Statistical Shape Modeling of the Calcaneal Osteotomy

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Introduction: Opening wedges of the calcaneus may be used to correct deformities of the foot including flexible pes planovalgus deformity [1, 2] Autografts, allografts, or synthetic spacers may be used to wedge the bone, potentially in combination with ancillary fixation (e.g. plates). Anatomical spacer designs offer the potential for increased load-bearing capacity, no graft collapse, and decreased subsidence by maximizing boney coverage, while avoiding component overhang and therefore not impinging soft tissues. General analyses of calcaneal morphology have been conducted [3], however the anatomical variability in the geometry of the calcaneus at the level of a calcaneal (Evans) osteotomy has not been quantified. The goal of this study was to characterize variability using statistical shape modeling in conjunction with a large database of calcaneal models.

Methods: Materials: Computed tomography (CT) scans of the lower limb were performed on 189 cadavers or patients. Patients spanned multiple ethnicities (Indian, Japanese, Caucasian, and South Korean), with the following characteristics: 103/86 male/female; age = 55 ± 8 years; height = 1.63 ± 0.10m. Scans were segmented (Amira, FEI VSG, Burlington, MA) to generate digital models of the tibia, talus, calcaneus, and cuboid.
Calcaneal osteotomy: Models were initially registered using an anatomical coordinate system based on the long axis of the talus and the anatomical axis of theibia. A reference point on each model was identified at the low point of the sinus tarsi, relative to the anatomical frame, suitable for a lateral referencing approach. The subtalar and calcaneocuboid joint surfaces on the calcaneus were identified, and used to orient the osteotomy from an axial and frontal perspective, respectively (Fig. 1a-b). A virtual osteotomy was then performed on each bone, and the contour around the periphery of the osteotomy was identified. Digitized contours from each model were extracted for further analysis.
Statistical shape modeling. Statistical shape modeling has been used on various bones to characterize anatomical variability [4-6]. Here, principal component analysis (PCA) was used to consolidate the individual profiles into a mean geometry and primary modes of variation. Contours were registered to each other by aligning to the long axis of the profile and lateralizing the resulting frame (Fig. 1c). Once registered, all profiles were resampled for consistent nodal positioning, and PCA was performed using established techniques [6]. The maximum inscribed diameter for each profile was also determined (Fig. 1c), as a metric of overall calcaneal size.

Results: Figure 2 shows a scatterplot of overall patient stature (height) versus calcaneal size (maximum inscribed diameter at the osteotomy) for all samples analyzed here. Additionally, the 10th and 90th percentile values for both stature and calcaneal size are indicated. Visual representations of each of the four modes of variation (mean ± two standard deviations of the given mode) are shown in Fig. 3, overlaid on the individual contours and the mean profile. These four modes reflect 71.9, 10.6, 7.7, and 3.2% of the total variation in anatomy across the dataset, for a cumulative variation of 93.4%.

Discussion: Statistical shape modeling (SSM) is a powerful tool for quantifying anatomical variability, and is being increasingly used within orthopaedics applications to understand variations in boney anatomy, tissue properties, and kinematics. Here, SSM reveals key modes of variation relevant to a calcaneal osteotomy. Modes of variation reflect overall size (mode 1), rotation about the axis of the calcaneus (modes 2 and 4, thus potentially impacting the orientation of the opening angle of a placed spacer), and profile proximal-distal width (mode 3). Resection profiles were extracted using an anatomically-referencing resection scheme (as opposed to a measured resection); subtle variations in identifying those references could meaningful impact the resulting osteotomy contour. Though this analysis benefits from spanning patient variability, there are thus opportunities to quantify the impact of surgical variability, both in terms of different surgical philosophies as well as expected variation while adhering to a single philosophy.

Significance: Increased understanding of anatomical variations in the profile associated with calcaneal osteotomies can guide improved designs of spacers as well as improved surgical approaches, potentially resulting in deformation corrections that are less susceptible to subsidence and soft tissue impingement.
Acknowledgments:


Figure 1. Virtual calcaneal osteotomy. Yellow lines represent (a) subtalar and (b) calcaneocuboid references. (c) Registration frame for contours.
Figure 2. Patient height versus calcaneal diameter (red = males; blue = females).

Figure 3. First four modes of variation (mean profile in black; ±2 standard deviations of mode in blue/green)