A Fiber-based Modelling Approach of Ankle Ligaments *in situ*

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I. INTRODUCTION

The ankle is the most vulnerable region in the lower extremity among athletic populations, with ligament sprains accounting for 10–30% of all single-sport injuries [1]. Ankle ligaments are soft, connective tissues consisting of densely packed collagen fibers [2] and exhibit characteristic toe and loading regions. Biofidelic detailed finite element (FE) models provide the capability to characterise the complex geometry and non-uniformity of the loading state built in soft tissues. However, the conventional modelling approaches of ankle ligaments used in sports-related injury studies have been largely limited to simplified geometry and have not been validated at the level of *in situ* ligament behaviour. The objective of this study was to develop a novel ankle ligament modelling approach that could be used to characterise the *in situ* ligament mechanics at the microstructural level during gross foot motions.

II. METHODS

A previously developed foot and ankle model was modified, with particular focus on the microstructure of nine major ligaments [3-4]: the anterior talofibular (ATaF), posterior talofibular (PTaF) and calcaneofibular (CF) ligaments on the lateral side; the anterior tibiotalar (ATaT), posterior tibiotalar (PTaT), tibiocalcaneal (CT), and tibionavicular (TiN) ligaments, which composed the deltoid on the medial side; and the anterior tibiofibular (ATiF) and posterior tibiofibular (PTiF) ligaments that composed the distal syndesmosis (Fig. 1(a)). Each of the major ligaments was represented as a group of collagen fibers, modelled by one-dimensional discrete elements and evenly distributed along the pre-determined insertion widths. The bones were treated as rigid bodies.

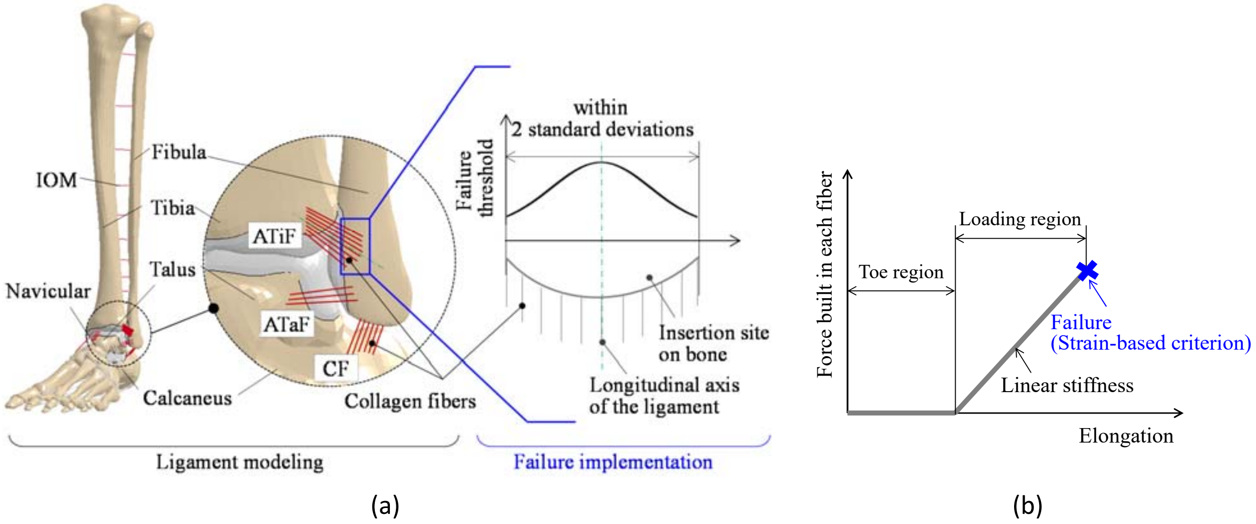

Fig. 1. (a) Major ligaments replicated as a bundle of fiber elements in the foot and ankle model (shown in detail: the ATiF, ATaF and CF ligaments). Failure threshold was implemented as a distribution of the ultimate strain at the fiber level. (b) Mechanical behaviour of one single fiber element (Force-elongation curve).

