

Analysis of Dynamic Angle of Gait and Radiographic Features in Subjects with Hallux Abducto Valgus and Hallux Limitus

Julie Taranto, MMedSc*
Michael J. Taranto, MMedSc*
Alan R. Bryant, PhD†
Kevin P. Singer, PhD*

Background: Hallux abducto valgus and hallux limitus are two commonly encountered foot deformities causing altered structure and function of the first metatarsophalangeal joint and subsequent compensatory mechanisms. This study was undertaken to determine the relationships between these two deformities and transverse plane position of the foot, or angle of gait, and several radiographic angular and linear parameters with established reliability.

Methods: A convenience sample of 23 subjects with hallux abducto valgus, 22 subjects with hallux limitus, and 20 control subjects was used. Radiographic parameters were standardized weightbearing views and included lateral stressed dorsiflexion of the first metatarsophalangeal joint, composite, dorsoplantar, and lateral views. Angle of gait was obtained from powdered footprints recorded on paper. Two left and two right footprints identified on each trial were used to calculate angle of gait.

Results: The findings of the study suggest that an association between angle of gait and the presence of hallux abducto valgus or hallux limitus does not exist. Possible explanations may relate to the large variability of normal angle of gait, the need to identify factors extrinsic to the foot capable of affecting transverse plane orientation of the foot, and the addition of information relating to symptoms.

Conclusions: In this study, the presence of hallux abducto valgus or hallux limitus did not correspond to an association with a particular angle of gait. Length and elevation of the first metatarsal were associated in subjects with hallux abducto valgus and hallux limitus. (J Am Podiatr Med Assoc 97(3): 175-188, 2007)

Hallux abducto valgus is one of the most common foot deformities,^{1,2} with hallux limitus representing the second most commonly encountered pathomechanical disorder affecting the first metatarsophalangeal joint.³ Alteration in angle of gait is a clinical feature often seen in hallux abducto valgus and hallux limitus; however, whether the abduction or adduc-

tion is a precursor or a compensatory mechanism remains unknown. Angle of gait has received little attention in the literature, and studies^{4,5} of this parameter have revealed variable normal reference ranges, reporting 5° to 13° of abduction from the midline of forward progression. Variability in measurement methods may have accounted for differences among observers. Investigation of angle of gait may provide further insight into the pathomechanics of hallux abducto valgus and hallux limitus and the effects of intervention to treat or correct these deformities.

Angle of gait refers to the transverse plane midsagittal position of each foot in midstance relative to the direction of forward movement during gait, or, clinically, the amount of in-toeing or out-toeing of the foot relative to the line of progression.^{4,6} Factors that

*Centre for Musculoskeletal Studies, University of Western Australia, and Department of Surgery and Pathology, Royal Perth Hospital, Perth, Western Australia, Australia.

†Faculty of Medicine and Dentistry, Podiatric Medicine, University of Western Australia, Nedlands, Western Australia, Australia.

Corresponding author: Julie Taranto, MMedSc, Centre for Musculoskeletal Studies, University of Western Australia, and Department of Surgery and Pathology, Royal Perth Hospital, Level 2, MRF Bldg, Rear 50 Murray St, Perth, Western Australia, 6000 Australia.

may affect angle of gait include walking speed; leg dominance⁷; tactile feedback and friction from the walking substrate^{6, 7}; soft-tissue or osseous torsional or positional changes in the hip, femur, and tibia; amount of malleolar torsion; and transverse plane deformities of the foot.⁸ In the present study, subjects walked at their normal speed so as not to alter the typical angle of gait of each subject. The walking substrate was kept consistent, and biomechanical assessment of each subject was undertaken to exclude soft-tissue and osseous factors capable of affecting angle of gait. Clinical and radiographic examinations were used to exclude transverse plane deformities of the foot, such as metatarsus adductus. Leg dominance was not controlled for because it was identified as having a potential effect on angle of gait only on completion of the study.

Review of the literature suggested abnormal biomechanics, specifically, excessive pronation of the foot, as a cause of hallux abducto valgus and hallux limitus,⁹ with reference to biomechanical causes of hallux abducto valgus being made as early as 1938.¹⁰ The direct relationship between angle of gait and hallux abducto valgus or hallux limitus has not been adequately investigated.

This study was undertaken to measure radiographic features and dynamic angle of gait, as measured by powdered footprints, in hallux abducto valgus and hallux limitus to determine possible correlations or predictive features. An additional purpose was to determine whether angle of gait is related to foot type. Calcaneal inclination angle was used as a measure of foot type, whereby a higher inclination angle reflected a higher-arched foot than a lower inclination angle.¹¹

Materials and Methods

Reliability and Validity

Reliability and validity analyses for measurement variables were undertaken as pilot studies before the present investigation. Quantification of angle of gait from powdered footprints has previously been reported by us¹² to be a reliable method, giving intrarater Pearson product moment correlations of 0.94 and 0.93 for two observers, with no significant difference between them ($t = -1.63$; $P = .108$), indicating that the method could be used with confidence in the present study. The validity of measuring angle of gait was established in the same pilot study. The mean difference between angle of gait from powdered footprints and the equivalent measurement of angle of gait known as “foot progression angle” as derived from

the EMED-SF (Novel GmbH, Munich, Germany) was 0.03 (95% CI, -0.54 to 0.59), indicating no significant difference ($t = 0.09$; $P = .93$).¹²

Results of a second pilot study¹³ indicated that all radiographic measurements could be used reliably. This was of particular importance for two uncommon views not widely used in the literature. Specifically, the lateral stressed dorsiflexion view of the first metatarsophalangeal joint was shown to be a reliable method of quantifying the amount of hallux dorsiflexion in the sagittal plane. Similar reliability was observed for the composite view of the foot, providing a unique method of assessing the rearfoot-to-forefoot relationship in the transverse plane. The composite view is achieved using a double-exposure weightbearing view of the foot that provides a complete radiographic image of the entire skeletal anatomy of the foot.

All measurement data were collected by the same researcher (J.T.) and recorded in exactly the same manner for each subject. To account for any discrepancies in data entry, the researcher randomly cross-checked raw data and spreadsheet entries for any processing errors.

Procedures

Angle of Gait. Footprint data were obtained using 10-m lengths of white paper (80 g/m²) measuring 91.5 cm wide. The test environment remained the same for all of the subjects. The paper was laid out over a linoleum-covered concrete floor for the entire 10-m length. A chair was positioned at either end of the paper along with a plastic container of commercially available talcum powder mixed with blue oxide (Diggers Oxide Colouring; Diggers Australia, Wingfield, Australia) to a mixture ratio of 1:100.

Before data collection, the subject was allowed a period of familiarization. The subject was then instructed to place his or her feet in the container and to gently shake off any excess powder. The container was removed and the subject was instructed to rise from the chair and walk at a comfortable self-selected cadence to the other end. The subject was told to commence with the right foot, look straight ahead, and, on reaching the other end of the walkway, sit down. After this, artists' fixative (Micador Fixative Workable Mat; Micador Group, Sydney, New South Wales, Australia) was sprayed on each footprint, and the subject's alphanumeric identification code was recorded on the paper, which was then moved aside to air-dry.

