Check for updates

Article

AMERICAN ORTHOPAEDIC FOOT & ANKLE SOCIETY

Foot & Ankle International®
2021, Vol. 42(8) 1040–1048
© The Author(s) 2021
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1071100721001015
journals.sagepub.com/home/fai

Normative Distribution of First Metatarsal Axial Rotation

Jesse Steadman, BS[1], Neil Bakshi, MD[1], Christopher Arena, MD[2], Richard Leake, MD[3], Alexej Barg, MD[1,4], and Charles L. Saltzman, MD[1]

Abstract

Background: First metatarsal (M1) axial rotation is recognized as a clinically relevant component of hallux valgus deformity. Methods to realign the M1 in 3 dimensions have been developed. One goal of these operations is to restore normal rotation of the first ray. The aim of this study is to provide estimates for the normal distribution of M1 rotation in patients without relevant anatomic pathology.

Methods: Using stringent clinical and radiographic criteria, we evaluated a set of plain radiograph and weightbearing computed tomography (WBCT) images of 62 feet from a consecutive patient database. Subjects included had normal foot alignment without bunion symptoms. M1 rotation of each foot was measured using 2 unique methods (Saltzman et al and Kim et al methods). Measurement of rotation was performed by 2 observers from coronal WBCT images. Mean values and confidence intervals (CIs) of M1 rotation were calculated for each method. Inter- and intraobserver reliability values were also reported.

Results: Mean M1 rotation values of 2.1 degrees (95% CI: 0.9-3.4) and 6.1 degrees (95% CI: 4.4-7.8) were identified using the Saltzman et al and Kim et al methods, respectively. Inter- and intraobserver reliability values were interpreted as excellent for both methods.

Conclusion: In this study, we describe the natural distribution of the M1 axial rotation in subjects without bunion or other identifiable bony foot deformities. This information should provide a normative reference for surgeons correcting rotational issues of the first metatarsal.

Level of Evidence: Level III, retrospective cohort study.

Keywords: hallux valgus, bunion, axial rotation, metatarsal pronation, hallux valgus corrective surgery

Introduction

For decades, hallux valgus (HV) has largely been interpreted as a 2-dimensional (2D) deformity in the sagittal and transverse planes. Subsequently, reliable and reproducible 2D measures of HV severity such as the hallux valgus angle and intermetatarsal angle were developed and are still used ubiquitously today.[2,16,17,21,27,36,46] Further, numerous operations to normalize these quantitative measures of HV deformity also exist.[9,16,46] Despite the use of these 2D quantitative measures and operative correction of sagittal and transverse plane deformities, consistent rates of poor outcomes and HV recurrence persist with operative correction.[1,7,14]

These relatively high rates of poor outcomes have prompted investigators to reconsider the understanding of HV pathoanatomy. In the last 10 years, axial rotation of the first metatarsal (M1) in the coronal plane has gained increasing attention as having a clinically meaningful impact in HV deformity.[15,19,43] This rotational deformity is referred to as "pronation" when the plantar aspect of the M1 faces inward, toward the second metatarsal, and "supination" when the plantar aspect of the M1 faces outward, away from the second metatarsal.[10,29,43]

[1]Department of Orthopaedics, University of Utah, Salt Lake City, UT, USA
[2]Orthopedic Sports Institute, Institute for Orthopedic Research & Innovation, Coeur d'Alene, ID, USA
[3]Department of Radiology and Imaging Sciences, University of Utah, Salt Lake City, UT, USA
[4]Department of Orthopaedics, Trauma and Reconstructive Surgery, University of Hamburg, Hamburg, Germany

Jesse Steadman, BS, and Neil Bakshi, MD, contributed equally to the development of this project.

Corresponding Author:
Alexej Barg, MD, Department of Orthopaedics, Trauma and Reconstructive Surgery, University Medical Center Hamburg-Eppendorf, Martinistr. 52, 20246 Hamburg, Germany.
Email: al.barg@uke.de

M1 rotation was initially identified in 1956,[24] and received appropriate attention in the years to follow.[12,20] Early methods were even proposed to measure M1 rotation.[10,33,37] However, after these novel measurement methods were reported, M1 rotation in the coronal plane was largely overlooked in literature for almost 2 decades. Now, the field recognizes M1 rotation to be a meaningful aspect of HV, making this deformity understood as a triplanar process.

Further work has revealed that M1 rotation is implicated in more than 75% of HV cases.[15] Resultantly, in an attempt to comprehensively describe and operatively correct HV as a triplanar deformity, numerous measurement methods and corrective techniques have subsequently appeared in literature.[43] Among these contributions, 2 well-cited and replicable methods of M1 axial rotation have emerged. First, the Saltzman et al[33] method, initially proposed using tangential view weightbearing plain radiography (WBPR) has been verified in literature and since been functionally adapted to weightbearing computed tomography (WBCT).[5,35,40] Next, the alpha angle (or Kim et al[15] method), developed using simulated WBCT, has also been verified by later articles.[19,30] Appearing concurrently in literature with these measurement methods are derotational operative techniques such as the modified Lapidus procedure,[6] proximal supination osteotomy,[47] and proximal rotational metatarsal osteotomy,[44] among others.

No studies to date have used true WBCT to quantify physiologic M1 rotation in patients with normal foot alignment and no forefoot symptomatology. This study will provide clinicians with normative context for M1 rotational correction and may influence operative decision making with regard to the chosen hallux valgus procedure and degree of correction. The aim of the current investigation is to report the mean and associated distribution of M1 axial rotation in nonpathologic feet in the general population using both the Saltzman et al[33] and Kim et al[15] methods on WBCT scans.

