Tibia fracture from multi-axial compression-torsion loading: experiment and simulation

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I. INTRODUCTION

Human Body Models (HBMs) are an important tool that is needed to better understand and prevent injuries. The ability of HBMs specifically to predict skeletal fracture, however, has been limited due to the use of simplified constitutive models and failure criteria. Cronin *et al.* [1] has developed a continuum damage-mechanics constitutive model coupled with a fracture criterion based on stress triaxiality, significantly improving fracture prediction in long bones. The model is still limited, however, in accounting for deformation-rate effects, and has not been validated extensively for mixed-mode loading and more complex structures. The aim of this study was to generate experimental data for mixed-mode loading of the whole bone, and use them to evaluate the ability of the damage model to predict failure.

II. METHODS

Materials and Experiment

A skeletally mature ovine tibia, which has similar geometry and material properties to the human tibia [2], was dissected of all soft tissue and the periosteum. The sample had been fresh frozen at -20°C, thawed at room temperature prior to testing, and kept moist with sprayed phosphate buffered saline during testing. The 217 mm long tibia was potted at both ends with polymethylmethacrylate and secured into the testing machine (Fig. 1A).

A servohydraulic Instron testing machine (Instron 8874) was used to apply simultaneous compression and torsion to the sample at rates of 0.5 mm s^{-1} and 0.1 deg s^{-1}. A pair of high-speed cameras (Phantom VEO 710, 960 × 216 resolution, 24700 fps) and a custom-made biplanar fluoroscopy system (VJ Technologies, 90 kVp / 100 mA X-ray production with detection resolution 808 × 256 and 13000 fps) were used to observe the response of the sample under load (Fig. 1B).

Computational Simulation

A finite-element (FE) model of a tibia was extracted from a contemporary small stature female HBM (GHBMC F05 v6.0, Elemance). The model of the tibia was scaled down in three dimensions such that the total length corresponded to that of the experimental specimen. The experimental boundary conditions were replicated. The material and damage-model parameters from [1] were used in the model. In addition, a multi-physics technique incorporating smoothed-particle hydrodynamics (SPH) was incorporated for modelling hard-tissue fracture in compression [3].

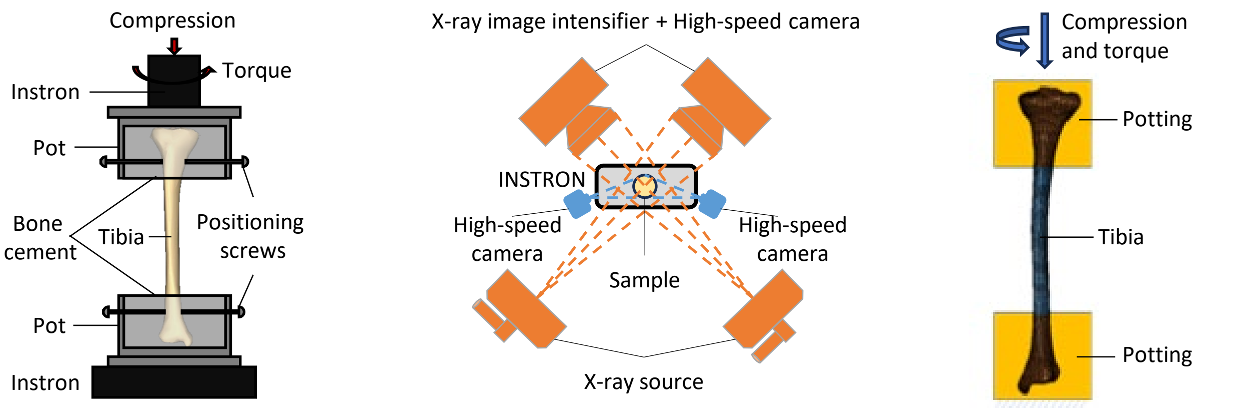

Fig. 1. (A) The potted tibia sample, (B) schematic of the experimental set-up, and (C) the computational model

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III. INITIAL FINDINGS

During the combined compressional-torsional loading, the tibia sample underwent a displacement of 4.4 mm axially and 0.84° rotationally prior to failure. The bone experienced a maximum compressive force of 14.8 kN and a maximum torque of 1.86 Nm. Snapshots from the high-speed footage of both the visible-light cameras and the X-ray imaging (Fig. 2) show the bone failure initiation and crack propagation; the failure initiated with a transverse fracture at the mid-diaphysis followed by the development of oblique cracks axially. The process resulted in comminution, including the generation of wedge-type fragments. In a similar manner, the FE model predicted fracture initiation at the mid-diaphysis, at an axial load of 12.8 kN and a torque of 1.9 Nm, followed by comminution of the material in the vicinity of the fracture (red SPH particles, Fig. 2C).

