Diametral Compression: Computational and Experimental Investigation of a New Bone Strength Test
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Introduction: Whole-bone four-point bending and other tests are used for strength testing of long bones, but recently diametral compression of short sections has been used to quantify transverse tensile strength of osseous tissue (Rudnick et al, 1963, ASTM, 2003). Testing of biologically-derived samples adds a number of complications, such as the non-circularity of bone sections, ambiguity of load orientation during testing, and variation in size and shape between sections in a sample and in thickness within a single section. Previous computational analyses of sections from human and ovine femurs and tibiae have indicated that arbitrary mid-diaphyseal bone sections may be compared, and section shape variation along the bone can be accommodated (Womack et al, 2007). Additionally, it has been shown that the aspect ratio, thickness, and thickness variation of cross-sections can be accommodated. In order to validate and expand on the previous computational results examining the viability of diametral compression testing of arbitrary bone sections, specimens from various animal models were evaluated and compared using physical, computational, and analytical methods.

Materials and Methods: Seventy-nine transverse slices (5.0 mm thickness) were sectioned from the mid-diaphyseal regions of ovine and bovine femora and tibiae, and were collectively scanned using qCT. Radiographic data were used to generate 2-D transverse sectional geometries, from which unique finite element models of each sample were generated using an automated gradient-based algorithm. The maximum stability load configuration was used in all physical tests, and duplicated in the computational models (Figure 1). Physical specimens were compressed diametrally until fracture, and each computational model utilized the measured failure load and sample width from the corresponding physical test. Correspondence of geometry and load orientation between the physical and computational states was verified by independently measuring the vertical and transverse spans and load orientation using manual and computational means. Load orientation was correlated by independently registering the sample alignment in qCT to both the FE models and physical tests. Bone was modeled as linearly elastic and transversely orthotropic, and large-deformation theory was applied.

Results: Previous computational work has shown that the maximum principal stresses for elliptic and anatomic sections under diametral compression are dependent on thickness, whereas aspect ratio has little effect. For anatomic sections, the mean thickness was the strongest factor affecting stress, and variation in the data was largely attributable to local thickness variations. In this work, the maximum principal stresses were consistently developed on the endosteal surface adjacent to the points of contact. Direct observation during the physical experiments revealed correspondence between the fracture initiation sites during physical tests and the locations of maximum principal stress in the computational models, supporting the use of the method with non-circular anatomic sections.

Discussion: The agreement between analytical and computational measures of transverse tensile strength observed during physical tests indicates that the simple analytical measure of strength can be used along with diametral compression testing to reliably measure transverse tensile strength of bones sections. The value of consistent section orientation during testing was observed, in agreement with previous work, as local geometric variations tended to be fairly consistent between slices.

The computational method used did not account for post-yield mechanical behavior, while slight yielding was apparent during the physical tests. Inclusion of nonlinear material behavior will reduce the maximum principal stresses predicted computationally, which is expected to improve the agreement between analytical and computational measures. In order to quantify the post-yield behavior of these bones for inclusion in the models, mechanical tensile testing of transverse dog-bone specimens is currently underway. The agreement between the analytical and computational methods in both the magnitude and variance of the maximum principal stresses supports the use of diametral compression as a means of determining transverse tensile strength in order to quantify the effects of injury and/or treatment on long bone material properties.


Figure 1. Computational and physical tests for a representative sample from bovine tibia.

Figure 2. Transverse tensile strengths of various bones obtained via computational (darker bar) and analytical (lighter bar) methods.

High correlation ($r^2=0.82$) was observed between analytical and computational measures of transverse tensile strength, which were within 1.2 standard deviations for all groups. Mean computational strength was 11% higher than mean analytical strength. Analytical strength exceeded computational strength only for bovine tibia, which also exhibited the greatest geometric deviation from circularity (Figure 2).

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