Four consecutive footprints were preserved by placing a piece of transparent self-adhesive contact plastic (3M Contact; 3M, Pymble, New South Wales,

Australia) over the entire footprint, starting with either the second or third footprint. Variability in the chosen initial footprint for analysis was related to differences in subject stride length and the desire to avoid the effects of acceleration and deceleration during the walking trial. In each case, two consecutive left and two consecutive right footprints were collected from the middle section of the footprint sample and preserved for analysis. Measurement of angle of gait using powdered footprints for all of the subjects was conducted in the same environment. A transparent acetate grid measuring 21 × 37.5 cm and composed of parallel lines was placed over the selected footprint. The vertical border of the grid was positioned parallel to the border of the paper closest to the medial side of the foot, aligning the top corner of the grid with the apex of the hallux and the medial side of the forefoot. To ensure that the vertical border of the grid was parallel to the right or left border of the paper, the distance between the vertical border of the grid and the border of the paper was measured at the top and bottom margins of the grid. At the level of the apex of the hallux, the angle of the line of the grid was transferred onto the paper and labeled line A. The grid was then used to transfer a similar line on the paper across the posterior aspect of the heel, parallel to line A. This line was called line B. The vertical border of the grid adjacent to the medial side of the forefoot was marked at either end. The grid was removed and the two points were joined to form the line of progression (Fig. 1).

The footprint was then divided to form line FX, which represented the axis of the foot (Fig. 2). The line corresponding to the medial side of the forefoot originally marked on the paper (line of progression) was extended to the point of intersection with line FX. The angle formed was the angle of gait.

Radiographic Views. Three radiographers from the same radiology clinic were used for the study. A period of training was undertaken in which the researcher informed the radiographers of the procedural protocol and specific views required. The same x-ray machine was used for all of the radiographs. All of the radiographic views were weightbearing and included dorsoplantar, lateral, lateral stressed dorsiflexion of the first metatarsophalangeal joint, and composite views. Focal film distance, position and angle of the central ray, and exposure were consistent for all of the views. Standard weightbearing dorsoplantar and lateral views were taken in the subject's normal angle and base of gait.

The lateral stressed dorsiflexion view¹⁴⁻¹⁶ of the first metatarsophalangeal joint was taken as per a standard lateral view but with the central ray directed

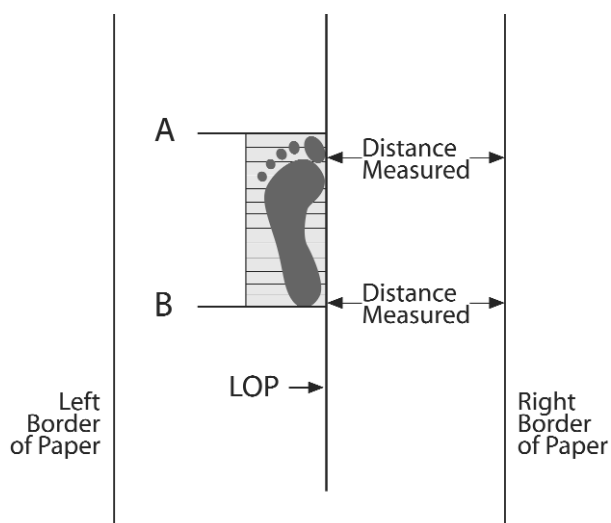


Figure 1. Placement of a transparent grid to ensure parallel lines representing the apex of the hallux (line A) and the posterior border of the heel (line B) and equal distances between the vertical border of the grid and the border of the paper was measured at the top and bottom margins of the grid. At the level of the apex of the hallux, the angle of the line of the grid was transferred onto the paper and labeled line A. The grid was then used to transfer a similar line on the paper across the posterior aspect of the heel, parallel to line A. This line was called line B. The vertical border of the grid adjacent to the medial side of the forefoot was marked at either end. The grid was removed and the two points were joined to form the line of progression (Fig. 1). (Adapted from Taranto et al,¹² with permission from Elsevier.)

at the first metatarsophalangeal joint. The knee was flexed 40°, and the heel was raised off of the ground to the point where the first metatarsophalangeal joint was in maximum dorsiflexion, without any obvious



Figure 2. The length of the footprint was measured from line A to line B and was divided into thirds (lines C and D), and the proximal third was further divided in half (line E). The width of the footprint was measured at 17% (E) and 66% (C) of the foot length and the mid-points were obtained, giving the foot axis (line FX). (Adapted from Taranto et al,¹² with permission from Elsevier.)

frontal or transverse plane movement. For the composite view,¹⁷ a double exposure was required (Fig. 3). Both exposures were set at 62 kV, 125 mA, and 0.05 sec.

Radiographic Angles. For each subject, seven dependent variables were measured for the left and right feet (14 per subject): hallux abductus angle, first intermetatarsal angle, first metatarsal protrusion distance, calcaneal inclination angle, lateral first intermetatarsal angle, rearfoot-to-forefoot axis angle, and degree of available first metatarsophalangeal joint dorsiflexion by measurement of lateral stressed dorsiflexion of the first metatarsophalangeal joint. These measurements were obtained using a previously validated method¹³ involving a series of bilateral weight-bearing radiographs taken by the same radiographers and following standardized parameters. A sheet of clear acetate was firmly secured over each radiograph so that there was no movement of the sheet and it was not necessary to mark the actual radiograph. Using a fine (0.5-mm) water-soluble pen, angular and linear measurements were marked on the radiographs and recorded.

Radiographic measurement of first metatarsophalangeal joint dorsiflexion was obtained using the lateral stressed dorsiflexion view. This view^{14, 15} is a reflection of the weightbearing or functional dorsiflexion of the first metatarsophalangeal joint. The dorsal and plantar cortices of the proximal and distal thirds of the first metatarsal shaft were identified and bisected. Similarly, this task was repeated for the proximal phalanx of the hallux. The angle formed by the intersection of these two lines represented the amount of first metatarsophalangeal joint dorsiflexion (Fig. 4).

Radiographic measurement of the rearfoot-to-forefoot axis angle was obtained using the composite view. This angle¹⁸ represents the amount of intrinsic

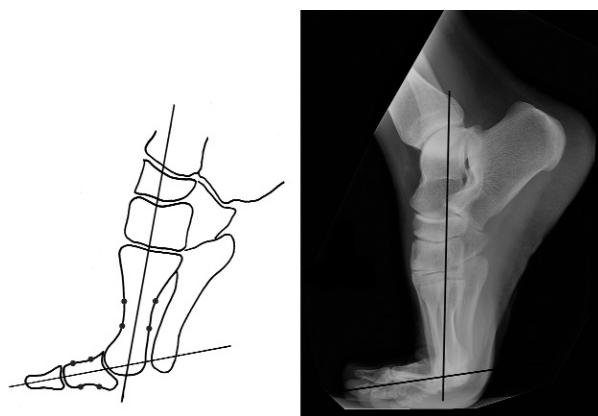


Figure 4. Measurement of weightbearing first metatarsophalangeal joint dorsiflexion using a weightbearing lateral stressed dorsiflexion radiograph. (Adapted from Taranto et al,¹³ with permission from Elsevier.)

rearfoot-to-forefoot abduction. The posterior sclerotic margin of the calcaneus was bisected to obtain the point representing the posterior border of the calcaneus. The most medial and lateral margins of the calcaneocuboid joint were identified and bisected to obtain the point representing the calcaneocuboid joint. A line connecting the two points was drawn and extended distally, representing the rearfoot axis. At the anatomical neck of the second and third metatarsals, the medial and lateral cortices were identified and bisected. The distance between these two points was measured and bisected. To obtain the forefoot axis, a line was drawn connecting the point between the second and third metatarsals to the point representing the bisection of the calcaneocuboid joint. The angle between the intersection of the rearfoot and forefoot axes was the rearfoot-to-forefoot axis angle (Fig. 5).