Methods

Following a granted compliance approval by our internal review board, an evaluation of electronic health records was performed. Electronic health records were retrospectively collected over an interval of 42 months, beginning with the start of WBCT utilization in our department, June 2015, to the end of December 2018. All consecutive patients who received a WBCT scan in this time period were assessed. In total, 761 consecutive WBCT images (pedCAT, CurveBeam LLC, Warrington, PA; medium view, 0.3-mm slice thickness, 0.3-mm slice interval, kVp 120, mAs 22.62) were reviewed and filtered for any duplicate patient feet. Encounters that did not have anteroposterior and lateral foot WBPRs performed within 26 weeks (6 months) of the WBCT or had surgery or an injury between image acquisition dates were excluded. Clinical and imaging inclusion criteria were then applied to the residual 606 feet.

To retrospectively define a normal, nonpathologic foot, stringent inclusion criteria were applied. To be included in this study, the patients had no forefoot symptomology either self-reported by the patient or found anywhere in the patient's clinic notes. Any formal diagnosis of forefoot pathology along with any reports of prior forefoot operations also resulted in exclusion. In addition, the following imaging parameters were required to be met: (1) calcaneal moment arm[34] within one-half of a standard deviation (SD) from the cohort mean; (2) hallux valgus angle[7] $\leq$15 degrees; (3) intermetatarsal angle[7] $\leq$9 degrees; (4) hallux interphalangeal angle[7] $\leq$10 degrees; and (5) Meary angle[23] between the values of 176 and 184 degrees. Although hallux valgus angle, intermetatarsal angle, interphalangeal angle, and Meary angle were assessed using the associated WBPR films, calcaneal moment arm was assessed using WBCT. Calcaneal moment arm was evaluated with WBCT because this modality allows high accuracy in the localization and measurement between the most inferior point of the calcaneus and the longitudinal axis of the tibia. The values used in parameters 2 to 5 were measured and defined as normal according to Coughlin et al.[7]

After these criteria were applied to the 606 feet with adequate image sets, we ended up with a cohort of 62 patient feet that met all inclusion criteria. A flow chart of inclusion is illustrated in Figure 1. Additionally, data associated with the M1 lateral head round sign (a radiographic observation associated with M1 rotation),[26] degeneration of the first metatarsophalangeal joint according to the Kellgren-Lawrence scale (a standardized scale of arthritis),[13] sesamoid wear according to the Stanmore classification scale (a graded measure of hallux-sesamoid joint space),[45] and sesamoid position relative to the intersesamoid ridge (a graded measure of sesamoid subluxation)[48] were also collected to further characterize our included cohort of convenience.

Once this final cohort of normally aligned feet was established, 2 observers, including a musculoskeletal radiologist (R.L., observer A) and a foot and ankle–trained orthopedic surgeon (N.B., observer B) independently accessed and measured the M1 axial rotation of each patient foot demonstrated on coronal-view WBCT. To standardize the approach of identifying a common coronal WBCT view, the following protocol was used (Figure 2):

1. A sagittal WBCT view is identified that offers the greatest projection of the tibial sesamoid bone.
2. The length of the dorsal edge of the tibial sesamoid bone is measured proximal to distal.
3. A second line originating proximally is drawn superimposed on the previous line, but 75% its length.

