Statistical Shape Modeling Enables Comparison of Subtalar Joint Contact Stress and Bone Mineral Density Differences Following Tibiotalar Arthrodesis and Total Ankle Replacement

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INTRODUCTION: Increased rates of subtalar osteoarthritis (OA) secondary to tibiotalar arthrodesis (TTA) have been identified when compared to total ankle replacement (TAR) but a paucity of evidence on impact of these interventions on subtalar mechanics hinders progress toward improving outcomes. Recent studies have identified biomechanical compensations when observing subtalar kinematics in individuals with tibiotalar arthrodesis. However, kinematics only account for individual bone motion while co-occurring factors like increased stress in the cartilage and bone may influence OA development more directly. Cartilage stress and subchondral bone mineral density (BMD) can be estimated in the context of these compensations from kinematic and imaging data and may identify degenerative changes that help to explain the incidence of secondary subtalar OA in these two patient groups. The objective of this study was to compare both subtalar joint contact stresses during an overground walking activity using discrete element analysis (DEA) and subchondral BMD between individuals treated with TTA and TAR using correspondence particles to enable higher resolution analyses. We hypothesized that 1) individuals with TTA would have higher contact stresses across the subtalar joint, and 2) differences in contact stress exposure would be associated with changes in BMD.

METHODS: With IRB approval, ten individuals with unilateral TTA (age: 53.2 ± 9.1 years; BMI: 28.6 ± 4.0 kg/m²; time post-op: 4.0 ± 1.8 years), and six individuals with unilateral TAR (age: 68.2 ± 9.5 years; BMI: 28.9 ± 6.6 kg/m²; time post-op: 5.4 ± 1.9 years) were imaged with biplane fluoroscopy as they completed a barefoot overground walking task [1,2]. DEA was performed to estimate subtalar joint contact stress using the tracked bone models from biplane fluoroscopy. Cartilage was modeled using linear-elastic material properties: Young's Modulus of 12 MPa and Poisson's ratio of 0.42. The cartilage layers were created as uniformly extruded compressible surfaces from rigid subchondral bone (0.98 mm talar side, 0.75 mm calcaneal side)[3]. A calcaneal statistical shape model (SSM) was created and resulting correspondence particles served as registered locations for comparison of cumulative stress across three phases of normalized stance (loading-response 0-24%, mid 25-54%, and terminal 55-87%). The intra-articular joint analysis was performed using a previously developed open-source toolbox [4]. Subchondral BMD on the calcaneal surface was approximated by CT derived Hounsfield units (HU) and both HU and DEA calcaneal cartilage estimated stresses (MPa) for each participant were mapped to their respective calcaneus correspondence model. The data was mapped one-to-one using minimum distance calculations on the subchondral bone surface. Cartilage stress and BMD measurements at each particle were tested for normality using a Shapiro-Wilk test, and then compared between groups using either a Mann-Whitney *t*-test or Wilcoxon rank-sum test based on their homoscedasticity. All statistical tests used an alpha value of 0.05.

RESULTS: There were significant differences in contact stress exposure and HU intensity between TAR and TTA groups. Contact stress differences were identified across all three phases of normalized stance along the superior-medial and anterolateral aspects of the posterior facet and within the anterior facet (Figure 2). Higher cumulative stresses were also observed along the border of the posterior facet and in the medial facet in TAR patients. The largest differences were observed in the anterolateral portion of the posterior facet with TAR patients having higher exposures. Significant global decreases in subchondral HU intensity were observed in the contralateral untreated limbs of the TAR group in line with a mean age difference of 15.0 years (Figure 1). In the context of similar overall HU decreases on the TAR treated limb, there were areas of significant localized increases in the anterolateral portion of the posterior facet on the same correspondence particles experiencing the highest cumulative stress differences. This study is limited by a lack of model validation, uniform cartilage thickness assumptions applied across groups, and that DEA only estimates contact stress without consideration of shear, and the absence of a calibration phantom during CT acquisition.

