Validating Stiffness of Bovine Trabecular Bone Cores from FEA Simulations in Abaqus with 3D Printed Models

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INTRODUCTION: Osteoporosis is a skeletal disease that causes bone deterioration and increases fracture risk [1]. Finite element analysis (FEA) and mechanical testing can inform the understanding of the biomechanical behaviors of bone and orthopedic treatments. The heterogeneity of bone mechanical properties makes experimental validation bone FEAs difficult [2]. Three-dimensional (3D) printed bone models with known and homogeneous material properties offer an opportunity for experimental validation of bone FEA mesh and boundary conditions. The objective of this study was to validate the FEA compression stiffness of trabecular bone cores against the measured stiffness of 3D printed trabecular bone cores.

METHODS: Twenty-three viable trabecular bone cores (height = 10 mm, diameter = ø 10 mm, n = 23) were excised from 18-month-old bovine sternum within two hours of slaughter for *ex vivo* testing as described in [3,4]. After completion of the *ex-vivo* experiment, all surviving bone cores were submerged in 70% ethanol solution and micro computed tomography (µCT) scanned using the Vector4CT pre-clinical scanner (MILABS B.V., Utrecht, Netherlands). Bone core µCT data were segmented in Materialise Mimics (Version 23.0) using a threshold of 200-5600 Hounsfield Units and region grow. The 3D surfaces were transferred to 3-Matic (Version 15.0) to reduce mesh sizes to allow for computational efficiency and to 3D print the samples (Fig 1 left). Ten bone cores, exported as STL files from 3-Matic, and five identical cylindrical material testing samples (height = 12 mm, diameter = ø 6 mm, n=5) were printed with an Objet30 Prime 3D printer and RGD525 and SUP706B support material (Stratasys, Edina, MN, USA). After printing, all visible exterior and interior support material was removed using a pick tool and SCA-1200HT support cleaning apparatus. Remaining support material was removed using a high-pressure water jet. The cylindrical material testing samples were compression tested to determine the elastic modulus for RGD525 for the FEA simulations. Quasi-static compression testing was performed at room temperature on a Mach-1 materials testing system (Biomomentum). Displacement was applied at rate of 0.02 mm/s after 10 N preload to a maximum force of 220 N. Mechanical testing system compliance was found using aluminum reference bodies and was accounted for in all mechanical tests [5]. The 3D surface models from Materialise Mimics were exported to Abaqus FEA (Version 2017). Uniaxial compression was completed with the compression pistons modelled as rigid bodies with 0.1 coefficient of friction at the interface. The top piston was displaced in uniaxial compression to -4000 µε. The bottom piston was fixed in all nodal degrees of freedom. The mechanical properties were assumed linear-elastic, isotropic and homogeneous. The experimentally determined elastic modulus, 1702 MPa and Poisson's ratio of 0.3 were assumed for the 3D printed material. Quasi-static compression testing was performed for each 3D printed bone core, with a preload of 10 N, followed by an applied strain of -4000 µε at a loading rate of 20 µε/s on the Mach-1 materials testing system (Biomomentum).

RESULTS: FEA predicted trabecular bone core stiffness was correlated with the experimental measurements ($R^2 = 0.92$, Fig 1 center). The median stiffness for the FEA simulations (n=10) was 829.7 N/mm (IQ 604-1380 N/mm) and the median stiffness for the experimental mechanical testing (n=10) was 824.3 N/mm (IQ 733-1260 N/mm) (Fig 1 right). The FEA predicted stiffness was not different from the measured stiffness (p = 0.88, non-parametric test). Therefore, the FEA mesh and boundary conditions were validated against the compression test results of the 3D printed trabecular bone core.

DISCUSSION: There were several limitations in this study. For the FEA, the 3D printed trabecular bone cores were assumed to have linear-elastic, isotropic and homogeneous mechanical properties. Only 10 cores were analyzed. The element size was increased to decrease computational resources. 3D printed trabecular bone cores with homogeneous material properties are an opportunity to validate the mesh and boundary conditions of µCT-FEAs.

SIGNIFICANCE/CLINICAL RELEVANCE: This study demonstrated a process to validate the mesh and boundary conditions µCT-FEAs. Accurate µCT- FEAs can assist in developing therapeutic strategies for the treatment of skeletal diseases like osteoporosis.

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IMAGES AND TABLES:

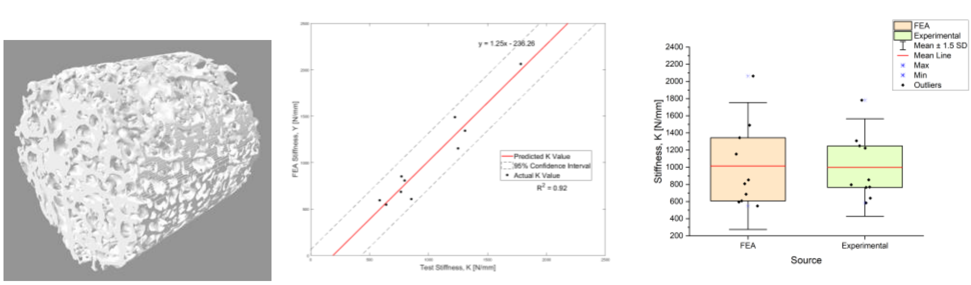

Figure 1. Left: Example model of trabecular bone core. Center: Linear correlation between FEA predicted and experimentally measured stiffness. Right: Box Whisker plot of FEA predicted, and experimentally measured stiffness of 3D printed trabecular bone cores.