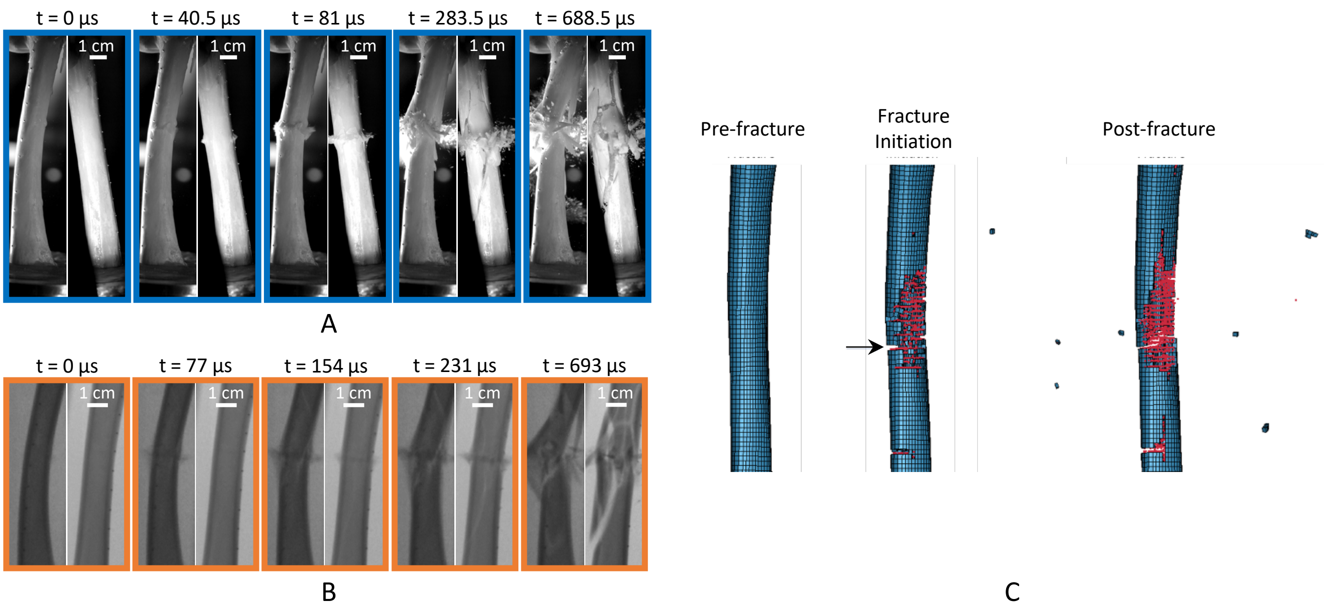

Fig. 2. Snapshots from (A) high-speed cameras, (B) X-ray high-speed camera detectors, and (C) FE model

IV. DISCUSSION

This preliminary study demonstrates the complex nature of the fracture process in a long bone subjected to mixed-mode loading. The majority of the applied load was axial compression with a small amount (relative to the axial load) of superimposed axial torsion and, because of the shape of the tibia, bending. The mechanism of the observed transverse fracture is unclear since a predominant compressive load should lead to oblique fracture, and bending superimposed on compression should lead to a butterfly fragment. Following the transverse fracture, ongoing compression led to impaction of the mid-diaphysis, where the two bone ends are driven into each other pushing the material outwards and causing fractures to run longitudinally in the bone.

The FE model predicted a comparable fracture pattern to the experimental test, with a transverse fracture initiating near the mid-diaphysis, followed by comminution of the material in the vicinity of the fracture, and extension of the fracture, along the long axis of the bone, away from the initiation site. The predicted axial load at failure was lower than the experimental value likely owing to a lower cross-sectional area of the tibia model resulting from the scaling. The SPH implementation allowed for visualization of the comminuted material and the predicted fracture was computationally stable over long simulation times.

The immediate next steps are to carry out experiments with more samples to provide robust experimental corridors against which FE models, including specimen-specific, can be compared and the damage model further examined. Future work will focus on 3D reconstruction of the crack tips to estimate the velocity of crack propagation. The experimental protocol is planned to be extended to include tension and shear in combination with torsion, thus providing a larger pool of relevant experimental corridors.

V. REFERENCES

[1] Cronin, D S, *et al., Front Bioeng Biotechnol*, **10**, 3389 (2022).
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[3] Ngan, S, *et al.*, *J Mech Behav Biomed Mater*, **151**, 106412 (2024).