Assessment of Residual Morphological Deformity using Statistical Shape Modeling in Adult Clubfoot Treated with the Ponseti Method

Kevin N. Dibbern[1], Rich Lisonbee[2], Amy Lenz[2], Cesar de Cesar Netto[3], Karen Kruger[1,4]
[1]Marquette University, [2]University of Utah, [3]Duke University, [4]Shriners Chicago
kevin.dibbern@marquette.edu

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INTRODUCTION: Ponseti serial casting is widely used to correct the broad and severe adduction, equinus, cavus, and varus deformities seen in clubfoot. While studies have demonstrated the effectiveness of this method in correcting overall foot deformity, few studies have evaluated residual changes in boney morphology that may persist into adulthood [1]. Recent work using functional and radiographic measures of foot morphology has suggested that residual changes occur and are associated with pain in adults with treated clubfoot [2]. However, to our knowledge, there are no studies that directly evaluate residual deformities in boney morphology after serial casting. Therefore, the purpose of this study was to directly assess changes in boney morphology of adult clubfeet after treatment with the Ponseti method using high resolution weightbearing CT and statistical shape modeling of the hindfoot and Chopart joint.

METHODS: This prospective comparative and controlled IRB-approved study included 37 patients treated for congenital clubfoot using the Ponseti method and 20 healthy control feet with no prior history of foot and ankle disease or injury. All participants were evaluated using low-dose high resolution weightbearing CT imaging (Curvebeam AI HiRise, 0.3mm isotropic voxels). For each participant, CT images were semi-automatically segmented using Disior Bonelogic 2.0 and verified in Slicer 3D and Geomagic Design X 2020 (3D Systems). Single domain statistical shape models were created for each of the four bones of the hindfoot and Chopart joint (Calcaneus, talus, navicular, and cuboid). Procrustes scaling was used to account for size variation in the model population. Differences in mean shapes for each bone and variance in the first 10 PCA modes were evaluated. Significant differences in mean morphology of control and clubfoot cohorts were evaluated using Hotelling's T-squared tests on all correspondence particles in the statistical shape models.

RESULTS: Significant differences between the mean control and clubfoot shapes were identified in some correspondence particles of all four bones (Figure 1). In the calcaneus, the first 10 PCA modes explained 73.6% of the variance in shape with the first mode (21.2% explained variance) identifying increases in the prominence (3.0mm compared to mean control shape) of the bone near lateral ligamentous attachment sites and along peroneal brevis and longus grooves in clubfeet. Additional changes were seen in the posterior facet with broad flattening occurring in the superior medial side. The second mode (12.7% explained variance) identified decreases in the prominence of the calcaneal tuberosity in clubfeet. In the talus, the first 10 PCA modes explained 76.6% of the variance in shape with the first mode (37.3% explained variance) identifying large decreases in the prominence of the entire medial shoulder of the talus along its tibiotalar articulation and a general flattening of the talar dome. Both the cuboid and navicular demonstrated compression of medial bone with corresponding circumferential increases in their first PCA modes (35.3% and 29.7% explained variance, respectively) and mean shapes.

DISCUSSION: Residual morphological deformities were seen in all bones with the largest changes seen through the medial Chopart and tibiotalar joints. Changes were also identified along major ligamentous attachment sites and tendinous tracts on the calcaneus particularly along the lateral peroneal tracts. Further research is needed to understand if lateral changes are explained by increased action of the peroneus longus and brevis everting the foot and counteracting deforming forces or if they are a component of underlaying deformity [3]. On the talus, talar dome flattening in clubfoot has been reported in the literature and recently shown to correlate with changes in gait [4]. The findings of this study suggest that flattening occurs asymmetrically with loss of medial gutter prominence greater than lateral. These changes may contribute to observed gait abnormalities. Residual clubfoot deforming forces may also explain medial sided changes in morphology observed on the navicular and cuboid. Future work will include multi-domain statistical shape models and consider how compensations and residual deformities are related to patient reported outcome measures and altered function.

SIGNIFICANCE/CLINICAL RELEVANCE: Medial deformities in the talus and Chopart joint combined with lateral prominence of bone along evertors may be indicative of residual deforming forces in treated adult clubfoot. It is important to understand how residual deformity impacts underlaying bone structure after clubfoot correction as it can inform potential problems during pediatric treatment or later in adulthood that may require consideration or monitoring.

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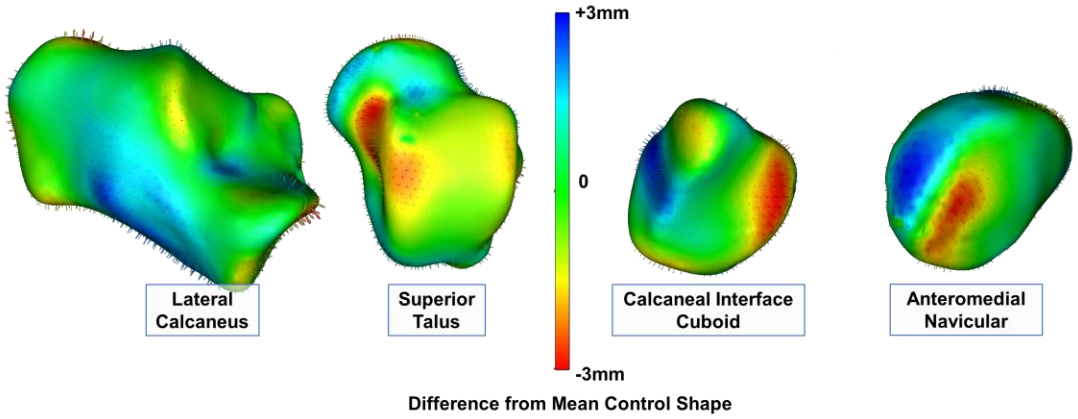

Figure 1: Difference maps from the mean clubfoot to the mean control statistical shape model plotted over the mean control bone shape for the calcaneus, talus, cuboid, and navicular.