Radiographic Image Distortion Between the Distal Edge of the First Metatarsal and the Tibial Sesamoid

Establishing a Reliable Radiographic Relationship

Michael Durrant, DPM, MPH*
Tucker McElroy, PhD†

Background: After failing to statistically confirm a perceived pattern noted on radiographs that the sesamoids were proximally positioned in patients with hallux limitus compared with a control population without evidence of the deformity, the probable causes of this failure were examined. Measurement error was briefly considered but rejected owing to the careful manner in which the measurements were taken. The most plausible explanations were that the observations were incorrect and that the radiographs, which were retrospectively analyzed, were taken in a manner that distorted the spatial relationships between the metatarsal and the tibial sesamoid to a point that the results did not reflect reality.

Methods: This study examines potential difficulties in obtaining consistently reliable radiographic data regarding the spatial relationships of the metatarsal and the tibial sesamoid and establishes guidelines to minimize experimental error. Criteria for measuring metatarsal sesamoidal distances to the radiographic plate are established, along with application of the criteria to a control population. The principle of radiographic image distortion as it relates to these objects is presented, and, based on a predetermined range of radiographic angles, radiographic image distortion is calculated for the metatarsal head and the tibial sesamoid separately.

Results: By using accepted trigonometric principles, a mathematical model is developed that makes it possible to collectively quantify image shift between the two objects.

Conclusions: Criteria are established that, if followed, should minimize image distortion when it is important to measure metatarsal sesamoidal distances. (J Am Podiatr Med Assoc 100(1): 1-9, 2010)

Morton[1] believed that proximal or posteriorly positioned sesamoids cause dysfunction in the metatarsophalangeal joint; more recently, Roukis et al,[2] Camasta,[3] and Prieskorn et al[4] reported observations that link proximally positioned sesamoids to hallux limitus deformities. Harris and Beath,[5] Hetherington et al,[6] Munuera et al,[7] and Prieskorn et al[4] measured metatarsal sesamoidal distances, but the study by Roukis et al[2] seems to be the only published study that examined the relationship between proximally positioned sesamoids and hallux limitus; they concluded that the sesamoids were positioned slightly proximal in hallux limitus. In an unpublished paper written in 1996, one of us (M.D.), Richard Bogdan, DPM, and Shelley Bogdan unsuccessfully attempted to demonstrate this pattern. Using radiographic measurement criteria established by Hetherington et al[6] and Prieskorn et al,[4] sesamoid distances in 60 patients with hallux limitus were compared to a control population of 122 patients without the deformity. Although the results demonstrated that both sesamoids were collectively positioned slightly more than 1 mm proximal in the cohort with hallux limitus, this hypothesis could not be proved because of significant overlap between the two groups. It was this failure, in part, and that of other researchers (Roukis et al,[2] Camasta,[3] Prieskorn et al,[4] and Munuera et al[7]) to unequivocally link proximally positioned sesamoids to

*Private practice, Redlands, CA; Borrego Community Health Foundation, Thermal, CA.

†University of California, San Diego, San Diego, CA; United States Census Bureau, Washington, DC.

Corresponding author: Michael Durrant, DPM, MPH, 16 E Fern Ave, Ste B, Redlands, CA 92373. (E-mail: Durrant .michael@gmail.com)

hallux limitus that precipitated the present examination into the potential adverse effects that radiographic image distortion may have had on the collective results.

Roukis et al[2] and Coughlin[8] noted the scarcity of metatarsal sesamoidal motion studies in the published record, and fundamental to a basic understanding of these kinematic relationships is an ability to accurately quantify their spatial relationships. These two objects (the metatarsal and the tibial sesamoid) were selected because of their perceived critical role in first metatarsophalangeal joint functionality, and they are part of specific criteria established by Homberger[9] and Lauder[10] when functional morphological features are being used as a tool. Potential difficulties in attempting to establish consistently reliable data between the first metatarsal and the tibial sesamoid are initially examined, followed by analysis of the principle of radiographic image distortion as it relates to these structures. Criteria for measuring metatarsal sesamoidal distances to the radiographic plate are established, along with application of the criteria to a control population. By using established trigonometric principles, a mathematical model is developed to quantify image shift of both structures relative to the radiographic plate. The results of the measurements are then analyzed to determine the degree to which their relationships can be expressed statistically and whether the current method of taking radiographs angled 15° from perpendicular permits sufficiently accurate spatial analysis between the metatarsal head and the tibial sesamoid.

Factors that Influence Radiographic Image Distortion

The adverse effects that changes in foot position and radiographic image distortion can have on resultant radiographic images are well documented. Venning and Hardy[11] were the first investigators, to our knowledge, to examine the sources and effects of radiographic image distortion in the foot. Hlavac[12] and later Bryant et al[13] examined the effects of foot position and image distortion, and Tanaka et al[14] observed that minor variations in foot position affected the resultant radiographic image at the metatarsocuneiform joint.[15] Condon et al[16] demonstrated a 1.5° increase in intermetatarsal angles when the foot was placed firmly versus lightly against the radiographic plate, and Fuhrmann et al[17] noted similar geometric changes in the forefoot with weightbearing on radiography.

