Structural characteristics associated with radiographic severity of first metatarsophalangeal joint osteoarthritis

Running heading: Structural characteristics associated with severity of 1st MTPJ OA

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Abstract

Objective

To determine whether foot structure varies according to the presence and radiographic severity of first metatarsophalangeal joint osteoarthritis (first MTPJ OA).

Methods

Weight-bearing dorso-plantar and lateral radiographs were obtained for the symptomatic foot of 185 participants (105 females, aged 22 to 85 years) with clinically diagnosed first MTPJ OA. A validated atlas was used to classify participants as having radiographic first MTPJ OA and to stratified into three categories of severity (none/mild, moderate, severe). Bone length, width and angular measures of the forefoot and medial arch were performed on radiographs, and differences between categories were compared using univariate general linear models, adjusting for confounders.

Results

One hundred and fifty participants were categorised as having radiographic first MTPJ OA, and participants were further stratified into none/mild (n = 35), moderate (n = 69) or severe (n = 81) OA categories. Participants with radiographically defined first MTPJ OA displayed a greater hallux abductus interphalangeal angle. Increasing radiographic severity of first MTPJ OA was associated with a larger hallux abductus interphalangeal angle, wider first metatarsal and proximal phalanx and smaller intermetatarsal angle. No differences in medial arch measurements were observed between the categories.

Conclusion

First ray alignment and morphology differ according to the presence and severity of first MTPJ OA. Prospective studies are required to determine whether the observed differences are a cause or consequence of OA.

Significance and Innovation

- This is the first study to evaluate foot structure of individuals with first metatarsophalangeal joint osteoarthritis determined using a validated radiographic atlas.
- Weight-bearing dorso-plantar and lateral radiographs were obtained for the symptomatic foot of 185 participants with clinically diagnosed first metatarsophalangeal joint osteoarthritis.
- Participants with radiographically defined first metatarsophalangeal joint osteoarthritis displayed a greater hallux abductus interphalangeal angle. Increasing radiographic severity of first metatarsophalangeal osteoarthritis was associated with a larger hallux abductus interphalangeal angle, wider first metatarsal and proximal phalanx and smaller intermetatarsal angle.
- First ray alignment and morphology differ according to the presence and severity of first metatarsophalangeal osteoarthritis.

Introduction

Osteoarthritis (OA) of the first metatarsophalangeal joint (first MTPJ) affects 7.8% of the population aged 50 years and older and is more prevalent in women and those who work in manual occupations (1). The clinical symptoms of first MTPJ OA include pain and stiffness in and around the joint, leading to significant reduction in quality of life and locomotor function, with 71% of people with the condition reporting disabling symptoms (1, 2). Greater radiographic severity of first MTPJ OA is associated with a higher prevalence of pain and deformity and lower range of joint motion, suggesting that it may be a progressive disorder (3). However, despite there being many risk factors suggested, such as age, female sex and trauma, the mechanisms responsible for the development and progression of first MTPJ OA are not well understood (4).

Variations in skeletal structure have been identified as an intrinsic risk factor for the development and progression of OA in a number of lower limb joints, including the knee and hip (5, 6). These variations have been attributed to altered joint biomechanics resulting in changes to the normal distribution of forces acting at the joint (7). For example, in individuals with medial compartment knee OA, varus alignment of the knee increases the knee adduction moment and alters joint compression forces within the medial compartment during gait (8, 9). This change in joint biomechanics has been shown to be associated with disease severity and progression (10, 11).

Although it is plausible that variations in skeletal structure of the foot are an intrinsic risk factor for first MTPJ OA, the association between first MTPJ OA and the structure of the foot is unclear. Our previous systematic review found evidence that people with first MTPJ OA exhibit a wider first metatarsal, wider proximal phalanx of the hallux, longer hallux, and

more dorsiflexed first metatarsal compared to people without the condition (12). However, the studies included in the systematic review were limited in that they defined first MTPJ OA using only clinical symptoms or did not use a valid atlas to confirm the presence of radiographically defined first MTPJ OA. These issues make the interpretation of results from previous research difficult, as the definition of first MTPJ OA varies between studies (12).

With this in mind, the aims of this study were to use a foot-specific radiographic atlas to determine: (i) if skeletal differences exist in people with and without first MTPJ OA, and (ii) whether skeletal variations are associated with first MTPJ OA severity.

