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Prediction of the First Ray Axis from Clinical Measurements: Implications for the Treatment of Bunion

Glasoe Ward M*, Wolff Kristina, Wicks Andrew, Shaw Andrea and Smith Janie

Program in Physical Therapy, Medical School, University of Minnesota, Minneapolis, USA

***Corresponding author:** Glasoe Ward M, Program in Physical Therapy, Medical School, 420 Delaware St SE, MMC 388, University of Minnesota, Minneapolis MN, 55455, USA, Tel: 612-624-9894; Fax: 612-625-4274; E-mail: glaso008@umn.edu.

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Abstract

Objective: Inclination of the first ray axis has been identified as a risk factor of bunion, but the actual orientation of a joint axis can only be quantified with motion analysis techniques. This investigation used a single-group regression design for the purpose of identifying a surrogate measure, or system of measurements, that could predict the orientation of the first ray axis.

Methods: The clinical measurements of the foot were performed on 20 women participants including 10 with, and 10 without bunion. Magnetic resonance images of the foot were acquired while the participant stood to simulate gait. Images were then rendered into virtual datasets from which first ray kinematics were decomposed into X, Y, and Z Cardan angles and helical axis direction cosine component parameters. Reliability of the clinical measurements was assessed, and multiple regression analysis determined the relationship amongst variables.

Results: Measurements of dorsum foot height, hallux dorsiflexion, hallux angle, intermetatarsal angle, and arch angle were reliable (ICC ≥ 0.67) and when used as variables in the regression analysis models, the curvilinear measure of hallux dorsiflexion and the linear measure of hallux angle combined to explain a significant (p=0.01) 49 percent (R2=0.49) of the overall variance in predicting the first ray axis.

Conclusion: Five of the clinical measurements, all except navicular drop and hindfoot valgus were judged reliable. Of these, only hallux dorsiflexion and hallux angle had a relationship with the first ray axis. This report marks the first attempt to identify measures that predict the loading behaviors of the first ray. Results may inform future work, as it is likely some other combination of measurements may more strongly predict inclination of the first ray axis which may, in theory, be amendable with non-operative treatment (i.e. orthoses) in the management of foot bunion.

Keywords: Human foot; Hallux valgus deformity; Kinematic measurements; Gait simulation

Introduction

Orthoses provide beneficial outcomes in the management of bunion (hallux valgus) [1,2]. The reason is not clear. One explanation is that foot segments follow a joint axis concept [3,4], and that orthoses fit to support the arch may level the first ray axis. This in turn may constrain the first ray from adducting - thereby slowing the complications and adverse sequelae of bunion [5].

Bunion disrupts the alignment of the first metatarsophalangeal (1-MTP) joint. The progression of deformity presents as ever-increasing abduction of the hallux and adduction of the first metatarsal. Adduction involves the combined first metatarsal and medial cuneiform (first ray) arch segment, with the angle of adduction measured in reference to the second metatarsal [6].

The first ray plays a central role in supporting body weight. Acting as a load-bearing strut [7,8], the first ray rotates about a single axis [9]. The locus of the axis passes from the navicular across the midfoot horizontal [3]. In a study on cadavers, Glasoe et al. [9] found that orientation of the axis was inversely (r -0.73) related to arch height and when the axis inclined (tilt towards vertical), the first ray adducted under an imposed load. They next used weightbearing imaging to study the change in tarsal kinematics associated with bunion deformity [10,11]. Adduction of the first ray was increased (≥ 5°) in women with bunion, and the joint axis inclined by as much as 30° from the horizontal during simulated gait. Although this past work described a potential mechanism of bunion, inclination of the axis or other anatomical risk factors [12-15] that alter the loading behaviours of the first ray can only be treated if identified with clinical measurements.

Presently, orientation of the first ray axis has been quantified in human subjects only with kinematic imaging techniques. Hence, this study was conducted for the primary purpose of identifying a surrogate measure, or system of measurements that could predict the first ray axis. A secondary aim was to assess the reliability of a series of 7 different clinical measurements (Figures 1 and 2), each selected to represent some unique characteristic of the first ray and its association with bunion.

To address the purposes of this study, it was hypothesized that some combination of clinical measurements, if demonstrated reliable, could predict inclination of the first ray axis.