Camasta et al[18] quantified the effects of magnification on images. Bryant et al[19] examined the effects of image distortion when examining hallux valgus angles. Robinson et al[20] noted changes in the distal metatarsal articular angle with increased metatarsal declination angles; even more significant variability was observed with axial plane metatarsal rotation. Additionally, they extrapolated that axial plane positions of the metatarsal could change the distal metatarsal articular angle 1.31° for every 5° of metatarsal rotation. Because we are referencing the distal aspect of the metatarsal, with its relative spherical surface, as opposed to contralateral borders of the metatarsal head (and proximal phalange), which are known to exhibit morphological asymmetry, it is likely that differing axial plane metatarsal positions would have less of an influence on image reproducibility in the selected objects. In constructs with a very high degree of axial plane eversion with concurrent sesamoid subluxation, standard dorsoplantar radiographs may not be reliable because the fibular sesamoid is likely to be more dorsally rotated and, thus, positioned further from the radiographic plate than the tibial sesamoid. Weijers et al[21] noted that image distortion increased as the angles between the first and second metatarsals also increased. In an in vivo study ($N = 10$), they used a three-dimensional apparatus to demonstrate that there was minimal distortion with intermetatarsal angles of 10° or less but that greater angles resulted in up to 1.5° of distortion when the foot was placed firmly versus lightly against the radiographic plate.

Shereff et al[22] examined radiographic changes in nonweightbearing and weightbearing positions in 20 normal feet and 30 with hallux valgus. They found that forefoot width increased 90% of the time in normal feet and 96% of the time in hallux valgus feet. Shereff et al[22] theorized that with weightbearing, the bones move relatively closer to the radiographic plate, which would decrease the distortion shadow. Conversely, because the bones deviate from their original plane to one more parallel to the cassette, their length would similarly increase.[22]

Variation in distance between the radiographic source and the two objects (the metatarsal and the tibial sesamoid) may also result in image distortion, and although this was not a focus of this investigation, the subsequent analysis seems to indicate that it is not likely to be a major problem. There are, however, anatomical factors that must be considered when attempting to establish a numeric relationship between these two structures that will reflect a population group. The variations in bone sizes associated with genetic and sex factors are obvious impediments. Munuera et al[7] addressed this issue by measuring distances based on metatarsal length, on a percentage basis, standardized to a 60-mm length. This study did not make this adjustment. Talbot and Saltzman[23] noted the unreliability of standard anteroposterior radiographs when attempting to assess true sesamoid position relative to the metatarsal head (regarding medial metatarsal drift) in a cohort study involving 60 patients; they recommended a weightbearing tangential (axial) view if it was deemed important to quantify their spatial relationships. They also noted that inaccuracies became more prevalent as the metatarsal declination angle increased, and they found a significant relationship between distal articular set angles and axial plane positions of the metatarsal head.[23] Open epiphyseal plates and incomplete ossification of the sesamoids make measurements before adulthood meaningless. Enthesiopathic changes in and around the joint in geriatric patients increase measurement errors. Additionally, the depth and morphological features of each groove and each sesamoid location in its respective groove may adversely affect image duplication accuracy; again, the present investigation did not address these issues. With age and certain metabolic disorders, it is possible to have a loss of intrinsic musculature and plantar fat pad, thus placing each of these bones closer to the radiographic plate, as noted by Klaue et al.[24]

It has been a long-standing and widely accepted practice to angle the radiographic beam 15° from perpendicular when performing dorsoplantar radiographs.[6, 15, 25] Because the approximate declination angle of a normal weightbearing forefoot is assumed to be approximately 15°, angling the radiographic beam so that it is perpendicular to the metatarsals minimizes foreshortening.[26, 27] In a first metatarsal with a high declination angle (typically associated with a high-arched foot type), a radiographic beam angled 15° from vertical intersects a slightly more dorsal portion of the metatarsal rather than its most distal point. In a foot type in which the first metatarsal has a relatively low declination angle (flatfoot deformity or metatarsus elevatus), the radiographic beam intersects a more plantar portion of the first metatarsal head rather than its most distal edge. Each of these situations can have an adverse effect on accurate image duplication shift when attempting to establish sample population parameters. Individually and collectively, the first metatarsal and the tibial sesamoid must demonstrate consistency in their relationship, otherwise it may not be possible to establish parameters that can be applied to a population to permit meaningful analysis and conclusions.