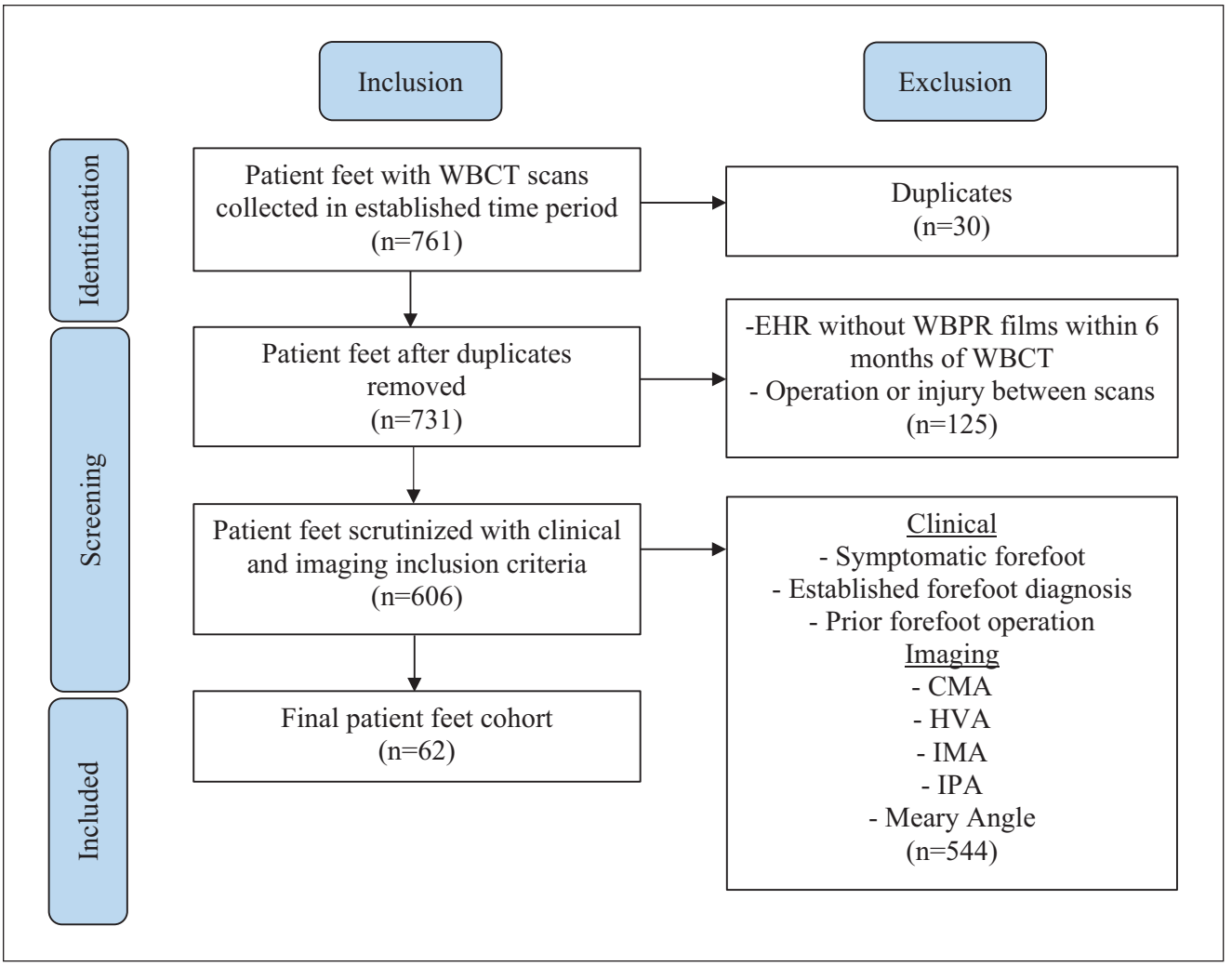

Figure 1. Inclusion-exclusion flow diagram. CMA, calcaneal moment arm; EHR, electronic health record; HVA, hallux valgus angle; IMA, intermetatarsal angle; IPA, interphalangeal angle; WBCT, weightbearing computed tomography; WBPR, weightbearing plain radiograph.

4. The distal tip of the shorter line serves as the desired coronal WBCT plane.

With a standardized coronal plane established, M1 axial rotation (pronation/supination) was measured using both the Saltzman et al[33] and Kim et al[15] methods. As proposed in their original texts,[15,33] each measurement method was performed as follows. Using the Saltzman et al[33] method, a line is drawn that touches the outer profile of the tibial and fibular sesamoid sulci at their most inferior edges; an angle created between this line, and a line parallel to a horizontal reference, quantifies the amount of M1 rotation present. Using the Kim et al[15] method, 2 individual lines are initially drawn that connect the lateral and medial corners of the first metatarsal head, superiorly and inferiorly. A third line is then drawn that bisects both the first and the second line. An angle created between the bisecting line, and a line perpendicular to a horizontal reference, quantifies the amount of M1 rotation present.[15] Schematics for both methods are demonstrated in Figure 3. Following initial measurement, observers A and B both waited a minimum of 4 weeks to experience washout, after which they repeated measurements on half of their respective cohorts to assess for intraobserver reliability.

Mean values and associated distribution of M1 rotation including SDs, 95% confidence intervals (CIs), and ranges were reported for each measurement method. Pronation was defined as positive rotation, where supination was negative.

Intraclass correlation coefficients (ICCs) quantified inter- and intraobserver reliability. The Shapiro-Wilk test and Smirnov-Kolmogorov test were performed to verify whether the data were normally distributed. The Spearman

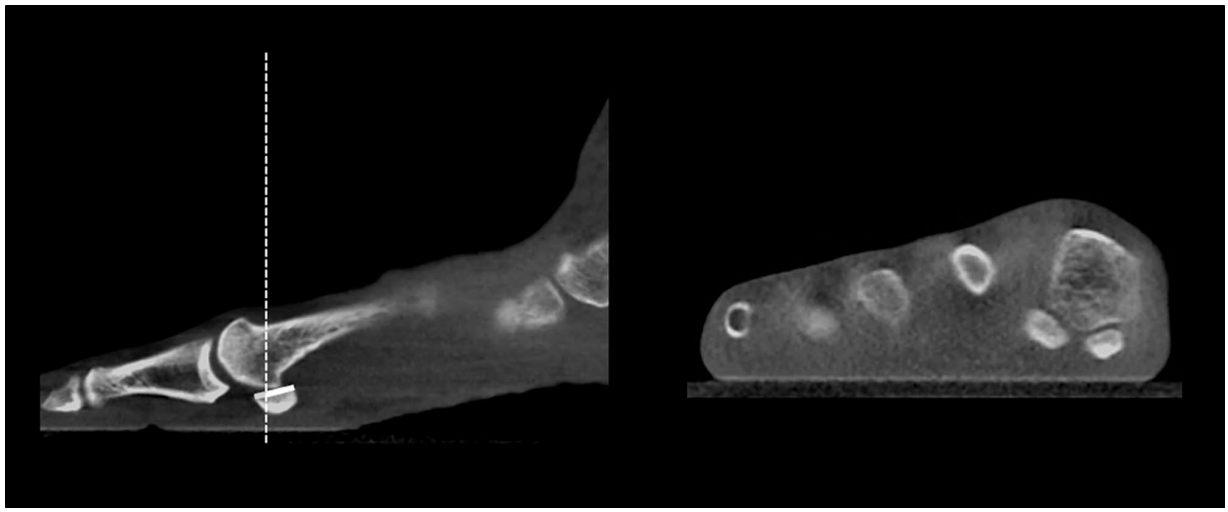

Figure 2. Weightbearing computed tomography (WBCT) sagittal view showing the greatest projection of the tibial sesamoid bone (left) and resultant coronal view (right). The superimposed solid white line indicates 75% of the dorsal length of the tibial sesamoid bone, which is estimated by the gray line. The distal end of the solid white line is approximated by the white dashed scout line, giving the standardized coronal WBCT view for rotation measurement on the right.

