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An FE-Experimental method for determining qCT-based cortical bone fracture toughness and ultimate stress

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Abstract
Cortical bone fracture prediction using Phase Field Models (PFMs) requires the data on the spatial distribution of bone fracture toughness and ultimate stress. However such correlations with qCT parameters or associated bone density are not yet available in the literature. Here, we proposed an FE-Experimental method to determine bone fracture toughness and ultimate stress for different densities and find out potential correlations. Digital Image Correlation (DIC) and diverse standards for K_{Ic} calculation show values ranging from 2 to 9 $MPa\sqrt{m}$. Although it is consistent with reported data in the literature, further work is being conducted using qCT-scans and micro-CT data as well as Finite Element Analysis (FEA) to estimate bone density and determine more accurately the associated fracture toughness and ultimate stress.

1. Introduction

CT-based FEA based on maximum principal strain criterion can predict fracture initiation load with 80% accuracy (conservative prediction) [1]. It cannot predict the crack path which may also be of interest for clinical application. PFMs may improve bone fracture predictions [2,3], however, PFM predictions are highly influenced by the heterogeneous critical Energy Release Rate (ERR) G_c, critical ultimate stress and Young modulus of the bone. In an attempt to improve fracture initiation and crack path prediction in human long bones by PFM we apply numerical-experimental methods to determine the material properties of bone tissue so to be used in conjunction with CT-based FEA. We first focus on the femoral cortex and failure in the transverse direction (perpendicular to osteons). Human fresh frozen femurs were CT-scanned to obtain bone density along the femur, then sliced to create three point bending specimens in which crack like defects were inserted. These specimens were then micro-CT scanned before being loaded to fracture. Since the specimens are highly heterogeneous and the specimens cannot be manufactured to be precise, FE methods must be used to determine G_c and critical ultimate stress while displacements are measured by DIC methods. Young modulus of the bone may be determined by correlation to qCT scans [4,5]. No standards are available for the determination of bone fracture toughness, so we used the standards for metal and concrete to compute the critical Stress Intensity Factor (SIF) K_{Ic} by a three-point bending test setup. These standards have been used in previous works ([6,7]) but we apply the DIC technique to estimate the Crack Opening Displacement (COD) involved in K_{Ic} determination and to perform post-processing FEA.

2. Preliminary results

Force-displacement curve and COD have been determined using Instron 68TM-30 testing machine (25 kN load cell capacity) and DIC on a cortical specimen extracted from a human femur– see Figure 1. This preliminary experiment was used to determine the feasibility of the methods.

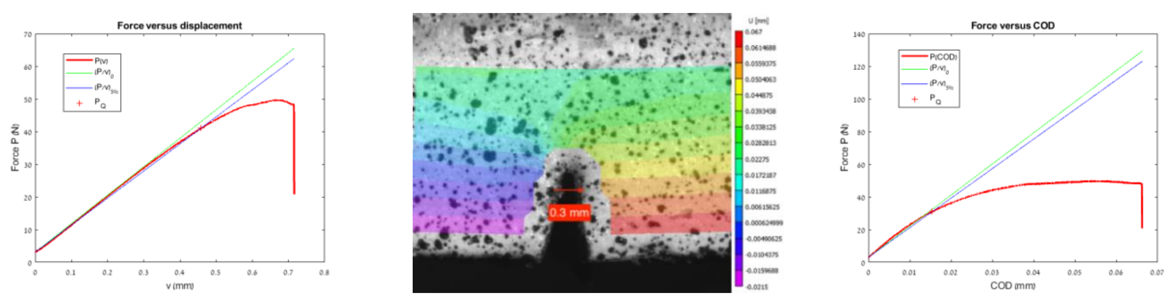

Figure. 1 – Bone specimen under three point bending test. (Left) Force-displacement curve. (Center) Horizontal displacement from DIC to measure COD. (Right) Force-COD curve.

3. Further work

New specimens were prepared from a human femur that was qCT-scanned and tested according to the flowchart below – see Figure 2. Fracture toughness and ultimate stress determination are under investigation and will be reported in this talk. These will be used in the PFM framework to determine the failure load and failure location of femurs and humeri.

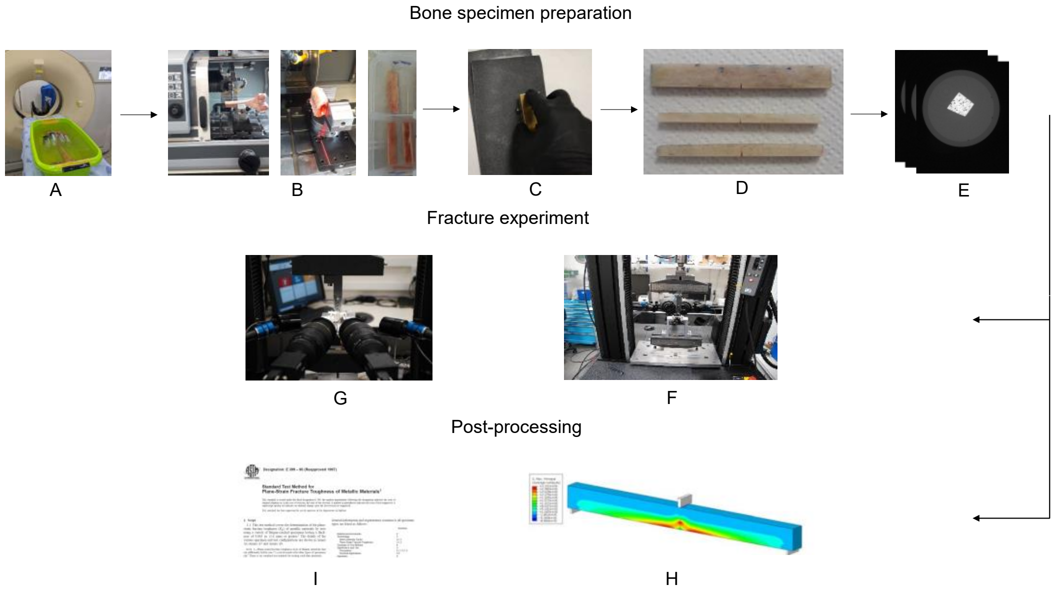

Figure. 2 – Flowchart of the experimental method. (A) Clinical CT scan of a human femur, (B) Bone cutting into rough specimens, (C) Specimen polishing, (D) Specimen notching, (E) Specimen micro-CT, (F) Three-point bending setup, (G) DIC setup, (H) Illustration of FEA, (I) Existing standards ASTM E399-90 for metallic materials

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