Principle of Radiographic Image Distortion of the First Metatarsal Head and the Tibial Sesamoid

By definition, radiographic image distortion is the misrepresentation of the size, shape, or positional relationship of objects being evaluated.[11] Angular variations between the radiographic source and an object, or changes in angle or distance between an object and the radiographic plate, cause an image shift.[11, 26, 27] If the distance between an object and its shadow is changed without varying the angle between them, the length of the shadow image will be inversely proportional to the distance between the object and its radiographic source.[11, 26, 27] Known as the *inverse square law*, it also states that the intensity of radiation is inversely proportional to the square of the distance.[11, 26, 27]

Christman et al[28] determined that lateral radiographs of the foot were not immune from the effects of radiographic image distortion; with a sectional grid superimposed on a lateral foot radiograph, they determined that image distortion could occur at the margins of the grid. Because the metatarsal head and the sesamoids are positioned comparatively close to the radiographic plate and are likely to be positioned perpendicular to the beam originating from the radiographic tube, we believe that as a result of the inverse square law, as long as the radiographic source is positioned a sufficient distance from the object, negligible image distortion should result from the radiographic source. Additionally, a radiographic beam with width and parallel rays creates the image, not a single point; this further minimizes image shift that can result from the distance between the radiographic source and the object. Of most concern are distance and angular changes from the distal aspect of the first metatarsal and the sesamoid to the radiographic plate.

Method for Measuring the Metatarsal Sesamoidal Relationship

Because the structures are relatively small and their spatial relationships are very small, any method of measuring them must be accurate, verifiable, and easily duplicated. The best radiographic view for evaluating sesamoid spatial relationships to the first metatarsal head is the dorsoplantar view. Both sesamoids are clearly visible, as is the distal aspect of the first metatarsal head, but because the sesamoids are located on a different plane relative to the radiographic plate, the reliability of this image must be of some concern.

Although distortion issues are also associated with lateral radiographic views, this is the view that most reduces image distortion of the first metatarsal head and the tibial sesamoid, provided both objects are placed adjacent to the radiographic plate and the radiographic beam is directed perpendicular to the plate. This is because the most distal aspects of the first metatarsal head and the sesamoid are fairly close to the sagittal plane bisection of the first metatarsal and, thus, are almost equal distance from the radiographic plate. These two landmarks are easily seen on a lateral radiograph and similarly can be measured without difficulty. Although this negates most image distortion, superimposition from other metatarsophalangeal joints makes measuring tibial and fibular sesamoid length, depth, and position difficult. Nevertheless, it is this lateral weightbearing radiographic view that was chosen to quantify the amount of radiographic image shift between the first metatarsal and the tibial sesamoid. Finally, for the initial analysis, we must assume that relative to the radiographic plate, fibular sesamoid position can be characterized as being similar to the tibial sesamoid in its transverse spatial position.

Criteria for Measuring Metatarsal and Sesamoid Distances

Using the longitudinal bisection of the metatarsal and sesamoid as a reference on lateral radiographs, we measured the distance from the most distal edge of the metatarsal head and the tibial sesamoid transected by an imaginary radiographic beam perpendicular to the radiographic plate in 122 selected foot radiographs of 89 patients (57 females and 32 males). Their ages ranged from 15 to 88 years. These were the only measurements performed; all of the other computations were based on a mathematical model developed later herein. The radiograph pool included only mature individuals with fully developed sesamoids and closed epiphyses, and no attempt was made to determine or make adjustments for foot size. Radiographs that demonstrated traumatic or degenerative changes of the sesamoids or first metatarsophalangeal articular surfaces, evidence of hallux valgus, or intermetatarsal angles greater than 12° were excluded. Because patients were randomly selected using the previously mentioned criteria, the randomized samples in this study probably reflected patients most likely to be encountered in office settings.

Results

In a cohort of 89 patients and 122 radiographs, all of which were deemed normal by the criteria established above, lateral weightbearing radiographs were used to measure metatarsal and sesamoid distances to the radiographic plate in each patient. Figures 1 and 2 indicate the frequency of each measured distance for the sesamoid and metatarsal.

Application of the Radiographic Image Distortion Principle to the Metatarsal and the Tibial Sesamoid

Figure 1 demonstrates an imaginary radiographic beam perpendicular to the radiographic plate tangential to the longitudinal bisection of the first metatarsal, designated M. This projected point on the radiographic plate is labeled x_m. Next, an imaginary radiographic beam was directed 15° from perpendicular, and because radiographs are not consistently taken at 15°, this imaginary 15° beam was bracketed, with one

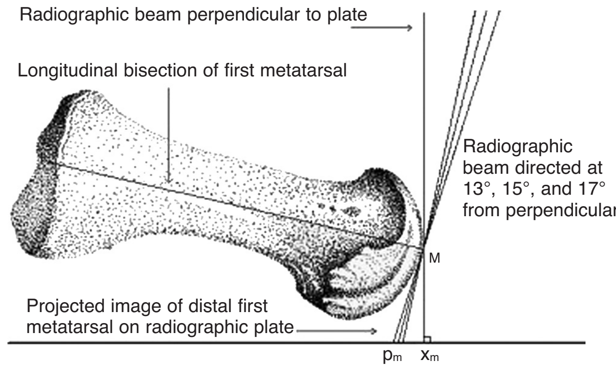

Figure 1. An imaginary radiographic beam is shown perpendicular to the radiographic plate tangential to the longitudinal bisection of the first metatarsal (M). p_m indicates the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point M; and x_m, the coordinate (measured with reference to some coordinate system) on the plate of the orthogonal projection of point M.

