# Ligament Wrapping in a Finite Element Model for Predicting Sprains within the Mid- and Forefoot

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## I. INTRODUCTION

Foot and ankle ligament strains are the most common (7–40%) injuries in sport for most disciplines and for all levels of play, with the majority of injuries occurring in the ankle (80–90%), followed by the forefoot, and midfoot [1-2]. Effective treatment and prevention depend on understanding the mechanisms leading to injurious ligament strain, in order to restore native function and prevent recurrence. A common tool for investigating these mechanisms is Finite Element (FE) modeling, wherein a model's ability to predict physiologic function depends on accurate representation of the *in vivo* structures. For the purposes of replicating soft-tissue injury, accurate representation of tissue structure is critical, yet has often proved difficult to model. Specifically, highly curved lines-of-action (LoA), off-axis loading and large ranges-of-motion (ROM) challenge modeling of the *in vivo* environment. Consequently, models created to investigate gross foot kinematics have typically idealised soft-tissue function using limited sets 1-D tension elements with straight LoAs, which offer greatly reduced complexity and cost at the expense of accurate ligament function. Alternatively, when local joint fidelity is paramount, fully 3-D FE representations of the ligaments have been employed with greater complexity and computational time and more limited scope. This study presents a novel and computationally efficient method to model the 3-D in situ function of ligaments as fiber-bundle models (FBM), in order to predict both gross kinematic and tissue-level behaviour in a FE model of the foot and ankle.

## II. METHODS

A high-resolution bony model of the lower extremity was recreated from CT and meshed as rigid shells. Cartilage was incorporated for all joints as a nonlinear viscoelastic material represented by submillimeter hexahedral solid and shell elements. Ligament origins and insertions were determined by dissection and subsequently modeled as evenly spaced parallel bundles of fibers. Each fiber was composed of serial nonlinear tension-only cable/beam elements. Soft-tissue stiffnesses and in situ strains were taken from literature and our previously validated foot and ankle model [3-6]. Element density within each fiber was a constant 1 mm; consequently, longer fibers included more elements than shorter fibers (Fig. 1).

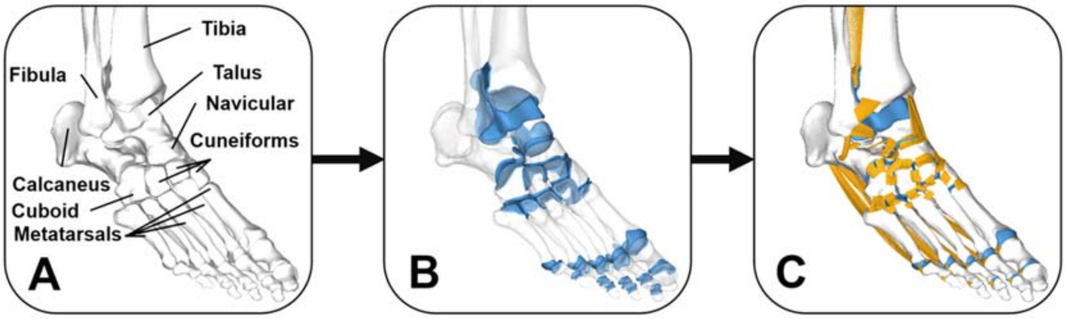

Fig. 1. Lower extremity model creation showing [A] bony reconstruction, [B] cartilage meshing, and [C] ligament wrapping.

A key consequence of having a uniform distribution of intra-fiber nodes is that, despite using a simple 1-D formulation for cable tension, each fiber bundle was able to resist non-axial deformation. This ability to resist mid-substance loads was leveraged to wrap the ligaments. This was achieved by first non-uniformly scaling down each bone around its centroid until no ligaments elements penetrated its surface. Then each bone was scaled-up

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to its original size while simulating contact between the mid-fiber nodes and the bones. Thus, the ligament element mid-substance interacted with, and deformed around, the bones to constrain the paths of the fibers along bony surface contours.

## III. INITIAL FINDINGS

The structure of the wrapped foot and ankle model approximated in situ ligament appearance better than 1-D models with substantially less complexity and computational cost relative to full 3-D FE soft-tissue representation. This effect was generally more pronounced in the plantar structures of the foot under load, as well as following large kinematic motions (Fig. 2).

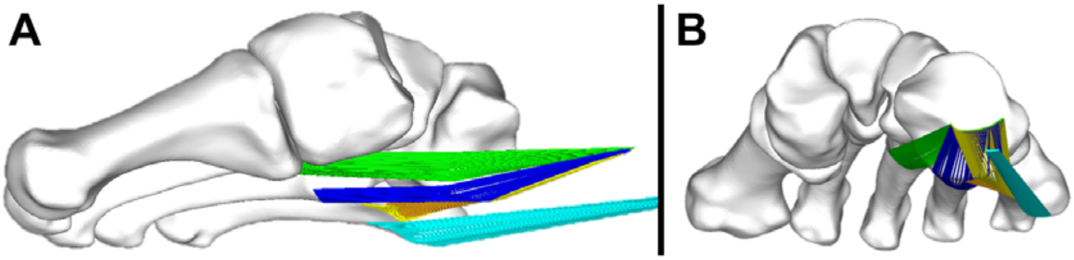

Fig. 2. Plantar midfoot ligament fiber bundles illustrating effect of wrapping: [A] medio-lateral view; [B] postero-anterior view.

Wrapping affected the ligament resting fiber lengths, resulting in increases of up to 2% over the unwrapped model, which alters strain distributions within the tissue. Computational cost for the FBM using this approach, with all ligaments modeled, was approximately two hours per 10 m/s of simulation time. Thus, the FBM is able to capture this in situ wrapping behaviour at a smaller computational cost than more complex, fully 3-D FE ligament modeling techniques.

## IV. DISCUSSION

Prevention and rehabilitation of ligament injuries in the foot and ankle depend on understanding injury mechanisms. FE models offer an attractive means of investigating these mechanisms, but their fidelity is reliant on accurate bony geometry, joint force transmission, contact stiffness, range-of-motion, and ligament-level strain behaviour. The ability to incorporate ligament wrapping that mimics in situ structure affects joint kinematics as well as predictions of ligament strain. In the current work, soft-tissue strain around the ankle syndesmosis, plantar midfoot and Lisfranc joints suggests that wrapped ligaments may be meaningfully more strained under motions relevant to injury, and thus will yield different kinematic tolerances.

These refined predictions have implications for determining kinematic and force tolerance to injury relative to those predicted by 1-D simplifications and thus are important for injury mitigation. The ability of an unwrapped ligament modeling methodology to predict tissue-level failure has been previously evaluated, but the sensitivity of FE models' predicted bone and ligament behaviour to the representation of wrapping remains an area for future research. The methodology described here can facilitate that work.

## V. ACKNOWLEDGEMENTS

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