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Bilateral Symmetry, Sex Differences, and Primary Shape Factors in Ankle and Hindfoot Bone Morphology

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Abstract

Background: Ankle injuries and joint degeneration may be related to ankle bone morphology. Little data exist to characterize healthy hindfoot bone morphology. The purpose of this study was to characterize side-to-side symmetry and sex differences in ankle and hindfoot bone morphology, and to identify the primary shape factors that differentiate ankle and hindfoot bone morphology among individuals.
Methods: Computed tomography was used to create 3D surface models of the distal tibia, talus, and calcaneus for 40 ankle and hindfoot bones from 20 healthy individuals. Morphologic differences between left and right bones of the same individual and between males and females were determined. Statistical shape modeling was performed to identify primary shape variations among individuals.
Results: Side-to-side differences in bone morphology averaged 0.79 mm or less. The average distal tibia in males was larger overall than in females. No significant sex difference was noted in the tali. The average female calcaneus was longer and thinner than the average male calcaneus. Variability in ankle and hindfoot bone morphology is primarily associated with articulating surface shape, overall length and width, and tendon/ligament attachment points.
Conclusion: In general, the contralateral ankle can serve as an accurate guide for operative restoration of native ankle morphology; however, specific regions demonstrate higher asymmetry.
Clinical Relevance: Knowledge of regions of high and low bilateral symmetry can improve hindfoot and ankle reconstruction. Design of ankle prostheses can be improved by accounting for differences in bone morphology associated with sex and shape differences among individuals.

Keywords: ankle, hindfoot, bone morphology, sex differences, symmetry, statistical shape modeling

Introduction

Fracture management is a large part of foot and ankle operative practice. From 2007 to 2011, more than 70 000 foot and ankle fractures occurred annually in the United States.[21] The majority of those fractures occurred in the ankle (56%) and hindfoot (17%).[21] Ankle and hindfoot fractures can be life-altering for the patient. Pilon (distal tibia),[6,10,24] talus,[7,8,15,17,20] and calcaneus[1-3,23] fractures are notorious for serious complications with potentially poor outcomes.

Precise fracture reduction is believed to improve outcomes and limit the progression of joint degeneration. One potential strategy to restore native anatomy and improve outcomes is to use the contralateral (uninjured) side in planning reconstruction after traumatic injury.[14,18] However, the assumption that ankle bones are symmetric is controversial because of a lack of research. One recent study of 11 subjects indicated that the mean 3-dimensional (3D) side-to-side deviation in talus bone morphology is between –0.74 and 0.62 mm.[9] Another recent study of 66 individuals showed average side-to-side differences ranging from 0.53 to

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0.87 mm in the fibula, tibia, talus, and calcaneus.[27] Unfortunately, those studies did not provide any visual representation of the side-to-side differences, making it impossible to determine if there are specific isolated regions of asymmetry or if the differences are evenly distributed across the entire bone surface. Knowledge of the typical side-to-side difference in morphology across the bone surface is important for the surgeon in planning and evaluating fracture reduction.

Another unresolved question related to hindfoot and ankle bone morphology is the extent to which sex affects bone morphology. Knowledge of sex-dependent differences in bone size and morphology may provide an explanation for the higher incidence of ankle sprains in females[28] and may inform the development of sex-specific ankle joint arthroplasty devices as has been done in the knee.[11,25] Early research investigating sex-dependent differences in ankle bone morphology focused on discrete anatomic features.[13,14,16,27,29] More recently, statistical shape modeling[16] or principal components analysis[27] has been performed to identify independent variations in ankle bone shape. Those studies were somewhat contradictory, with one study identifying male-female differences in the tibia, calcaneus, and talus[27] and the other reporting only that sex differences in ankle bones were subtle.[16] More evidence is required to clarify the effect of sex on ankle bone morphology. In addition, more research is needed to identify morphologic differences in bone shape that may predispose individuals to abnormal ankle kinematics or increase their susceptibility to injury.

We hypothesized that ankle and hindfoot bones are bilaterally symmetric so that the contralateral ankle and hindfoot bones can serve as an accurate guide for operative restoration of native ankle morphology, that male ankle and hindfoot bones are larger than female bones, and that the primary shape factors that differentiate among individuals are related to bony prominences comprising articulating surfaces and ligament attachment sites. Therefore, the aims of this study were to determine the bilateral symmetry of ankle and hindfoot bones, identify the size and morphologic differences between male and female ankle and hindfoot bones, and identify the primary shape differences in ankle and hindfoot bone morphology among individuals.