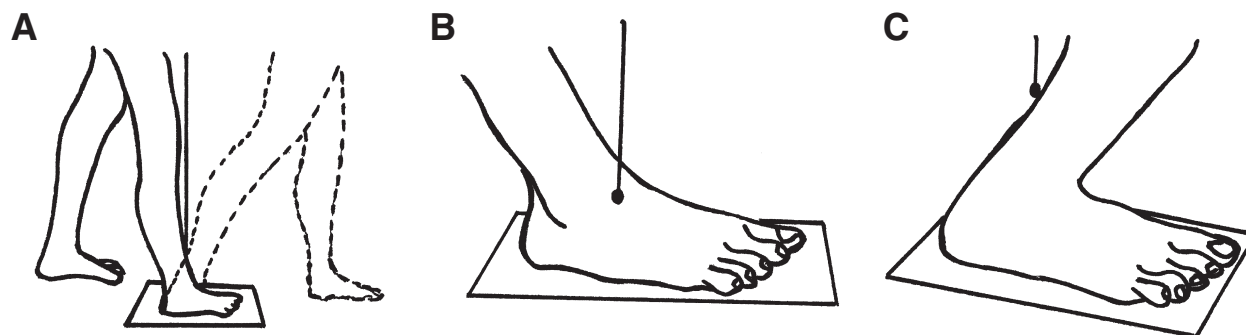


Figure 3. Radiographic technique for the composite view showing the position of the subject and the central ray: the plantar aspect of the foot in contact with the ground (A), the central ray centered over the anterior aspect of the ankle joint for the first exposure (B), and the central ray passing through the posterior aspect of the ankle joint for the second exposure (C). (Reprinted from Taranto et al,¹³ with permission from Elsevier.)

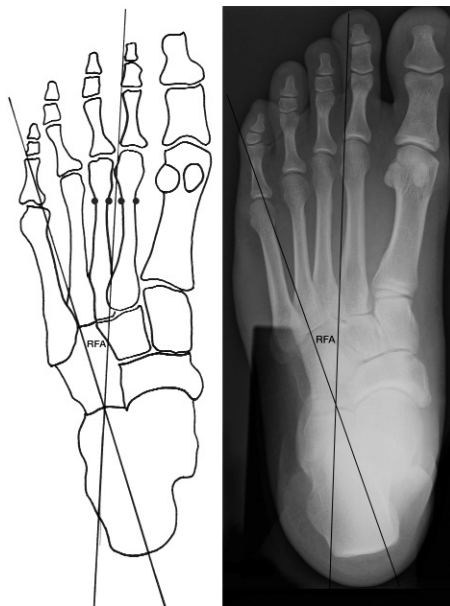


Figure 5. Measurement of the rearfoot-to-forefoot axis (RFA) angle using a weightbearing composite radiograph. (Adapted from Taranto et al,¹³ with permission from Elsevier.)

The lateral view was used to obtain the calcaneal inclination angle and the lateral first intermetatarsal angle (Fig. 6). For the calcaneal inclination angle, a line was drawn representing the weightbearing surface of the foot. Another line was drawn from the anterior plantar margin of the calcaneal tuberosity extending through the plantar margin of the anterior portion of the calcaneus. The lateral first intermetatarsal angle describes the sagittal plane angular relationship between the first and second metatarsals.¹⁹ For this angle, the central region of the dorsal cortex of the first and second metatarsal shafts was marked, with the resultant angle formed by the intersection of

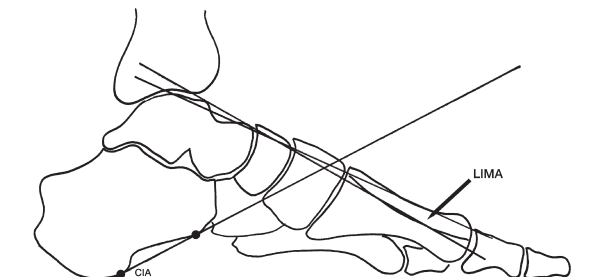


Figure 6. Lateral view of the foot showing measurement of the calcaneal inclination angle (CIA) and the lateral first intermetatarsal angle (LIMA). (Adapted from Taranto et al,¹³ with permission from Elsevier.)

these two lines representing the lateral first intermetatarsal angle.

The dorsoplantar view was used to obtain the hallux abductus angle, the first intermetatarsal angle, and the first metatarsal protrusion distance (Fig. 7). The hallux abductus angle represents the degree of lateral deviation of the hallux and is the angle formed by the longitudinal axis of the proximal phalanx of the hallux and the longitudinal axis of the first metatarsal. For the hallux abductus angle, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified and bisected. Similarly, this task was repeated for the proximal phalanx of the hallux. The angle formed by these intersecting lines was measured. A normal value is considered to be less than 20°.¹

The first intermetatarsal angle is the angle between the longitudinal axis of the first and second metatarsal bones. To calculate this angle, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified and bisected. This task was repeated for the second metatarsal. The angle formed by these intersecting lines was measured. A normal value is 8° to 14°.¹ The first metatarsal protrusion distance¹⁶ is the distal-to-proximal distance between the most distal articular surfaces of the first and second metatarsals. Calculation of the first metatarsal protrusion distance was under-

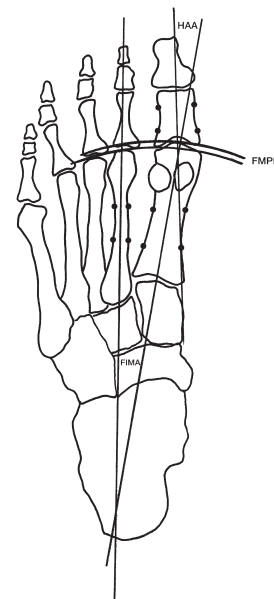


Figure 7. Dorsoplantar view of the foot showing measurement of the hallux abductus angle (HAA), the first intermetatarsal angle (FIMA), and the first metatarsal protrusion distance (FMPD). (Adapted from Taranto et al,¹³ with permission from Elsevier.)

taken using a compass containing a 0.5-mm water-soluble felt-tipped marker as follows. The point of the proximal arm was positioned at the intersection of the first intermetatarsal angle, and a line was drawn with the distal arm at the level of the central articulating surface of the first metatarsal head. This line was extended laterally to be in line with the second metatarsal. Keeping the proximal arm of the compass stationary, the distal arm was then positioned at the central articulating surface of the second metatarsal head, and a line was drawn and extended medially in line with the first metatarsal. The first metatarsal protrusion distance was the distance between these two lines measured in millimeters. A positive value denoted that the distal articular surface of the first metatarsal was more distal than that of the second metatarsal. Conversely, a negative value indicated that the distal articular surface of the first metatarsal was more proximal than that of the second metatarsal.

Study Design and Subjects

Two separate pathologic groups (hallux abducto valgus and hallux limitus) were studied by the two principal authors (J.T. and M.J.T.), respectively, between May 2003 and September 2004 as part of a research master's thesis. A common control group was used. Each study involved a prospective observational quasi-experimental case-control study design. All of the radiographic angular and linear measurement variables and angle of gait powdered footprint data were collected for each subject in accordance with the method established in the pilot studies.

Convenience sampling was used to select all of the subjects, including control subjects, involved in the studies. Participants were recruited from the private practice podiatry clinic of two of us (J.T. and M.J.T.). The demographic characteristics of the hallux abducto valgus, hallux limitus, and control subjects are presented in Table 1. Subjects were screened by the researcher to satisfy the criteria for inclusion or exclusion (Table 2). The Human Research Ethics Committee at the University of Western Australia approved the

Table 2. Inclusion and Exclusion Criteria for Study Subjects

Inclusion Criteria

- Reached skeletal maturity
- Had the specified set of radiographs taken by the radiographer assigned to the study; radiographs were angle and base of gait weightbearing views and included bilateral dorsoplantar and lateral views of the foot, a composite view of the foot, and a lateral stressed dorsiflexion view of the first metatarsophalangeal joint
- Hallux abducto valgus subjects exhibited a measured hallux abductus angle of $>20^\circ$ on a weightbearing dorsoplantar radiograph¹²
- Hallux limitus subjects exhibited a radiographic measured limitation of first metatarsophalangeal joint dorsiflexion on a stressed lateral radiograph of $<65^\circ$

Exclusion Criteria

- Reached skeletal maturity and exhibited a hallux abductus angle of $<20^\circ$ and radiographic first metatarsophalangeal joint dorsiflexion of $>65^\circ$
- A history of lower-limb surgery
- A history of trauma to the lower limb
- Neurologic disorders that directly affect gait
- Use of walking aids
- Gait abnormalities; soft-tissue or osseous torsional or positional changes in the hip, femur, and tibia; an excessive amount of malleolar torsion; or an intrinsic adduction or abduction deformity of the foot as detected by clinical biomechanical assessment
- A history of congenital hip dysplasia
- Any systemic disease, eg, seronegative or seropositive pathology
- Any hypermobility syndromes, such as Ehlers-Danlos' or Marfan's syndrome

study, and subjects provided informed consent before participation. Subjects were coded alphanumerically into each group before data collection.

