Incorporating Hierarchical Soft-Tissue Failure in Whole Body Finite Element Models

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I. INTRODUCTION

Whole-body finite element (FE) models are becoming increasingly prevalent tools for assessing injury risk in high-impact scenarios in automotive [1] and military applications [1-2]. Predictions of anatomical kinematic behaviour from human body models such as the Global Human Body Models Consortium (GHBMC) [2] and the Computational Anthropomorphic Virtual Experiment MAN (CAVEMAN) [2] have been validated against post-mortem human subject (PMHS) data, leading to accurate hard tissue (bone) fracture localisation and severity analysis [3]. In contrast, relatively little emphasis has been placed on incorporation of soft-tissue failure models into whole-body simulators. This is partly attributed to the paucity of PMHS soft-tissue failure data, and also due to the complicated mechanics characterising soft-tissue failure [4-5]. Without an explicit failure formulation, soft-tissues in human body models need to be manually deleted to avoid numerical instabilities due to excessive element distortion, or individual elements need to be eroded based on mesh/geometric parameters. Incorporation of physics-based soft tissue failure can have a strong influence on injury localisation and overall load transfer characteristics in the human musculoskeletal system.

In this work, we report preliminary results obtained by incorporating explicit hierarchical failure into existing transverse isotropic (TI) hyperelastic models for use in whole-body FE simulators. We first validated our approach on published experimental data on anterior cruciate ligament (ACL) tear, and subsequently incorporated the failure model into a lower leg CAVEMAN simulation for high-rate impact.

II. METHODS

Incorporation of failure within soft-tissue models is implemented numerically by a modification to the pre-failure constitutive model. Since most biological soft-tissue exhibit anisotropy, failure was incorporated into a TI hyperelastic model originally proposed by [6]. A strain-based failure criterion was used for the fiber and matrix components individually in a hierarchical manner. Local fiber failure in an element is assumed when the maximum principle strain (MPS), given by the largest eigenvalue of the Green-Lagrange strain tensor **E**, exceeds a user-defined strain threshold (*FIBER_FAIL). In the element, the fiber stress is zeroed, while the hydrostatic and isotropic (deviatoric) stresses are retained. Subsequently, if MPS exceeds a second user-defined higher threshold (*MATRIX_FAIL), the entire stress is zeroed, and the element is eroded. An integer state variable, *FIB_FLAG is used to track the state of fiber to ensure that once the fiber fails in an element, the fiber stress is repeatedly zeroed even if the MPS goes below the *FIBER_FAIL threshold.

Numerical implementation of the proposed failure model is carried out in Velodyne®, which is a parallelised explicit finite element solver developed by Corvid Technologies, and has been used for validating the lower leg response to vertical loadings [2]. Validation of the proposed approach is carried out by setting up a virtual matched pair test of a PMHS ACL uniaxial tension test from [7]. Briefly, the simulation comprises two steps, first, a repositioning simulation to orient the knee at 15^o flexion to replicate the experimental setup in [7] (Fig. 1(a)), and second, a uniaxial displacement-controlled motion is applied to the femur while keeping the tibia fixed to load the ACL. The material properties of the ACL were selected from a curve fit carried out by [8].

Additionally, to demonstrate the applicability of the hierarchical failure in a high-fidelity human model, a pendulum impact simulation was carried out on the left lower leg of the CAVEMAN model. The simulation was set up based on an experimental protocol for testing 15 PMHS lower limbs at the Medical College of Wisconsin (MCW) [9]. The upper end of the tibia was potted, while the sole of foot was impacted by a 5.7 kg pendulum with 7 m/sec initial velocity, as shown in Fig. 1(d). In both numerical implementations, the soft tissue were assigned solid hexahedral meshes created in Cubit and TruGrid [2], and the fiber direction in each element of

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the soft tissue components were determined by the nodal connectivity in the element.