Methods

Twenty healthy individuals (age 30.7 ± 6.3 years; 10 men: average BMI 24.2, height 179.2 cm, weight 77.6 kg; 10 women: average BMI 23.9, height 165.2 cm, weight 65.3 kg) with no history of major ankle injury or surgery were imaged using computed tomography (CT) from 10 cm above the ankle joint down through the toes after providing informed consent to participate in this IRB-approved study. From these CT scans, 3-dimensional surface models of each distal tibia, talus, and calcaneus were created based on reformatted scans with cubic voxel sizes ranging from 0.59 to 0.72 mm^3 using Mimics software (Materialise, Leuven, Belgium). A previous validation study, using a high-precision laser scanner to obtain the ground truth bone morphology, determined the accuracy of bone models using these methods is ± 0.63 mm.[26] All 40 3D surface models of corresponding bones (eg, all distal tibias) were resampled in Geomagic Design X (3D System, Morrisville, NC) to a similar mesh resolution. The 3D surface models were rigidly coregistered using a coherent point drift algorithm (MATLAB, MathWorks, Inc, Natick, MA) to create an average bone model. A Procrustes transformation was performed to scale the individual bone models and eliminate bone size as a shape factor.[19] Surface nodes from the average bone model were projected onto their corresponding anatomic points for each individual bone model using a custom MATLAB program (Figure 1).

Side-to-side differences (SSDs) were determined by calculating the average distance between corresponding points on the left and right bones for each individual. SSDs beyond our measurement accuracy of 0.63 mm were identified using a 1-tailed *t* test. Similarly, all corresponding female (or male) bones were coregistered to create an average female (or male) tibia, talus, and calcaneus. Points on the average female bone were subtracted from the corresponding points on the average male bone to calculate sex differences.

Finally, statistical shape modeling (SSM) was performed following the methods described by Landsdown et al[12] to qualitatively identify variations in bone shape (modes) among individuals. SSM reveals differences in shape and variability in shape across subjects by identifying independent modes of variation, with the first mode corresponding to the highest variation in shape, the second mode the second highest variation in shape, and so on. SSM is more comprehensive than landmark-based analysis, which can only evaluate shape differences at predefined landmarks. The first 3 modes of variation were qualitatively observed using custom software that allowed the user to interactively visualize the changed bone shape for each mode of variation. Three authors (A.G., T.G., W.A.) independently recorded their own qualitative description of the first 3 modes of variation for each bone. The authors then compared their descriptions for each mode to achieve consensus on the qualitative description for each mode.

Results

Symmetry

The average SSD in 3D morphology for the tibia was 0.76 ± 0.31 mm, for the talus was 0.76 ± 0.29 mm, and for the calcaneus was 0.79 ± 0.32 mm. None of these SSD values were significantly greater than our 3D reconstruction error (0.63 mm).

The color maps of SSDs demonstrated that the SSDs on the tibia were greatest on the anterior-lateral portion of the tibia shaft (Figure 2A), whereas SSDs on the talus were greatest on the center of the talar dome and the posterior process (Figure 2B). SSDs on the calcaneus were greatest

