Three-Dimensional Foot Shape and Plantar Pressure Scanning in a Large Physically Active Cohort

Michelle Meyers[1], Elana Renae Lapins[2], Amy Lenz[2], Josh Baxter[1]

[1]University of Pennsylvania, Philadelphia, PA, [2]University of Utah, Salt Lake City, UT

meyersm9@seas.upenn.edu

Disclosures: Authors have no disclosures according to ACCME guidelines.

INTRODUCTION: Structural changes of the foot have been linked to pain and functional impairments, with foot complications affecting 46% of adults [1]. Factors such as sex, exercise, foot dominance, and body mass index (BMI) have been reported to affect foot structure, function, and health [2-5]. Additionally, arch structure has been linked with injuries within the running population, with high arch runners sustaining ankle injuries and low arch runners sustaining knee and soft tissue injuries [6]. The action of long-distance running has also been associated with increased pronation, reduced arch, and increased medial plantar pressure [7,8]. The foot is typically evaluated using 2D metrics which do not address its multifaceted structure and function, therefore, there is a need for unique tools to elucidate a full analysis of the foot. 3D foot scanning has been found to be reliable to quantify foot morphology and has been used in medical and footwear development applications [9,10]. This tool, in conjunction with statistical shape modeling and plantar pressure analysis, enables greater insight into the foot and illuminates subtle differences within a population that may be missed with 2D measurements. The purpose of this study is to utilize innovative tools to identify foot structural and functional differences in a large, physically active cohort of adults while also evaluating factors such as weekly running volume, BMI, pain, sex, and foot sidedness.

METHODS: We recruited a cohort of 231 individuals (female: n = 143, male: n = 88) from the 2025 Philadelphia Broad Street Run Health Expo. Participants provided verbal informed consent, and the University of Pennsylvania's Institutional Review Board approved this study. Individuals were participating in the 10-mile run as well as accompanying runners or working the event. Upon receiving consent, participants completed a short survey providing height, weight, sex, and weekly running volume. Additionally, we recorded whether participants were currently experiencing foot and ankle pain. If participants reported having pain, they completed a visual analog scale from 0-10 ranking their current pain then provided a description of the pain. These survey questions were used to categorize the cohort into different groups based on running volume, BMI, pain, and sex. We used an Aetrex Albert 2 Pro Scanner to collect 3D scans and plantar pressure distribution in the standing position. This device is equipped with four cameras and 5,184 gold-plated pressure sensors to collect these metrics. We utilized statistical shape modeling (ShapeWorks) to identify modes of variation within the population as well as to compare group mean shapes based on sex, running volume, pain level, and BMI [11]. Statistical shape modeling is a correspondence particle-based method that captures anatomical modes within a population. We developed two separate statistical shape models for the left and right foot due to significant differences in foot structure between sides. We used 4,096 particles for each model and implemented Procrustes scaling correction to normalize foot length within the population. We performed group particle comparisons using a Hotelling T^2 test ($\alpha = 0.05$). Using plantar pressure scanning, we quantified the percent of plantar contact and the plantar center of pressure of the midfoot. The midfoot center of pressure was calculated as the distance from a line running through the forefoot and rearfoot center of pressure and was normalized by foot width. We used a Shapiro-Wilk test to evaluate normality of the data followed by a Kruskal-Wallis ($\alpha = 0.05$) and Dunn-Sidak ($\alpha = 0.025$) test to evaluate group differences.

