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Size and Shape Differences Between Male and Female Foot Bones

Is the Female Foot Predisposed to Hallux Abducto Valgus Deformity?

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This study introduces a new technique to measure bone size and shape. A three-dimensional laser scan was taken of the talus, navicular, medial cuneiform, and first metatarsal from 107 skeletons of known age and sex. The bones were analyzed for differences in bone morphology between the sexes and the ability of each bone to contribute to the adducted position of the first metatarsal. Linear measurements showed that male bones were larger than female bones. Measurements of articular surfaces suggested that female bones had the potential for more movement to occur in the direction of adduction, possibly resulting in the female first metatarsal being more adducted than that in the male skeleton. Such differences may underlie the predisposition of the female foot to develop hallux valgus deformity. (J Am Podiatr Med Assoc 94(5): 434-452, 2004)

The bones of the feet have been measured in many previous studies when investigating fossil remains and in the identification of sex from skeletons. In most of the fossil studies, identification of bipedal characteristics has been sought on the basis of comparisons with modern humans, ancient humans, and apes, with little consideration as to whether a female bone may be morphologically different from a male bone. Kidd et al[1] attempted to use equal numbers of male and female bones in a comparison of the features of the 1.7 million–year-old fossil *Homo habilis* (OH8) with apes and humans. No significant differences were found between the sexes except for the measurement of the calcaneal facet angle in orangutans. In a recent study, Kidd and Oxnard[2] found distinct morphologic discriminatory features in modern foot bones based on their size and geographic location as well as on their sex, but the differences between the sexes was not discussed.

In forensic science, the measurement of foot bones has been undertaken to determine foot size and thus to estimate height. Only linear measurements have been considered. Byers et al[3] found good correlation between the lengths of the metatarsals and stature, with differences being noted between men and women. Steele[4] observed sexual dimorphism in the talus and calcaneus (n = 61), with male bones being significantly larger, but found that the overlap between individual measurements was so great that a combination of measurements was required to predict sex accurately. For the talus, the use of three discriminant functions gave an accuracy of predic-

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tion ranging from 83% to 88%. Smith[5] found a similar level of accuracy of discrimination for sex and race in a study of 160 metatarsals and phalanges.

The increased prevalence of hallux abducto valgus in women has led some authors to state that the deformity is due to an underlying predisposition, without indicating the form that the predisposition would take.[6, 7] Other researchers have examined the inheritance of hallux abducto valgus deformity,[8] considering factors such as metatarsal formulae, arch height, and hypermobility to be the inherited, underlying problems.[9] The podiatric medical literature cites many functional causes for hallux abducto valgus, including excessive foot pronation,[10] abnormal metatarsal head shape,[11] and metatarsus adductus,[12, 13] with emphasis placed on development of the adducted alignment of the first metatarsal in metatarsus primus varus.[14-16] The etiologies cited in the literature apply to male and female feet alike and would not account for the increased female prevalence. Few studies have considered differences in the anatomy of the female foot to determine variables that may cause the foot to function differently; studies that have considered differences in anatomy used radiographs, taking two-dimensional (2-D) data from a three-dimensional (3-D) structure.[17-19]

The first metatarsal position could be related to the anatomical structure of any of the bones in the medial column of the foot that results in a more medially facing first metatarsocuneiform joint. The adducted position of the first metatarsal, so frequently seen with hallux abducto valgus, has been described among the evolutionary changes of the foot, and the return of the foot to an earlier evolutionary stage, when the hallux was used for grasping, is sometimes described among the etiologies of hallux abducto valgus deformity.[20]

To measure foot bones, forensic studies have tended to use the measurements of bone lengths and widths that, in general, have been based on the descriptions by Martin and Saller.[21] These have also been used in anthropology alongside the detailed methods developed by Lisowski and coworkers,[22, 23] which are based on the earlier measurements of Martin and Saller.[21] Lisowski detailed the use of standardized reference planes when taking measurements using calipers and a protractor. This hands-on method has changed little during the past 35 years. The use of standardized reference planes allowed for the bone to be positioned relative to the body planes, and this has permitted comparison between species and between studies. The reference planes are described only for the larger bones. Standardized positions for the smaller bones, such as the navicular and the cuboid, are based on the morphology of the bone rather than with reference to a body plane.[1]

Although simple techniques, such as direct measurement with calipers and a protractor, are still used, technology is beginning to be developed that allows for more accurate measurement. Digital photographs have been introduced, but taking measurements from these is subject to error from the original camera angle and the ability to locate reference points. Computerized systems, such as Microscribe (Immersion Corp, San Jose, California), allow for more accurate measurement whereby a computer-generated model is created through visual location of reference points, and the linear and angular measurements are calculated from the 3-D data sets. Microscribe is limited by its graphic representation of the bone. If additional or repeated measurements are required, the investigator needs to return to the original bones. In most cases, the method of measurement is limited by the ability to take the technology to the bone sets, as most are, rightly, cosseted by the various museums.