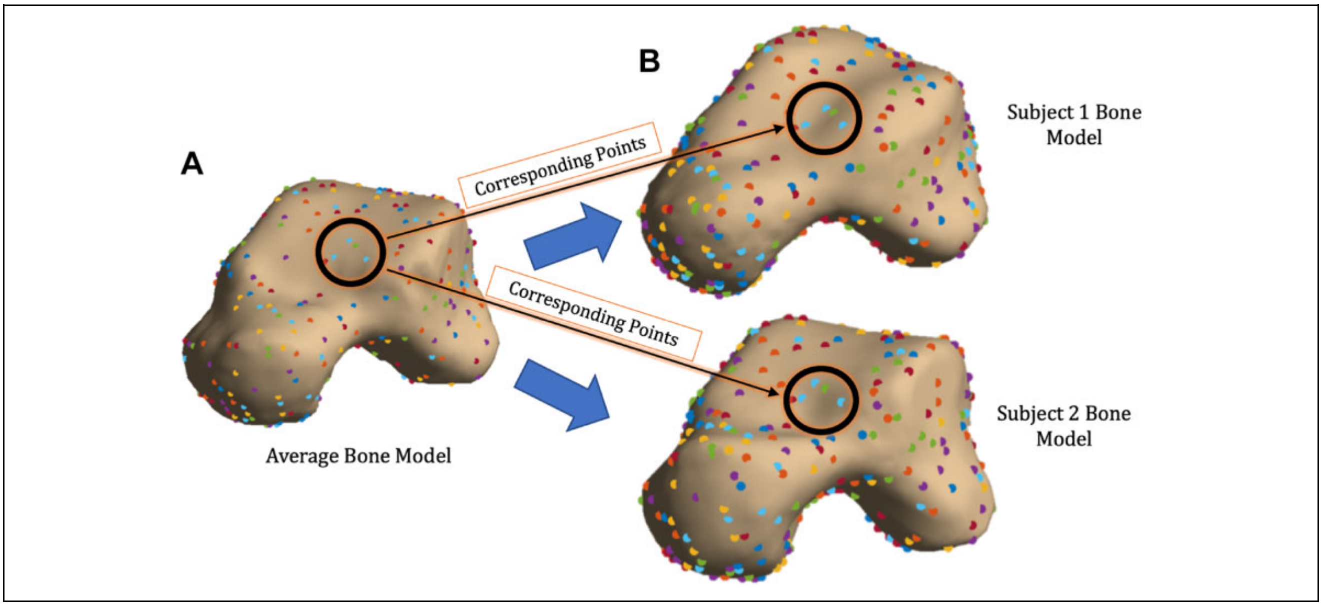

Figure 1. Work flow for generating bone models with corresponding points. (A) An average bone model, composed of 4000 evenly distributed surface nodes, was created based on all 40 3D surface models. The average bone model was nonrigidly registered to each individual bone model, (B) resulting in bone models with the geometry of the individual bone and corresponding surface points across individuals.

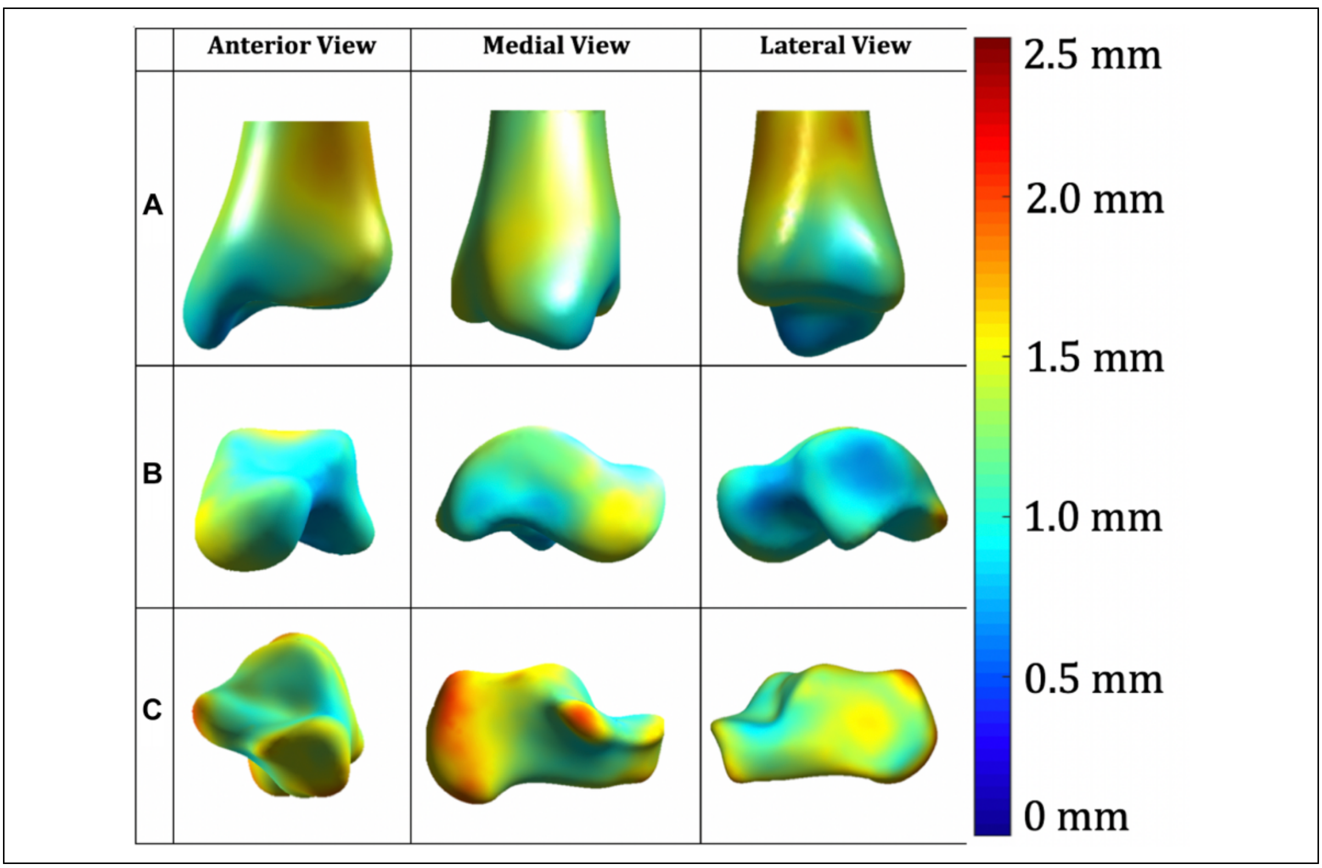

Figure 2. Side-to-side differences (SSDs) in ankle bone morphology. Anterior, medial, and lateral views of SSDs between left and right bones, with differences color-coded according to the color scale on the right. (A) SSDs on the tibia were greatest on the anterior-lateral portion of the tibia shaft, (B) whereas SSDs on the talus were greatest on the center of the talar dome and the posterior process. (C) SSDs on the calcaneus were greatest at the sustentaculum tali and along the superior portion of posterior surface extending down to the medial process.