Methods

Participants

The study sample consisted of 185 individuals who participated in two clinical trials of non-surgical interventions for first MTPJ OA (13, 14). All participants had a clinical diagnosis of first MTPJ OA and met the following inclusion criteria: (i) aged at least 18 years, (ii) reported having pain in the first MTPJ on most days for at least 12 weeks, (iii) reported having pain rated at least 30 mm on a 100 mm visual analogue scale, (iv) described pain on palpation of the dorsal aspect of the first MTPJ (v) restricted dorsiflexion of the first MTPJ (<64° of dorsiflexion range of motion), and (vi) were able to walk household distances (greater than 50 m) without the aid of a walker. Exclusion criteria included: (i) previous first MTPJ surgery, (ii) currently pregnant, (iii) significant first MTPJ deformity including hallux valgus, (defined as a score of 2 or 3 using the Manchester scale (15), (iv) presence of any condition within the foot or ankle that could confound pain and functional assessments of the first MTPJ, or (v) presence of inflammatory conditions such as gout or rheumatoid arthritis.

The La Trobe University Human Ethics Committee approved the studies from which participants were drawn (HEC15128 and HEC18375). All radiographic procedures were performed according to the National Health and Medical Research Council of Australia National Statement on Ethical Conduct in Human Research (16).

Radiographic assessment

Weightbearing dorso-plantar and lateral radiographic projections were obtained for all participants while standing in a relaxed weightbearing position. If the participant had clinically-defined first MTPJ OA in both feet, radiographs were taken on the most symptomatic foot. All radiographs were taken by the same medical imaging group using a Shimadzu UD150LRII 50 kW/30 kHz Generator and 0.6/1.2 P18DE-80S high speed x-ray tube from a ceiling suspended tube mount. AGFA MD40 CR digital phosphor plates in a 24 cm × 30 cm cassette were also used. For dorso-plantar projections, the x-ray tube was positioned at an angle of 15° cephalad and centred at the base of the third metatarsal. For the lateral projection, the x-ray tube was positioned at an angle of 90° and centred at the base of the third metatarsal. The film focal distance was 100 cm for both projections.

Radiographs were assessed to confirm the presence and severity of radiographically defined first MTPJ OA. The La Trobe University Radiographic Atlas for First MTPJ OA was used to assess radiographs (17). The atlas has moderate to excellent intra-rater reliability and moderate to excellent inter-rater reliability and is used to determine the severity of osteophytes and joint space narrowing at the first MTPJ (17). The presence of osteophytes was graded as being either absent (score = 0), small (score = 1), moderate (score = 2), or severe (score = 3). The presence of joint space narrowing was graded as being either none (score = 0), definite (score = 1), moderate (score = 2), or severe (score = 3). All assessments

were conducted by two experienced raters (HBM and SEM) who contributed to the development of the atlas.

Participants were defined as having radiographic first MTPJ OA if they recorded a score of 2 or greater for either osteophytes or joint space narrowing in either projection (17). Participants were also assigned to one of three radiographic severity categories: (i) none/mild OA (defined as one score of at least 1 and no score of 2 or greater for either osteophytes or joint space narrowing from either the dorso-plantar or lateral radiographs), (ii) moderate OA (defined as one score of at least 2 and no score of 3), or (iii) severe OA (defined as one score of 3).

Radiographic measurements of foot structure

The selection of radiographic measurements was based on the need to comprehensively characterise both the structure and architecture of the foot in individuals with first MTPJ OA using measures that had adequate reliability and validity. For all participants, the following variables were measured from dorso-plantar radiographs: first metatarsal length, first metatarsal width, proximal phalanx length, proximal phalanx width, distal phalanx length, total hallux length, intermetatarsal angle, hallux abductus angle, hallux abductus interphalangeal angle, metatarsus adductus angle (simplified technique), and metatarsal protrusion distance (18-21). For the lateral radiographs, the following variables were measured: calcaneal-first metatarsal angle, first metatarsal declination angle, lateral intermetatarsal angle, dorsal proximal metatarsal angle, dorsal proximal hallux angle, dorsal proximal phalangeal angle, plantar distal metatarsal angle, and plantar distal hallux angle (20, 22-24). Measurements are shown in Figures 1 and 2 and detailed explanations are provided in Supplementary File 1. All measurements were made on digital radiographs in the same

manner for each participant by the same examiner (AKB). Test-retest (intra-rater) reliability was evaluated by repeating all radiographic measurements on two separate occasions, two weeks apart.