Methods

Participants

The study used a prospective single-group regression design. Participants were the first 20 (of 29 total) women enrolled in Glasoe's 2-part imaging study of bunion [10,11]. Women comprise 90 percent of the patient cohort [16]. The abduction offset in 1-MTP joint posture was ≥ 15° in ten of the women sampled, indicating bunion [16]. Group demographics were age=43 ± 18 years; height=167 ± 6 cm; weight=69 ± 12 kg. Informed consent was obtained in accordance with University Institutional Review Board (#0709M16823) guidelines.

Our original intent was to include participants with rheumatoid arthritis (RA), as there is a high revalence of bunion in the RA population [16]. Participation in this study, however, required standing in an upright magnetic resonance (MR) scanner for one hour. This requirement proved too strenuous for women deconditioned from the comorbidities of bunion and active RA [10,11]. Also excluded were those having contraindications to imaging, foot deformity other than bunion or sensory deficits that could indicate peripheral neuropathy, history of foot or ankle surgery, or stiffness of the 1-MTP joint of greater than 50° which could alter gait.

Clinical Measurement Procedures

All measurements [17-23] shown in Figures 1 and 2 were made by one examiner. The examiner (WMG) is a physical therapist by training and has a 20-year history of translating research into practice [15,24]. The measures of foot mobility are listed, with the baseline recorded in sitting:

- Navicular drop (Figure 1a) was quantified by palpating the congruency of the talotibial and talonavicular joints and once neutral alignment was identified, height of the navicular tuberosity was marked on a card placed next to the foot [17]. The participant stood, and height of the navicular was again marked on the card. The linear distance between marks quantified navicular drop [17].
- Foot height (Figure 1b) was measured using a caliper (Model #599-579-4, Brown & Sharp, Providence, RI, USA). The arm of the caliper was placed on the dorsum of the foot at 50% of its length. The participant then stood, and the height of the foot was re-measured. Foot height was quantified as a percent (%) by dividing the change in height by the length of the truncated foot [23].
- Hindfoot valgus (Figure 1.c) was assessed from lines drawn on the leg and calcaneus. The relative change in the angle where the lines bisected as the participant moved to standing quantified hindfoot valgus [19].
- Hallux dorsiflexion (Figure 1d) was measured in a position that simulated gait push-off.
- Posing the foot in this manner assessed the stabilizing action of the 1-MTP joint capsule,sesamoid ligaments, and the plantar fascia [20,25].