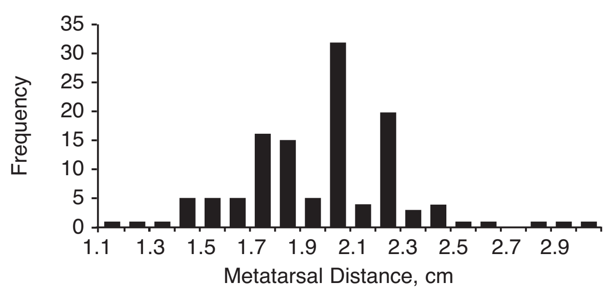

Figure 2. The metatarsal distance to the radiographic plate in all 122 radiographs.

angle directed 13° and the other 17° from perpendicular. The bracketing was done after it was determined that it was virtually impossible to visually distinguish differences between the 13° and 17° tangential points. These projected images were collectively designated p_m. The difference between points x_m and p_m is the amount of image shift or distortion resulting from a change in the angle of the radiographic beam.

Vertical Distance of the Distal Metatarsal to the Radiographic Plate

The metatarsal distance to the radiographic plate is plotted in Figure 2 using all 122 radiographs from 89 patients in the control pool. The distance ranged from 1.1 to 3.0 cm. Excluding the four values that exceeded 2.5 cm and the three that were less than 1.4 cm, the remaining 115 measured distances fell within a 1.4- to 2.4-cm range. A 1.0-cm distance separated 93% of all metatarsal distances measured.

Figure 3 demonstrates an imaginary radiographic beam perpendicular to the radiographic plate tangential to the longitudinal bisection of the tibial sesamoid, designated s. The projected image is designated x_s. Imaginary beams of 13°, 15°, and 17° pass through the same sesamoid bisection, with their projected points on the radiographic plate collectively designated p_s. The distance difference between x_s and p_s is the amount of sesamoid image shift resulting from changes in the radiographic angle.

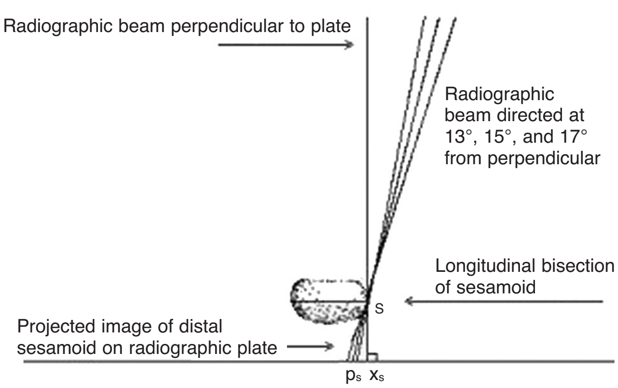

Figure 3. An imaginary radiographic beam is shown perpendicular to the radiographic plate tangential to the longitudinal bisection of the tibial sesamoid (s). p_s indicates the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point s; and x_s, the coordinate (measured with reference to some coordinate system) on the radiographic plate of the orthogonal projection of point s.

Vertical Distance of the Distal Aspect of Tibial Sesamoid to the Radiographic Plate

In Figure 4, the tibial sesamoid distance from point s to the radiographic plate is plotted using all 122 radiographs in the control pool. The distance range was 0.4 to 1.8 cm, but, excluding the six measurements that were 1.5 cm or more and the five that were less than 0.5 cm, all of the measurements fell within a range of 0.5 to 1.4 cm. One hundred eleven of all sesamoid positions measured (91%) were separated by 0.8 cm.

Distal Metatarsal Head and Sesamoid Distances to the Radiographic Plate

Figure 5 demonstrates metatarsal head image shift relative to that of the sesamoid as the angle of the radiographic beam is shifted from perpendicular. Because the tangential angle of both of these structures diminishes relative to perpendicular, the most distal aspect of the first metatarsal head, because of its greater vertical distance from the radiographic plate, shifts more proximally than the sesamoid. The result is a radiographic image in which the metatarsal will appear short with the sesamoid appearing to be closer to the distal edge of the metatarsal than it really is. The greater the vertical separation between the first metatarsal and the sesamoid, the closer these objects appear relative to each other. Additionally, because the lesser metatarsals may occupy a transverse plane closer to that of sesamoids rather than the first metatarsal, true anatomical first metatarsal length may be longer than its projected image relative to the lesser metatarsals. It is this unequal image projection between the distal edge of the first metatarsal and the sesamoid that determines whether the true anatomical relationship between these structures can be quantified with radiographic analysis.

Figure 6 plots metatarsal and tibial sesamoid distances to the radiographic plate. A positive correla-

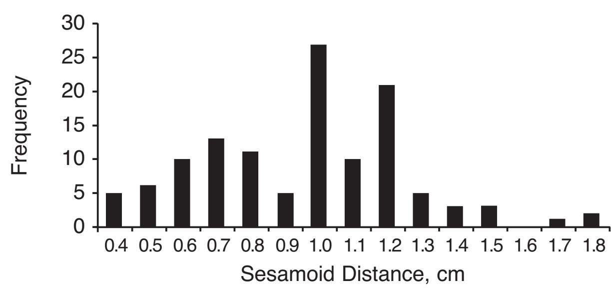

Figure 4. The sesamoid distance to the radiographic plate in all 122 radiographs.