With the introduction of new 3-D measuring systems, the method of taking the individual measurements needs to be reconsidered. For example, when measuring the talus, the angle between the neck and body of the talus has been found to be useful when distinguishing between different species.[24] Lisowski et al[23] described the measurement of the talar neck-body angle as being made by the intersection of the sagittal talar plane and the median talar neck plane. However, the measurements were originally made with calipers and, by connecting only two points, were linear and not planar. Lisowski's method created a horizontal line superimposed on the trochlear surface that divided the talar body into left and right halves and a horizontal line superimposed on the talar neck that separated it into left and right halves. The angle between these lines formed the talar neck-body angle. However, such an angle does not really describe the position of the body relative to the neck because the dividing line on the body of the talus would not be in the horizontal plane given the shape of the trochlear surface that runs from posteroinferior to anterosuperior. The line superimposed on the talar neck runs from posterosuperior to anteroinferior. Because these lines are contained in more than one plane, no single angle between them exists. With new technology, there is a need to return to the original descriptions by Lisowski and to create reference planes with the use of three reference points (a line is created between two coordinates, a plane is formed between three coordinates). The angle between the two planes can then be calculated.

This study introduces a new method of measuring foot bones using the measurements described by Lisowski[22] and considers whether the morphology of the bones differs between the sexes in such a way that the sex of an individual in a population can be identified. The study considers whether the bones in the medial column of the foot, particularly the articular surfaces, differ in a way that may result in a greater degree of adduction of the first metatarsal in women or that may highlight factors that may predispose the female foot to hallux abducto valgus deformity.

Methods

The Natural History Museum, London, granted us permission to access the Spitalfields Collection, which consists of Victorian British skeletons of known age and sex. The talus, navicular, medial cuneiform, and first metatarsal bones were taken from fully ossified subjects that were in good condition.

Each bone was scanned using a handheld 3-D laser scanner (Polhemus, Colchester, Vermont) to create a digital image. The bone was mounted, using a standardized method, on a black stand in a darkened room. The laser scanner repeatedly swept the bone in all planes until the reflected light had formed a suitable image of all sides of the bone, as shown on a computer screen. The images were analyzed using the "Cloud" software system (http://www.medphys.ucl.ac.uk/research/mgi/vis-lasr.htm).[25] This optical scan viewer system allows the exact 3-D image of the object to be rotated so that any surface can be viewed. Virtual markers can be added interactively to the bone surface, and the software can provide linear, planar, and angular measurements. For example, linear distances between surface markers can be measured, lines between two points can be created, and angles between lines can be found. Planes through sets of points can be formed and measurement of angles between planes can be made. Surface reference points can be located visually and with the use of contour lines that run horizontally and vertically, revealing any change in direction of the bony surface.

The measurements for each bone were selected from published anthropometric studies.[1, 22, 23]

The Talus

When placing marker points, the 3-D image of the talus was viewed from standardized positions unless otherwise stated.[1] When viewing the anterior or posterior surfaces, the talar head was positioned so that it was level with the posterior tubercle as if it were resting on a horizontal surface. The dome of the trochlea was kept horizontal with the bone positioned in the sagittal plane so that the medial surface was not visible. For medial and lateral views, the opposite side of the talar dome was just evident around the whole curve of the surface.

Talar Neck-Body Angle

This measurement distinguishes the human talus from that of other species, such as the primates, and has been linked to adduction of the first metatarsal.[1] The angle between the longitudinal bisection of the trochlear surface (median sagittal talar plane) and the longitudinal bisection of the neck of the talus (median talar neck plane) is measured. The original description of this measurement does not define the marker placements used to create the bisection but superimposes a line to bisect the body and neck of the talus into left and right halves.