Statistical analysis

All analyses were performed using IBM SPSS Statistics Release 24 for Windows (SPSS, Chicago, IL, USA). Reliability was calculated using intraclass correlation coefficients (ICCs) (model 3,1) [28] with 95% confidence intervals (CI) (25). To determine if there were any significant differences in radiographic measurements (i) between participants with and without radiographically defined first MTPJ OA or (ii) in participants with different first MTPJ OA radiographic severity categories, univariate general linear models were calculated for all variables. To determine appropriate covariates for the models, a series of independent samples *t*-tests or chi-squared tests were conducted for the comparison of cases and non-cases. Covariates were identified where there were significant differences between severity categories (p-values < 0.05 were considered significant). General linear models with the entry of covariates and least significant difference (LSD) adjustment were conducted to determine differences in structural variables between cases and non-cases, and between severity categories of first MTPJ OA. For all analyses, adjusted mean differences were calculated with p-values < 0.05 considered significant. Effect sizes (Cohen's d) were calculated for all significant structural differences to allow comparison of magnitude of differences across measures.

Results

Reliability

Means and standard deviations for tests and re-tests for all radiographic measures, along with ICCs and 95% confidence intervals are shown in Supplementary file 2. All measures displayed good to excellent intra-rater reliability with ICCs ranging between 0.82 and 0.98.

Participant characteristics

Participant characteristics for participants with and without radiographic 1st MTPJ OA are shown in Table 1. Of the 185 participants, 150 (81.1%) had radiographic first MTPJ OA. Participants with radiographic first MTPJ OA exhibited significantly greater weight (mean difference = 5.8 kg, 95% CI = 1.0 to 10.6), Body mass index (BMI) (mean difference = 1.9 kg/m^2, 95% CI = 0.2 to 3.5), and duration of symptoms (mean difference = 35.9 months, 95% CI = 7.3 to 64.5) compared to those without radiographic OA. For the general linear models, BMI and duration of symptoms were considered to be confounders and were entered as covariates. Although weight was significantly different between cases and non-cases, it was not included in addition to BMI as a covariate in order to avoid possible over-adjustment as the two variables were strongly correlated ($r = 0.799$, $p < 0.001$).

Participant characteristics for the comparison between radiographic severity categories are shown in table 3. There were 35 (18.9%) participants in the none/mild category, 69 (37.2%) in the moderate category, and 81 (43.8%) in the severe category. Participants in the severe category were significantly older than the none/mild (mean difference = 4.9 years, 95% CI = 0.7 to 9.1) and moderate (mean difference = 3.8 years, 95% CI = 0.5 to 7.2) categories and exhibited significantly greater weight compared to both the none/mild (mean difference = 9.1 kg, 95% CI = 4.1 to 14.2) and moderate (mean difference = 7.0 kg, 95% CI = 2.9 to 11.1) categories. The severe category also exhibited significantly greater BMI compared to the none/mild category (mean difference = 2.5 kg/m^2, 95% CI = 0.7 to 4.3). Finally, the severe

category exhibited significantly greater self-reported duration of symptoms compared to the none/mild (mean difference = 51.9 months, 95% CI = 21.5 to 82.3) and moderate (mean difference = 33.2 months, 95% CI = 8.7 to 57.8) categories.

Structural differences between participants with and without radiographic first MTPJ OA

Structural characteristics in case and non-case categories are shown in Table 2. The case category exhibited greater hallux abductus interphalangeal angle compared to the non-case category (mean difference = 4.1°, 95% CI = 2.0 to 6.3, d = 0.77). There were no other statistically significant differences in measures of structure between those with and without radiographic first MTPJ OA.

Structural differences according to radiographic severity in those with radiographic first MTPJ OA

Structural characteristics according to radiographic severity are shown in Table 4. The severe radiographic OA category exhibited a significantly wider first metatarsal compared to the moderate severity category (mean difference = 1.0%, 95% CI = 0.1 to 1.9, d = 0.54), a wider proximal phalanx compared to the moderate severity category (mean difference = 1.7%, 95% CI = 0.2 to 3.1, d = 0.51), a smaller intermetatarsal angle compared to both the none/mild (mean difference = -1.2°, 95% CI = -2.1 to -0.3, d = 0.37) and moderate severity (mean difference = -0.9°, 95% CI = -1.7 to -0.2, d = 0.36) categories, and a significantly greater hallux abductus interphalangeal angle compared to the none/mild (mean difference = 4.3°, 95% CI = 1.9 to 6.7, d = 0.79) category. The moderate severity category displayed a greater hallux abductus interphalangeal angle compared to the none/mild category (mean difference = 3.9°, 95% CI = 1.6 to 6.2, d = 0.77).