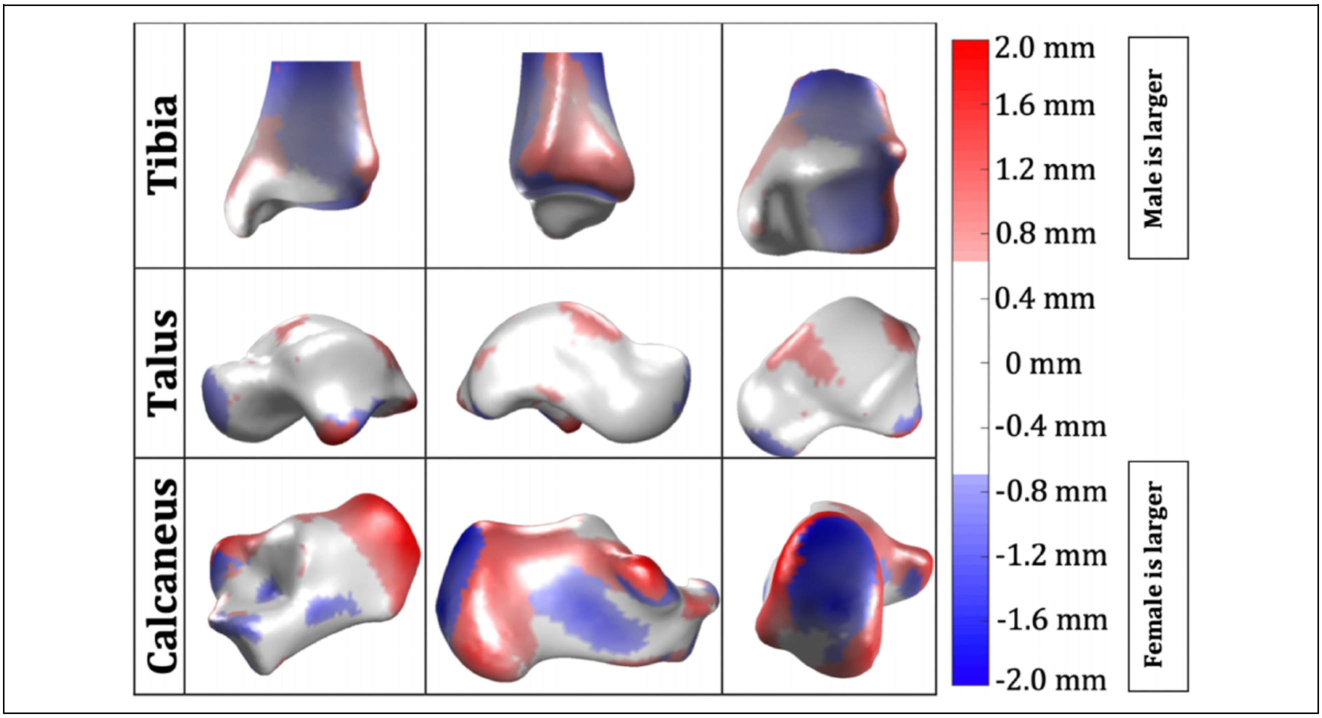

Figure 3. Sex differences in ankle bone morphology. The average male tibia was larger than the average female tibia in the most medial and lateral portions of the bone. The average male and female talus were within a voxel size of each other (0.49 mm). The average female calcaneus was longer (∼2 mm) and thinner (∼3 mm) than the average male calcaneus. *White represents the accuracy of our 3D morphology measurement, ±0.63 mm.

at the sustentaculum tali and along the superior portion of the posterior surface extending down to the medial process (Figure 2C).

Sex Differences

The average male distal tibia was larger overall than the average female distal tibia (average difference 0.94 ± 0.55 mm), with the differences concentrated in the most medial (∼0.8 mm) and lateral (∼1 mm) portions of the bone, whereas the female talus appeared slightly larger in the anterior-posterior (AP) dimensions (Figure 3A). The differences between the average male and the average female talus were, on average, less than the uncertainty of our measurement system (average difference 0.46 ± 0.33 mm) (Figure 3B). The average female calcaneus was longer (∼2 mm) and thinner (∼3 mm) than the average male calcaneus (average overall difference 1.06 ± 0.50 mm) (Figure 3C).

