Estimating Bone Stiffness in the Proximal Humerus using Single Energy CT and Internal Density Calibration for Stemless Shoulder Arthroplasty

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Abstract: Shoulder arthroplasty is a common surgical treatment for individuals with end-stage osteoarthritis (OA) within the glenohumeral joint. New stemless humeral components require only the removal of diseased bone for fixation to the proximal humerus, thereby preserving non-diseased bone for future surgical revisions. However, current pre-operative clinical measures of bone quality fail to account for the mechanical properties of the bone in the region directly supporting the component. The purpose of this study is to determine the predictive value of proximal humerus bone stiffness in patients undergoing shoulder arthroplasty for end-stage OA with patient-specific validated computational models created from retrospective pre-operative single energy computed tomography (CT). Quantitative information from single energy CT images will be used to determine vBMD and FEM estimated stiffness values in the proximal humerus. This is a first step in predicting bone strength through patient specific CT images.

Introduction

Individuals in need of shoulder replacement surgery, also known as shoulder arthroplasty, often have bone diseases such as osteoarthritis (OA) which alters the bone density and morphology of the humeral head, altering bone stiffness and strength (Knowles et al., 2020). Bone stiffness and strength are strongly correlated to bone morphology and density in OA populations, and link quantitative bone parameters to bone mechanics. A decrease in bone stiffness and strength directly compromises the long term surgical success of shoulder arthroplasty, increasing the need for surgical revisions (Knowles et al., 2020, 2022; Kusins, Knowles, Martensson, et al., 2022; Kusins, Knowles, Targosinski, et al., 2022; Zhang et al., 2020). New stemless humeral components require only the removal of diseased bone for fixation to the proximal humerus, thereby preserving non-diseased bone for future surgical revisions (Tabarestani et al., 2023). However, current clinical measures are poor predictors of bone mechanics since they do not account for the mechanical properties of bone in the specific region supporting the humeral component. While several studies have compared diseased bone relative to non-diseased bone in the humeral head (Blakeney et al., 2021; Knowles et al., 2016; Reeves et al., 2018, 2021), validated models that link bone mineral density, and mechanical properties of bone while incorporating patient demographics and outcomes, in patients undergoing shoulder arthroplasty, have yet to be compared.

Additionally, while phantom calibration is the gold standard for determining volumetric bone mineral density (vBMD) from a clinical CT image, most clinical CT images are taken without a phantom (Michalski et al., 2020), requiring alternate methods for accurate BMD across individuals (Matheson et al., 2024). Recently, an internal density calibration method has been developed that uses internal tissues as references to establish the linear standardized relationship for subject specific CT images (Michalski et al., 2020). While this method has been validated in the spine and hip, it has yet to be validated in the proximal humerus. This validation is needed since attenuation values are skeletally site-specific and differences in anatomy can lead to challenges in selecting referent tissues.

The purpose of this study is to determine the predictive value of proximal humerus bone stiffness in patients undergoing shoulder arthroplasty for end-stage OA through patient-specific validated computational models created from retrospective pre-operative single energy computed tomography (CT) images using both phantomless and phantom-based measures of volumetric bone mineral density (vBMD). Quantitative information from single energy CT images will be used to compare vBMD and FEM estimated stiffness within proximal humerus sections.

Methods

Validating Internal Calibration

The first step of this study was to determine the correlation between vBMD from phantom density calibration and internal density calibration in the proximal humerus. Non-pathologic cadaveric single-energy computed tomography images containing a liquid dipotassium phosphate phantom (K_2HPO_4) were taken from a pre-existing cadaveric database (n = 42). The proximal humerus was segmented within each image using a semi-automated method of applying a Hessian-based bone enhancement filter combined with a graph cut technique (Besler et al., 2021; Boykov & Funka-Lea, 2006). A 10 mm region was aligned directly below the anatomic neck and a Boolean subtraction was applied to isolate a common volume of interest (VOI) for analysis. Phantom calibration was performed by manually identifying the phantom rods in each specimen. For internal calibration (Michalski et al., 2020), air, adipose, and skeletal muscle were segmented manually, then the humerus was thresholded to determine the highest HU value between 1000 – 1500 HU for cortical bone. The isolated VOIs were overlayed with the specimen specific density calibrated images for both the phantom and internal calibration to yield vBMD.

