Computational Evaluation of Bone Density and Fixation Feature Design Influence on Total Ankle Micromotions

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INTRODUCTION: In uncemented applications, total ankle replacement (TAR) tibial components rely on geometric fixation features to impart stability and adequate load transfer to the surrounding tibia. However, the contribution of patient-specific bone density on TAR performance is poorly understood, especially for implants that rely upon interference fit for stable primary fixation. Therefore, our goal was to computationally evaluate how bone density influences implant-bone interface micromotions between two modern TAR tibial component designs (resurfacing vs. stemmed).

METHODS: Finite element analysis (FEA; performed in Abaqus) was conducted in four patients selected from a TAR surgical planning database for having disparate bone density as judged from anonymized CT scan data. Global bone density T-scores were approximated by converting average CT Hounsfield unit (HU) values over a defined distal tibia region of interest[1] first to bone mineral density,[2] then to DEXA equivalent values based on established relationships,[1,3] before finally expressing in terms comparable to clinical femoral T-scores.[4] Tibia geometries were obtained from CT scan data. Two implants were evaluated – a bone-sparing resurfacing implant (APEX 3D™ Flat Tibia Implant; Paragon 28) and a generalized representation of a common bone-removing modular stemmed implant designed to provide intramedullary stability. Tibial implants were positioned at the distal tibia according to surgical guidelines for APEX 3D™. Models for each patient were generated with an interference fit (100 µm) around the pegs/stem and sidewalls of the respective implant (Fig. 1). All geometries were meshed using quadratic tetrahedral elements. Tibia bone was assigned isotropic (ν=0.3), inhomogeneous, bilinear elastic-plastic material properties[5] based on local HU values to model permanent deformation during simulated implantation. Implants were assigned properties of titanium alloy. Bone yield was simulated using a von Mises criterion, with post-yield modulus reduced to 5% of the pre-yield value.[5] Implant-bone contact was defined with a coefficient of friction of μ=0.6.[6] Press-fit and subsequent elastic recoil were modeled before loading. Then forces and moments from the stance phase of gait were applied using TAR cadaveric robotic simulation and musculoskeletal modeling outputs from literature.[6] Discrete quasi-static loading steps were applied to the implant center of rotation coupled kinematically to the distal implant surface, while the tibia proximal end was fixed. Micromotions were computed as the difference in displacement between implant-bone closest nodal pairs. Average micromotions were compared throughout stance. Micromotion distributions were qualitatively compared at 73% stance where the overall peak micromotion occurred.

RESULTS: Femoral T-scores calculated for Patient's 1, 2, 3, and 4 were 1.62, 2.10, -0.85, and -2.03, respectively. In general, patients with higher bone density (T-score>0) had lower micromotions than patients with lower bone density (T-score<0; Fig. 2). Implant design appeared to factor less in patients with higher bone density (peak micromotion range 2 to 23 µm; average micromotion 2.9±1.2 µm). Though higher micromotion was observed in patients with lower bone density, micromotions were lower for stemmed implant (29 and 32 µm peak values for Patient's 3 and 4, respectively) compared to resurfacing implant (108 and 67 µm peak values), which showed greater variability throughout stance. Larger bone-implant interface regions deformed permanently after press-fit in patients with lower bone density than higher bone density (5% more for APEX implant on average, for example).

DISCUSSION: Bone density plays an important role in primary fixation stability of TAR tibial components. Bone densities were quite heterogeneous, even within the high- and low-density patient sub-groups (Fig. 2), which may explain why the observed micromotions did not trend with the simplistic assessment of global bone density (i.e., T-score). Predictions of micromotion may improve by limiting density calculations to interfacial regions of interest. Stresses generated during press-fit in the presence of adequate bone density appear sufficient to restrict micromotion during gait regardless of implant design. The resurfacing implant achieved similar primary fixation stability as the modular stemmed implant without the trade-off of larger resected bone volume (40% less resected tibia volume for APEX implant). While continuum assumption of trabecular bone was a limitation, we showed that implant micromotion, a known contributor to implant loosening and ultimately failure,[6] depends in part on patient-specific local bone density. Understanding how local bone density, implant fixation and design features together contribute to implant stability in TAR is necessary to improve overall implant performance.

SIGNIFICANCE/CLINICAL RELEVANCE: We investigated effects of patient-specific bone density on implant-bone micromotion with realistic primary fixation (interference fit) and physiologic loading. Micromotion appears to be minimized (within the 50 µm threshold for bone ingrowth) with adequate bone compaction in the presence of sufficient bone quality independent from implant design. However, a stemmed primary fixation feature may lead to decreased micromotion in less dense bone given the trade-off of a more disruptive surgical technique.

REFERENCES: [1] Chirvi et al, J Mech Behav Biomed Mater, 2020; [2] Jyoti et al, Med Eng Phys, 2022; [3] Cann et al, PLoS One, 2014; [4] Looker et al, J Bone Miner Res, 1995; [5] Bayraktar et al, J Biomech, 2004; [6] Quevedo Gonzalez et al, J Orthop Res, 2020.

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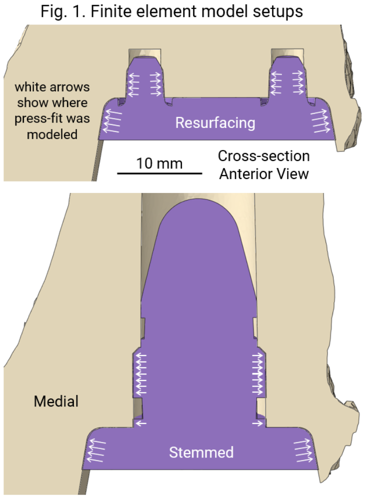
Fig. 1. Finite element model setups



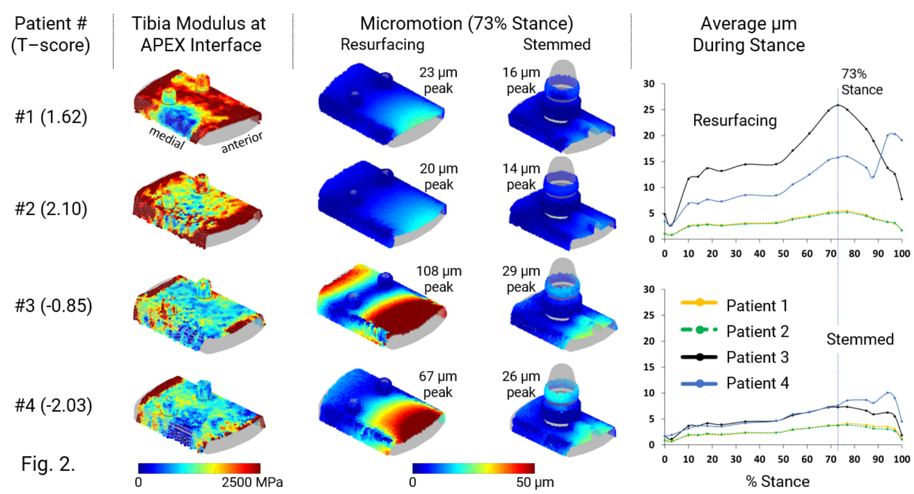


Fig. 2.