To create the bisections in this study, multiple points were first placed along the midline of the body of the talus. The Cloud software created a plane that formed the "best fit" to these points using a least-squares regression function. The system then applied points on the plane that were closest to the originally chosen markers. Three of these points were chosen to create plane ABC (Fig. 1). The process was repeated along the midline of the neck of the talus, and the representative plane was created, with three points being chosen on that plane (points D, E, and F). The

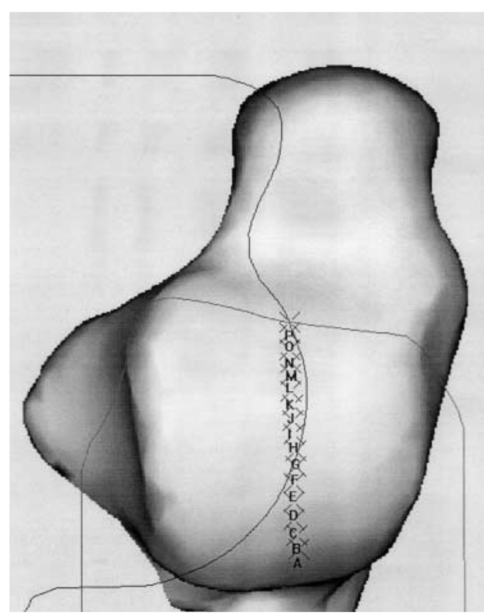

Figure 1. Dorsal view of the talus.

software then measured the angle between the two planes (ABC:DEF) (Figs. 2–4).

Talar Head Torsion Angle

This measurement distinguishes the human talus from that of other species.[22] The angle is related to the position of the forefoot on the rearfoot and is reported to decrease during the early stages of development.[10] The angle between the trochlea-head plane (a horizontal plane created by points joining the superior points of the trochlear margins to the talar head) and the longitudinal axis (median axis) of the head has been described elsewhere.[1]

In this study, plane ABC was used to represent the vertical bisection of the talus, and it was used instead of the horizontal bisection suggested by Lisowski (90° – this angle = Lisowski's angle). Multiple points were placed along the center of the talar head facet. The plane that is common to these points was created, and three points on this plane were selected (points G, H, and I) (Fig. 2). The talar neck angle was measured from the angle created between planes ABC and GHI.

Maximum Functional Length

This measurement is used to compare bone sizes and is described by Steele,[4] based on the work of Martin and Saller.[21] The length is usually measured from the sulcus of the flexor hallucis longus tendon on the posterior surface (at the maximum curvature) to the most anterior point on the articular surface of the navicular (at the maximum curvature) using calipers.

In this study, the maximum curve of the talar head facet was located with the bone viewed superiorly using the contour lines provided; it was then rechecked with the bone viewed anteriorly (point J). The maximum vertical curve at the posterior edge of the trochlear surface was used with the bone viewed from the posterior aspect (point K). The straight-line distance between points J and K was computed.

Maximum Width

This measurement has been used to compare bone sizes.[4] The maximum projection lines laterally and medially perpendicular to the sagittal plane are created. The most prominent point on the lateral, fibular facet was located (point L). The point on the medial surface of the talus was located directly perpendicular to point L (point M). The straight-line distance between points L and M was computed.

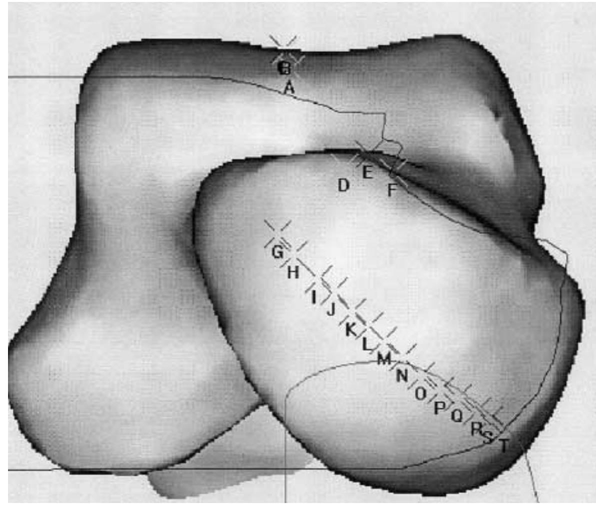

Figure 2. Anterior view of the talus.