FEM Generation

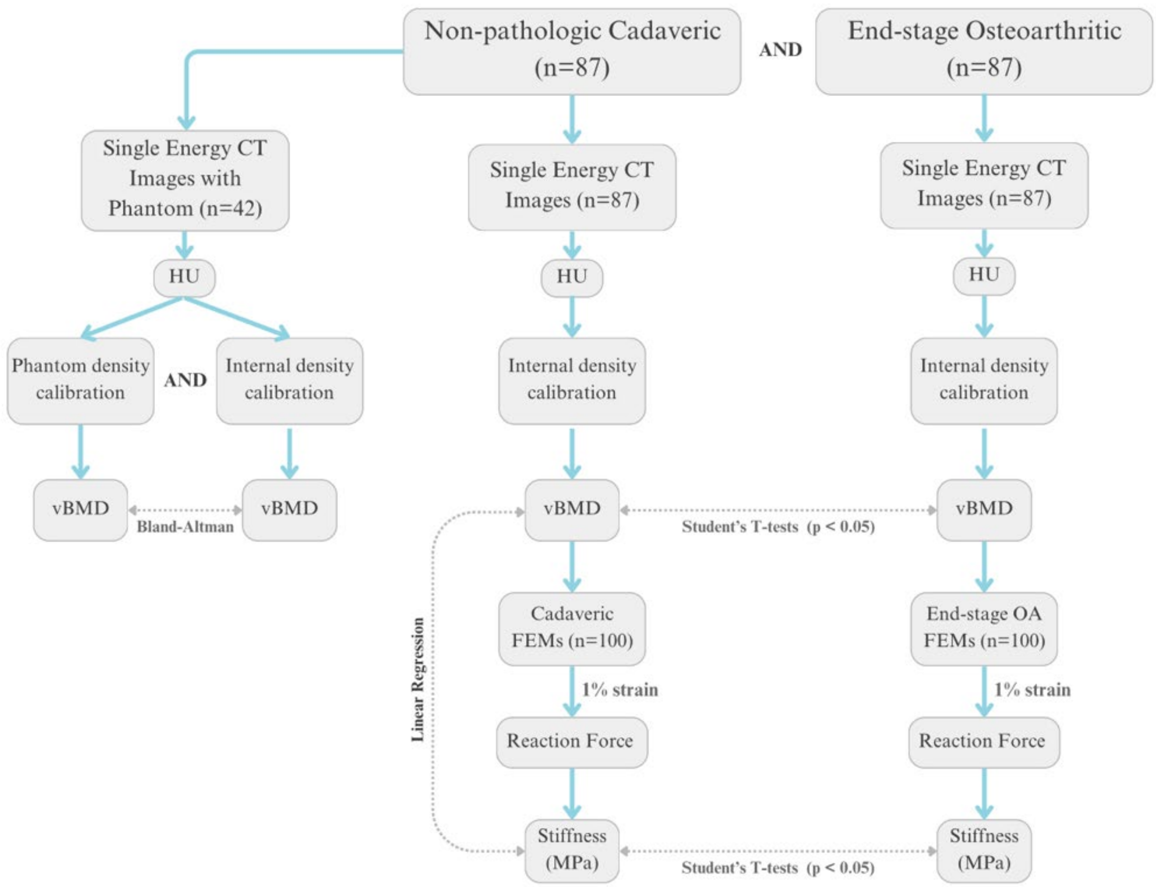
Retrospective clinical CT images from patients who have previously undergone shoulder arthroplasty to treat end-stage OA in the glenohumeral joint (n=87) will be compared to a group of age- and sex-matched non-pathologic cadaver CT images selected from a pre-existing cadaveric database (n=87). All images (n=174) were captured using the GE Discovery CT750 HD scanner and reconstructed using the Boneplus convolution kernel. Internal calibration will be performed in each image according to the method outlined above. The proximal humerus will then be segmented manually using Mimics. A 10 mm region will be aligned directly below the anatomic neck and a Boolean subtraction applied to isolate the common VOI. VOIs will be overlayed with the specimen specific internal density calibrated image to yield vBMD. A volume mesh of the VOI will then be generated, and material properties assigned in Bonemat. A finite element model generated in Abaqus will apply a 1% apparent strain to yield an apparent stiffness value.

Statistics

Results from the internal validation step were compared using linear regression and Bland-Altman analysis. Future results from the FEM will be assessed using two-tailed independent samples student's t-tests to determine the difference between vBMD and stiffness values in the end-stage OA group vs. values in the non-pathologic cadaveric group. For both the end-stage OA group and the non-pathologic cadaveric group the degree of variation in stiffness relative to variation in vBMD will be determined using simple linear regression.

Figure 1

Flow chart depicting methods and statistical analysis



Results

Linear regression (y = 40 + 0.86x) showed a strong correlation between vBMD values from phantom and internal density calibration (R^2= 0.9) and a slope not significantly different from 1 ($p < 0.001$) (See Figure 2). Bland-Altman analysis revealed a mean bias of 19.77 mgK_2HPO_4/cc with 95% limits of agreement ranging from -7.50 to 47.05 mgK_2HPO_4/cc (See Figure 3). On average internal density calibration overestimated phantom-based vBMD.

