Morphological Analysis of Isolated Subtalar Osteoarthritis via 21-Bone Statistical Shape Modeling of the Foot

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INTRODUCTION: Isolated Subtalar Osteoarthritis (STOA) occurs for a variety of reasons, but most commonly is a result of calcaneal fracture or previous trauma [1]. STOA predominately affects the talocalcaneal joint in the ankle that plays a crucial role in the movement and biomechanics of the human foot. The connection between foot deformities and STOA hasn't been thoroughly investigated, and a comprehensive understanding could potentially lead to more targeted interventions, enhanced patient care, and informed preventive measures. Morphological analysis can be performed on WBCT via Statistical Shape Modeling (SSM) to quantify and compare shapes models of the foot between different groups [2]. The objective of this study was to create a 21-bone SSM project to investigate the morphology of patients experiencing isolated subtalar OA and compare them with healthy control models. We hypothesized that multi-bone SSM would indicate significant morphological differences between the isolated subtalar OA group and the healthy controls - encompassing significant variations not only within the subtalar joint, but also in other bones.

METHODS: In this study, WBCT (0.37 x 0.37 x 0.37 mm voxels) data from 30 total participants (15 healthy and 15 with STOA) was acquired with IRB approval. Patients were grouped as STOA based on evaluations from a musculoskeletal radiologist and an orthopaedic surgeon. Semi-automatic segmentation software (DISIOR v2, *Bonelogic*) was used to generate preliminary bone segmentations for 21 bones in the ankle: tibia, fibula, calcaneus, talus, navicular, cuboid, cuneiforms (medial, intermediate, lateral), metatarsals, proximal phalanges, and sesamoids. These initial segmentations were verified and revised, if needed, using Mimics 24.0 (*Materialise*). 3-Matic 16.0 (*Materialise*) was used to smooth and decimate all segmented bones, then perform a global plane cut across all patient models based on the shortest tibia and fibula. All 21 bones from each patient were used to create a multidomain SSM project in ShapeWorks 6.4.2 (*SCI Institute*) to determine mean shape and quantify morphological differences between STOA and healthy patients [3]. Principal Component Analysis (PCA) was utilized to assess the modes of variation from the SSM model, and MATLAB R2023a (*Mathworks Inc.*) parallel analysis determined significant PCA modes. To identify localized regions with notable disparities in both overall morphology and alignment, a Hotelling's T^2 test was employed with a false discovery rate p-value correction. Additionally, PCA scores from each mode were exported from ShapeWorks and compared to another using a t-test or Wilcoxon rank sum test with a Holm-Sidak correction (α=0.05). ShapeWorks 6.4.2 built-in Linear Discriminant Analysis (LDA) was also applied to investigate shape variation between the healthy and STOA groups.

RESULTS: Figure 1 illustrates the results from the Hotelling's T^2 test comparing the healthy and STOA groups. Red indicates areas where there are significant differences, and mainly encompasses the tibia, fibula, talus, calcaneus, cuboid, and cuneiforms. The parallel analysis determined 6 significant modes of variation out of the 19 modes that represented 95% of overall variation. Modes 1, 2, and 3 accounted for 75.0% of the cumulative variance (Fig.2). Red and blue regions represent areas that are smaller and larger than the mean model, respectively. The first mode (49.6% explained variance) presented cuneiform movement in the radial direction, tibia/fibia movement from the posterior to anterior and subtalar joint movement in the anterior direction. The second mode (14.3% explained variance) demonstrated apparent twisting of the lamina pedis in the direction opposite of the subtalar joint rotation. Lastly, the third mode (11.1% explained variance) represented midfoot bending in the sagittal plane which changed the subtalar, calcaneal and talonavicular orientation. Mode 3 was the only mode that produced PCA scores that were significantly different from another (p=0.014) and bending in this mode was more prominent in the STOA group.