RESULTS: Using the developed statistical shape models, we identified 5 clinically relevant modes of variation in right feet: Mode 1: Achilles tendon thickness (26.3%), Mode 2: hindfoot pronation (18.8%), Mode 3: arch height (12.9%), Mode 4: instep/girth (12.1%), Mode 5: foot width (5.7%). We also identified 5 modes of variation in left feet: Mode 1: Achilles tendon thickness (27.2%), Mode 2: arch height (19.4%, Figure 1A), Mode 3: instep/girth (14.1%), Mode 4: foot width (10.6%), and Mode 5: hindfoot pronation (5.9%, Figure 1B). We found significant differences in left foot structure between runners with moderate and high running volume compared to identified non-runner that centralized in the medial region of the foot, specifically the arch. However, we found limited differences in right foot structure and no significant differences in plantar pressure distribution metrics. We identified that plantar pressure measurements and foot structure were highly dependent on BMI. We found that left and right midfoot percent plantar contact was significantly increased in extremely obese (left: $p = 0.004$, right: $p = 0.005$), obese (left: $p = 0.001$, right: $p = 0.005$), and overweight (left: $p = 0.003$, right: $p = 0.009$) individuals compared to individuals with normal BMI (Figure 1C). We found no significant differences in normalized midfoot center of pressure. Using statistical shape modeling we identified significant differences (particle $p < 0.05$) in 3D foot structure comparing normal BMI individuals to overweight, obese, and extremely obese individuals, these differences were predominantly surrounding the ankle, medial, and lateral regions of the foot (Figure 1D). Also, female's midfoot percent plantar contact was significantly decreased compared to males (left: $p < 0.001$, right: $p < 0.001$). We found no significant differences in plantar pressure distribution and foot structure according to foot/ankle pain.

DISCUSSION: Anatomical modes were consistent between left and right feet but differed in percent variance explained in the population. Mode 1 in both foot models demonstrated deviations in Achilles tendon thickness within the population which is clinically important because thicker tendons are correlated with painful symptoms in running populations [12]. Additional clinically important anatomical modes of variation included arch height, pronation, and instep/girth which are useful in identifying foot deformities and risk factors for pain and injury [6,13,14]. Although literature shows that running increases hindfoot pronation, we found that in the standing position moderate and high-volume runners experienced less pronation compared to non-runners upon evaluation of 3D foot structure. We also observed that runners have higher arches. We hypothesize that these structural differences in cohorts are due to foot fitness and continuous foot engagement in runners. Foot structure and function were highly dependent on body habitus in which obese and overweight individuals sustained increased midfoot plantar percent contact, decreased arch height, increased pronation, and increased foot girth. Obesity is thought to significantly affect foot structure and function due to increased weight and stresses on the foot during everyday activities that weaken the structure [15]. In particular, the medial longitudinal arch bears nearly three times more load in obese individuals than those of normal weight [16]. We also observed decreased midfoot plantar contact in females suggesting lower arches compared to males, corresponding with literature findings [4].

SIGNIFICANCE/CLINICAL RELEVANCE: 3D foot shape and plantar pressure scanning is a high-throughput method of monitoring foot structure in a large population. Using this tool in conjunction with statistical shape modeling, we developed a foot monitoring paradigm for identifying clinically important anatomical modes of variation within a large cohort.

REFERENCES: [1] Lopez+2018, [2] Stanković+2018, [3] Butterworth+2015, [4] Edama+2022, [5] Ilnicka+2013 [6] Williams+2001, [7] Nagel+2018, [8] Cowley+2013, [9] Telfer+2010, [10] Jurca+2019, [11] Cates+2017, [12] Tillander+2019, [13] Tang+2020 , [14]Menz+2013, [15] Mickle+2015, [16] Hills+2001.

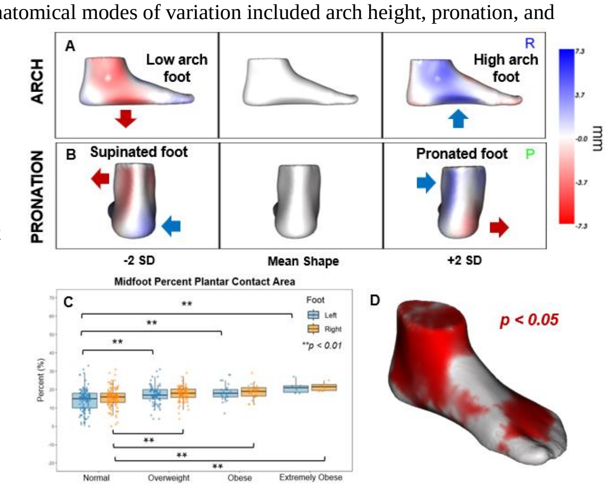

Figure 1. Left foot arch (A) and pronation (B) modes of variation within the cohort. Red regions indicate increase of feature from mean shape and blue indicates decrease. Midfoot percent plantar contact increased with body habitus (C). Mean foot structure is significantly different between normal BMI and obese cohorts (D).