Primary Shape Factors

The first 3 modes of variation among distal tibias were (1) the overall thickness of the tibial shaft (30.3% of the variability) (Figure 4), (2) the prominence of the anterolateral border of the distal tibia and medial malleolus (17.3% of the variability), and (3) the fibular notch depth and depth of the anterior articular surface of the medial malleolus (11.3% of the variability).

The first 3 modes of variation among talus bones were (1) the prominence of the posterior process, slope of the talar neck, and concavity of the talar dome (17.9% of the variability) (Figure 5); (2) the talar neck width and size of the lateral process, which varied along with the size of the anterior facet (14.2% of the variability); and (3) the depth of sulcus tali, which varied along with head and neck circumference (12.1% of the variability).

The first 3 modes of variation among calcanei were (1) the bone length, the sustentaculum tali rotation about the long axis of the bone, and the depth of the articular surfaces (20.3% of the variability) (Figure 6), (2) the overall diameter of the bone, the prominence of the Achilles insertion (14.7% of the variability), as well as (3) the overall width of the medial and lateral processes, the slope of the posterior talar articular surface, and the size of the retrotrochlear eminence (11.8% of the variability).

Discussion

The first aim of this study was to characterize the bilateral symmetry of ankle and hindfoot bones. Our results indicate that, on average, ankle bones are symmetric. Given our sample size and the submillimeter accuracy of our reconstructions, we were unable to identify any statistically significant side-to-side differences in bone morphology. This aligns with our hypothesis and previous studies that have investigated single-bone symmetry.[9,27] Traumatic injury of the ankle and hindfoot bones is common, and clinical

