Bone Mineral Density Correlates to Risk of Bone Failure under TKA Tibial Implants

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INTRODUCTION: As cementless fixation becomes increasingly popular in total knee arthroplasty (TKA), surgeons must identify appropriate candidates for this type of fixation. Successful, long-term cementless fixation requires sufficiently strong bone to avoid collapse of the tibial baseplate, which is the main mechanism of aseptic loosening [1], a common mode of failure of TKA [2]. In a prior study, we characterized the bone mineral density (BMD) at the planned tibial cut as a marker for bone strength [3]. However, the relationship between BMD and the biomechanical risk of bone collapse, or failure, under demanding loads from daily activities has not been established. In this study, we sought to establish the relationship between BMD and the risk of bone failure under the implant throughout the stair ascent loading cycle. We hypothesized that patients with higher BMD would demonstrate a lower risk of bone failure.

METHODS: Patient-specific finite element (FE) models were created (Abaqus, Dassault Systemes) from standard-of-care preoperative CT scans of 62 patients (38 male, age: 64±7 years, BMI: 31.8±5.5 kg/m^2) who received a robotically assisted TKA (Mako, Stryker). All patients received the same design of cementless tibial baseplate (Triathlon, Stryker) with a cruciate sparing tibial insert. Three-dimensional (3D) bone geometries were reconstructed from CT scans and virtually implanted with the appropriate tibial baseplate size. The implant components were reverse engineered from 3D scans (HandySCAN, Creaform) of physical implants, according to the robotic plan information. Bone was modeled as non-homogeneous, linear elastic isotropic material by relating BMD, derived from CT scans using calibration phantoms, to elastic moduli using empirical relationships [4]. Implants were modeled as solid Ti6Al4V alloys (E=110GPa, v=0.33) with porous Ti6Al4V backsides (E=6.2GPa, v=0.3). The friction coefficient was 0.6 between bone and solid implant surfaces and 1.1 between bone and porous implant surfaces. Bones were meshed with 0.8-mm linear tetrahedral elements at interfaces with the implant to 3-mm elements at 100 mm distal. Implants were meshed with 0.8-mm linear tetrahedral elements. Three-dimensional forces and moments corresponding to 72% of the stair ascent loading cycle, the most critical condition for bone-implant interactions [5], were adjusted per patient body weight, applied to the baseplate center, and distributed across the implant through coupling constraints. The area of bone at risk of failure under the baseplate was calculated from elements of the tibial cut surface reaching at least 10% of bone's yield strain [6,7] and correlated via Spearman rank (rs) to BMD.

RESULTS: The area of bone at risk of failure was significantly correlated (rs=0.59, p<0.001) to the average BMD under the tibial baseplate (**Figure 1**), demonstrating an exponential increase in risk of failure as BMD decreases. Across the cohort, area at risk of failure was generally concentrated along the implant's posterior edge (**Figure 2**) and represented 0.15±0.36% of the bone area under the baseplate. When categorized by sex, females showed moderately higher risk of failure (0.77±1.01%; rs=0.44) than males (0.19±0.34%; rs=0.52) despite having similar average BMD levels.

DISCUSSION: Our results suggest that as BMD decreases, particularly below 150 mg/cm^3, the risk of bone failure rapidly increases exponentially, following a similar power law relationship to that described for the strength of cancellous bone from in vitro experiments.[8] However, since all patients in our cohort remain clinically successful and showed small risk of failure for BMD as low as 80 mg/cm^3, the threshold for at risk patients remains unknown. In this way, we observed that the risk of failure concentrated over small areas at the posterior edge of the implant, highlighting the localized nature of bone failure under tibial baseplates for TKA, and suggesting the need of taking into account the load transfer between implant and bone in addition to BMD to characterize the burden placed on the implant fixation.

SIGNIFICANCE / CLINICAL RELEVANCE: Identifying appropriate candidates for cementless fixation remains challenging in TKA. Our results suggest that the risk of failure increases rapidly for patients with less dense bone, like women, whom may benefit from cement fixation to compensate for the increased risk of bone failure. Additional research on the relationship between BMD, load transfer, and the bone failure under daily loads is warranted to establish thresholds that could identify appropriate patients for cementless TKA.

REFERENCES: [1] Li, 2017 *CORR* [2] *AJRR* 2023 [3] Borsinger, 2024 *J Arthroplasty* [4] Morgan, 2003 *J Biomech* [5] Quevedo Gonzalez, 2018 *JOR* [6] Morgan, 2001 *J Biomech* [7] Bayraktar, 2004 *J Biomech* [8] Carter and Hayes, 1977 JBJS

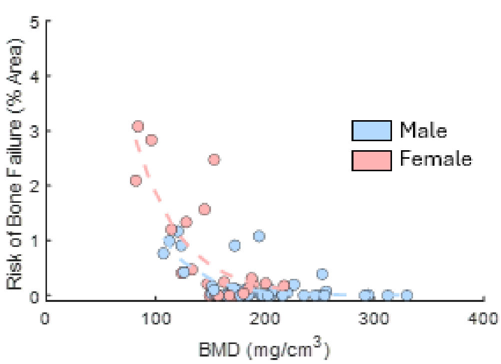

Figure 1 Both male (blue) and female (pink) with higher bone mineral density had lower risk of bone failure than those with low bone mineral density. On average, 0.77% of the bone was at risk in female patients compared to only 0.19% in males.

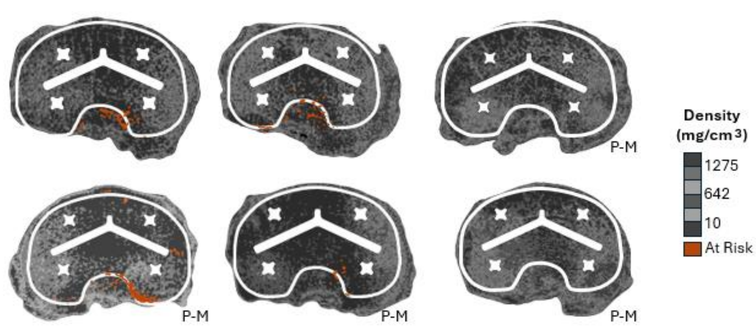

Figure 2 Risk of bone failure distributions (red) mapped onto representative patient bone mineral density (left: low average BMD, middle: moderate average BMD, right: high average BMD). In the low BMD patients, it is clear to see risk of failure is localized in the posterior-medial (P-M) quadrant under the baseplate (white outline).