A COMPUTATIONAL MODEL TO INVESTIGATE SHOE AND SHOE-SURFACE INTERFACE EFFECTS ON ANKLE LIGAMENT STRAINS DURING A SIMULATED SIDESTEP CUTTING TASK

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Ankle sprains account for 10% to 15% of reported sports injuries. High ankle sprains are currently thought due to torsional loads and potentially debilitating to the athlete. In the current study a computational model was developed to investigate the human response in shoes on different athletic playing surfaces during a simulated sidestep cutting task. Ankle ligament strains were obtained from the model to help predict ankle injury. The model may provide a computational basis for studying shoes and shoe-surface interfaces that can be used to help optimize player performance and minimize injury risk.

KEYWORDS: ligament, ankle injury, foot constraint, shoe-surface interface, model.

INTRODUCTION: Ankle sprains are one of the most frequent injuries in sports and often account for 10% to 15% of reported injuries (Villwock et al. 2009a). In the National Football League high ankle sprains, also known as syndesmotic sprains, constitute approximately 20% of ankle injuries (Boytim et al. 1991). These injuries receive considerable attention due to their relatively long recovery time. While high ankle torque is implicated as a risk factor, a cadaver study by Villwock et al. (2009a) suggests foot rotation may be a better predictor of injury. In addition, Villwock et al. (2009b) investigated the effects of various cleated shoe designs and playing surfaces on torsional responses using a surrogate ankle. Their study shows that synthetic surfaces yield higher torques and rotational stiffnesses than natural grass surfaces. The study also suggests that a shoe with a pliant upper, allowing more subtalar motion, may provide less foot constraint than a rigid upper, and consequently help protect the foot from rotational injuries.
The objective of current study was to develop a computational model, guided by the above cadaver and playing surface studies, to investigate the effects of foot constraint and shoe-surface interface on ankle ligament strains. The model may have utility in providing a computational basis for shoe and playing surface designs that will optimize player performance and minimize injury risk.

METHOD: Joint anatomical features were taken from one computed tomography (CT) set in the cadaver studies (Villwock et al. 2009a). Detailed features of the ankle were obtained by importing Digital Imaging and Communications in Medicine (DICOM) files of individual CT scans into Materialise's Interactive Medical Imaging Control System (MIMICS) (Materialise, Ann Arbor, MI). This yielded a three-dimensional surface model of the bones as Stereolithography (STL) files. To reduce the size of the surface files and subsequent model, the STL files were remeshed in MIMICS to smooth the surfaces of each bone. Exported files were then imported into the 3-D solid modelling software SolidWorks (TriMech Solutions, LLC, Columbia, MD) as Mesh Files (.stl) (Liacouras et al. 2007). SolidWorks, along with its ScanTo3D package, was used to further construct each bone and simplify the bone surfaces. A rigid plane (200 x 100 x 10 mm) was created in SolidWorks to represent the playing surface. The SolidWorks Motion package was then used to assemble the bones and surface, obtain proper positioning, add necessary components, and run simulations.
The ligaments were represented as linear springs (Fig 1), and their stiffness values, origins and insertions were based on the literature (Liacouras et al. 2007; Netter et al. 2003). The foot model was composed of 14 bones. A compressive pre-load of 1600 N, approximately 2X BW, was distributed between the tibia and fibula. Two kinds of foot constraint were

simulated, representing rigid and pliant shoes. The rigid shoe model had 3 contacts and 10 ligaments. The tibia was fixed in space, and the fibula and remaining bones (acting as a rigid body) were free to move (Fig 1 left). The pliant shoe model had 6 contacts and 12 ligaments. The tibia was fixed in space, and the fibula, calcaneus and the remaining bones (acting as a rigid body) were free to move, allowing subtalar motion (Fig 1 right).

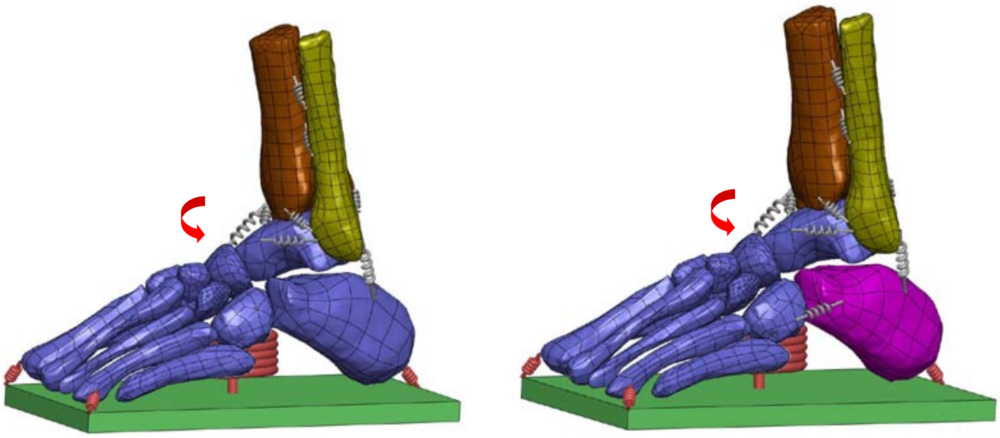

Figure 1. Foot and surface models. Left: rigid shoe; Right: pliant shoe.