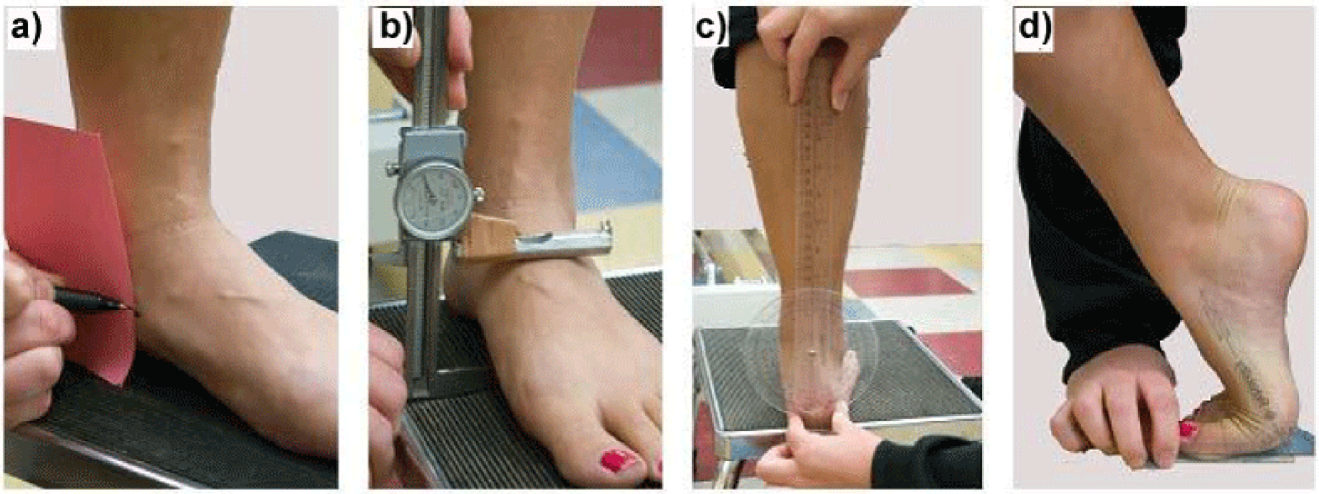

Figure 1: Foot Mobility Measurements. The person had moderate bunion and joint laxity. The reliability coefficients for the measurements are abbreviated: ICC=Intraclass Correlation Coefficient; SEM=Standard Error of Measurement. a. Navicular Drop. Linear displacement of the navicular. ICC=0.45; SEM=1.9 mm. b. Foot Height. Percent change in dorsum height of the foot. ICC=0.69; SEM=1%. c. Hindfoot Valgus. Angular excursion in hindfoot position. ICC=0.32; SEM=1.6°. d. Hallux Dorsiflexion: Angular position of the 1-MTP joint. ICC=0.67; SEM=7.9°.

The measurements of foot structure as shown in Figure 2 were acquired on reconstructed image datasets (methods described in next section). Hallux angle, intermetatarsal (IM) angle, and arch angle were measured by placing a goniometer over a planar projection of the magnetic resonance image acquired in the midstance (MS) gait condition. Each angle is influenced by the alignment of the first ray, and the set of angles is often quantified when making surgical decisions in the correction of late-stage bunion [16]. Hallux angle (Figure 2a) quantified the offset in abduction in 1-MTP joint alignment, and IM angle (Figure 2b) the adduction separation between the first and second metatarsal. Arch angle (Figure 2c) measured height of the arch in the sagittal plane.

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All of the clinical measurements were retaken by a second examiner, and reliability was assessed using an Intraclass Correlation Coefficient (ICC) value based rating criterion [26]. An ICC below 0.50 indicates poor reliability, 0.50 to 0.75 indicates moderate reliability, and 0.75 to 1.00 indicates good-to-excellent reliability [26]. Only measurements having ICC ≥ 0.50 were judged worthy of inclusion as predictor variables in the regression equation. For completeness, reliability was also evaluated by calculating the standard error of measurement (SEM). The SEM calculation is expressed in the unit of measurement, and gives an estimate of the range of values expected when a measurement is repeated [27].