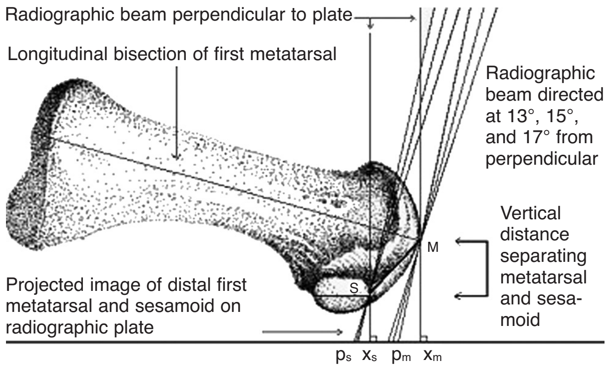

Figure 5. Metatarsal head image shift relative to that of the sesamoid as the angle of the radiographic beam is shifted from perpendicular. p_m indicates the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point M; x_m, the coordinate (measured with reference to some coordinate system) on the plate of the orthogonal projection of point M; p_s, the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point S; and x_s, the coordinate (measured with reference to some coordinate system) on the radiographic plate of the orthogonal projection of point S.

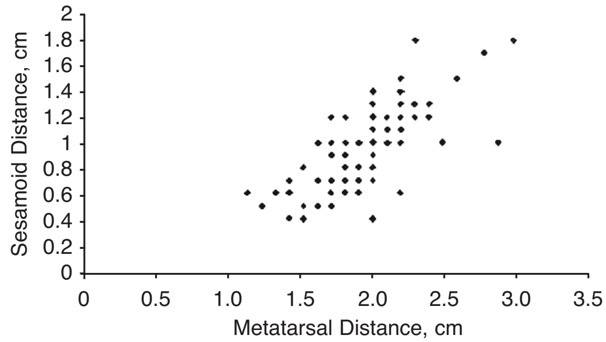

Figure 6. Distal metatarsal head and sesamoid distances to the radiographic plate in each patient.

tion (Pearson correlation coefficient of 0.73) between the distal edge of the metatarsal and the tibial sesamoid is seen (Fig. 5). This denotes a strong statistical relationship between the distal metatarsal edge and the sesamoid.

Mathematics of Metatarsal Sesamoidal Distortion

Figure 7 illustrates the distortion in measured distances caused by radiographic projection. The radiographic image of the metatarsal is projected upon an underlying radiographic plate, and the failure of the metatarsal's long axis to lie parallel to the plate is the cause of distortions in measured distances, as shown below.

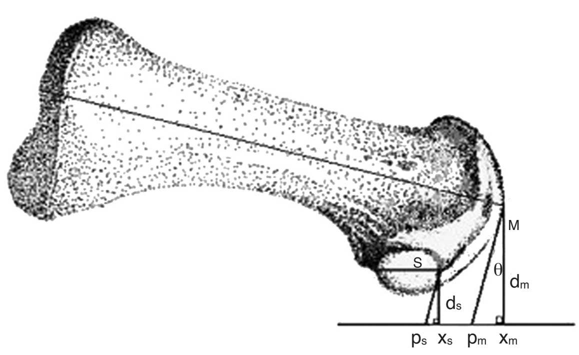

Figure 7. The mathematics of metatarsal sesamoidal distortion. See the "Mathematics of Metatarsal Sesamoidal Distortion" subsection for an explanation of abbreviations.

M denotes a point on the distal aspect of the first metatarsal longitudinal axis that the radiographic beam strikes tangentially. d_m is the perpendicular distance of the first metatarsal to the radiographic plate, measured from point M. x_m is the coordinate (measured with reference to some coordinate system) on the plate of the orthogonal projection of point M. p_m denotes the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point M. S denotes a point on the distal end of the sesamoid, through which the same radiographic beam strikes. d_s is the perpendicular distance of the sesamoid to the radiographic plate, measured from point S. x_s denotes the coordinate (measured with reference to some coordinate system) on the radiographic plate of the orthogonal projection of point S. p_s denotes the coordinate (measured with reference to some coordinate system) on the plate of the radiographic projection of point S. θ denotes the angle between the radiographic beam and the perpendicular to the plate.