Discussion

The objective of this study was to determine whether skeletal foot structure varies according to the presence and radiographic severity of first MTPJ OA. This is the first study to evaluate foot structure of individuals with first MTPJ OA determined using a validated radiographic atlas. A comprehensive suite of radiographic measurements was used, and we found that some radiographic measurements related to first ray alignment and morphology differ according to the radiographic severity of first MTPJ OA.

Among all structural variables, the hallux abductus interphalangeal angle was the only measure that was significantly different between those with and without first MTPJ OA and between severity categories. The magnitude of the differences, determined by effect sizes, were also largest for this measurement. These findings indicate that there is greater lateral deviation of the distal phalanx relative to the proximal phalanx in individuals with radiographically defined first MTPJ OA. Furthermore, there was evidence of a dose-response relationship as the degree of distal phalanx deviation increased with increasing severity of radiographic first MTPJ OA.

Two previous studies found no difference in hallux abductus interphalangeal angle between cases and controls (20, 26). However, in these studies, the inclusion criteria used to recruit participants were either clinical symptoms or first MTPJ range of motion testing. In addition, one study only recruited participants with early signs of first MTPJ OA (26). Therefore, as our study recruited participants that exhibited a range of radiographic severities, the findings suggest a temporal relationship may exist between longer duration of first MTPJ OA and lateral deviation of the distal phalanx.

The mechanism that leads to greater hallux abductus interphalangeal may involve alterations in forces acting on the interphalangeal joint of the hallux when walking. This is supported by

biomechanical research conducted on individuals with and without first MTPJ OA that found both greater force on the hallux when walking and greater lateral deviation of the centre of pressure in those with OA (27, 28). These findings imply a greater deviating force is placed on the hallux in people with first MTPJ OA compared to people without the condition. However, more research is needed to understand the long-term effects that biomechanical variations related to first MTPJ OA have on adjacent joints of the foot.

We found that the first metatarsal and proximal phalanx were significantly wider in individuals with severe first MTPJ OA compared to individuals with moderate first MTPJ OA. This finding is consistent with a previous study that found a significantly wider first metatarsal and proximal phalanx in cases of first MTPJ OA compared to asymptomatic controls (21). However, our findings are novel in that no difference was found between individuals with and without radiographic first MTPJ OA. There are two possible explanations for these findings. Firstly, a wider first metatarsal and proximal phalanx may provide a relatively square (as opposed to round) joint surface that causes uneven and increased joint compression, leading to the initial development and progression of the condition over time (21). Secondly, bony remodelling may occur in response to altered loading in individuals with first MTPJ OA, resulting in increased width of the first metatarsal and proximal phalanx.

Individuals with severe first MTPJ OA also exhibited a smaller angle between the first and second metatarsals compared to both the none/mild and moderate categories, indicating a less medially deviated first metatarsal relative to the lateral forefoot. Studies of normal foot mechanics indicate that the first metatarsal moves in a direction of adduction relative to bones of the midfoot, allowing for abduction of the hallux during the propulsive phase of gait (29). Our findings suggest that in people with first MTPJ OA, the first metatarsal does not move

into adduction to adequately facilitate normal function of the first MTPJ. Such a mechanism may lead to increased joint compression in the first MTPJ. However, it is also possible that this observation is a consequence of first MTPJ pathology.

No significant differences were found for any angular measurements from lateral projections that characterise foot posture. This suggests that sagittal plane measures of the medial longitudinal arch are not associated with first MTPJ OA. In terms of previous research that investigated foot medial arch shape characteristics in people with first MTPJ OA, our findings differ from Mahiquez et al, who found individuals with a rearfoot valgus angle of 5°, indicative of a flatter foot, were 23% more likely to develop first MTPJ OA (30). However, the findings of this prospective study used frontal plane heel position as an indicator of medial arch shape characteristics, whereas our study used a suite of lateral radiographic angular measurements. Further prospective work should use both sagittal plane and frontal plane measures of foot posture to provide further insights into the association between medial arch shape characteristics and the development of first MTPJ OA.