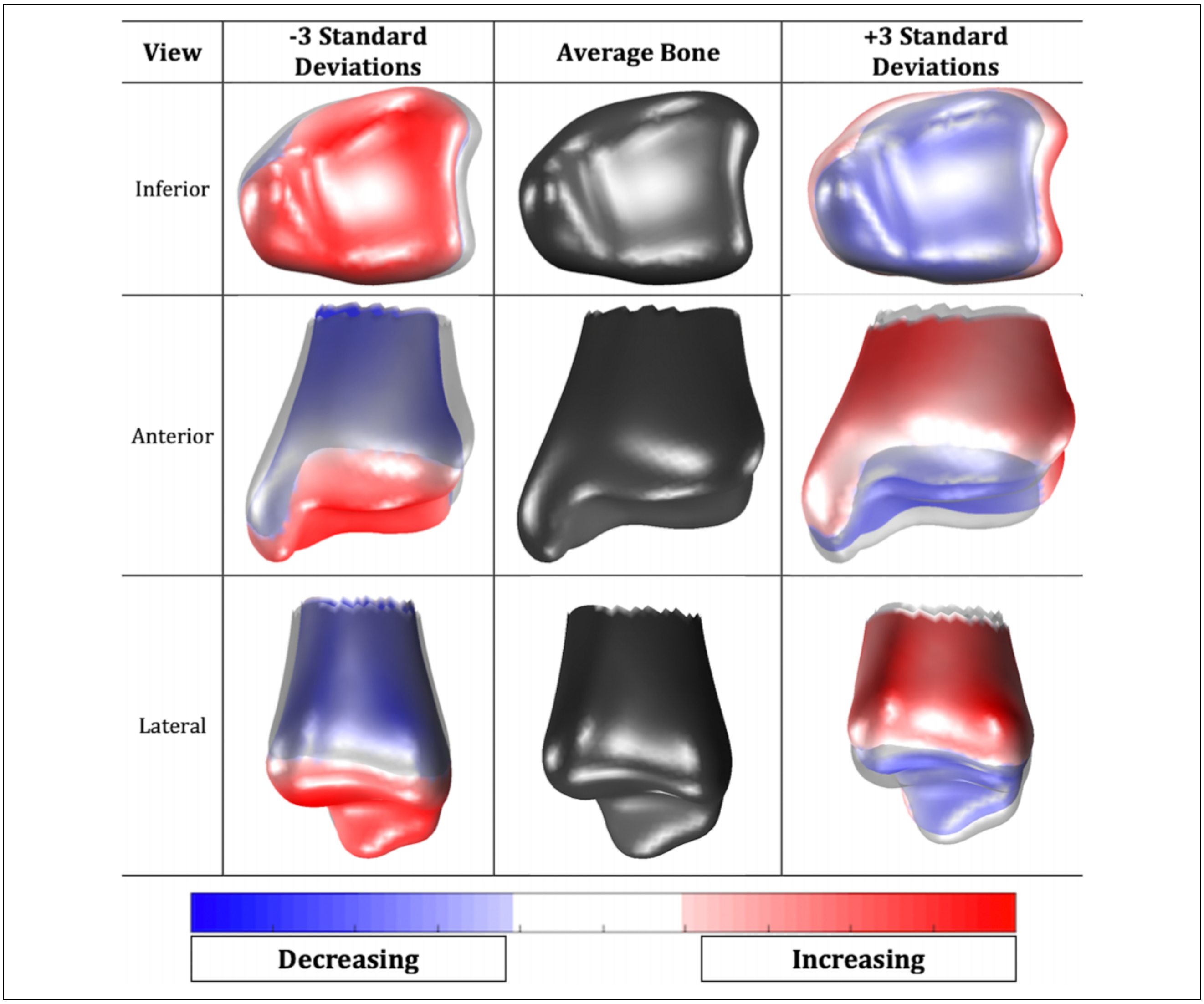

Figure 4. Inferior, anterior, and lateral views of the first mode of variation in tibial shape. The largest amount of variability in distal tibia shape was related to the overall thickness of the tibial shaft and articular tibial surface (30.3% of variability). Note the inverse relationship between shaft diameter and articular surface shape changes.

interventions can be improved by knowing that the contralateral ankle and hindfoot bones can serve as reliable templates for reconstruction and development of patient-specific prostheses. Average SSDs in our study (0.76-0.79 mm) were similar to those reported previously (from 0.53 mm to 0.87 mm).[9,27] However, the average overall SSD may be misleading. As demonstrated by our color map visualization of SSD, there are specific regions within each bone that are well above the average SSD. Knowing that SSDs are likely to be larger in these specific regions can be considered when using the contralateral side as a template for reconstruction or subject-specific implant design.

The second aim of this study was to investigate differences in ankle and hindfoot bone morphology between males and females. We found that the distal tibia was larger, overall, in males, despite the female being slightly larger in the AP dimension. Contrary to our hypothesis, the male and female tali were similar in size, whereas the calcaneus in females was overall longer but thinner than in males. A recent study by Moore et al[16] employed SSM to identify sex-dependent differences in the talus, calcaneus, cuboid, and navicular. Contrary to our results, they identified subtle differences between male and female tali, and reported no sex differences in the calcaneus. A potential explanation for this discrepancy is that the distribution of foot types (and therefore bone shapes) may have been different between studies. Moore et al[16] enrolled an equal number of subjects in each of 4 foot type groups, which may not reflect the distribution of foot types in our study or the population (eg, the population distribution may be closer to 73% planus, 20% rectus, and 6% cavus based on a recent sample of 2180 young adults).[22] Our results demonstrating sex differences in the calcaneus are in agreement with Tümer et al,[27] who used 3-dimensional CT-generated bone models and principal