DISCUSSION: Contrary to our primary hypothesis, the results of this study found the largest increases in contact stress exposure were in the TAR cohort. Prior research has established that elevated contact stress exposure in joints can be a strong predictor of joint degeneration and even regional cartilage damage. However, stress exposure thresholds that lead to damage in the subtalar joint are not well established. Therefore, we sought to evaluate stress results in the context of subchondral BMD changes to see if there was evidence of change related to stress exposure. These results supported our second hypothesis identifying the largest increases in BMD on the same anterolateral correspondence particles where the highest contact stresses were observed in the TAR cohort. These ostensibly counterintuitive findings of higher TAR stress and BMD changes may relate to the pre-existence of subtalar OA which is a common indication of TAR versus fusion. Additionally, there were regions of relative increases in contact stress exposure seen around the posterolateral portion of the posterior facet in TTA, regions that may be associated with morphological changes indicative of subtalar degenerative joint disease. However, BMD results were difficult to interpret in the direction of TTA increases compared to TAR due to the TAR cohort being 15 years older and having lower globally decreased BMD (as seen in the non-operative limb comparisons Figure 1). This difference also serves to further evince the abnormal mechanical environment seen in the anterolateral portion of the TAR cohort's posterior facet and may portend subsequent joint degeneration.

SIGNIFICANCE/CLINICAL RELEVANCE: This study identified localized regional differences in subtalar joint stress for individuals having undergone TAR and TTA and found that those differences also corresponded to subchondral bone changes. Interestingly, individuals with TAR experienced higher peak stress exposures in this study compared to those with arthrodeses. Given that subtalar OA is an indication for TAR, future work is needed to determine whether elevated stress exposures are pre-existing and whether they are exacerbated or decreased by TAR.

REFERENCES: [1] Lenz, A. L. et al. JBJS. 2020; 102:600-608, [2] Lenz, A. L. et al. ASB. 2021, [3] Akiyama, K. et al. (2012) Osteoarthritis Cartilage., 20(4):296-304, [4] Lisonbee, R. (2023). JMA Toolbox (Version 1.0.0) [Computer software]. https://github.com/Lenz-Lab/JMA

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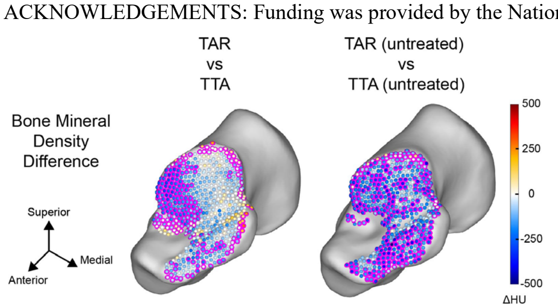

Figure 1: BMD differences between TAR and TTA limbs (Left). Contralateral BMD differences between untreated TAR and untreated TTA limbs (Right) shown for comparison. Note the global BMD decreases seen in TAR limbs outside of the large focal increases in BMD seen in the inferolateral region of the posterior facet. (significant results (p<0.05) highlighted in pink).

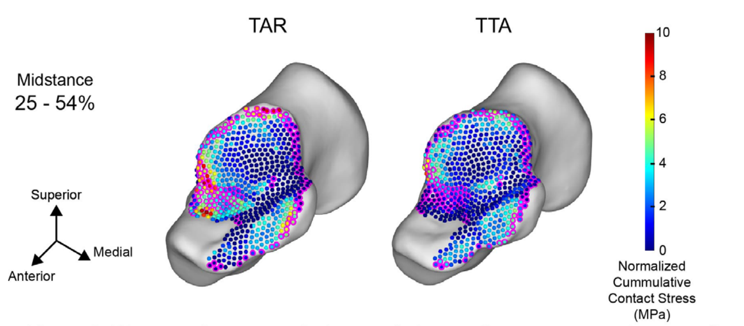

Figure 2: Discrete element analysis cumulative cartilage stress results normalized within a phase of stance (mid 25-54%).