Toward A Better Understanding of High Ankle Sprains in Athletes: Injury Pattern, Sequence and Tolerance in Combined Flexion and External Rotation

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INTRODUCTION: High ankle sprains, also known as syndesmotic sprains, result in significantly greater time lost and long-term disability than the usual lateral ankle sprain among athletic population, and the incidence rates are believed to be largely underreported [1, 2]. The mechanics of syndesmotic sprains primarily involve external rotation of the foot within the ankle joint, with concomitant particular patterns of ligament trauma associated with foot flexion [3, 4]. A precise description of ankle sprains due to loads generated *in situ* by athletes, which must preclude investigations in injury countermeasures, is absent in the literature. The objective of this study was to determine the relationship between combining foot flexion with external rotation and the associated ligament injury propagation and tolerance.

METHODS: We used a previously developed and comprehensively validated finite element (FE) model of a mid-sized adult male foot and ankle to replicate mechanical characteristics of the ankle and subtalar joints [5] (Fig. 1). It consisted primarily of bony structures, articular cartilage layers and ligaments. The complex geometry and non-uniform loading characteristic of ankle ligaments were taken into account by considering the microstructure as a group of collagen fibers [6]. We modeled each fiber by one-dimensional discrete element, aligned with the longitudinal axis, and utilized nonlinear properties to describe initial strain and sequential uncrimping of the collagen fascicles during tension. To incorporate the progressive nature of ligamentous injury, the limit strain at the occurrence of fiber failure was described by a Gaussian distribution function along the width of the insertion site. Model validation was performed by comparing structural foot responses obtained from a parallel cadaveric investigation (N=3, 54±4 yrs, 178±4 cm; all procedures approved by the University of Virginia institutional review board) using the design by Mait et al. (2015) [7]. Kinetic, audio, and kinematic data were recorded under well-controlled external rotation. The model provided a precise prediction of the measured translation and rotation of ankle bones relative to the tibia and ligamentous injuries identified from post-test necropsies.

To investigate the ligament responses to combining foot rotation, the ankle model was initially positioned in neutral with the proximal end of the tibia fixed. The other bones (fibula, talus, navicular, etc.) were free in all six degree-of-freedom so that their motions were dictated by the ligaments. Flexion angle, ranging from 20° of plantar flexion to 15° of dorsiflexion, followed by a 60° of external rotation of was applied in sequence to the calcaneus quasi-statically. The applied torque to generate the prescribed bony motion was recorded to indicate the injury tolerance of the foot complex. Gross force-elongation behavior of major ankle ligaments was derived from the combination of their fiber elements.

RESULTS: Under externally applied foot rotations, failure occurred to single fiber ('injury initiation') and then propagated across fibers ('injury propagation') to form a complete rupture of the ligament (indicated as the bars in Fig. 2). Compared to a neutral position, plantar flexion or dorsiflexion of the foot resulted in a ligament injury that initiated at a lower angle of external rotation (crosses in Fig. 2). Plantar flexion was protective of the syndesmotic ligaments with the injury initiation at the medial side, with lateral ligament injuries being absent for foot with a 0-12° of plantar flexion prior to external rotation. Dorsiflexion focused loading through the syndesmosis during external rotation; subfailure or failure of the deltoid and/or the lateral ligaments occurred after an almost complete loss of the high ankle ligament. The maximum magnitude of ankle torque ranged from 40 to 70 Nm except for a foot with a plantar flexion angle exceeding 12°, which reveals a significantly higher torque by 40-80 Nm to achieve an external rotation of 60° (circles in Fig. 2).

DISCUSSION: Representation of ligament microstructure as bundles of fibers allowed replication of the *in situ* ligament slack, sequential and heterogeneous uncrimping of collagen fascicles and failure propagation over a wide range of loading conditions. Change in ankle flexion prior to forceful external foot rotation altered the transfer path of force among ligaments and the distribution of loads between the fiber microstructure. This observed trend in change of ligament injuries was also in agreement with recent experimental studies performed in our group. Dorsiflexion widens the ankle mortise as the talar dome is forced into the syndesmotic joint space. As external rotation was applied, the talus created lateral tibiofibular diastasis and led to ankle sprains initiated at the high ankle area. In contrast, plantar flexion moved the talus progressively forward, out of the mortise by the malleoli and the joint, and put the deltoid ligaments in tension. The subsequent lateral motion of the talus elongated the high ankle ligaments, led to evenly distributed force among ligaments and eventually built a higher torque tolerance.

SIGNIFICANCE: The results suggest a mechanism for distributing loads across ligaments and maximizing injury tolerance inherent to a foot and ankle. It also demonstrated the feasibility of biofidelic models to link the gross structural behavior and the underlying ligament mechanics that generate them. Such improved understanding of ankle sprains in athletes is necessary to facilitate treatment by clinicians and countermeasure development by biomechanists.

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Fig.1. The foot and ankle model. Ligaments shown in detail: the anterior tibiofibular (ATiF) ligament at the distal syndesmosis, the anterior talofibular (ATaF) and calcaneofibular (CF) ligaments on the lateral side.

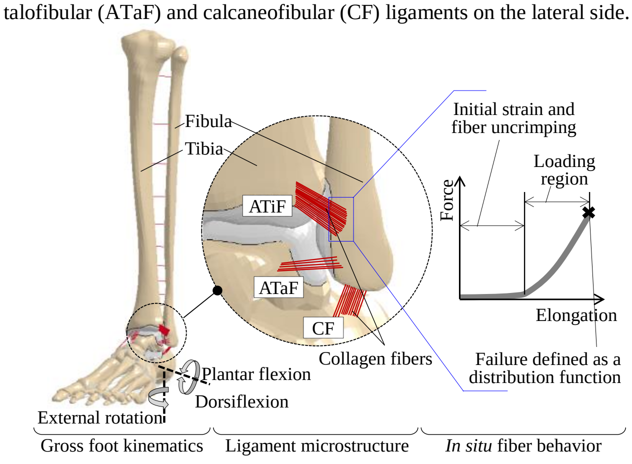

Fig. 2. Ankle ligament injury initiation, propagation and tolerance under a combining flexion with external rotation.