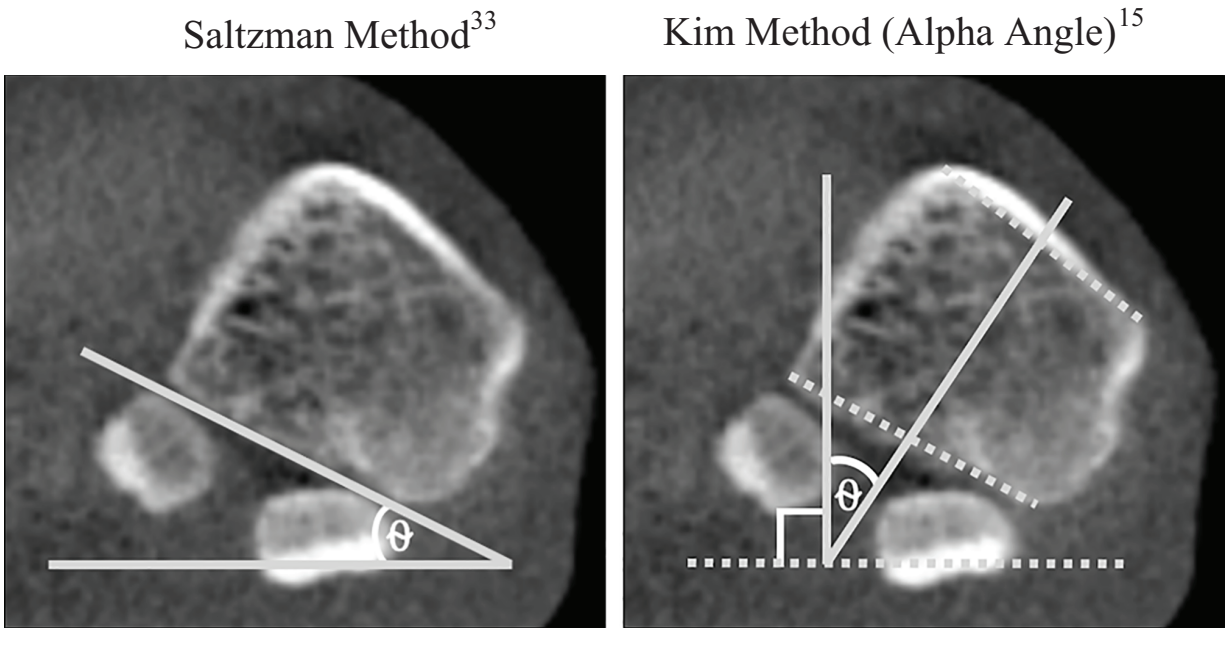

Figure 3. First metatarsal rotation measurement methods. Solid patterns indicate lines directly forming the θ angle. Dotted patterns indicate references drawn to guide solid lines. (θ angle of interest: quantification of first metatarsal rotation.)

rank and Pearson correlation coefficients were used to assess the linear dependence between data that were not normally, and normally, distributed, respectively. An unpaired *t* test and analysis of variance were used for comparison of normally distributed data. A P value $<.05$ was considered significant in all tests. All data were

Table 1. Descriptive Summary of Baseline Demographic and Imaging Information.[a]

Variable	Amount
Total patients/feet, n	59/62
Demographic information	
Age, y	46.8 ± 18.5 (18-86)
Male/female	33/29
Body mass index	28.3 ± 4.5 (18.1-34.7)
Right/left	29/33
Clinical imaging information	
Patient chief complaint	
Ankle pain	56 (90.3)
Midfoot pain	6 (9.7)
Indication for WBCT and WBPR	
Tibiotalar OA	24 (38.7)
Subtalar OA	13 (21.0)
Midfoot OA	4 (6.5)
Other	21 (33.9)
Time between WBCT and WBPR, d	14.4 ± 15.5 (0-72)

Abbreviations: OA, osteoarthritis; WBCT, weightbearing computed tomography; WBPR, weightbearing plain radiograph.
[a]Values are reported as mean ± 1 SD (range) or counts (percentage of total).