Data Analysis

All of the data were transferred into Statview (SAS Institute Inc, Cary, North Carolina) for descriptive statistical reporting and subsequent analysis. Data obtained for angle of gait consisted of four footprints, two from the left and two from the right. For data

Table 1. Demographic Characteristics of the Hallux Abducto Valgus (HAV), Hallux Limitus (HL), and Control Groups

Group	Subjects (No.)	Feet (No.)		Sex (No.)		Age		BMI	
		Total	Left/Right	M	F	Mean (SD)	Range	Mean	SD
HAV	23	36	18/18	2	21	61.3 (9.9)	45.0–79.0	25.8	4.4
HL	22	34	16/18	9	13	54.9 (12.0)	29.0–76.0	26.6	3.6
Control	20	40	20/20	8	12	58.8 (15.9)	28.0–82.0	28.2	4.3

Abbreviation: BMI, body mass index (the weight in kilograms divided by the square of the height in meters).

analysis, the mean of each side (left and right) was used. In all of the tests of statistical significance, an α level of $P < .05$ was adopted.

Analysis of the data was performed using descriptive and inferential statistics involving the use of Pearson product moment correlations, t tests, and nonparametric analyses with and without tertile assessments based on the hallux abductus angle threshold for hallux abducto valgus subjects and the lateral stressed dorsiflexion threshold for hallux limitus subjects. The purpose of the tertile assessment was to exclude the values of the hallux abductus angle or lateral stressed dorsiflexion in close proximity to normal values and to observe for differences when only extreme values of these dependent variables were seen, assuming that perhaps clinical differences were evident only for extreme or late-stage deformities. For the tertile assessments, hallux abductus angle values between 15° and 25° were excluded in the hallux abducto valgus group and lateral stressed dorsiflexion values between 60° and 70° were excluded in the hallux limitus group.

Of subjects who had a unilateral hallux abducto valgus or hallux limitus deformity, the unaffected foot was excluded from the analysis. The rationale for not using the contralateral normal foot in the control group was based on the assumption that subjects with a unilateral pathology may have had an altered angle of gait between the feet owing to potential compensatory mechanisms.

Results

Descriptive statistics for each radiographic dependent variable under investigation are presented for the hallux abducto valgus, hallux limitus, and control groups in Table 3. Descriptive statistics for angle of gait in the left and right feet for all three groups are highlighted in Table 4 and Figure 8.

Normality

All three groups showed statistical evidence of normality according to Kolmogorov-Smirnov analysis, with $P > .05$.

Laterality

For the reader's benefit, a summary table is provided showing the tested parameters and the results of the statistical tests performed (Table 5). For subjects with bilateral hallux abducto valgus, the data were examined for differences between left and right angle of gait using paired t tests. A significant difference was found

whereby the right foot was more abducted ($t = -2.63$; $P = .02$) (Fig. 9). No significant difference was found in subjects with bilateral hallux limitus ($t = -1.98$; $P = .07$) or in the control group ($t = -1.13$; $P = .27$). Similarly, no significant difference was found for angle of gait between left and right feet for subjects who presented with unilateral hallux abducto valgus or unilateral hallux limitus.

Unpaired t tests were used to assess for differences between control group subjects and those with bilateral hallux abducto valgus and hallux limitus. The right foot was significantly more abducted than the left ($t = 2.43$; $P = .02$) in the bilateral hallux abducto valgus group compared with the control group (Fig. 10). No significant difference was seen between subjects who exhibited bilateral hallux limitus and the control group.

The Pearson product moment correlation between the group that exhibited bilateral hallux abducto valgus and the control group showed no significant association between angle of gait and the hallux abductus angle ($R = 0.18$; 95% CI, -0.06 to 0.41). Similarly, the Pearson product moment correlation between the group that exhibited bilateral hallux limitus and the control group showed no significant association between angle of gait and lateral stressed dorsiflexion ($R = -0.05$; 95% CI, -0.30 to 0.19).

Associations

A variety of significant associations were found by means of Pearson product moment correlations for each group (Table 6). The strength of a correlation is determined by the amount of scatter of the points around an underlying linear trend. A weak but significant correlation refers to a correlation that is significant but that has a great amount of spread around the linear trend.

Group Differences

Hallux Abducto Valgus Group versus Control Group. Results of unpaired t tests between the hallux abducto valgus and control groups showed significant differences between groups bilaterally for hallux abductus angle, first intermetatarsal angle, and lateral stressed dorsiflexion ($P < .001$). This was also seen in the tertile assessments using nonparametric rank analysis and the Mann-Whitney U statistic, in which hallux abductus angles of 15° to 25° were excluded.

Hallux Limitus Group versus Control Group. Unpaired t tests between the hallux limitus and control groups showed significant differences between groups

Table 3. Measurement Values of the Radiographic Variables for the Hallux Abducto Valgus (HAV), Hallux Limitus (HL), and Control Groups

Radiographic Variable	Left Feet		Right Feet	
	Mean (SD)	Range	Mean (SD)	Range
HAV group^a				
CIA	23.9 (4.1)	15.0 to 31.5	23.6 (4.0)	17.0 to 31.0
LIMA	3.3 (2.4)	1.0 to 9.0	3.0 (2.7)	0 to 11.0
HAA	27.7 (5.0)	21.0 to 37.0	26.1 (6.3)	21.0 to 45.0
FIMA	12.7 (2.8)	6.5 to 17.0	11.7 (2.4)	7.5 to 18.0
FMPD	2.4 (3.0)	-5.0 to 8.0	0.9 (3.1)	-5.0 to 5.5
LAT SD	56.9 (10.7)	26.0 to 69.0	63.2 (10.2)	46.0 to 85.0
RFA angle	17.4 (6.8)	7.0 to 28.0	16.0 (6.4)	7.0 to 25.0
HL group^b				
CIA	25.1 (5.2)	17.0 to 34.0	24.6 (5.0)	17.0 to 35.0
LIMA	3.6 (2.2)	0 to 9.0	4.4 (2.7)	0.5 to 12.0
HAA	11.6 (5.1)	3.5 to 20.0	12.4 (5.2)	5.0 to 23.5
FIMA	8.9 (2.2)	6.0 to 13.0	9.2 (3.6)	0 to 15.5
FMPD	0.8 (3.0)	-5.0 to 6.0	2.1 (4.6)	-4.5 to 11.0
LAT SD	50.0 (14.4)	11.0 to 64.0	50.0 (14.5)	14.0 to 64.0
RFA angle	17.8 (7.5)	5.0 to 28.0	16.7 (6.7)	5.0 to 25.0
Control group^c				
CIA	25.1 (5.1)	15.0 to 38.5	24.8 (5.3)	17.0 to 38.0
LIMA	2.8 (1.7)	1.0 to 7.0	3.8 (3.1)	0 to 10.0
HAA	9.2 (4.7)	0 to 17.5	10.5 (5.0)	0 to 18.0
FIMA	8.6 (2.7)	0.5 to 13.0	8.5 (1.8)	5.5 to 12.0
FMPD	1.1 (3.8)	-6.5 to 10.0	1.2 (3.4)	-5.5 to 7.0
LAT SD	76.5 (7.1)	66.0 to 87.0	78.2 (7.2)	66.0 to 90.0
RFA angle	19.1 (6.9)	9.0 to 35.0	17.5 (7.1)	5.5 to 35.0

Abbreviations: CIA, calcaneal inclination angle; LIMA, lateral first intermetatarsal angle; HAA, hallux abductus angle; FIMA, first intermetatarsal angle; FMPD, first metatarsal protrusion distance; LAT SD, lateral stressed dorsiflexion; RFA, rearfoot-to-forefoot axis.