Figure 2

Association between vBMD values from internal and phantom calibration

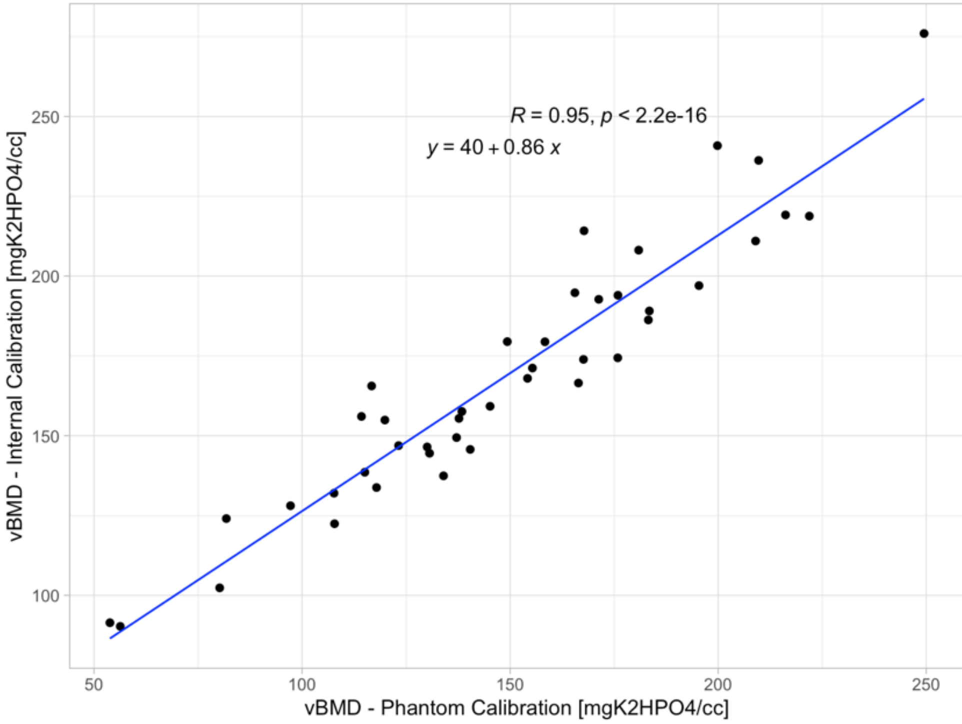
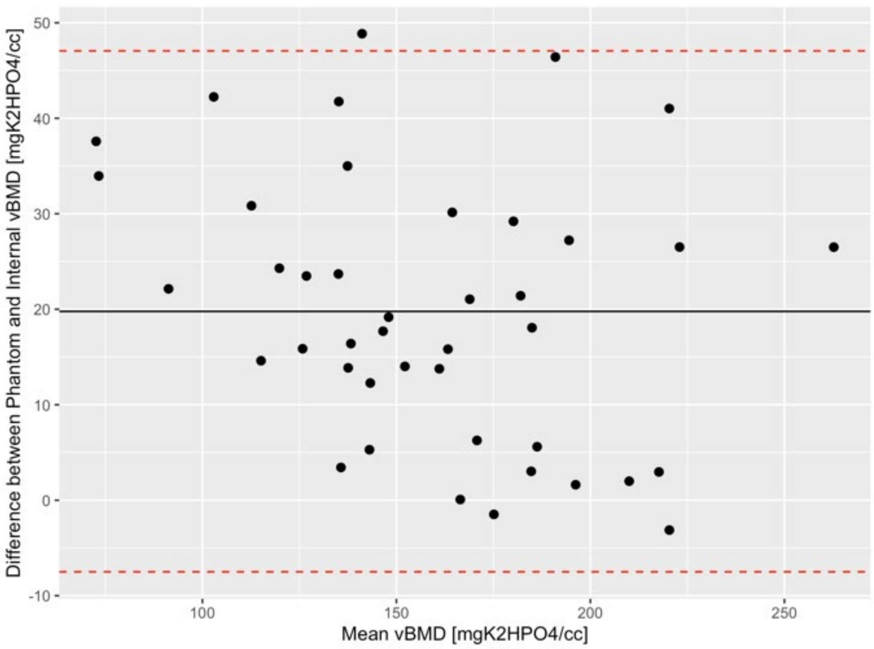


Figure 3

Bland-Altman plot for vBMD values for phantom vs. internal calibration



*Red dashed lines indicate ± 1.96 standard deviations (SD) of the mean (solid black line)

It is expected that vBMD and stiffness values will be lower in the ed-stage OA group compared to the non-pathologic cadaveric group. It is anticipated that there will be a strong correlation between vBMD, and bone stiffness in both the end-stage OA and non-pathologic cadaveric groups, but the slopes and intercepts between groups will differ.

The results of this study support the use of internal density calibration as a valid method for determining vBMD in the proximal humerus. Clinically, this provides a solution for determining bone mineral density in patients undergoing shoulder arthroplasty for end-stage OA where phantoms were not present in the CT images. The benefit of using bone stiffness as a predictive measure of bone strength is that it allows for both the morphology and the mechanical properties of the bone segment to be considered, reducing the ambiguity of using vBMD alone. Considering the mechanical behavior of the proximal humerus allows for a practical application of bone stiffness in the context of shoulder arthroplasty. In future, this method may be used for retrospective analysis, clinical diagnosis, and preoperative planning for shoulder arthroplasty.

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