We expected the plantar distal hallux angle, indicative of distal phalanx dorsiflexion, to be greater in severe first MTPJ OA as a compensatory response to the lack of dorsiflexion range of motion available in the first MTPJ. Such a finding was reported in a study whereby individuals with limited first MTPJ range of motion (less than 55°) displayed significantly greater dorsiflexion of the hallux interphalangeal joint compared to controls with normal first MTPJ range of motion (31). However, no such significant difference was found. Rather, a comparatively greater variance in plantar distal hallux angle was found compared to other angular measures, particularly among individuals with severe first MTPJ OA. This suggests that while some individuals displayed a dorsiflexed distal phalanx of the hallux, others displayed a plantarflexed hallux, similar to that observed in a hammertoe deformity.

Strengths of this study include the use of a validated atlas for first MTPJ OA and the analysis of a comprehensive suite of radiographic measurements of foot structure. However, several limitations also need to be considered. Firstly, as this was a cross-sectional study, temporal relationships cannot be inferred. Long term prospective studies are needed to determine whether structural differences identified in this study influence the progression of first MTPJ OA. Secondly, although structural factors have been identified as important factors that may contribute to the progression of first MTPJ OA, there are likely other factors, such as previous trauma, work/occupation, biomechanics or genetics that could contribute to its development and progression (32). Thirdly, the investigator taking radiographic measurements was not blinded to the pathology – a factor that is inherently difficult to achieve – introducing the risk of measurement bias. Fourthly, we were limited to radiographic measures obtained from dorso-plantar and lateral radiographic views. Further studies could include measures from other views, such as frontal plane calcaneal measures from frontal plane views. Finally, all participants were symptomatic as they were recruited for clinical trials. Therefore, further study is required to understand the relationships between structure, radiographic severity and the development of symptoms.

Conclusion

The presence and severity of radiographic first MTPJ OA is associated with larger hallux abductus interphalangeal angle, a wider first metatarsal and proximal phalanx, and a smaller intermetatarsal angle. These findings suggest that foot structure may be involved in the development and progression of first MTPJ OA. However, long term prospective studies are required to further understand the role of these factors in the development of this condition.

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Table 1. Characteristics of participants with (case) and without (non-case) radiographically defined first MTPJ OA*.

	Non-case (n=35)	**Case (n=150)**	***p*-value**
Age (years)	55.0 (13.4)	58.1 (9.9)	0.12
Female, n (%)	22 (62.9)	85 (56.9)	0.45
Height (cm)	166.7 (8.5)	166.9 (8.6)	0.68
Weight (kg)	74.2 (13.2)	80.1 (13.1)	0.02
BMI (kg/m^2)	26.8 (4.6)	28.7 (4.5)	0.03
Self-reported duration of symptoms (months)	35.8 (42.3)	72.9 (83.2)	0.01

* Values shown represent mean (SD) unless otherwise stated.

Table 2. Comparison of structural characteristics between participants with (cases) and without (non-case) radiographically defined first MTPJ OA*.

