first metatarsophalangeal (MTP) joint, commonly referred to as a “turf toe,” are a debilitating athletic injury. Despite the diminutive size of the hallux, it plays a pivotal role in an athlete’s ability to run, jump, and cut. This review has summarized both the clinical and biomechanical literature relevant to the anatomy and function of the first MTP joint, as well as material specific to turf toe injuries.

The anatomy of the first MTP joint is a complex system of bones, cartilage, ligaments, and tendons. The mechanical behavior and interactions of these components, along with the failure properties, are poorly understood and characterized. In particular, the dimensions, the mechanical behaviour and the failure properties of the joint ligaments must be measured if first MTP sprains are to be modeled.

The kinematics of the first MTP joint are relatively well described. The range of motion and the centers of rotation have all been quantified experimentally; however, the kinetics remain unaddressed. The magnitudes of the forces and mo-
ments on the first MTP joint must be measured to understand the physical limits of these structures. Moreover, whereas first MTP sprain have been suggested to result from hyperextension, hyperflexion, and varus/valgus motions, these mechanisms have yet to be demonstrated conclusively.

Whereas much of the turf toe literature is devoted to the diagnosis and treatment of first MTP joint sprains, very little epidemiologic data exist. The risk of injury in various sports, particularly as compared with other foot and ankle injuries, would enable a thorough assessment of the danger of this injury. Situational factors would also shed valuable light on the biomechanics of injury and on potential strategies for injury prevention.

In light of our critical review, five specific areas for future work have been highlighted, including the need for improved epidemiologic data, the development of experimental and numerical models of injury, the development of injury countermeasures, and the biomechanical characterization of the components of the first MTP joint. These areas must be addressed if reductions in the frequency and severity of first MTP sprains are to be achieved.

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