Note: All measurements are given in degrees.

^aThe HAV group consists of 23 subjects (13 with bilateral HAV and 10 with unilateral HAV) and 36 feet (18 left and 18 right). Of the 10 subjects with unilateral HAV, 5 had right HAV and 5 had left HAV.

^bThe HL group consists of 22 subjects (12 with bilateral HL and 10 with unilateral HL) and 34 feet (16 left and 18 right). Of the 10 subjects with unilateral HL, 6 had right HL and 4 had left HL.

^cThe control group consists of 20 subjects and 40 feet (20 left and 20 right).

Table 4. Angle of Gait Values for the Hallux Abducto Valgus (HAV), Hallux Limitus (HL), and Control Groups

Group	Subjects (Feet) (No.)	Left Feet		Right Feet	
		Mean (SD)	Range	Mean (SD)	Range
HAV	23 (36)	10.4 (5.0)	2.0 to 19.8	13.2 (6.3)	3.8 to 32.5
HL	22 (34)	9.4 (5.1)	0 to 16.0	13.2 (5.2)	3.0 to 25.3
Control	20 (40)	9.0 (4.7)	0 to 17.0	10.4 (5.1)	0 to 21.5

Note: All measurements are given in degrees.

bilaterally for lateral stressed dorsiflexion ($P < .001$). The results of tertile assessment using the Mann-Whitney U statistic in which lateral stressed dorsiflexion between 60° and 70° was excluded showed a significant difference for the variable lateral stressed dorsiflexion.

Hallux Abducto Valgus Group versus Hallux Limitus Group. Results of unpaired t tests between

the hallux abducto valgus and hallux limitus groups are presented in Table 7. Significant differences ($P < .05$) between groups were found bilaterally for hallux abductus angle and first intermetatarsal angle and unilaterally (right foot) for lateral stressed dorsiflexion. These findings support the concept that the two radiographic variables most indicative of hallux abducto valgus and hallux limitus were the best predic-

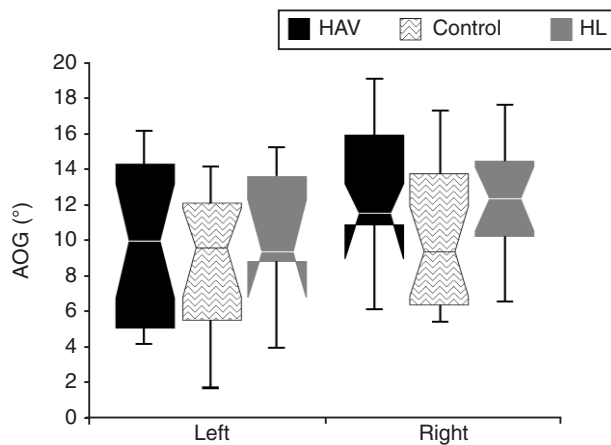


Figure 8. Notched box plot of median angle of gait (AOG) values for the left and right feet for the hallux abducto valgus (HAV), hallux limitus (HL), and control groups. Error bars represent 95% confidence intervals.

tors of them, thereby affirming the inclusion and exclusion criteria. There were no differences in any of the other dependent variables, including angle of gait, between the hallux abducto valgus and hallux limitus groups.

Discussion

Angle of Gait

The results of this study show a significant difference in angle of gait between the left and right feet of subjects with bilateral hallux abducto valgus, whereby the right was more abducted ($t = -2.63$; $P = .02$); however, no difference was observed in subjects with hal-

Table 5. Angle of Gait Between the Left and Right Feet in the Unilateral and Bilateral Hallux Abducto Valgus (HAV) and Hallux Limitus (HL) Groups and the Control Group

Group	Subjects (No.)	<i>t</i> Value	<i>P</i> Value
Bilateral HAV	13	-2.63 ^a	.02
Unilateral HAV	10	0.85 ^a	.42
Bilateral HL	12	-1.98 ^a	.07
Unilateral HL	10	1.48 ^a	.17
Control group	20	-1.13 ^a	.27
Bilateral HAV versus control	13 HAV and 20 control	2.43 ^b	.02
Bilateral HL versus control	12 HL and 20 control	-0.02 ^b	.99

^aPaired *t* test.

^bUnpaired *t* test.

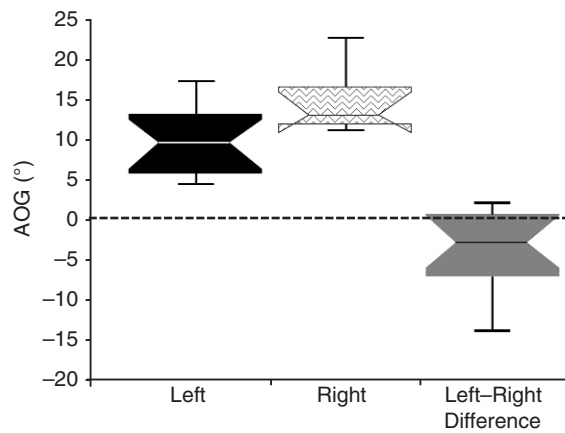


Figure 9. Box plot showing median angle of gait (AOG) values for the left and right feet and the distribution of the difference between the left and right sides of the AOG for the 13 subjects with bilateral hallux abducto valgus. Error bars represent 95% confidence intervals.

lux limitus. When subjects with bilateral hallux abducto valgus were compared with control subjects, there was also a significant difference in angle of gait between the left and right feet, with the right foot being more abducted ($t = 2.43$; $P = .02$). How this asymmetry may relate to issues of dominance,^{20, 21} however, is speculative because information relating to dominance was not included in the subject profile; thus this issue warrants further study.

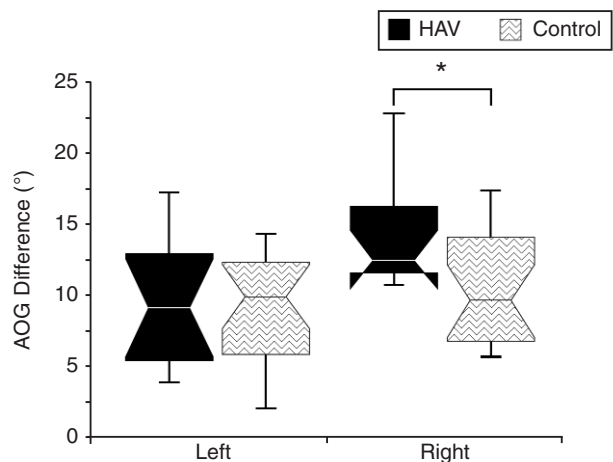


Figure 10. Box plot showing the median difference in the angle of gait (AOG) of the right and left feet between subjects with bilateral hallux abducto valgus (HAV) ($n = 13$) and the control group ($n = 20$). *Significant difference ($P < .05$). Error bars represent 95% confidence intervals.