Table 2. Imaging Parameter Values of Included Patients.[a]

Variable	Value
Calcaneal moment arm, mm	6.5 ± 3.5 (0.0-12.3)
Intermetatarsal angle, degrees	7.3 ± 1.4 (3.0-9.0)
Hallux valgus angle, degrees	8.1 ± 3.0 (1.0-15.0)
Hallux interphalangeal angle, degrees	7.8 ± 2.1 (1.0-10.0)
Meary angle, degrees	181.5 ± 2.8 (176.0-184.0)
First metatarsal lateral head round sign[26]	
Angular (A) type	46 (74.2)
Intermediate (I) type	12 (9.4)
Round (R) type	4 (6.5)
First metatarsophalangeal joint degeneration[13]	
Grade 0	40 (64.5)
Grade I	21 (33.9)
Grade II	1 (1.6)
Grade III or V	0 (0)
Sesamoid wear[45]	
Grade A	41 (66.5)
Grade B	21 (33.9)
Grade C or D	0 (0)
Sesamoid position[48]	
Grade 0	57 (91.9)
Grade I	5 (8.1)
Grade II or III	0 (0)

[a]Values are reported as mean ± 1 SD (range) or counts (percentage of total).

analyzed using IBM SPSS Statistics, version 26.0 (IBM, Armonk, NY).

Results

Baseline patient characteristics and imaging information of 59 included patients and 62 feet are described in Table 1. The most common chief complaint of the patient cohort was "Ankle Pain"; subsequently, the most common indication for ordering plain films and advanced imaging was for "tibiotalar osteoarthritis" (Table 1). Radiographic and computed tomographic characterization of the feet within the cohort can be viewed in Table 2. All feet were within the specified parameter ranges necessary for inclusion. Additionally, the majority of inclusions demonstrated angled lateral heads, no present signs of osteoarthritis, and normal sesamoid wear and position.

Mean M1 rotation was found to be 2.1 degrees pronated (SD 4.9, 95% CI 0.9-3.4) as measured by the Saltzman et al[33] method, and 6.1 degrees pronated (SD 6.6, 95% CI 4.4-7.8) as measured by the Kim et al[15] method (Table 3). A correlation coefficient of 0.774 ($P < .001$) was also found among these 2 measurement methods. All ICC values were interpreted as excellent agreement (Table 3).[11,22] Additional findings included a low positive correlation between the intermetatarsal angle and M1 axial rotation for both the Saltzman et al[33] (0.448, $P < .001$) and Kim et al[15] (0.405, $P = .001$) methods. Additionally, a negligible, negative correlation was found between the Meary angle and the Saltzman et al[33] method rotational angle (0.289, $P = .023$).[4,25]

Lastly, a significant difference in mean M1 rotation was found between the subgroup of feet with an angular lateral M1 edge (n = 46) and the subgroup of feet with an intermediate or round lateral M1 edge (n = 16). Using the Saltzman et al[33] method, the mean values for the angled subgroup and intermediate/round subgroup were 1.1 and 5.1 degrees, respectively ($P = .004$). For the Kim et al[15] method, these mean values were 4.7 and 10.1 degrees ($P = .005$). No other significant correlations between M1 axial rotation and demographic or imaging parameters were found. Notably there was no significant correlation between M1 rotation and patient age (Saltzman et al[33] method, $P = .413$; Kim et al[15] method, $P = .961$).

Discussion

This study reports the mean and associated distribution of M1 axial rotation in nonpathologic feet in the general population using the Saltzman et al[33] and Kim et al[15] methods on WBCT. The 95% CIs demonstrate that mean normative M1 rotation lies slightly pronated, rather than parallel to a ground reference (Figure 4). However, the relatively wide ranges reported with both methods suggest significant natural variability in M1 rotation,[19] even among feet without

Table 3. First Metatarsal Rotation Values and Reliability Coefficients.

	Saltzman et al[33] Method	Kim et al[15] Method (Alpha Angle)
Mean rotation ± SD, degrees	2.1 ± 4.9	6.1 ± 6.6
95% confidence interval, degrees	0.9-3.4	4.4-7.8
Range,[a] degrees	–7.5 to 15.5	–9.0 to 24.0
Interobserver ICC	0.983[b]	0.977[b]
Intraobserver ICC	0.998/0.991[b,c]	0.988/0.997[b,c]

Abbreviation: ICC, intraclass correlation coefficient.; SD, standard deviation
[a]Negative values represent a supinated first metatarsal.
[b]Interpreted as excellent agreement.[11]
[c]Observers A/B.

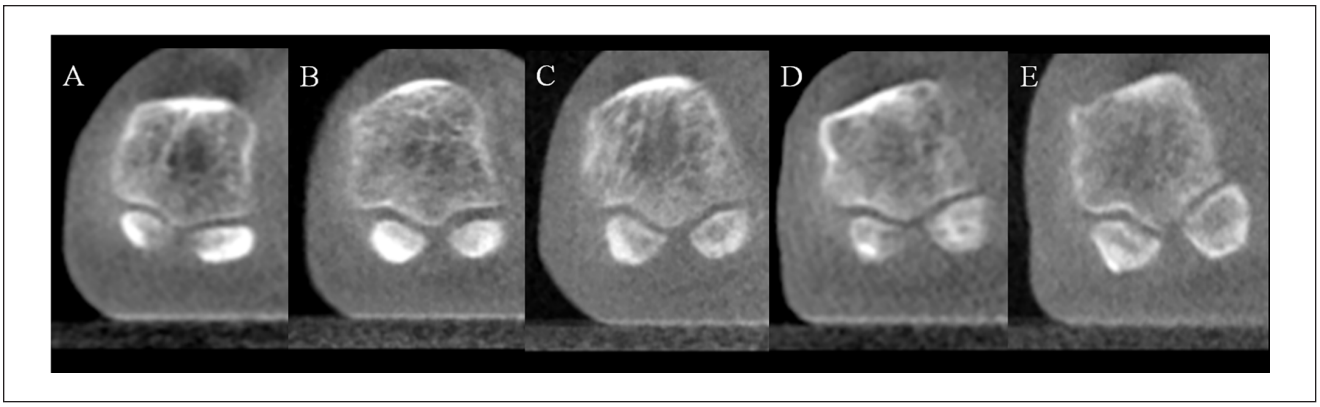

Figure 4. Distribution of first metatarsal (M1) rotation. (A) Slightly supinated, (B) largely parallel to the ground, (C) slightly pronated (closest approximate to cohort mean value), (D) slightly greater pronation, (E) moderate pronation. An appreciable difference of first metatarsal dorsal head morphology is also noted; this morphology is accounted for the Kim method.