Now the quantity $x_m - x_s$ (without loss of generality, let the origin of the coordinate system be such that $x_m > x_s$, so that $x_m - x_s$ represents a veritable positive distance) is simply the perpendicular projection of the distance between points M and S. On the other hand, $p_m - p_s$ is the radiographic projection of the distance between points M and S. The distortion D due to the radiographic projection is the difference between these two quantities:

$$D = (x_m - x_s) - (p_m - p_s).$$

By simple trigonometry, we have:

(1) $d_m \tan\theta = x_m - p_m$
(2) $d_s \tan\theta = x_s - p_s$

from which it follows, putting equations (1) and (2) together, that

$$D = (x_m - p_m) - (x_s - p_s) = d_m \tan\theta - d_s \tan\theta = (d_m - d_s)\tan\theta.$$

With a knowledge of θ and the orthogonal distances d_m and d_s, it is possible to compute the distortion in each case.

Table 1 is a standard trigonometric transform table demonstrating the amount of distortion, in millimeters, that occurs by changing the radiographic beam angle between 13° to 17° and varying the distance from the first metatarsal head and the sesamoid to the radiographic plate. A 13° angle distorts 0.92 mm when the object is 4 mm vertically from the flat plane of the radiographic plate and 5.52 mm when the point of intersection is 24 mm. A 17° angle will cause a shift of 1.24 mm when the object is 4 mm from the radiographic plate and 7.44 mm when it is positioned 24 mm from the plate.

Table 1. Relationship of Radiographic Angular Variation to Distance Distortion

Distance to Radiographic Plate (mm)	Radiographic Angle		
	13°	15°	17°
4	0.92	1.08	1.24
5	1.15	1.35	1.55
6	1.38	1.62	1.86
7	1.71	1.89	2.17
8	1.85	2.14	2.45
9	2.03	2.41	2.76
10	2.31	2.68	3.06
11	2.54	2.95	3.37
12	2.77	3.22	3.68
13	3.00	3.49	3.99
14	3.23	3.76	4.29
15	3.46	4.02	4.59
16	3.69	4.29	4.89
17	3.92	4.56	5.20
18	4.14	4.86	5.58
19	4.37	5.13	5.89
20	4.60	5.40	6.20
21	4.83	5.67	6.51
22	5.06	5.94	6.82
23	5.29	6.21	7.13
24	5.52	6.48	7.44

Note: Data are given as millimeters of distortion.

Statistics

For each patient, a measurement of metatarsal distortion (d_m) and tibial sesamoid distortion (d_s) was made. Although these variables are correlated, we are concerned only with their difference. For each patient we computed the distortion:

$$D = (d_m - d_s)\tan\theta.$$

This collection of measurements is denoted $x_1, x_2, \ldots x_n$ for the n patients, where x_i measures the amount of distortion secondary to radiography experienced by the *ith* patient. Because of the random sampling of patients, we will assume that the observations are identically distributed and are independent.

The distortion distribution of the sample is crucial to determining the probability that image distortion will fall within a specific range as the radiographic angle is changed. To determine the bottom 90% or 95% of the patient data values, a nonparametric (we do not assume a specific distribution, such as normal, because it is evident from Figures 2 and 4 that the data are not bell shaped; even when the data are separated for sex, it is still abnormal) approach was used, with the empirical estimates of the desired percentiles yielding the results given in Table 2.

Discussion

Image distortion, although at times small, can become significant as the radiographic angle is shifted from vertical, and the vertical distance separating the object and the radiographic plate is increased. As the vertical separation between the bisection of the sesamoid and the metatarsal increases, the image becomes more unreliable, resulting in a metatarsal head that is incorrectly projected closer to the sesamoids and, coincidentally, the lesser metatarsals. At 15° from vertical, a minimum of 3.43 mm in variation or distortion between the metatarsal and the sesamoid must be accepted to incorporate 95% of the sample and 3.21 mm to incorporate 90% of the sample. Although it is currently unclear whether a variation of 3 mm or more in position is acceptable when attempting to establish meaningful quantifiable data between these two objects, it would seem, considering the relative small distances separating the two objects, to be substantial. If anteroposterior radiographs are angled 9° from perpendicular, the distortion will be less than 2.0 mm with a 90% probability and 2.06 mm with a 95% probability.

The in vivo motion study by Hetherington et al[6] of metatarsal sesamoidal relationships in 30 patients demonstrated a 2-mm mean metatarsal excursion

Table 2. Distortion Distribution of Sample Population Based on Angular Degrees

	Angulation						
	3°	5°	7°	9°	11°	13°	15°
90th percentile	0.63	1.10	1.47	1.90	2.33	3.21	3.21
95th percentile	0.68	1.14	1.59	2.10	2.52	3.48	3.48

Note: Data are given as millimeters of distortion.

over the tibial sesamoid from its initial 15° declination position to a 90° declination angle; the sesamoidal metatarsal distance was 6 to 12 mm at 15° and 3 to 10 mm with the metatarsal elevated 90°. The small metatarsal excursion motion over each sesamoid described by Hetherington et al[6] requires highly accurate information if metatarsal sesamoidal relationships are to be correlated with a high degree of accuracy (<1 mm of distortion); to accomplish this, dorsoplantar radiographs must be taken within 4° of vertical.