The shoe-surface interface was simulated with a torsional spring at the surface center and 3 lateral surface springs, as shown in Figure 1 (red springs). Two kinds of surfaces, synthetic turf and natural grass, were simulated with stiffnesses of 3.6 Nm/deg and 2.2 Nm/deg, respectively, based on the literature (Villwock et al. 2009b). The stiffness of the 3 lateral surface springs was 1 N/mm. A rotary motor was applied to the surface aligned at the ankle center between the malleoli. The external rotation angle was set to 30° to simulate a common sidestep cutting task (Dowling et al. 2010).

RESULTS: Critical ligament strains were measured in the computational models for various test conditions. For clarity, only strains of the ligaments injured in the previous cadaver experiments (Villwock et al. 2009a) were plotted in Figure 2 and Figure 3; namely, the posterior talofibular ligament (PTaFL), the deltoid ligament (representing the anterior tibiotalar ligament), and the anterior tibiofibular ligament (ATiFL).
The maximum strains in each ligament were greater on the synthetic turf than on natural grass, and the order, from the highest to the lowest, was rigid shoe on turf, pliant shoe on turf, rigid shoe on grass, and pliant shoe on grass (Fig 2). This indicated that shoe-surface interface influenced ankle ligament strain and consequently the potential for ankle injury. For the rigid shoe condition, the maximum strain occurred in the PTaFL, while the deltoid ligament experienced the highest strain in the pliant shoe, suggesting that the location of ankle injury might depend on foot constraint. On the same surface, higher ligament strains were developed for the rigid than pliant shoe, indicating that less rotation might be required to fail ligaments with a rigid upper design. Finally, two large changes in ligament strain were noted in the PTaFL, namely, from Rigid/Turf to Pliant/Turf and from Rigid/Grass to Pliant/Grass. Apparently, these were due to foot constraint, and therefore, the effect of foot constraint on ligament strain seemed to be greater for the PTaFL than the other two ligaments. Comparably, significant changes due to surface were noted in both the PTaFL and the deltoid ligament, such as from Rigid/Turf to Rigid/Grass and from Pliant/Turf to Pliant/Grass. This finding indicated that shoe-surface interface affected strains in the PTaFL and deltoid ligament in a similar fashion.
The strain-rotation behaviours of each ligament were plotted in Figure 3. While linear springs were used to represent ligaments in these models, the strain-rotation behaviour was non-linear due to the complex joint geometry.

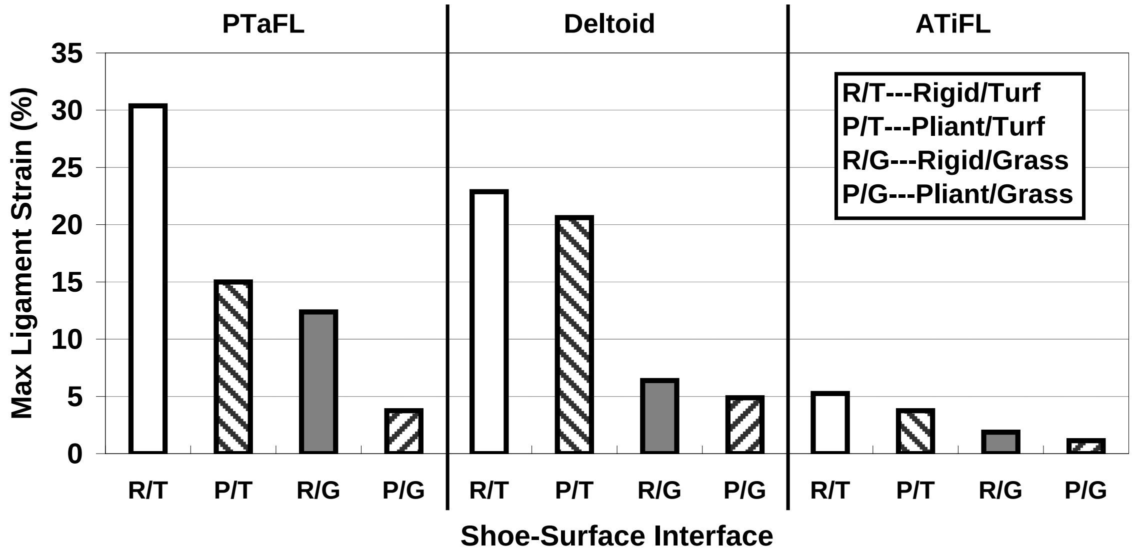

Figure 2. Strains in various ligaments at 30° of external surface rotation for different shoes and shoe-surface interface conditions.