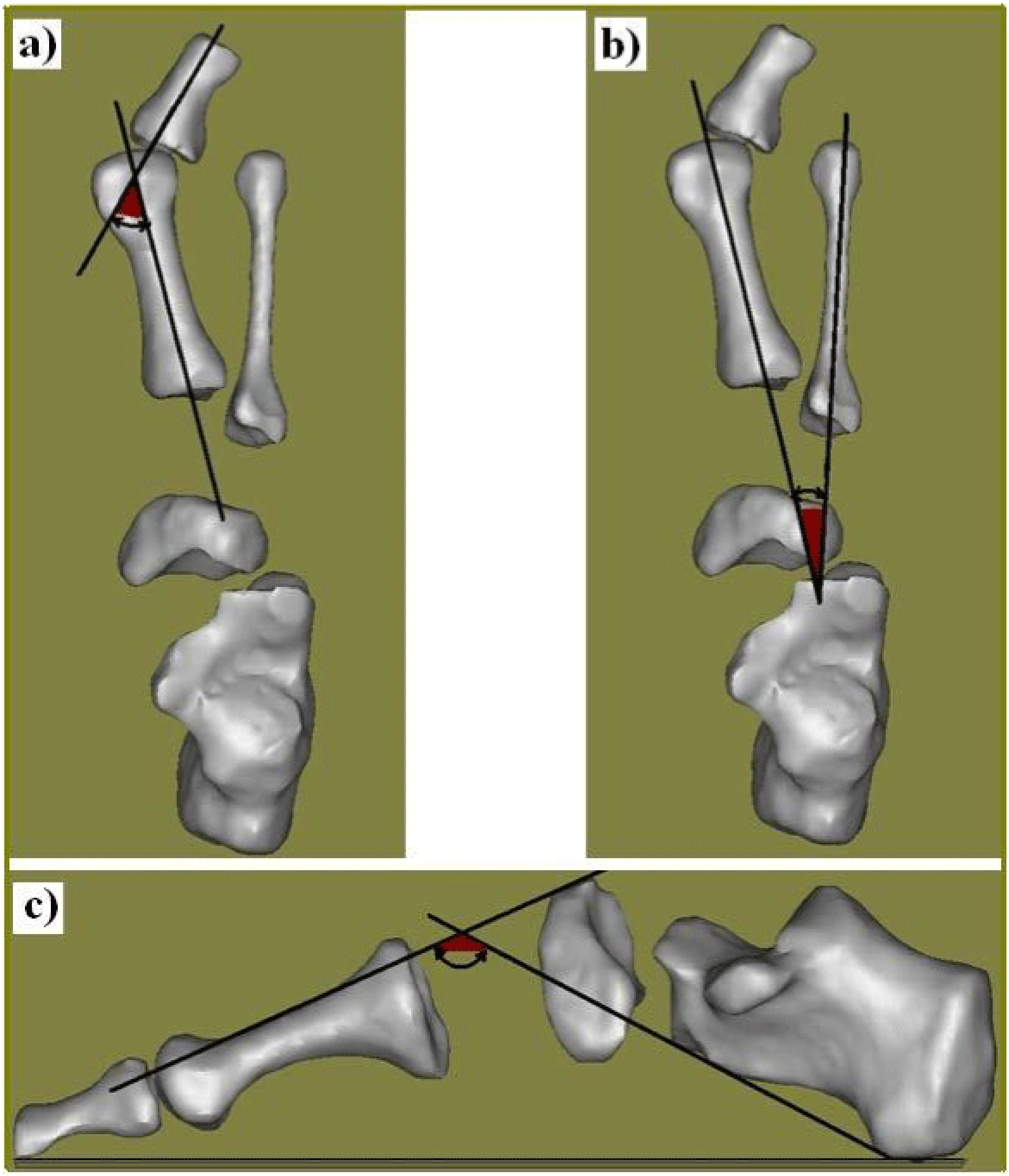

Figure 2: Foot Structure Measurements. The bone models are the proximal phalanx of the hallux, first and second metatarsals, navicular, and calcaneus. Abbreviations: ICC=Intraclass Correlation Coefficient; SEM=Standard Error of Measurement. a. Hallux Angle. ICC=0.99; b. SEM=1.6°. Intermetatarsal Angle. ICC=0.97; c. SEM=0.7°. Arch Angle. ICC=0.98; SEM=0.7°.

Scan Protocol and Image Preparation

The foot was scanned using a FONAR (Melville NY, USA) Upright 0.6 Tesla magnet. The participant stood to simulate gait midstance (MS), heel off (HO), and terminal stance (TS). Conditions were standardized by placing the foot on identical wedges to pose the ankle joint at a predetermined angle, targeting values reported in the literature [28]. The ankle was dorsiflexed 5° at MS, dorsiflexed 10° at HO, and plantar flexed 10° at TS. A complete description of the weightbearing imaging protocol has been published elsewhere [10,11,32].

The digital images were imported into MIMICS (Materialise, Leuven Belgium) software for reconstruction [10,11]. Computer processes then rendered the first ray, the navicular, and other selected tarsals into virtual bone models, and linked the reconstructed bone datasets together in the MR laboratory frame of reference [29]. Figure 3 displays the bones of one participant across gait events.

Each bone model was embedded with an inertial coordinate system using computer processes. The definitions of the coordinate system axes correspond to the Y-axis projecting up, Z-axis lateral, and X-axis forward. Position of the first ray (Figure 3) was then determined in relation to the navicular in the transverse, sagittal, and frontal planes of motions [10,11]. Data processing error was <3° [29], and the measurement was reliable and valid across simulated gait conditions [10,11,29]. Validity was judged by comparing the trajectory of the navicular to data published in the gait literature [30,31].