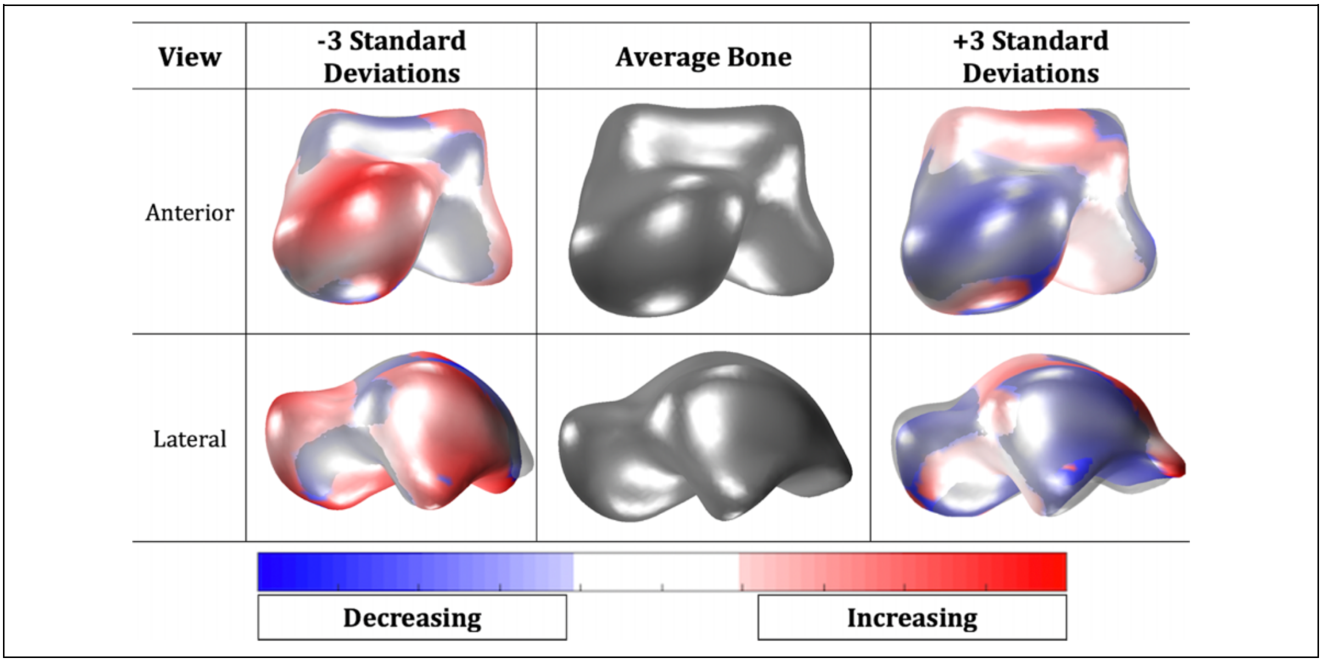

Figure 5. Anterior and lateral views of the first mode of variation in talus shape. The largest amount of variability in talus shape was related to the posterior process, the slope of the talar neck, and concavity of the talar dome (17.9% of the variability).

components analyses to identify sex differences in the length and height of the calcaneus. Contrary to our results, they observed no sex differences in the distal tibia morphology. Prior to these recent studies, ankle and hindfoot bone morphology was assessed by performing predefined measurements (eg, length, width, facet size) on cadaver specimens[29] or as part of forensic anthropology studies.[4,5] A limitation of those techniques is that only predefined parameters were analyzed, potentially missing key morphologic differences. In contrast, statistical shape modeling does not restrict analysis to specific features and can provide a more comprehensive evaluation of bone morphology.

Our final aim was to identify primary shape factors that lead to variability in ankle and hindfoot bone shape in healthy individuals. In our SSM analysis, it was confirmed that many of the primary shape factors that differentiate ankle bones are related to the size of specific bony features and bony prominences. With respect to the primary shape factors in the tibia, our results were similar to those of Tümer et al,[27] who found height and width differences in the distal tibia (their mode 3) and differences in the diameter of the tibia (their mode 4). Regarding the primary shape factors in the talus, our results were similar to Tümer et al[27] who identified differences in lateral rotation of the talar head as mode 1. We described this variability as a change in the slope of the talar neck. Our results for primary shape factors in the calcaneus were very similar to previous reports[16,27] indicating mode 1 was related to the length and height of the calcaneus, mode 2 was related to differences in the inclination of the sustentaculum tali or height and width, and mode 3 was related to differences in the talar articulating surfaces (mode 3 for Tümer et al[27]). It is important to consider the analysis methods in SSM analysis when comparing results among studies. For example, our study and the study by Moore et al[16] included a Procrustes transformation to eliminate bone size as a shape factor, whereas Tümer et al[27] did not. Second, our analysis focused on the distal tibia, whereas Tümer et al[27] included the entire tibia in their shape model. This allowed Tümer et al[27] to identify primary shape factors related to the proximal tibia that we could not assess. However, including the proximal tibia may have influenced the primary shape factors identified in the distal tibia. Finally, and most importantly, identifying the primary shape factors is a qualitative assessment that is dependent on the interpretation of the investigator. To minimize the impact of individual interpretation, we had 3 reviewers independently identify the first 3 modes of variation and, in cases of disagreement, we reviewed the data until achieving a consensus on the primary shape factors for each of the first 3 modes of variation.

One limitation of this study is that all participants were young healthy adults, and therefore the results should not be extrapolated to older or pathologic individuals. Second, the foot type of each participant was not determined and therefore the results could not be further analyzed by foot type. This study was a qualitative and quantitative secondary analysis of data collected as part of a project focused on ankle kinematics, and therefore, a prior power calculation was not completed for this analysis. However, our study sample size (20 subjects, 40 total ankles) was similar to previous SSM studies involving ankle and hindfoot bones.[13,14,16,27] Melinska et al[14] generated 18 bilateral calcanei models using 28 subjects and, in a subsequent study, 15 bilateral models of the cuboid, navicular, and talus using 30 subjects. Those studies, however, did not