	Non-case (n=35)	**Case (n=150)**	***p*-value**	**Adjusted mean difference (95% CI)[¥]**
Dorso-plantar projection				
First metatarsal length[†]	85.4 (3.6)	84.6 (3.1)	0.36	-0.5 (-1.7 to 0.7)
Proximal phalanx length[†]	43.6 (3.3)	43.6 (4.4)	0.58	0.3 (-1.2 to 1.9)
Distal phalanx length [†]	30.9 (2.9)	31.4 (3.2)	0.40	0.3 (-0.8 to 1.5)
Hallux length [†]	74.6 (5.2)	74.9 (6.5)	0.90	0.1 (-2.4 to 2.2)
First metatarsal width[#]	19.8 (2.5)	20.1 (2.6)	0.72	0.3 (- 0.9 to 0.9)
Proximal phalanx width[#]	38.5 (4.9)	38.8 (4.7)	0.96	-0.1 (- 1.8 to 1.6)
Intermetatarsal angle (°)	10.1 (2.7)	9.6 (2.2)	0.90	-0.6 (- 1.5 to 0.2)
Hallux abductus angle (°)	12.4 (5.6)	10.9 (4.7)	0.11	-1.4 (-3.3 to 0.4)
Hallux abductus interphalangeal angle (°)	11.2 (5.5)	15.6 (5.8)	<0.01	4.1 (2.0 to 6.3), d = 0.77
Metatarsal protrusion distance (mm)	2.2 (3.6)	1.7 (3.6)	0.48	-0.6 (-1.9 to 0.8)
Lateral projection				
Metatarsus adductus angle (°)	22.5 (5.4)	22.9 (5.5)	0.74	0.2 (-1.8 to 2.3)
Calcaneal – first metatarsal angle (°)	131.1 (8.9)	132.3 (7.2)	0.75	0.3 (-2.6 to 3.2)
First metatarsal declination angle (°)	24.2 (3.6)	23.1 (3.2)	0.19	-0.7 (-2.0 to 0.5)
Lateral intermetatarsal angle (°)	1.9 (1.4)	1.9 (1.2)	0.82	-0.1 (-0.5 to 0.4)
Dorsal proximal metatarsal angle (°)	89.9 (2.3)	89.1 (2.6)	0.19	0.6 (-0.3 to 1.6)
Dorsal proximal hallux angle (°)	84.8 (4.0)	83.8 (5.8)	0.29	1.1 (-0.9 to 3.2)
Dorsal proximal phalangeal angle (°)	76.3 (4.4)	77.6 (5.6)	0.15	-1.5 (-3.6 to 0.6)
Plantar distal metatarsal angle (°)	82.1 (4.9)	81.4 (5.6)	0.89	1.0 (-1.9 to 2.2)
Plantar distal hallux angle (°)	89.6 (9.8)	90.5 (7.9)	0.35	-1.7 (-5.2 to 1.9)

* BMI and duration of symptoms entered as covariates in general linear model. Values shown represent mean (SD) unless otherwise stated.

[¥] Effect size (d) included for significant difference.

[†] Expressed as percentage length of second metatarsal.

[#] Expressed as a percentage of length of the corresponding bone.

Table 3. Participant characteristics according to radiographic severity of first MTPJ OA*.

	None/mild (n=35)	**Moderate (n=69)**	**Severe (n=81)**	***p*-value**
Age (years)	55.0 (13.4)	56.1 (10.8)	59.9 (8.9)	0.02†#
Female, n (%)	22 (62.9)	44 (64.3)	39 (48.1)	0.10
Height (cm)	166.7 (8.5)	165.2 (8.7)	168.4 (8.3)	0.57
Weight (kg)	74.2 (13.2)	76.3 (11.3)	83.4 (13.7)	<0.01†#
BMI (kg/m^2)	26.8 (4.5)	28.0 (4.6)	29.3 (4.6)	0.02†
Duration (months)	35.8 (42.3)	56.6 (66.6)	86.5 (93.8)	<0.01†#

* Values shown represent mean (SD) unless otherwise stated.
† Significant difference between none/mild and severe.
# Significant difference between moderate and severe.

Table 4. Comparison for radiographic measures according to radiographic severity of first MTPJ OA[¥].

					Between-group adjusted mean difference (95% CI)		
	None/mild (n=35)	**Moderate (n=69)**	**Severe (n=81)**	***p*-value**	**None/mild vs moderate**	**None/mild vs severe**	**Moderate vs severe**
Dorso-plantar projection							
First metatarsal length[†]	85.4 (3.6)	84.8 (3.1)	84.4 (3.1)	0.74	0.4 (-0.8 to 1.7)	0.5 (-0.8 to 1.8)	0.1 (-1.0 to 1.1)
Proximal phalanx length[†]	43.6 (3.3)	43.6 (5.7)	43.7 (2.9)	0.79	-0.2 (-1.9 to 1.5)	-0.6 (-2.2 to 1.2)	-0.3 (-1.7 to 1.0)
Distal phalanx length[†]	30.9 (2.9)	31.3 (3.3)	31.6 (3.1)	0.82	-0.3 (-1.6 to 0.9)	-0.5 (-1.8 to 0.8)	-0.1 (-1.1 to 0.9)
Hallux length[†]	74.6 (5.2)	74.5 (7.7)	75.3 (5.2)	0.89	0.2 (-2.3 to 2.8)	-0.3 (-2.9 to 2.3)	-0.5 (-2.6 to 1.6)
First metatarsal width[#]	19.8 (2.6)	19.5 (2.3)	20.6 (2.8)	0.07	0.3 (-0.7 to 1.4)	-0.7 (-1.8 to 0.4)	-1.0 (-1.9 to -0.1), *d* = 0.54*
Proximal phalanx width[#]	38.5 (4.9)	37.6 (3.6)	39.9 (5.3)	0.03	0.9 (-1.0 to 2.8)	-1.3 (-3.2 to 0.7)	-2.2 (-3.7 to -0.6), *d* = 0.51*
Intermetatarsal angle (°)	10.1 (2.7)	10.0 (2.3)	9.2 (2.1)	0.03	0.3 (-0.6 to 1.2)	1.1 (0.2 to 2.1), *d* = 0.37*	0.8 (0.1 to 1.6), *d* = 0.36*
Hallux abductus angle (°)	12.4 (5.6)	10.7 (4.7)	11.2 (4.8)	0.27	1.6 (-0.4 to 3.7)	1.4 (-0.7 to 3.4)	-0.3 (-1.9 to 1.4)