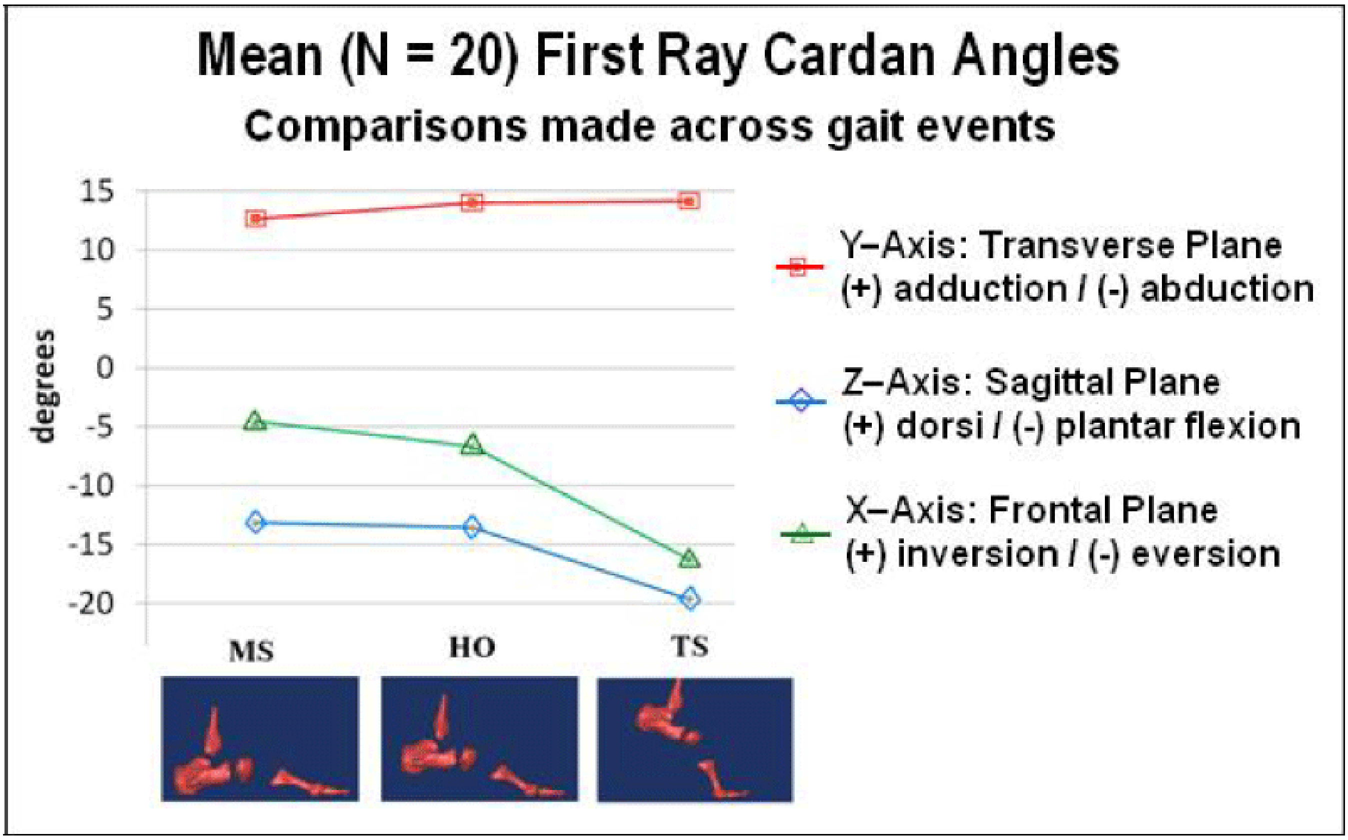

Figure 3: First ray angles plotted across midstance (MS), heel off (HO) and terminal stance (TS). Gait events are represented by a sagittal view of virtual bones reconstructed from the images. The bone models are the proximal phalanx of the hallux, first metatarsal, navicular, calcaneus, and distal fibula.

Cardan Angle and First Ray Axis Calculations

First ray kinematics was computed as Cardan angles and finite helical axis parameters. Cardan angles represent joint motion, quantified as ordered rotations whereby add-/abduction was calculated first, dorsi-/plantar flexion second, and in-/eversion last [10,11,32]. The helical axis computation defined a direction cosine vector (line) in 3-dimensional space [33] that expressed the path about which the position of the first ray changed in relation to the navicular between MS and HO (middle stance), and between the HO and TS (late stance) gait events. The selection of gait conditions and the subsequent finite interpolation was based on the arch being lowest at heel off across gait events [34]. The helical axis parameters output as "Phi" total rotation, and as an array of X, Y, Z, direction cosine components. Important for this study, the Y component (Yc) defined inclination of the axis. Phi rotation, and the X and Z components are reported as mean values, but not analyzed further.