clinical/radiographic deformity. Additionally, this study showed that measuring the M1 head lateral edge shape can also give clinicians an estimate of M1 rotation using anteroposterior (AP) radiographs.

The results of our current investigation can be compared to those reported in each respective control group involved with the original studies that proposed the Saltzman et al[33] and Kim et al[15] methods. For their control cohort of 30 patients, Saltzman et al[33] reported, with high reliability, a mean M1 pronation of 1.6 degrees and an SD of 9.8 degrees. This is comparable to the mean value of 2.1 degrees and SD of 4.9 degrees measured in the current investigation with a larger cohort size. Conversely, Kim et al,[15] in their control group of 19 patients, reported a mean M1 pronation of 13.8 degrees and an SD of 4.1 degrees. This mean value is noticeably greater than that of the current investigation. The results of our study may differ from these previously reported measures for many conceivable reasons. First, the Saltzman et al[33] method was initially proposed using WBPR, and the Kim et al[15] method with simulated WBCT, where our study utilized standing cone-beam WBCT images. The difference in imaging modality may have altered the perspective angle and subsequent measurements thereof. In fact, Kim et al[15] describes their common coronal CT view as one that is perpendicular to the longitudinal bisection of the third metatarsal, which is different from the plane used in our study, which was first metatarsosesamoid reference based.[15] Additionally, the inclusion and exclusion criteria applied to our cohort was relatively more strict than what was described by either method's text. Saltzman et al[33] defines their control patients as having no first ray complaints, clinically, and no apparent radiographic deviation of the first metatarsophalangeal joint. Kim et al[15] describes their control group, consisting solely of women, as not having HV deformity, without any further description. Although we found some differences between our and the published initial values, literature supports the use of standing cone-beam WBCT in the measurement of M1 axial rotation in the future as this technology combines true weightbearing with the precision of 3-dimensional measurement.[3,5,8,30,31] Therefore, it is the belief of the authors that these reliable, replicable, adapted versions of the Saltzman et al[33] and Kim et al[15] methods for standing WBCT, and associated reported values, should be used to guide future research and clinical practice related to M1 rotation.

Ultimately, the goal of this study is to assist surgeons in understanding what "normal" rotation is if they decide to derotate the M1. Although there is high correlation between the Saltzman et al[33] and Kim et al[15] methods,[11] the actual mean numbers and distributions are different. A key operative question is which of these mean/distributions to use and why. For several reasons we favor the use of the Saltzman et al[33] method. First, the distribution of rotational values is more precise with the Saltzman et al[33] method. Second, the measure is simpler, and, in general, simpler generally leads to more reliability. Notably, in this study, both measures were very reliable; however, this is in the setting of a controlled experiment with 2 experienced observers spending time together to ensure similar protocol. This is a condition that is unlikely to be generalizable to practice where we would expect more variation in measurement, so we prefer the simpler of the 2 approaches requiring 2 rather than 4 lines to be drawn. Additionally, the Kim et al[15] method requires consideration of the morphology of the dorsal aspect of the M1 head, which is not relevant to understanding the pathomechanics of the metatarso-sesamoid articulation.

Irrespective of the chosen measurement method, these results have operative considerations. The severity of measured axial malrotation in comparison to "normal" could guide a surgeon to choose a corrective procedure with derotational capabilities vs one that provides translational correction only. If derotation is indicated, numerous techniques have been developed to correct this deformity. These operations include a combination of novel derotational techniques such as the Proximal Oblique Sliding Closing Wedge Osteotomy[41] and the Proximal Rotational Metatarsal Osteotomy[44] as well as modifications of existing procedures such as the Lapidus procedure[6] and Scarf[39] osteotomy, among others.[18,28,32,38,42,47] Understanding the severity of a patient's first metatarsal malrotation compared with physiologic rotation may guide a surgeon to use a technique with more/less derotational power, depending on the deformity. Although the 95% CIs associated with the mean M1 rotation values found using both measurement methods were relatively precise, the ranges associated with our results remain large. Thus, "normal" M1 rotation for a patient who has unilateral forefoot pathology may best be specified within this range by acquiring a preoperative bilateral WBCT to allow for assessment of rotation in the unaffected contralateral M1. Although most nonpathologic forefeet should demonstrate an M1 that is slightly pronated, some patients may have asymptomatic moderate M1 pronation, and their affected foot may be corrected with a goal of matching the contralateral rotation. In cases of bilateral pronated hallux valgus, the authors recommend correcting rotation as close to the mean values reported in this study as possible.