Table 6. Significant Pearson Product Moment Correlations Between Dependent Variables for the Hallux Abducto Valgus (HAV), Hallux Limitus (HL), and Control Groups

Association	Correlation (95% CI)
HAV group	
LIMA and FIMA	-0.49 (-0.71 to -0.20)
LIMA and FMPD	0.50 (0.21 to 0.71)
FIMA and LAT SD	0.41 (0.10 to 0.65)
FIMA and RFA angle	-0.41 (-0.65 to -0.10)
FMPD and LAT SD	-0.37 (-0.62 to -0.04)
HL group	
CIA and RFA	0.42 (0.10 to 0.67)
LIMA and FIMA	-0.52 (-0.73 to -0.22)
LIMA and FMPD	0.62 (0.36 to 0.79)
LIMA and LAT SD	-0.64 (-0.80 to -0.39)
HAA and LAT SD	-0.36 (-0.62 to -0.03)
HAA and RFA	-0.36 (-0.62 to -0.02)
HAA and AOG	-0.38 (-0.64 to -0.05)
FIMA and LAT SD	0.34 (0.002 to 0.61)
LAT SD and RFA angle	0.45 (0.13 to 0.68)
Control group	
CIA and LAT SD	0.32 (0 to 0.57)
CIA and AOG	0.38 (0.83 to 0.62)
LIMA and FIMA	-0.33 (-0.58 to -0.02)
HAA and FIMA	0.33 (0.02 to 0.58)
FIMA and FMPD	-0.39 (-0.62 to -0.08)

Abbreviations: CI, confidence interval; LIMA, lateral first intermetatarsal angle; FIMA, first intermetatarsal angle; FMPD, first metatarsal protrusion distance; LAT SD, lateral stressed dorsiflexion; RFA, rearfoot-to-forefoot axis; CIA, calcaneal inclination angle; HAA, hallux abductus angle; AOG, angle of gait.

Bilateral pathology may alter angle of gait more than unilateral pathology because the person with bilateral hallux abducto valgus is more mechanically unstable, which may, in turn, lead to compensatory in-

creases in angle of gait. An abducted foot position and a wide base of gait are assumed by people who require increased stability, such as toddlers and the elderly.²² However, this concept needs to be investigated in a larger population because the severity of the deformity, as assessed by the tertile analysis, did not show significant differences in angle of gait. Furthermore, the unilateral groups did not show differences in angle of gait despite asymmetry of deformities, although a larger population of unilateral subjects would be needed to investigate this fully.

When subjects with bilateral hallux abducto valgus or hallux limitus were compared with the control group, no association was identified between angle of gait and the degree of hallux abducto valgus or hallux limitus deformity. That is, angle of gait was found to not increase as the hallux abductus angle increased in hallux abducto valgus subjects ($R = 0.18$; 95% CI, -0.06 to 0.41) or as lateral stressed dorsiflexion decreased in hallux limitus subjects ($R = -0.05$; 95% CI, -0.30 to 0.19). In the case of hallux abducto valgus, this may be considered to be counter to the cited literature, which suggested abnormal pronation as a cause of hallux abducto valgus,^{9, 23} assuming that angle of gait is reflective of foot type and degree of pronation.

It has been suggested in the literature that as the amount of first metatarsophalangeal joint dorsiflexion decreases with time, angle of gait subsequently changes as a secondary mechanism.²⁴ Chapman²⁵ similarly proposed that with the forward transfer of body weight during the terminal stage of midstance, a lateral shift in body weight, and subsequent out-toeing or in-toeing, occurs to ensure adequate sagittal plane motion of the foot. It is believed that the observed gait compensation occurs as a result of the subject's

Table 7. Values for Radiographic Variables Between the Hallux Abducto Valgus (HAV) and Hallux Limitus (HL) Groups Obtained from Unpaired *t* Tests

Radiographic Variable	<i>t</i> Value		<i>P</i> Value		95% CI		Mean Difference	
	L	R	L	R	L	R	L	R
CIA	-0.74	0.62	.46	.54	-4.42 to 2.06	-4.02 to 2.13	-1.18	-0.94
LIMA	-0.40	1.60	.69	.12	-1.94 to 1.30	-3.24 to 0.38	-0.32	-1.42
HAA	9.27	7.10	≤.05	≤.05	12.52 to 19.57	9.80 to 17.65	16.04	13.72
FIMA	4.41	2.43	≤.05	≤.05	2.07 to 5.63	0.41 to 4.60	3.85	2.50
FMPD	1.58	0.92	.12	.36	-0.47 to 3.73	-3.82 to 1.43	1.63	-1.19
LAT SD	1.60	3.16	.12	≤.05	-1.89 to 15.68	4.71 to 21.68	6.89	13.19
RFA angle	-0.15	0.34	.88	.73	-5.39 to 4.66	-5.20 to 3.70	-0.36	-0.75
AOG	0.57	0.01	.58	.99	-2.57 to 4.54	-3.92 to 3.90	0.99	-0.01

Abbreviations: CI, confidence interval; L, left foot; R, right foot; CIA, calcaneal inclination angle; LIMA, lateral first intermetatarsal angle; HAA, hallux abductus angle; FIMA, first intermetatarsal angle; FMPD, first metatarsal protrusion distance; LAT SD, lateral stressed dorsiflexion; RFA, rearfoot-to-forefoot axis; AOG, angle of gait.

Note: There were 18 left feet and 18 right feet in the HAV group and 16 left feet and 18 right feet in the HL group.

predisposition to a more abducted or adducted gait, or, simply, the tendency of the body's biomechanics to take the path of least resistance. The results of this study, however, suggest that there is no association between angle of gait and the severity of hallux abducto valgus or hallux limitus in the patient population examined.

First Metatarsal Characteristics

The results of this study did not show an association between hallux abducto valgus, as measured by the hallux abductus angle, and the presence of a long or short first metatarsal. This finding is in contrast to those of some authors²⁶⁻²⁸ but in support of others.^{29,30} Instead, an association was found between the first metatarsal protrusion distance and the lateral first intermetatarsal angle in the hallux abducto valgus ($R = 0.50$; 95% CI, 0.21–0.71) and hallux limitus ($R = 0.62$; 95% CI, 0.36–0.79) groups. This finding suggests that the length of the first metatarsal may be a determining factor in whether it becomes elevated. That is, when the first metatarsal protrusion distance is positive, there may be a mechanical predisposition to elevation of the first metatarsal as a result of a greater lever arm effect and first-ray hypermobility.^{9,31} This observation is consistent with the literature, which proposes a positive first metatarsal protrusion distance and a hypermobile first metatarsal as etiologic factors in the development of hallux limitus.³¹ In contrast, Bryant et al²⁶ reported no relationship between first metatarsal protrusion distance and the presence of hallux limitus, as was also reported by Villadot.³⁰

In the hallux abducto valgus group, first metatarsal protrusion distance was also significantly associated with lateral stressed dorsiflexion ($R = -0.37$; 95% CI, -0.62 to -0.04), suggesting that the length of the metatarsal may have implications regarding first metatarsophalangeal range of motion. The findings of Incel et al,³² who proposed that an elevated first metatarsal was an etiologic factor in hallux abducto valgus, were in contrast to the findings of this study. In the present study, the first intermetatarsal angle was inversely associated with the lateral first intermetatarsal angle in the hallux abducto valgus ($R = -0.49$; 95% CI, -0.71 to -0.20) and control ($R = -0.33$; 95% CI, -0.58 to -0.02) groups. This implied that as the first intermetatarsal angle increased, elevation of the first metatarsal decreased, suggesting that an elevated first metatarsal may not necessarily be a precursor to hallux abducto valgus.