Hallux abductus interphalangeal angle (°)	11.2 (5.5)	15.3 (5.1)	15.9 (6.3)	<0.01	-3.9 (-6.2 to -1.6), *d* = 0.77*	-4.3 (-6.7 to -1.9), *d* = 0.79*	-0.3 (-2.2 to 1.6)
Metatarsus adductus angle (°)	22.5 (5.4)	22.4 (4.8)	23.3 (6.0)	0.63	0.1 (-2.1 to 2.4)	-0.7 (-3.0 to 1.6)	-0.9 (-2.7 to 1.0)
Metatarsal protrusion distance (mm)	2.2 (3.6)	1.7 (3.4)	1.8 (3.7)	0.78	0.5 (-0.9 to 2.1)	0.3 (-1.2 to 1.8)	-0.2 (-1.4 to 0.9)
Lateral projection							
Calcaneal – first metatarsal angle (°)	131.1 (8.9)	131.2 (7.7)	133.3 (6.7)	0.43	0.3 (-2.8 to 3.4)	-1.1 (-4.3 to 2.1)	-1.4 (-3.9 to 1.1)
First metatarsal declination angle (°)	24.2 (3.6)	23.7 (3.0)	22.6 (3.3)	0.12	0.3 (-1.0 to 1.6)	1.3 (-0.1 to 2.6)	0.9 (-0.1 to 2.0)
Lateral intermetatarsal angle (°)	1.8 (1.4)	1.7 (1.1)	2.1 (1.2)	0.33	0.2 (-0.3 to 0.7)	-0.1 (-0.6 to 0.4)	-0.3 (-0.7 to 0.1)
Dorsal proximal metatarsal angle (°)	89.9 (2.3)	89.1 (2.7)	89.1 (2.6)	0.40	0.7 (-0.4 to 1.8)	0.6 (-0.5 to 1.7)	-0.1 (-1.0 to 0.7)
Dorsal proximal hallux angle (°)	84.8 (4.0)	83.8 (5.4)	84.0 (6.1)	0.59	1.1 (-1.1 to 3.4)	1.1 (-1.2 to 3.4)	-0.1 (-1.9 to 1.8)
Dorsal proximal phalangeal angle (°)	76.3 (4.4)	77.9 (5.3)	77.1 (5.8)	0.32	-1.6 (-3.8 to 0.5)	-0.7 (-2.9 to 1.5)	0.9 (-0.9 to 2.7)
Plantar distal metatarsal angle (°)	82.1 (4.9)	82.1 (4.9)	80.8 (5.5)	0.79	-0.4 (-2.6 to 1.8)	0.2 (-2.0 to 2.5)	0.6 (-1.2 to 2.4)
Plantar distal hallux angle (°)	90.5 (7.9)	90.6 (9.5)	88.7 (10.2)	0.19	0.5 (-3.4 to 4.4)	3.0 (-0.9 to 7.0)	2.5 (-0.6 to 5.7)

[¥] Age, BMI and self-reported duration of symptoms entered as covariates in general linear model. Values shown represent mean (SD) unless otherwise stated.
* Significant adjusted mean difference and effect size (*d*).
[†] Expressed as percentage length of the second metatarsal.
[#] Expressed as percentage of length of the corresponding bone.

Figure 1. Dorso-plantar radiographic measurement techniques – Bone length and width measurements. (A) Second metatarsal length, (B). First metatarsal length, (C) Proximal phalanx length, (D) Distal phalanx length, (E) First metatarsal width, (F) Proximal phalanx width, Dorso-plantar radiographic measurement techniques – angle measures. (G) Intermetatarsal angle, (H) hallux abductus angle, (I) Hallux abductus interphalangeal angle, (J) Simplified metatarsus adductus angle, (K) Metatarsal protrusion distance.