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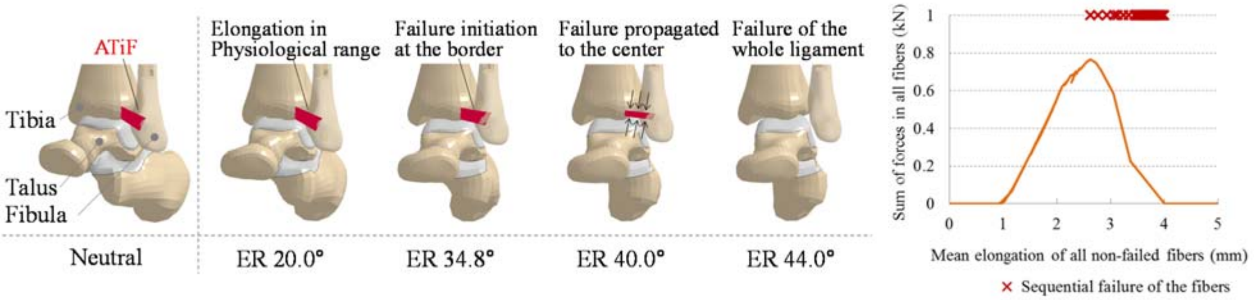
The mechanical behaviour of each fiber element was characterised by a bilinear force-displacement curve with a zero-force toe region and a region of constant stiffness up to failure (Fig. 1(b)). The toe region and the loading region were determined via optimisation driven by experimentally derived bony kinematics [5]. To represent the ligament damage at the fiber level, the failure threshold was built in as a normalised Gaussian function of ultimate strain along the insertion width, with the mean value aligned with the longitudinal axis of the ligament and two standard deviations accounting for half of the insertion width (Fig. 1(a)). For the bony kinematics analysis of the ankle model, the proximal end of the tibia was fixed in space; continuous rotation was applied to the calcaneus to enforce different gross foot motions. Other bones, e.g. the fibula, talus and navicular, etc., were free in all six degrees of freedom (DOF) so that the motion was dictated by the ligaments.

III. INITIAL FINDINGS

The simulation results under different gross foot motions replicated the 6-DOF kinematics of the fibula, talus, calcaneus and navicular and, by implication, the *in situ* deformations of the ligaments. Take the ATiF ligament under external rotation (ER), for example. As the rotation loads were applied, the talus moved towards the fibula, loaded the fibers preferentially along the longitudinal axis (Fig. 2(a)). The tension force within the ligament was built up associated with the fiber recruitment. The addition of the failure threshold as a distribution along the insertion replicated the failure propagation and the associated force reduction as the fiber deformation reached the pre-defined critical value. The gross behaviour of the whole ligament, which was derived from the fibers, exhibited comparable stiffness to existing experimental studies [6-8] (Fig. 2(b)).



(a) (b)

Fig. 2. Simulated response of the ATiF under external rotation: (a) the recruitment of the fiber elements and the subsequent failure propagation as the fibula moved; (b) gross structural response of the ATiF.

IV. DISCUSSION

Ligament modelling, with considerations of the microstructures as functional bundles of fiber elements, provided a biomechanically realistic, interpretable and computationally efficient approach to characterise the *in situ* behaviour of ankle ligaments at loading levels up to and exceeding failure. It allows take-up of *in situ* ligament slack, representation of sequential and heterogeneous uncrimping of collagen fascicles as the external load is applied, and failure propagation as the load increases. The behaviours of this model are consistent with the field observation that ankle ligament injury has a progressive nature, with the initial tear occurring to the fibers at the border. Further investigation is underway to evaluate the injury predictivity along with a parallel experimental study. Applications of this model include functional ankle joint mechanics, injury prevention and countermeasure design for athletes.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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