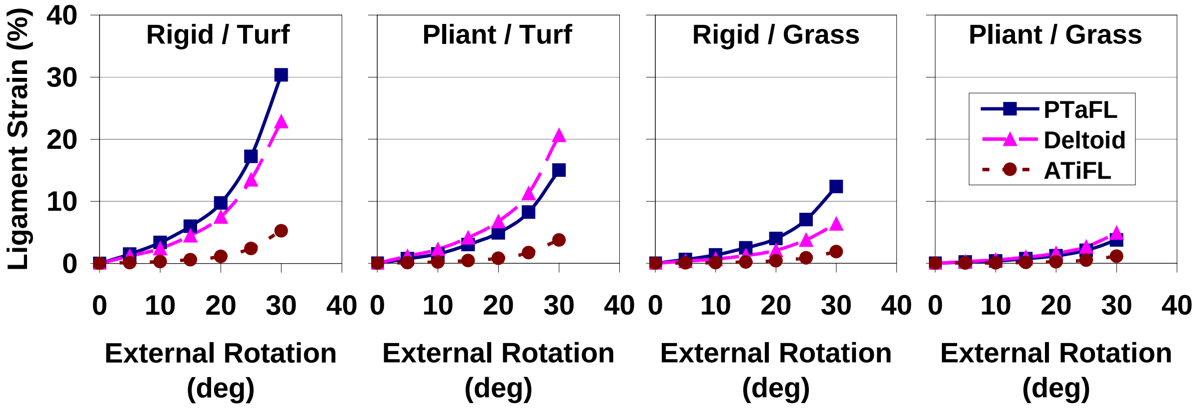

Figure 3. Strains in various ligaments during external rotation of the surface for different shoes and shoe-surface interface conditions.

DISCUSSION: The results from the current models were consistent with ligament injuries in the cadaver study (Villwock et al. 2009a), suggesting that ankle injury depends on foot constraint. Models of the shoe and shoe-surface interface conditions in the current study indicated that larger strains were developed in ankle ligaments on synthetic turf than on natural grass for a simulated sidestep cutting task.

Subtalar motion of the foot was allowed in the pliant shoe model by freeing up the calcaneus (Fig 1 right). Consequently, ankle ligaments in the pliant shoe experienced less strain than in the rigid shoe on the same surface. This agreed with the Villwock et al. (2009b) study suggesting that a pliant shoe upper may help reduce the risk of ankle injury. For performance purposes, however, football and soccer players tend to wear tight fitting shoes with relatively rigid uppers to provide more foot constraint. An in vivo study by Dowling et al. (2010) showed that during the sidestep cutting task, subjects were able to obtain the desired cut of approximately 30° on the high friction surface but only 24° on the low friction surface. Their study, together with Villwock et al. (2009b), suggests that synthetic surfaces with high friction may benefit player performance. Yet, according to the current study, the synthetic turf may compromise ankle mechanics and increase the risk of injury.

A recent study by Drakos et al. (2010) investigated the effect of different shoe-surface combinations on ACL strain and suggests that a cleat-grass interface may result in fewer noncontact ACL injuries than the turf shoe-turf interface. Similarly, Dowling et al. (2010) suggests high friction synthetic turfs may be associated with an increased incidence of ACL injury. While the current study documented only ankle ligament strains, the results support the notion that synthetic surfaces may be a potential risk factor for rotational injuries of the lower extremity, especially when using a rigid shoe design.

Some limitations of the model should be noted. A study by Beumer et al. (2003) determined the strength and stiffness of the tibiofibular and tibiotalar ligaments of the ankle and showed no differences between these ligaments having an average strength and stiffness of 550 N and 98 N/mm, respectively. Ligament elongation at failure was estimated to be approximately 5.6 mm. Based on an estimated length of these ligaments from the current study, this level of elongation may suggest failure strains on the order of 25% to 31%. While this level of strain was predicted by the rigid shoe and synthetic turf condition for the simulated sidestep cutting task, our model did not include any nonlinearity in response of the ligaments. We would suggest future simulations incorporate this well documented nonlinear response of ankle ligaments for failure prediction studies. While cleat pattern at the shoe-surface interface is an important factor in shoe design, its effect on failure analyses is yet unknown and should be studied in the future.

CONCLUSION: Computational models of shoe and shoe-surface interface conditions were developed to measure ankle ligament strains during a simulated sidestep cutting task. The results showed that the maximum ankle ligament strains were generated with a rigid shoe model on synthetic turf. The ability of the current models to incorporate various shoe-surface interface characteristics and show differences in predicted ankle ligament strains was encouraging. While more failure data are needed on ankle ligaments, additional experiments using human cadavers and in vivo tests with human subjects will also be needed to validate computation models. Ultimately, such models may provide a basis for optimizing shoe designs and shoe-surface interface characteristics to enhance player performance and minimize injury risk.

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