The helical axis components were analyzed in the MR laboratory frame of reference. This extra rocessing step allowed the direction cosine result to be interpreted in the Cardinal planes. Thus inclination of the first ray axis is reported in relation to horizontal for all participants. When interpreting the helical axis component result, recall that cosine values range between -1 and 1. Should Yc=1, the first ray axis would point-up and vertical. Rotation about an upwardly pointing vertical axis indicates the occurrence of adduction joint motion. Should Yc=0, the axis would point lateral indicating dorsiflexion.

Statistical Methods

Descriptive statistics and reliability coefficients were computed for the 7 clinical measurements. All measures identified as reliable (ICC>0.50) were next explored for normal distribution. The strength of correlation between the measures was then assessed with a Pearson product-moment coefficient (r). Should correlation be identified, only one of the two measures was entered as a variable in the multiple regression equation for continued analysis [35]. Level of significance was p<0.05.

An all-possible multiple regression analysis assessed the relationship between the variables retained, and inclination of the first ray axis (Yc). Second order quadratic variables were added to the analysis to account for data having a non-linear line of best fit. A plateau in R2 value was objectified as the point when adding subsequent predictors to the all-possible model did not account for greater than 5% of the variance explained. Once the number of variables was determined from the run of the all-possible regression model, a multiple regression analysis was performed to estimate the overall variance in predicting Yc over middle stance, and late stance.

Results

A descriptive display of the 7 clinical measurements is reported Table 1. The reliability of the measures (Figures 1 and 2) ranged widely. Reliability of the hallux angle, IM angle, and arch angle was excellent (ICC ≥ 0.97) in all cases; foot height and hallux dorsiflexion was moderate (ICC ≥ 0.67); navicular drop and hindfoot valgus was poor (ICC ≤ 0.45). Based on the ICC cut-off criterion, navicular drop and hindfoot valgus were not reliable and therefore, not retained as predictor variables in the regression equation.

	*Navicular Drop (mm)	*Foot Height (%)	*Hindfoot Valgus (°)	Hallux Dorsiflexion (°)	Hallux Angle (°)	IM 1-2 Angle (°)	Arch Angle (°)
Mean	8.6	3.0	3.0	96	21	14	134.0
SD	2.0	2.0	1.2	14	15	3.7	5.1
Range	5 to 12	1 to 7	0 to 5	60 to 120	-3 to 47	9 to 20	126 to 143

Table 1: Descriptive Summary of Clinical Measurements. *Recorded as the change in position measured between sit-and-stand.

Table 2 shows the correlation matrix for all clinical measurements judged reliable (ICC>0.50). The Pearson's r value amongst measures ranged from -0.08 to 0.90. Correlation between the hallux and IM angles was significant (p<0.001; r=0.90). Correlation between IM angle and foot height, although not significant (p=0.16), was second highest (r=0.33). Based on the a priori decision to input only non-correlated variables into a regression equation, the IM angle was not retained for use as a predictor variable in the regression equation.

	Foot Height	Hallux Dorsiflexion	Hallux Angle	IM 1-2 Angle	Arch Angle
Foot Height	1.00	-0.08	0.18	0.33	0.17
Hallux Dorsiflexion	-0.08	1.00	-0.27	-0.30	0.24
Hallux Angle	0.18	-0.27	1.00	0.90	-0.22
IM 1-2 Angle	0.33	-0.30	0.90	1.00	-0.24
Arch Angle	0.17	0.24	-0.22	-0.24	1.00

Table 2 : Correlation (r) Matrix of Clinical Measurements.

Figure 3 displays the first ray Cardan angles (about the Y, Z, X coordinate system axes) across conditions. Table 3 reports the corresponding helical axis parameters. Phi rotation averaged 5.5° over middle stance, with Yc=0.29 being the dominant component. Phi averaged 13.4° over late stance, with Yc=0.02 being the smallest component. Use of an arc-cosine trigonomic function converts cosines to angles. Inclination of the first ray axis averaged 13° (Yc=0.29) over middle stance, and 1° (Yc=0.02) over late stance.