This study has limitations that should be considered when interpreting the findings. First, this investigation assessed patient electronic health records retrospectively. Each evaluated WBCT and WBPR was indicated as a result of some sort of foot and ankle condition not related to the forefoot. This adjacent pathology may have affected our results. A prospective study that collected WBCT and WBPR of patients presenting without foot and ankle problems and without any clinically recognizable deformity could be the standard. However, it may be of limited benefit given this study's current strict exclusion criteria and would expose asymptomatic subjects to unnecessary radiation. Second, the mean rotation values measured in this study used only the Saltzman et al[33] method and Kim et al[15] methods and cannot be generalized to other methods that have been proposed in literature.

This study has established the normative values for the distribution of first metatarsal rotation using the Saltzman et al[33] and Kim et al[15] methods with coronal view imaging on weightbearing computed tomography. These values should be used to guide future research and correction of M1 rotation.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Alexej Barg, MD, reports other from WBCT Society, personal fees from Medartis, other from Springer Publishing, outside the submitted work. Charles L. Saltzman, MD, reports being the Editor-In-Chief of Foot & Ankle International. ICMJE forms for all authors are available online.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Jesse Steadman, BS, https://orcid.org/0000-0002-1798-9367
Richard Leake, MD, https://orcid.org/0000-0002-1806-8543
Alexej Barg, MD, https://orcid.org/0000-0003-0682-1961

References

1. Barg A, Harmer JR, Presson AP, Zhang C, Lackey M, Saltzman CL. Unfavorable outcomes following surgical treatment of hallux valgus deformity: a systematic literature review. *J Bone Joint Surg Am*. 2018;100(18):1563-1573.
2. Biz C, Crimì A, Fantoni I, Tagliapietra J, Ruggieri P. Functional and radiographic outcomes of minimally invasive intramedullary nail device (MIIND) for moderate to severe hallux valgus. *Foot Ankle Int*. Published online December 15, 2020. doi:10.1177/1071100720969676.
3. Campbell B, Miller MC, Williams L, Conti SF. Pilot study of a 3-dimensional method for analysis of pronation of the first metatarsal of hallux valgus patients. *Foot Ankle Int*. 2018;39(12):1449-1456.
4. Clarke GM, Cooke D. *A Basic Course in Statistics*. New York, NY: John Wiley; 2005.