The results of this study identified an association between lateral first intermetatarsal angle and lateral stressed dorsiflexion in the hallux limitus group ($R =$

-0.64; 95% CI, -0.80 to -0.39). This association indicated that the more elevated the first metatarsal was, the less dorsiflexion was observed at the first metatarsophalangeal joint. This finding remained consistent with the literature^{3, 19, 24, 33, 34}; however, some authors have reported no such relationship to exist,^{26, 35} and differences in findings could be attributed to measurement techniques used to quantify elevation of the first metatarsal.

First Metatarsophalangeal Joint Dorsiflexion

Review of the literature supported the concept of first metatarsophalangeal joint deterioration and pathology associated with an increased first intermetatarsal angle ($R = 0.34$; 95% CI, 0.002–0.61) and increased severity of hallux limitus as represented by decreased lateral stressed dorsiflexion.^{3, 24, 36, 37}

Rearfoot-to-Forefoot Abduction and Foot Structure

If excessive pronation, as indicated by the calcaneal inclination angle, was in fact related to forefoot abduction, one would expect that as the calcaneal inclination angle increased and the arch of the foot became higher, the angle of gait would decrease. This was not demonstrated, however, in the hallux abducto valgus and hallux limitus groups, and only the control subjects exhibited a weak association between angle of gait and calcaneal inclination angle ($R = 0.38$; 95% CI, 0.83–0.62). This finding may suggest, in accordance with findings from Wearing et al,³⁸ that calcaneal inclination angle should not be used as a measure of foot function, specifically pronation. It is possible that arch height is not associated with abduction of the foot as a whole and may instead result in abduction of the forefoot on the rearfoot, as indicated by Bojsen-Moeller.³⁹ This concept is supported by Neylon et al,⁴⁰ who demonstrated arch collapse without excessive abduction of the foot. It also highlights the concept of planal dominance as explained by Green and Carol,⁴¹ suggesting that the degree of compensation in a foot will take place in the plane with the most available motion for that particular foot. Consideration must also be given to the fact that calcaneal inclination angle is a static radiographic measurement, whereas pronation represents dynamic function.

A relationship was not seen between the rearfoot-to-forefoot axis angle and the angle of gait in either the hallux abducto valgus or the hallux limitus group. This finding may indicate either that the amount of rearfoot-to-forefoot abduction was not associated with angle of gait or that being such a small value, the

rearfoot-to-forefoot axis angle was not sensitive enough to detect larger variations in angle of gait. An association was found between the first intermetatarsal angle and the rearfoot-to-forefoot axis angle in the hallux abducto valgus group ($R = -0.41$; 95% CI, -0.65 to -0.10), logically suggesting that the more adducted the forefoot is on the rearfoot, the smaller the value of the first intermetatarsal angle. This finding may also lend support to published literature suggesting an association between metatarsus adductus and hallux abducto valgus.⁹

Unilateral Pathology

The observation that angle of gait was not affected by the degree of first metatarsophalangeal joint pathology was further supported by the results of a paired t test that showed that the means of the angle of gait were not different between the left and right feet of the subjects who exhibited a unilateral hallux abducto valgus ($t = 0.85$; $P = .42$) or hallux limitus ($t = 1.48$; $P = .17$) deformity.

Significant Findings of Dependent Variables

Results of unpaired t tests for dependent variables between the hallux abducto valgus and control groups expectedly showed significant differences for left and right values of the hallux abductus angle, the first intermetatarsal angle, and lateral stressed dorsiflexion ($P < .001$). A significant difference was also seen between the hallux limitus and control groups for left and right lateral stressed dorsiflexion ($P < .001$).

Results of tertile assessments for the hallux abducto valgus group revealed significant findings for the first intermetatarsal angle and lateral stressed dorsiflexion and for the hallux limitus group revealed significant findings for lateral stressed dorsiflexion ($P < .001$ for all). This supported the concept that the radiographic variables most indicative of each deformity were the best predictors of them, thereby affirming the inclusion criteria chosen for this study.

Results of unpaired t tests showed no differences in most of the dependent variables between the hallux abducto valgus and hallux limitus groups, including angle of gait. As expected, a significant difference was found for the variables hallux abductus angle and first intermetatarsal angle bilaterally and for lateral stressed dorsiflexion on the right foot ($P < .05$ for all). The absence of a significant difference in lateral stressed dorsiflexion on the left foot may indicate another reason why the influence of dominance may be important.

Limitations of this study included the size and sex demographics of the sample population. Despite the hallux abducto valgus and control groups containing similar numbers and means regarding age distribution, the few age-matched females in the control group was a limitation, particularly given that hallux abducto valgus is more prevalent in females than in males.⁴² Another limitation was the difficulty associated with identifying differences in angle of gait given that it has such a large reference range and the many extrinsic factors that can affect angle of gait. In support of the literature, this study showed a large variation in angle of gait reference ranges in the control group, with a mean \pm SD of $9.0^\circ \pm 4.7^\circ$ for the left foot and $10.4^\circ \pm 5.1^\circ$ for the right foot. There was a large range of values, from 0° to 21.5° , even larger than the range of 5° to 13° found in the literature.^{4,5} Furthermore, the range of angle of gait for hallux abducto valgus and hallux limitus subjects was also very large and not significantly different from that of the control group. It is possible that the large variability in angle of gait was responsible for the lack of significant differences between the pathologic and control groups.

A recommendation for further studies would be to undertake a longitudinal age-matched investigation so that the effect of age can be assessed. Furthermore, an attempt should be made to quantify the relative contribution to angle of gait of soft-tissue, osseous, and torsional changes at the hip, knees, and ankles, respectively. Also, in light of the asymmetrical findings between the right and left feet, further investigation of the importance of dominance of feet would be worthwhile. Finally, specific information relating to symptoms should be included to determine whether subjects with symptoms related to first metatarsophalangeal joint pathology have different gait or structural characteristics than those without symptoms. However, it should be mentioned that if angle of gait is in fact as variable as found in this study, it may be difficult to obtain significant results, even in larger populations. Consideration and careful attention should be given to the identification and control of other biomechanical and proprioceptive parameters that may influence the variability of angle of gait.

Use of a computerized system, for example, RSscan (RSscan International, Olen, Belgium), allowing subjects to walk or run for a long time without interruption, would be desirable. Such systems enable data collection on a variety of parameters, including speed, force, pressure, and angle and base of gait, and enable more subjects to be tested in a more time-efficient manner. Finally, a motion-analysis system could be used to collect additional information on kinematic parameters of the lower extremity.

Conclusion

This study investigated angle of gait and selected radiographic variables in subjects with hallux abducto valgus or hallux limitus and a control group. No differences were found in angle of gait between any of the groups except for asymmetrical differences in subjects with bilateral hallux abducto valgus. Perhaps the clinical observation of increased foot abduction in the presence of first metatarsophalangeal joint pathology is not related to the foot deformity itself, and practitioners should look for other causative factors for increased angle of gait in the individual.

In addition, angle of gait was not influenced by the amount of first metatarsophalangeal joint dorsiflexion, the amount of rearfoot-to-forefoot abduction, or foot type as measured by calcaneal inclination angle, and it did not differ in subjects with unilateral first metatarsophalangeal joint pathology. This may have implications for practitioners in terms of the importance placed on clinically observed abduction of the foot and whether it is pathologic. However, this area needs further investigation to establish whether an association exists among the static measurement calcaneal inclination angle, rearfoot-to-forefoot axis angle, and dynamic pronation.

Despite the absence of correlations between angle of gait and foot type in the hallux abducto valgus and hallux limitus groups in the present study, the relationship between first metatarsal protrusion distance and elevation was common to both deformities. That is, length and elevation of the first metatarsal were associated in hallux abducto valgus and hallux limitus subjects. Metatarsal length seems to have an inverse relationship with the amount of dorsiflexion available in the first metatarsophalangeal joint in hallux abducto valgus subjects but not in hallux limitus subjects, in whom metatarsal elevation was more important. This finding may have implications for surgical intervention of the first metatarsal.