DISCUSSION: The 21-bone SSM model indicated significant differences between the morphology and alignment of patients with STOA and the control group. P-values suggest that bones distal from the cuneiforms have less deformity than more proximal bones (Fig.1). LDA confirmed significant morphological and alignment differences between the two different groups, as the probability distribution functions of the two groups were distinct and had limited overlap with one another. Lastly, the SSM model identified 6 significant modes of variation out of the 19. These modes, capturing substantial variability, provide valuable insights into the distinct patterns of joint deformity and structural changes associated with STOA. While mode 1 produced insignificant differences in PCA component scores (p>0.05), it appears that this mode may represent variants in the specific foot type, ranging from planus to cavus when standing. Analysis of different types of OA using SSM will yield more specific insights into morphological patterns and alignment trends. This, in turn, will enable physicians to identify associated deformities such as planus/cavus in Mode 1 (49.6% variance) or anticipate the potential restoration of lamina pedis in cases of midfoot twisting opposing the direction of the subtalar joint rotation seen in Mode 2 (14.3% variance). Ultimately, this comprehensive understanding gained through SSM and WBCT will contribute to the development of more tailored treatment strategies for patients.

SIGNIFICANCE/CLINICAL RELEVANCE: The findings of this study hold significant implications for orthopaedic physicians and surgeons, offering a deeper insight into the morphological changes associated with isolated subtalar OA. This understanding may help clinicians formulate patient specific orthopedics or surgical care plans for patients experiencing STOA.

REFERENCES: [1] Glazebrook M, et al. J Bone Joint Surg Am. 2008;90(3):499-505 [2] Krähenbühl N, et al. J Orthop Res., 38 (2020), p. 1-9. [3] Cates J, et al. Statistical Shape and Deformation Analysis (2017):257-298

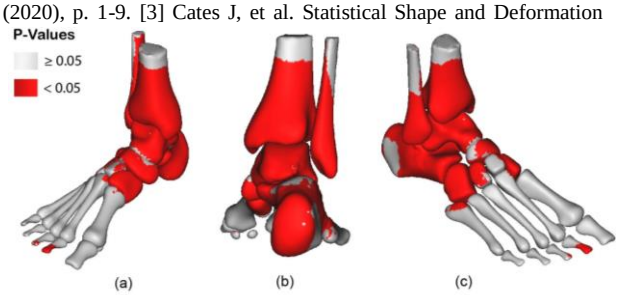

Figure 1: (a) medial-lateral (b) posterior and (c) dorso-lateral views of the mean foot shape obtained from SSM. The data represented illustrates p-values from Hotelling's T^2 test with false discovery rate correction comparing the STOA group with the healthy group. Red indicates significantly different areas with p-values less than α = 0.05. Grey areas show non-significant differences where p is greater than or equal to 0.05.

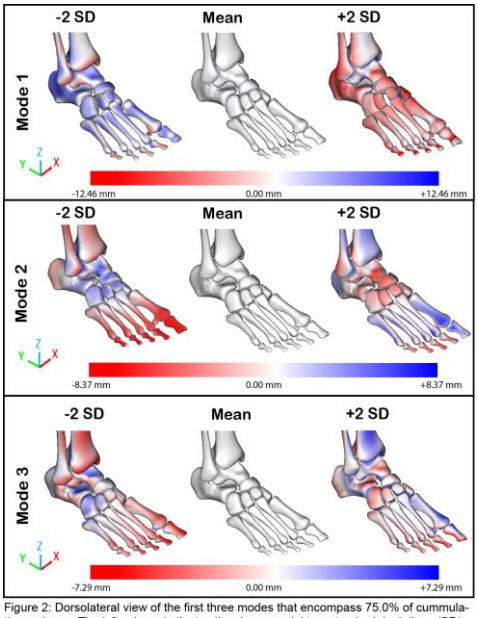

Figure 2: Dorsolateral view of the first three modes that encompass 75.0% of cummulative variance. The left column indicates the shape model two standard deviations (SD) below the mean, and the right column indicates two SDs above the mean. The mean model for each mode is shown in the middle column. Red regions are smaller than the mean model and blue regions are larger.