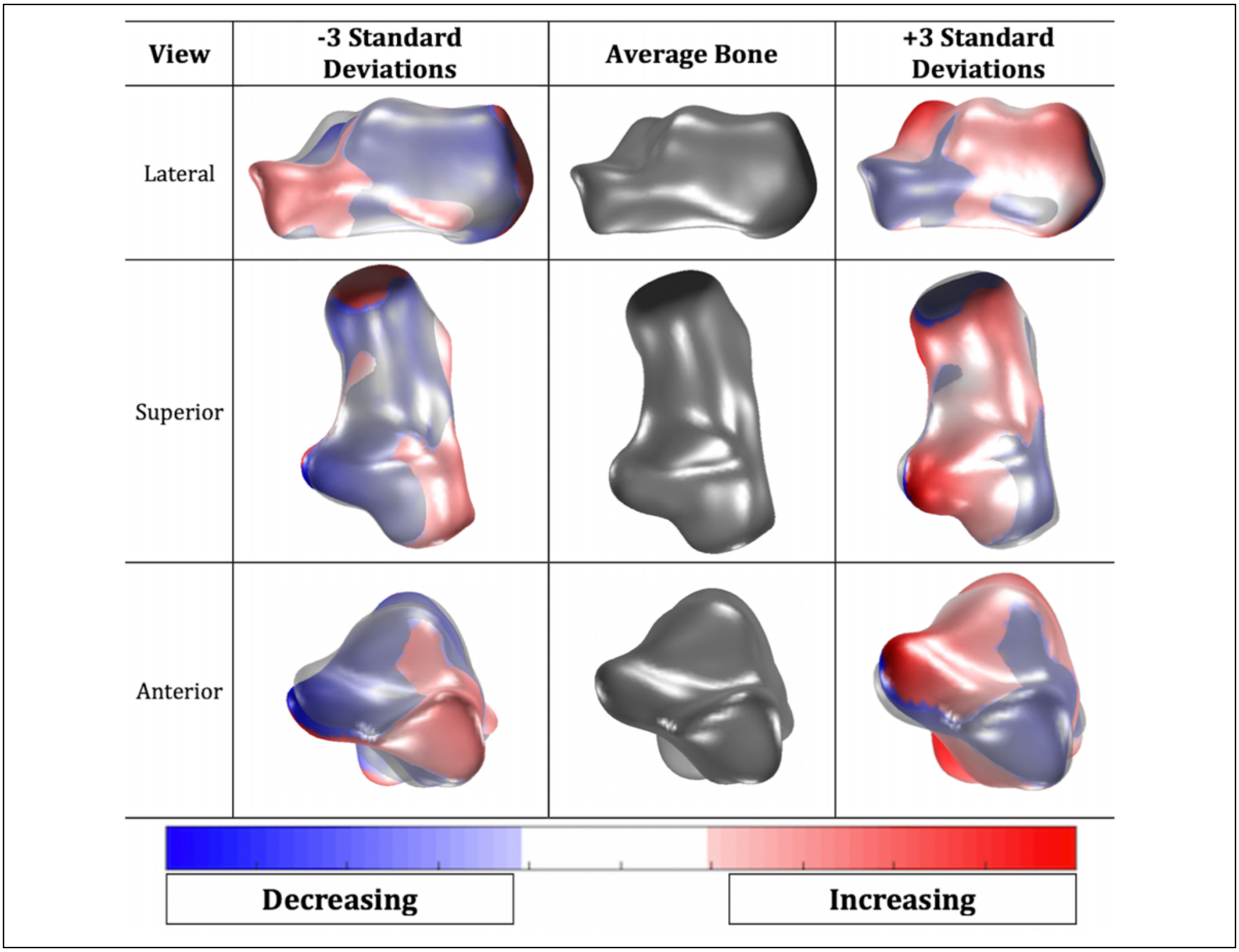

Figure 6. Lateral, superior, and anterior views of the first mode of variation in calcaneus shape. The largest amount of variability in calcaneus shape was related to length, rotation of the sustentaculum tali about the long axis of the bone, and the depth of the articular surfaces (20.3% of the variability).

include bilateral scans from the same individual and instead age-matched left- and right-sided bones. Moore et al[16] used 40 subjects and Tümer et al[27] used 66 subjects, and both studies used bilateral scans from the same individuals to generate their models, similar to our study. A post hoc power analysis indicated that 35 subjects would have been required for the SSDs we observed to reach statistical significance. Because of the qualitative interpretation of SSM results, it is not clear how many subjects are necessary for robust and reliable results; however, as noted in our discussion, the primary shape factors comprising the first 3 modes of variation (ie, the greatest variability among subjects) are fairly consistent between our study and previous research.

Conclusion

This study quantified the side-to-side symmetry in ankle and hindfoot bone morphology, identified sex differences in tibia and calcaneus bone morphology, and identified the primary shape factors that differentiate bone morphology among healthy individuals. This work provides a foundation for exploring the relationship between bone morphology and ankle-hindfoot kinematics, and for assessing the ability of operative intervention to restore bony morphology and kinematics in young adults.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. ICMJE forms for all authors are available online.

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