The combination of foot height, hallux dorsiflexion, hallux angle, arch angle measurements were run in the regression models as predictor variables of Yc. For middle stance: hallux dorsiflexion and hallux angle combined to explain a significant 49% (p=0.01; R2=0.49) of the overall variance in Yc. Hallux dorsiflexion (Figure 4A) was the largest predictor accounting for 40% of the variance in a curvilinear relation; hallux angle (Figure 4B) accounted for 14% of the overall variance in a linear relation. For late stance: hallux dorsiflexion, hallux angle, and arch angle combined to explain a non-significant 34% (p=0.41; R2=0.34) of the variance in Yc.

Middle Stance (MS to HO)			
Phi	**Yc**	**Zc**	**Xc**
5.5° (3.0°)	0.29 (0.4)	0.02 (0.6)	-0.26 (0.7)
Late Stance (HO to TS)			
Phi	**Yc**	**Zc**	**Xc**
13.4° (6.7°)	0.02 (0.3)	-0.30 (0.3)	-0.68 (0.52)

Table 3 : Helical axis parameters reported as total rotation (Phi) and Y, Z, X direction cosine components. Group means (SD) computed between designated gait events.

Discussion

This study investigated the usefulness of clinical measurements (Figures 1 and 2) in predicting the inclination of the first ray axis. After performing the prerequisite reliability and correlation analyses, only foot height, hallux dorsiflexion, hallux angle, and arch angle were retained as potentially useful predictor variables. A brief discussion of each of these measurements follows: • Foot height (Figure 1b) lowered by an average of 3% when the participant moved from sit-to-stand. Williams and McClay [23] found a similar result (2.4%) in 50 adults.

- Hallux dorsiflexion (Figure 1d) ranged from 60 to 120°. Greater than 100° of motion was measured in 9 of the women (Figure 4A). Since 6 of these individuals did not have bunion, we attribute this generally larger than normal amount of 1-MTP joint motion to how the foot was positioned for testing. Standing with the foot pressed into the floor for the purpose of maximally dorsiflexing the hallux tightened the plantar fascia thereby stabilizing the foot skeleton [25], which allowed a more forceful assessment [20].
- Hallux angle (Figure 2a) ranged from -3 to 47°. A negative value indicates adduction; positive indicates abduction of the hallux. Such variability in 1-MTP joint posture was expected, as 10 women had bunion. The non-homogenous inclusion of participants ensured related variance in first ray kinematics. If minimal variance were present, the association of variance to other variables cannot be statistically assessed with methods of multiple regression analysis [35].
- Arch angle (Figure 2c) averaged 134°. This amount is normal in adults [36], which argues against the notion that flatness of the arch is by itself, a risk factor of bunion [37].

First ray motion was represented with Cardan angles. Rotation across gait conditions occurred predominantly in the frontal and sagittal planes. Note Figure 3, especially between HO and TS (late stance), where plantar flexion (7°) and eversion (12°) are the primary rotations. A similar pattern of biplanar joint motion has been recorded in gait trials [8,12].

Methods of multiple regression analysis were next used to identify the clinical measures that predict inclination of the first ray axis. Computed as helical axis vector, inclination of the axis was expressed by the direction cosine Yc. For middle stance, the measurements of hallux dorsiflexion and hallux angle combined to explain a significant (P=0.01) amount (R2=0.49) of the overall variance in Yc. Hallux dorsiflexion accounted for 40% of the variance in a 2nd order (curvilinear) relation, and hallux angle accounted for 14% of the variance in a linear relation.

The relationship between variables is shown in Figure 4. The axis was most inclined in women demonstrating a mid-range (70 to 100°) amount of hallux dorsiflexion, and most inclined in those demonstrating the largest offset of hallux angle (43 to 47°). No combination of measurements predicted the first ray axis in late stance. These results may inform future research, as it is likely that some other combination of measurements may more directly predict the first ray axis.

This study investigated the predictiveness of navicular drop, foot height, and hindfoot valgus as variables in a regression model. All 3 measurements were difficult to perform, mostly because the change in posture between sitting and standing is small (Table 1), and small displacements are not easily detected or accurately measured with hand-held tools. The reliability of the navicular drop and hindfoot valgus measurement was poor (ICC ≤ 0.45). This same result has been reported in 2 previous studies [19,22]. Should researchers have continued interests in predicting the first ray axis from clinical measurements, we surmise it might work better to quantify external loading forces or certain aspects of foot type (planus vs. cavus) instead of measuring the small increments of change associated with variations in the weightbearing status of the foot.