Figure 2. Lateral radiographic measurement techniques. (L) Calcaneal-first metatarsal angle, (M) First metatarsal declination angle, (N) Lateral intermetatarsal angle, (O) Dorsal proximal metatarsal angle, (P) Dorsal proximal hallux angle, (Q) Dorsal proximal phalangeal angle, (R) Plantar distal metatarsal angle, (S) Plantar distal hallux angle.

Figure 1.

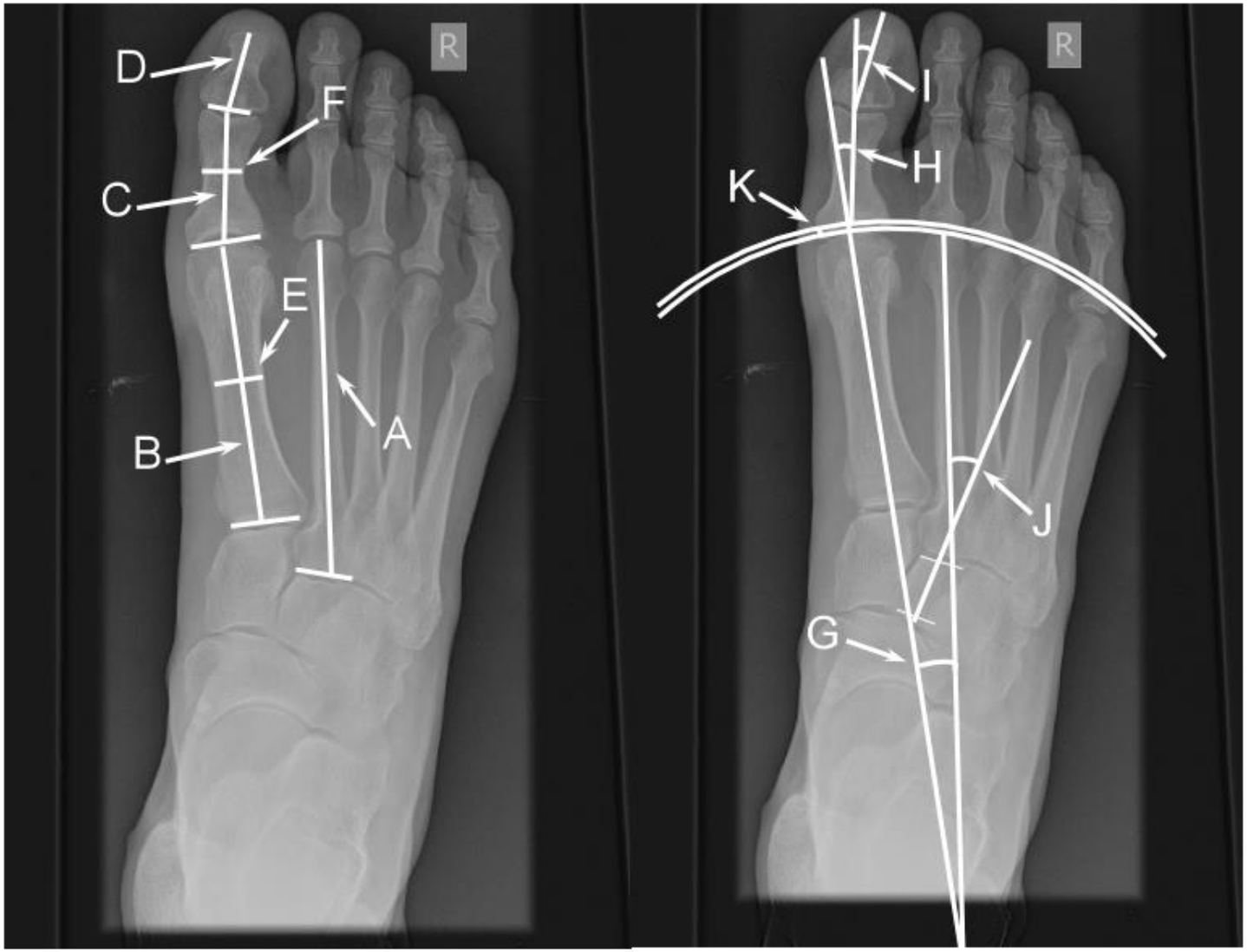
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Figure 2.