5. Collan L, Kankare JA, Mattila K. The biomechanics of the first metatarsal bone in hallux valgus: a preliminary study utilizing a weight bearing extremity CT. *Foot Ankle Surg*. 2013;19(3):155-161.
6. Conti MS, Willett JF, Garfinkel JH, et al. Effect of the modified lapidus procedure on pronation of the first ray in hallux valgus. *Foot Ankle Int*. 2020;41(2):125-132.
7. Coughlin MJ, Saltzman CL, Anderson RB. *Mann's Surgery of the Foot and Ankle*. Philadelphia, PA: Saunders; 2014.
8. Cruz EP, Wagner FV, Henning C, Sanhudo JAV, Pagnussato F, Galia CR. Does hallux valgus exhibit a deformity inherent to the first metatarsal bone? *J Foot Ankle Surg*. 2019;58(6):1210-1214.
9. Easley ME, Trnka HJ. Current concepts review: hallux valgus part II: operative treatment. *Foot Ankle Int*. 2007;28(6):748-758.
10. Eustace S, O'Byrne J, Stack J, Stephens MM. Radiographic features that enable assessment of first metatarsal rotation: the role of pronation in hallux valgus. *Skeletal Radiol*. 1993;22(3):153-156.
11. Fleiss JL. *Statistical Methods for Rates and Proportions*. New York, NY: John Wiley; 1981.
12. Grode SE, McCarthy DJ. The anatomical implications of hallux abducto valgus: a cryomicrotomy study. *J Am Podiatry Assoc*. 1980;70(11):539-551.
13. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. *Ann Rheum Dis*. 1957;16(4):494-502.
14. Kilmartin TE, O'Kane C. Combined rotation scarf and Akin osteotomies for hallux valgus: a patient focussed 9 year follow up of 50 patients. *J Foot Ankle Res*. 2010;3:2.
15. Kim Y, Kim JS, Young KW, Naraghi R, Cho HK, Lee SY. A new measure of tibial sesamoid position in hallux valgus in relation to the coronal rotation of the first metatarsal in CT scans. *Foot Ankle Int*. 2015;36(8):944-952.
16. Langan TM, Greschner JM, Brandão RA, Goss DA Jr, Smith CN, Hyer CF. Maintenance of correction of the modified lapidus procedure with a first metatarsal to intermediate cuneiform cross-screw technique. *Foot Ankle Int*. 2020;41(4):428-436.
17. Lucattelli G, Catani O, Sergio F, Cipollaro L, Maffulli N. Preliminary experience with a minimally invasive technique for hallux valgus correction with no fixation. *Foot Ankle Int*. 2020;41(1):37-43.
18. Lucijanic I, Bicanic G, Sonicki Z, Mirkovic M, Pecina M. Treatment of hallux valgus with three-dimensional modification of Mitchell's osteotomy: technique and results. *J Am Podiatr Med Assoc*. 2009;99:162-172.
19. Mahmoud K, Metikala S, Mehta SD, Fryhofer GW, Farber DC, Prat D. The role of weightbearing computed tomography scan in hallux valgus. *Foot Ankle Int*. 2021;42(3):287-293.
20. Maldin RA. Axial rotation of the first metatarsal as a factor in hallux valgus. *J Am Podiatry Assoc*. 1972;62:85-93.
21. Matthews M, Klein E, Youssef A, Weil L Jr, Sorensen M, Weil LS Sr, Fleischer A. Correlation of radiographic measurements with patient-centered outcomes in hallux valgus surgery. *Foot Ankle Int*. 2018;39(12):1416-1422.
22. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Med (Zagreb)*. 2012;22(3):276-282.
23. Meary R. On the measurement of the ankle between the talus and the first metatarsal. *Rev Chir Orthop*. 1967;53(1):389-391.
24. Mizuno S, Sima Y, Yamaxaki K. Detorsion osteotomy of the first metatarsal bone in hallux valgus. *J Jpn Orthop Assoc*. 1956;30:813-819.
25. Mukaka MM. Statistics corner: a guide to appropriate use of correlation coefficient in medical research. *Malawi Med J*. 2012;24(3):69-71.
26. Okuda R, Kinoshita M, Yasuda T, et al. The shape of the lateral edge of the first metatarsal head as a risk factor for recurrence of hallux valgus. *J Bone Joint Surg Am*. 2007;89(10):2163-2172.
27. Okuda R, Kinoshita M, Yasuda T, Jotoku T, Shima H, Takamura M. Hallux valgus angle as a predictor of recurrence following proximal metatarsal osteotomy. *J Orthop Sci*. 2011;16(6):760-764.
28. Okuda R, Yasuda T, Jotoku T, Shima H. Supination stress of the great toe for assessing intraoperative correction of hallux valgus. *J Orthop Sci*. 2012;17(2):129-135.
29. Orthopaedic Foot and Ankle Society Ad Hoc Committee Report, January 1996. *Foot Ankle Int*. 1997;18(5):310-311.
30. Ota T, Nagura T, Kokubo T, et al. Etiological factors in hallux valgus, a three-dimensional analysis of the first metatarsal. *J Foot Ankle Res*. 2017;10:43.
31. Ota T, Nagura T, Yamada Y, et al. Effect of natural full weight-bearing during standing on the rotation of the first metatarsal bone. *Clin Anat*. 2019;32(5):715-721.
32. Prado M, Baumfeld T, Nery C, Mendes A, Baumfeld D. Rotational biplanar Chevron osteotomy. *Foot Ankle Surg*. 2020;26:473-476.
33. Saltzman CL, Brandser EA, Anderson CM, Berbaum KS, Brown TD. Coronal plane rotation of the first metatarsal. *Foot Ankle Int*. 1996;17(3):157-161.
34. Saltzman CL, El-Khoury GY. The hindfoot alignment view. *Foot Ankle Int*. 1995;16(9):572-576.
35. Scheele CB, Christel ST, Fröhlich I, et al. A cone beam CT based 3D-assessment of bony forefoot geometry after modified Lapidus arthrodesis. *Foot Ankle Surg*. 2020;26(8):883-889.
36. Schilde S, Delank KS, Arbab D, Gutteck N. Minimally invasive vs open akin osteotomy. *Foot Ankle Int*. 2021;42(3):278-286.
37. Scranton PE Jr, Rutkowski R. Anatomic variations in the first ray: part I. Anatomic aspects related to bunion surgery. *Clin Orthop Relat Res*. 1980;151:244-255.
38. Seki H, Suda Y, Takeshima K, et al. Minimally invasive distal linear metatarsal osteotomy combined with selective release of lateral soft tissue for severe hallux valgus. *J Orthop Sci*. 2018;23:557-564.
39. Swanton E, Mason L, Molloy A. How do I use the scarf osteotomy to rotate the metatarsal and correct the deformity in three dimensions? *Foot Ankle Clin*. 2018;23:239-246.

40. Talbot KD, Saltzman CL. Assessing sesamoid subluxation: how good is the AP radiograph? *Foot Ankle Int*. 1998;19(8):547-554.
41. Wagner E, Ortiz C, Gould JS, et al. Proximal oblique sliding closing wedge osteotomy for hallux valgus. *Foot Ankle Int*. 2013;34(11):1493-1500.
42. Wagner E, Ortiz C, Wagner P. Using the center of rotation of angulation concept in hallux valgus correction: why do we choose the proximal oblique sliding closing wedge osteotomy? *Foot Ankle Clin*. 2018;23(2):247-256.
43. Wagner E, Wagner P. Metatarsal pronation in hallux valgus deformity: a review. *J Am Acad Orthop Surg Glob Res Rev*. 2020;4(6):e20.00091.
44. Wagner P, Wagner E. The use of a triplanar metatarsal rotational osteotomy to correct hallux valgus deformities. *JBJS Essent Surg Tech*. 2019;9:e43.1-2.
45. Welck MJ, Singh D, Cullen N, Goldberg A. Evaluation of the 1st metatarso-sesamoid joint using standing CT—the Stanmore classification. *Foot Ankle Surg*. 2018;24(4):314-319.
46. Wu DY, Lam EKF. Radiological evaluation of a preoperative first metatarsal realignment test for metatarsus primus varus and hallux valgus correction by the syndesmosis procedure. *Foot Ankle Int*. 2020;41(3):342-349.
47. Yasuda T, Okuda R, Jotoku T, Shima H, Hida T, Neo M. Proximal supination osteotomy of the first metatarsal for hallux valgus. *Foot Ankle Int*. 2015;36(6):696-704.
48. Yildirim Y, Cabukoglu C, Erol B, Esemenli T. Effect of metatarsophalangeal joint position on the reliability of the tangential sesamoid view in determining sesamoid position. *Foot Ankle Int*. 2005;26(3):247-250.