Nilsonne,[29] Mayo,[30] and Simon,[31] were the first of many researchers to associate hallux limitus deformities with elongated first metatarsals and lower arches; more recently Coughlin and Mann[32] have made the same observations. Calvo et al[33] found a statistically significant relationship between first metatarsal length and hallux rigidus, and Mancuso et al[34] demonstrated a strong statistical relationship ($P < .001$) between zero-plus metatarsals and hallux valgus. It would be interesting to know the true anatomical lengths of each metatarsal in the studies that examined these relationships. Our original cohort of 60 patients with radiographic evidence of hallux limitus did not specifically differentiate metatarsal sesamoidal distances in zero-minus or zero-plus metatarsals, and we are unaware of studies that have specifically examined these spatial relationships in the context of hallux limitus. Perhaps another cohort study designed to minimize image distortion that evaluated proximally positioned sesamoids in hallux limitus deformities that involve only zero-plus metatarsals may be able to resolve with some finality whether proximally positioned sesamoids are associated with hallux limitus deformities. It would also be interesting to know whether the incidence of hallux limitus is higher in zero-plus metatarsals when both sesamoids are an equal distance from the distal edge of the metatarsal as opposed to when the tibial sesamoid is positioned closer to the distal metatarsal edge.

Precise knowledge of the true anatomical length of the first metatarsal should translate into more predictable surgical outcomes in forefoot reconstructive procedures, particularly when surgeons are contemplating multiplaned osteotomies that involve metatarsal shortening and plantarflexing.

An obvious weakness in this analysis is that it does not account for positional or torsional variations (eversion) in the metatarsal head, which are not only known to exist[1, 10, 35-40] but also have been implicated in hallux valgus deformities.[41-48] How these torsional or positional constructs affect one's ability to define these spatial relationships is currently unknown but probably should not be underestimated. From an imaging perspective, it may be possible to quantify axial plane metatarsal position and torsion by examining the first metatarsal head from a plantar tangential (axial) weightbearing perspective.

Conclusions

This analysis seems to demonstrate that as long as the metatarsal head is not excessively everted because of a positional or torsional construct it should be possible, using dorsoplantar radiographic images, to define metatarsal sesamoidal spatial relationships with a high level of accuracy.

Acknowledgment: Richard Bogdan, DPM, for his early support, assistance, and help; Shelley Bogdan for her methodical radiographic measurements; and Joan Durrant and Lara Durrant for their figures and tables.
Financial Disclosure: None reported.
Conflict of Interest: None reported.

References

1. Morton D: *The Human Foot*, p 156, Columbia University Press, New York, 1935.
2. Roukis TS, Jacobs PM, Dawson DM, et al: A prospective comparison of clinical, radiographic, and intraoperative features of hallux rigidus. J Foot Ankle Surg **61:** 76, 2002.
3. Camasta CA: Hallux limitus and hallux rigidus: clinical examination, radiographic findings, and natural history. Clin Podiatr Med Surg **13:** 423, 1996.
4. Prieskorn D, Graves SC, Smith RA: Morphometric analy-