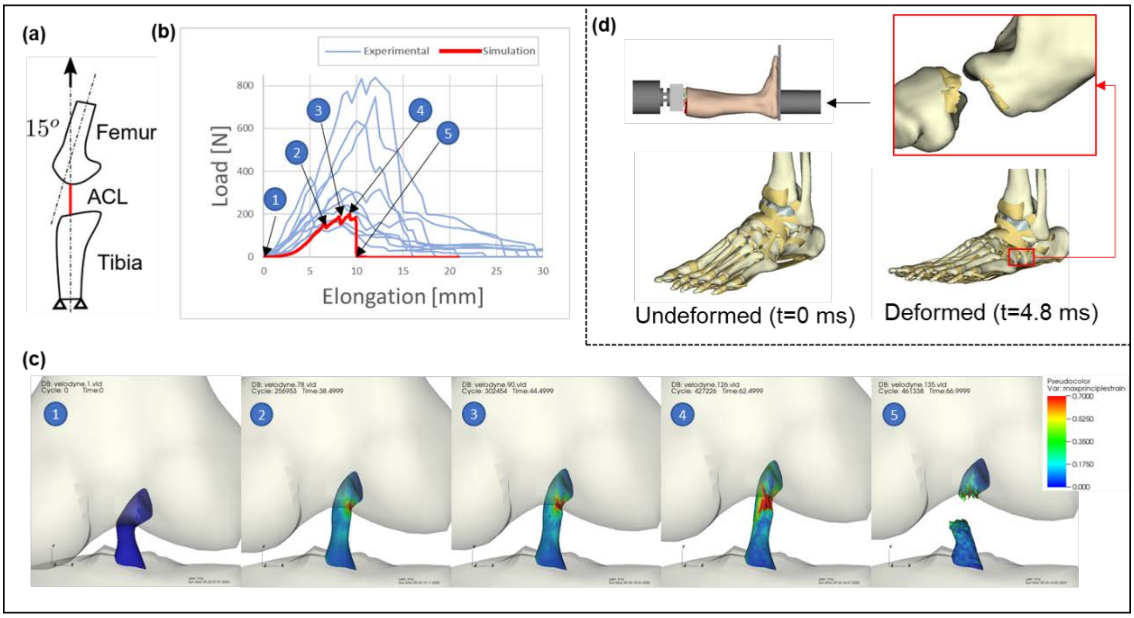

Fig. 1(a). Schematic of the ACL tension simulation setup, (b) ACL Load-Elongation curves for ten ACL specimens with Velodyne simulation, (c) simulation of a mid-substance ACL tear at five time points during the loading process, and (d) CAVEMAN lower leg impact simulation showing tears at the dorsal calcaneocuboid ligaments.

III. INITIAL FINDINGS

The tensile responses from ten ACL PMHS specimens from [7] were superposed with a Velodyne simulation of the ACL tension in Fig. 1(b). The thresholds *FIBER_FAIL and *MATRIX_FAIL were selected to be 70% and 200% respectively to achieve the tensile response shown in Fig. 1(b), which shows good qualitative agreement with the experimental data. Additionally, a non-monotonic sawtooth-like profile could be observed in the tensile response when the fibers of individual elements started to fail, which qualitatively agrees with the experimental tensile response, indicating a multifiber construction of the ACL instead of a single-fiber component structure [7]. The deformation patterns in the ACL at five different time points on the load-elongation curve is shown in Fig. 1(c), from the inception of the tear to the total failure of the ACL, indicating a mid-substance ligament tear. The CAVEMAN lower-leg simulation (Fig. 1(d)) indicates failures in three dorsal calcaneocuboid ligaments. As with the ACL simulation, the thresholds *FIBER_FAIL and *MATRIX_FAIL were selected to be 70% and 200%, respectively. In the absence of a strain-based failure criterion, excessive deformation in these ligaments would necessitate mesh-based element erosion to avoid numerical instabilities. The proposed failure model alleviates these, and early results indicate that the proposed failure model can easily be integrated into existing whole-body simulation studies for injury prediction.

IV. DISCUSSION

In this work, we report preliminary progress towards integration of soft-tissue failure in whole body FE models. Since the failure criterion is incorporated within the material model, minimal changes are required in existing simulation setups, and by using two-failure thresholds, realistic soft-tissue failure can be qualitatively observed. Building upon these results, advanced damage models [5] can be integrated into whole-body FE models, which could potentially elucidate biomechanical characteristics of grades of ligament sprains.

V. REFERENCES

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