Opportunistic use of clinical CT-based FE modeling to assess fracture during sideways fall in hip osteoarthritis

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INTRODUCTION: Osteoarthritis (OA) is a currently incurable disease characterized by structural deterioration and loss of function of synovial joints, such as the hip. While OA is generally thought to be inversely associated with fracture [1-3], other studies have challenged the idea that OA is protective against fracture [4-6]. Additionally, hip fractures tend to be in a different region of the femur – trochanteric rather than femoral neck – with OA [7,8]. These findings suggest that OA may alter mechanical loading and failure mechanisms within the proximal femur, changing which regions are most predisposed to failure while also not lowering the risk of fracture. Finite element (FE) modeling of computed tomography (CT) scans is a commonly used research tool to assess bone strength and fracture risk at the hip; however, the possibility of using CT scans collected without a calibration phantom would substantially increase the number of individuals who can be screened, as scans obtained for other reasons can be used "opportunistically" to build the FE models [9]. The goal of this work was to use CT-based FE modeling to investigate OA-related alterations in mechanical loading within the proximal femur during sideways falls and whether those alterations may modulate which regions are at greatest risk of hip fracture.

METHODS: Under IRB approval, CT scans were obtained from OA patients (n=5, 2F/3M, age (mean ± stdev) = 47.0 ± 22.5 years) undergoing elective total hip arthroplasty. Scans were also performed on non-OA cadaveric femora (n=13, 6F/7M, age (mean ± stdev) = 54.5 ± 17.1 years) immersed in water. The geometry of the proximal femur was converted to a second-order tetrahedral volume mesh (mean element size = 2.5 mm) (MITK-GEML, SimTK). Phantom-less CT calibration was achieved by referencing air, adipose tissue, and skeletal muscle in the pre-operative OA patient scans to convert grayscale values to apparent density (mgHА/cm) [9]. For the cadaveric femur, a density calibration phantom enabled conversion of CT density to apparent density [10]. Element-wise material property assignments followed an established density-modulus power relation [11] and a Poisson’s ratio of 0.3. Boundary conditions representative of sideways fall 10-deg abduction and 15-deg internal rotation were applied to the femur [12] with the distal end fully fixed, a roller constraint on the greater trochanter, and a distributed vertical load of 2000 N applied to the femoral head (Abaqus, Dassault Systemes Simulia). Whole bone stiffness, the 90th percentile minimum and maximum principal strains, mean volumetric bone mineral density (BMD), and bone mineral content (BMC) were computed. Femur strength was assessed with an asymmetric maximum principal strain criterion (0.73% tension, 1.04% compression) to predict failure load and location [13,14]. Nonparametric Wilcoxon tests were used to compare age, BMI, and CT-estimated (elastic modulus, BMD, BMC) and FE-computed (whole bone stiffness, 90th percentile minimum and maximum principal strains, and failure load) measures between OA and non-OA groups. A Pearson’s chi-squared test was used to check for differences in distribution of sex between OA and non-OA. Significance level was 0.05.

RESULTS: No difference in age (p=0.379), BMI (p=0.375), or sex (p=0.912) was found between cohorts. Both OA and non-OA displayed similar spatial distributions of displacements and strains during simulated sideways falls: high compressive strains toward the supero-lateral aspect of the femoral neck and within the greater trochanter (Fig.1), and high tensile strains in the infero-medial aspect of the femoral neck, within the greater trochanter, and in some of the mid-neck region. No difference was found between cohorts in whole bone stiffness (p=0.889), 90th percentile maximum principal strain (p=0.247), or failure load (p=0.179), but the OA group exhibited lower (i.e., more compressive) minimum principal strains (p=0.037) (Fig.2). There was no difference in median elastic modulus (p=0.379), proximal femur model volume (p=0.211), or BMD (p=0.126) between OA and non-OA, though there was a trend towards lower BMC (p=0.057) with OA. Failure was predicted to occur either on the supero-lateral surface of the femoral neck (n=1 (OA) and n=9 (non-OA)) or internally within the greater trochanteric region (n=4 (OA) and n=4 (non-OA)) (Fig.3).

DISCUSSION: This preliminary study is the first to use CT-based FE modeling of osteoarthritic proximal femora under sideways falls, a scenario of high fracture risk. Results suggest no difference in femoral strength, stiffness, or BMD between OA and non-OA, though there were greater compressive strains and a trend toward lower BMC in OA. This finding of no difference in strength is consistent with recent reports of similar fracture risk in OA vs. non-OA populations [4-6]. Interestingly, there was no discernable difference in failure location between OA and non-OA, contrary to prior reports. This discrepancy may be due to focal changes on our focus of location of fracture initiation (due to our use of linear FE analyses), whereas clinical observations pertain to the entirety of the failure process, and to minor differences in elastic modulus assignments between our calibration methods. Small sample size notwithstanding, the results here suggest that non-bone differences in OA vs. non-OA (e.g. how someone falls, soft tissue composition, pelvis orientation, etc.) may matter more than OA-related changes in characteristics for driving specific fracture location.

SIGNIFICANCE: Motivated by findings that challenge the prior notion that OA is protective against hip fracture, this study used “opportunistc” (phantom-less) CT-based FE analysis for a preliminary comparison of hip fracture in OA vs. non-OA cohorts. Our results suggest no difference in bone strength between cohorts and indicate that non-bone-specific factors may be a greater driver of specific fracture location in OA.


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Images and Tables:

![Min principal strain (ε)](image1.png)

Fig. 1: Mid-coronal view of minimum principal strains of representative specimen models.

![Comparisons of FE-predicted whole bone stiffness (A), 90th percentile minimum principal strain (B), and failure load (C) in OA and non-OA cohorts.](image2.png)

![Non-OA OA](image3.png)

Fig 3: Top-view schematic of FE-predicted fracture location.