sis of the plantar plate apparatus of the first metatarsophalangeal joint. Foot Ankle **14:** 204, 1993.
5. Harris RI, Beath T: The short first metatarsal: its incidence and clinical significance. J Bone Joint Surg Am **31:** 553, 1949.
6. Hetherington V, Carnett J, Patterson B: Motion of the first metatarsophalangeal joint. J Foot Surg **28:** 13, 1989.
7. Munuera PV, Dominguez G, Lafuente G: Length of the sesamoids and their distance from the metatarsophalangeal joint space in feet with incipient hallux limitus. JAPMA **98:** 123, 2008.
8. Coughlin MJ: Sesamoid pain: causes and surgical treatment. Instr Course Lect **39:** 23, 1990.
9. Homberger DG: Models and tests in functional morphology: the significance of description and integration. Am Zool **28:** 217, 1988.
10. Lauder GV: "On the Inference of Function from Structure," in *Functional Morphology in Vertebrate Paleontology*, ed by JJ Thomason, p 1, Cambridge University Press, Cambridge, England, 1995.
11. Venning P, Hardy RH: Sources of error on the production and measurement of standard radiographs of the foot. Br J Radiol **24:** 18, 1951.
12. Hlavac HF: Differences in x-ray findings with varied positioning of the foot. JAPA **57:** 465, 1967.
13. Bryant A, Mahoney B, Tinley P: Lateral intermetatarsal angle: a useful measurement of metatarsus primus elevatus? JAPMA **91:** 251, 2001.
14. Tanaka Y, Takakura, Y, Kumai T: Radiographic analysis of hallux valgus: a two dimensional coordinate system. J Bone Joint Surg Am **77:** 205, 1995.
15. Myerson MS: *Foot and Ankle Disorders*, Vol 1-2, p 42, WB Saunders, Philadelphia, 2000.
16. Condon F, Kaliszer M, Conhyea D, et al: The intermetatarsal angle in hallux valgus: an analysis of measurement reliability and the error involved. Foot Ankle Int **23:** 717, 2002.
17. Fuhrmann RA, Layher F, Wetzel WD: Radiographic changes in forefoot geometry with weightbearing. Foot Ankle Int **24:** 326, 2003.
18. Camasta CA, Pontious J, Boyd RB: Quantifying magnification in pedal radiographs. JAPMA **81:** 545, 1991.
19. Bryant JA, Tinley P, Singer K: A comparison of radiographic measurements in normal, hallux valgus, and hallux limitus feet. J Foot Ankle Surg **39:** 39, 2000.
20. Robinson AH, Cullen NP, Chhaya NC, et al: Variation of the distal metatarsal articular angle with axial rotation and inclination of the first metatarsal. Foot Ankle Int **27:** 1036, 2006.
21. Weijers R, Kemerink G, Mameren HV, et al: The intermetatarsal and metatarsal declination angles: geometry as a source of error. Foot Ankle Int **26:** 387, 2005.
22. Shereff MJ, Bejjani FJ, Kummer FJ: Kinematics of the first metatarsophalangeal joint. J Bone Joint Surg Am **68:** 392, 1986.
23. Talbot KD, Saltzman CL: Assessing sesamoid subluxation: how good is the AP radiograph? Foot Ankle Int **19:** 547, 1998.
24. Klaue K, Hansen S, Masquelet A: Clinical, quantitative assessment of first tarsometatarsal mobility in the sagittal plane and its relation to hallux valgus deformity. Foot Ankle Int **15:** 9, 1994.
25. Gamble FO, Yale I: *Clinical Foot Roentgenology*, p 279, Williams & Wilkins, Baltimore, 1966.
26. Weissman SD: *Radiology of the Foot*, p 9, Williams & Wilkins, Baltimore, 1983.
27. Christman RA: *Foot and Ankle Radiology*, p 50, 82-83, Churchill Livingstone (Elsevier Science), St. Louis, 2003.
28. Christman RA, Flanigan KP, Sorrento DL, et al: Radiographic analysis of metatarsus primus elevatus: a preliminary study. JAPMA **91:** 294, 2001.
29. Nilsonne H: Hallux rigidus and its treatment. Acta Orthop Scand **1:** 295, 1930.
30. Mayo CH: The surgical treatment of bunions. Ann Surg **48:** 300, 1908.
31. Simon WV: Der hallux valgus und seine chirurgic behandlung, mit besonderer berucksichtigung der ludloffschen operation. Brus Beitr Lin Chir **111:** 467, 1918.
32. Coughlin MJ, Mann R: *Surgery of the Foot and Ankle*, 7th Ed, Vol 1, p 622, Mosby, St. Louis, 1999.
33. Calvo A, Viladot R, Gine J, et al: The importance of the length of the first metatarsal and the proximal phalanx of hallux in the etiopathogeny of the hallux rigidus. Foot Ankle Surg **15:** 69, 2009.
34. Mancuso JE, Abramow SP, Landsman MJ, et al: The zero-plus first metatarsal and its relationship to bunion deformity. J Foot Ankle Surg **42:** 319, 2003.
35. Trinkaus E: Functional aspects of Neandertal pedal remains. Foot Ankle **3:** 377, 1983.
36. Drapeau MS, Harmon EH: "Metatarsal Head Torsion in Apes, Humans, and *A. Afarensis* E," in *Abstract Program of the 74th Annual Meeting of the American Association of Physical Anthropologist*, Columbus, OH, April 2008.
37. Largey A, Bonnel F, Canovas F, et al: Three-dimensional analysis of the intrinsic anatomy of the metatarsal bones. J Foot Ankle Surg **46:** 434, 2007.
38. David RD, Delagoutte JP, Renard MM: Anatomical study of the sesamoid bones of the first metatarsal. JAPMA **79:** 536, 1989.
39. Elftman H, Manter J: The evolution of the human foot, with especial reference to the joints. J Anat **70:** 56, 1935.
40. Lewis OJ: The joints of the evolving foot. Part III: the fossil evidence. J Anat **131:** 275, 1980.
41. Scranton PE Jr, Rutkowski R: Anatomic variations in the first ray: part 1. Anatomic aspects related to bunion surgery. Clin Orthop Relat Res **151:** 244, 1980.
42. Olson TR, Seidel MR: The evolutionary basis of some clinical disorders of the human foot: a comparative survey of the living primates. Foot Ankle **3:** 326, 1983.
43. de Britto SR: The first metatarso-sesamoid joint. Int Orthop **6:** 61, 1982.
44. Yoshioka Y, Siu DW, Cooke DV, et al: Geometry of the first metatarsophalangeal joint. J Orthop Res **6:** 878, 1988.
45. Grode SE, McCarthy DJ: The anatomical implications of hallux abducto valgus: a cryomicrotomy study. JAPA **70:** 539, 1980.
46. D'Amico JC, Schuster RO: Motion of the first ray: clarification through investigation. JAPMA **69:** 17, 1979.
47. McGlamry ED: Hallucal sesamoids. JAPMA **55:** 693, 1965.
48. Dykyj D: Pathologic anatomy of hallux abducto valgus. Clin Podiatr Med Surg **6:** 1, 1989.