Financial Disclosures: None reported.

Conflict of Interest: None reported.

References

1. LANDERS P: "Introduction and Evaluation of Hallux Abducto Valgus," in *Comprehensive Textbook of Foot Surgery*, 2nd Ed, Vol 1, ed by ED McGlamry, AS Banks, MS Downey, p 459, Williams & Wilkins, Baltimore, 1992.
2. LYNCH FR: "Juvenile Hallux Abducto Valgus," in *Comprehensive Textbook of Foot Surgery*, 2nd Ed, Vol 1, ed by ED McGlamry, AS Banks, MS Downey, p 566, Williams & Wilkins, Baltimore, 1992.
3. BANKS AS, MCGLAMRY ED: "Hallux Limitus and Rigidus,"

- in *Comprehensive Textbook of Foot Surgery*, 2nd Ed, Vol 1, ed by ED McGlamry, AS Banks, MS Downey, p 600, Williams & Wilkins, Baltimore, 1992.
4. MURRAY MP, KORY RC, SEPIC SB: Walking patterns of normal women. *Arch Phys Med Rehabil* **51**: 637, 1970.
5. MURRAY PM, DROUGHT B, KORY RC: Walking patterns of normal men. *J Bone Joint Surg Am* **46**: 335, 1964.
6. HOLDEN JP, CAVANAGH PR, WILLIAMS KR, ET AL: "Foot Angles During Walking and Running," in *Biomechanics IX-A*, ed by D Winter, R Norman, R Wells, et al, p 451, Human Kinetics, Champaign, IL, 1985.
7. CLARKSON BH: Absorbent paper method for recording foot placement during gait. *Phys Ther* **63**: 3, 1983.
8. TOLLAFIELD DR, MERRIMAN LM: "Assessment of the Locomotor System," in *Assessment of the Lower Limb*, ed by LM Merriman, DR Tollafield, Churchill Livingstone, Edinburgh, 1995.
9. ROOT ML, ORIEN WP, WEED JH: *Normal and Abnormal Function of the Foot*, Vol 2, Clinical Biomechanics Corp, Los Angeles, 1977.
10. STEIN HC: Hallux valgus. *Surg Gynecol Obstet* **66**: 889, 1938.
11. GAMBLE FO, YALE I: *Clinical Foot Roentgenology*, 2nd Ed, Williams & Wilkins, New York, 1975.
12. TARANTO J, TARANTO MJ, BRYANT A, ET AL: Angle of gait: a comparative reliability study using footprints and the EMED-SF®. *The Foot* **15**: 7, 2005.
13. TARANTO MJ, TARANTO J, BRYANT A, ET AL: Radiographic investigation of angular and linear measurements including first metatarsophalangeal joint dorsiflexion and rearfoot to forefoot axis angle. *J Foot Ankle Surg* **44**: 190, 2005.
14. JOSEPH J: Range of movement of the great toe in men. *J Bone Joint Surg Br* **36**: 450, 1954.
15. BUELL T, GREEN DR, RISSER J: Measurement of the first metatarsophalangeal joint range of motion. *JAPMA* **78**: 439, 1988.
16. ROUKIS TS, JACOBS PM, DAWSON DM, ET AL: A prospective comparison of clinical, radiographic, and intraoperative features of hallux rigidus. *J Foot Ankle Surg* **41**: 76, 2002.
17. MONTAGNE J, CHEVROT A, GALMICHE JM: *Atlas of Foot Radiology*, Masson, Paris, 1981.
18. FREYCHAT P, BELLI A, CARRET JP, ET AL: Relationship between rearfoot and forefoot orientation and ground reaction forces during running. *Med Sci Sports Exerc* **28**: 225, 1996.
19. BRYANT AR, MAHONEY B, TINLEY P: Lateral intermetatarsal angle: a useful measurement of metatarsus primus elevatus? *JAPMA* **91**: 251, 2001.
20. BAUM I, SPENCER AM: Limb dominance: its relationship to foot length. *JAPA* **70**: 505, 1980.
21. HERRING KM: Injury prediction among runners: preliminary report on limb dominance. *JAPMA* **83**: 523, 1993.
22. SKINNER S: "Development of Gait," in *Human Walking*, 2nd Ed, ed by J Rose, J Gamble, p 123, Williams & Wilkins, Baltimore, 1994.
23. ROSS FD: The relationship of abnormal foot pronation to hallux valgus: a pilot study. *Prosthet Orthot Int* **10**: 72, 1986.
24. CAMASTA CA: Hallux limitus and hallux rigidus: clinical examination, radiographic findings and natural history. *Clin Podiatr Med Surg* **13**: 423, 1996.
25. CHAPMAN C: Functional hallux limitus: the essentials. *Br*

- J Podiatry **2**: 40, 1999.
26. BRYANT A, TINLEY P, SINGER K: A comparison of radiographic measurements in normal, hallux valgus, and hallux limitus feet. *J Foot Ankle Surg* **39**: 39, 2000.
 27. HARDY RH, CLAPHAM JCR: Observations on hallux valgus based on a controlled series. *J Bone Joint Surg Br* **33**: 376, 1951.
 28. DUKE H, NEWMAN LM, BRUSKOFF BL, ET AL: Relative metatarsal length patterns in hallux abducto valgus. *JAPA* **72**: 1, 1982.
 29. SARAGAS NP, BECKER PJ: Comparative radiographic analysis of parameters in feet with and without hallux valgus. *Foot Ankle Int* **16**: 139, 1995.
 30. VILLADOT A: Metatarsalgia due to biomechanical alteration of the forefoot. *Orthop Clin North Am* **4**: 165, 1973.
 31. DRAGO JJ, OLOFF L, JACOBS AM: A comprehensive review of hallux limitus. *J Foot Surg* **23**: 213, 1984.
 32. İNCEL NA, GENÇ H, ERDEM HR, ET AL: Muscle imbalance in hallux valgus: an electromyographic study. *Am J Phys Med Rehabil* **82**: 345, 2003.
 33. CAMASTA CA: "Radiographic Evaluation and Classification of Metatarsus Primus Elevatus," in *Reconstructive Surgery of the Foot and Leg: Update '94*, ed by C Camasta, N Vickers, J Ruch, p 122, The Podiatry Institute, Tucker, GA, 1994.
 34. CICHINELLI LD, CAMASTA CA, MCGLAMRY ED: Iatrogenic metatarsus primus elevatus: etiology, evaluation, and surgical management. *JAPMA* **87**: 165, 1997.
 35. MEYER JO, NISHON LR, WEISS L, ET AL: Metatarsus primus elevatus and the etiology of hallux rigidus. *J Foot Surg* **26**: 237, 1987.
 36. BINGOLD AC, COLLINS DH: Hallux rigidus. *J Bone Joint Surg Br* **32**: 214, 1950.
 37. BIRKE JA, CORNWALL MW, JACKSON M: Relationship between hallux limitus and ulceration of the great toe. *J Orthop Sports Phys Ther* **10**: 172, 1988.
 38. WEARING SC, URRY SR, PERLMAN PR, ET AL: Serial measurement of calcaneal pitch during midstance. *JAPMA* **89**: 188, 1999.
 39. BOJSEN-MOELLER F: Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off. *J Anat* **129**: 165, 1979.
 40. NEYLON TA, JOHNSON BA, LAROCHE RA: Use of the Lapidus bunionectomy in first ray insufficiency. *Clin Podiatr Med Surg* **18**: 365, 2001.
 41. GREEN DR, CAROL A: Planal dominance. *JAPA* **74**: 98, 1984.
 42. GARROW AP, PAPAGEORGIU A, SILMAN AJ, ET AL: The grading of hallux valgus: the Manchester Scale. *JAPMA* **91**: 74, 2001.