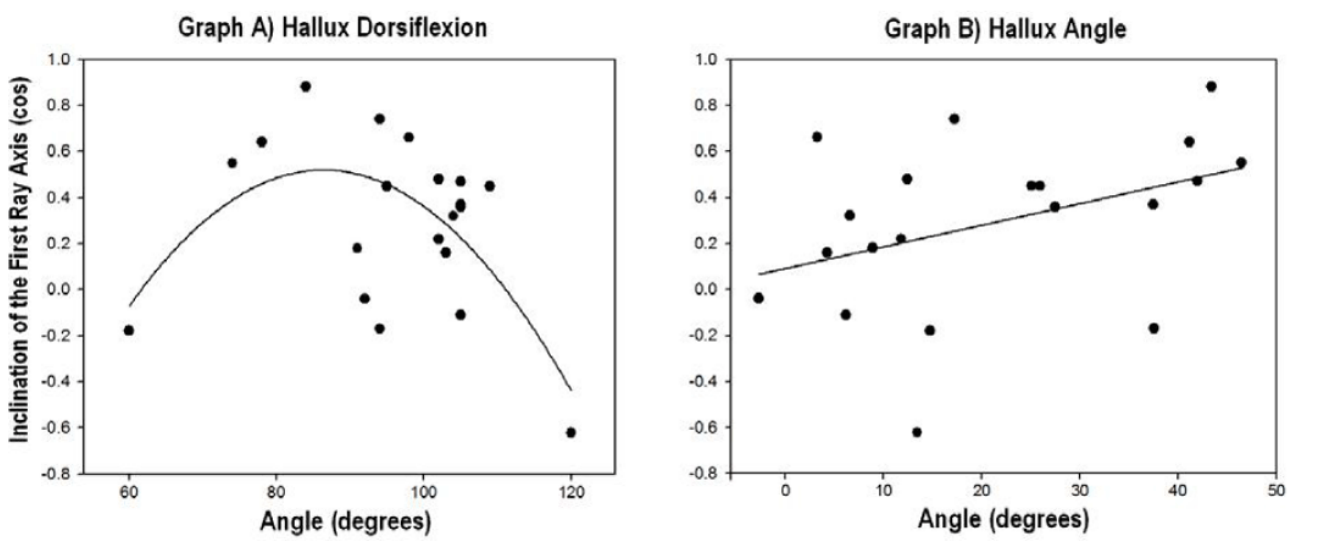

Figure 4: Scatterplots (N=20) of hallux dorsiflexion (Graph A) and hallux angle (Graph B). The two measurements combined to explain a significant (P=0.01) amount of the variance in the inclination of the first ray axis, expressed by the Y component (Yc) direction cosine (cos).

The study had several limitations. Kinetics was not measured, and standing upright in a scanner precludes the transfer of load and the body and limb accelerations that occur during gait. Despite this limitation in methods, the magnitude and direction of Cardan angles reported in this study (Figure 3) are comparable to the angular results published in gait trials [8,12,31,38]. A possible exception may be the slight amount of plantar flexion measured between first metatarsal and navicular over middle stance. Leardini et al. [39] found the same. Other gait trials [8,31,34], however, report dorsiflexion (~3°) to occur from early weight acceptance until the instant of heel off. Additionally, the sample was small (N=20), and gait was simulated with only 3 conditions (MS, HO, TS). These limitations may potentially reduce the generalizeability of the results.

Conclusion

The first ray rotates about a single joint axis, and inclination of the axis has been implicated as a risk factor of bunion. To identify a surrogate measure of the first ray axis, this investigation used a regression analysis design to assess the usefulness of 7 clinical measurements in predicting the first ray axis. All of the clinical measurements, except navicular drop and hindfoot valgus, were determined reliable (ICC $\geq$ 0.67). Hallux dorsiflexion and hallux angle combined to explain a statistically significant ($p=0.01$) amount of the overall variance in the first ray axis.

Results demonstrate how research can predict the first ray axis, and these study methods may be adopted in future work to help develop new treatment strategies for the care of bunion.

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