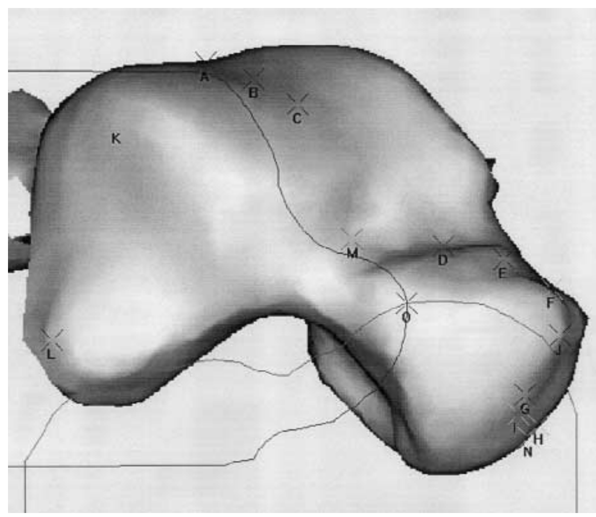

Figure 3. Anterolateral view of the talus.

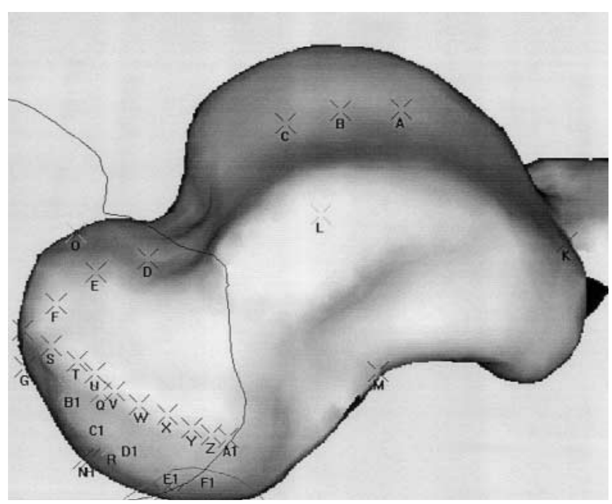

Figure 4. Medial view of the talus.

Ratio of the Maximum Talar Head Long Dimension to the Maximum Talar Head Short Dimension

This functional measurement was described by Kidd et al,[1] who referenced Lisowski.[22] Kidd et al reported that excessive length of the long dimension compared with the width would indicate the direction of movement at the talonavicular joint. From this it may be supposed that increased movement in the direction of adduction will have an influence on the position of distal bones and thus will lead to an adducted first ray. It may be supposed that a higher ratio or greater value of the length (medial to lateral) compared with the width (dorsal to plantar) indicates that the movement will occur in the medial-to-lateral direction. A value closer to 1 would indicate that the joint surface is round and, therefore, that movement is equal in each direction.

The dorsomedial edge of the talar head facet was identified where it joins the neck of the talus (point O). From a dorsal view, the point was located where the vertical projection shows the surface to be flat but then curves sharply away onto the dorsal surface; the horizontal line shows a flat area just as the curve of the head finishes (Fig. 3). From a medial view, the point was marked where the talar head facet joins the horizontal. The bone was then tilted so that this marker could be moved into the center of the facet at that level. The contour lines showed the facet to be flat where the head rests on the sustentaculum tali. This point was marked P. The center of the articular facet was identified (point N), and the widest points of the facet to the perpendicular to the central marker on the dorsal and plantar edges were found (points Q and R). The straight-line values of O-P/Q-R were calculated to indicate the shape of the joint surface.

Functional Angle of the Talar Head Facet

This angle was calculated using the equation of Latimer and Lovejoy,[26] and it has been described with reference to the shape of the first metatarsal head.[17] The radius of the curve through points O, P, and N was calculated, the chord length (OP) was measured, and the functional angle was calculated:

$$\text{Functional Angle of the Curve} = 2\sin^{-1}\left(\frac{\text{Chord Length}}{2 \times \text{Radius of Curve}}\right)$$

Proximal Articular Set Angle

This is a functional measurement originally described with reference to the first metatarsal head to describe the position of the articular surface compared with the longitudinal axis of the bone.[27] Here the method was applied to the talar head. The angle formed between the talar neck plane bisection (DEF) and the plane bisection of the talar head was found. This angle will affect the alignment of the forefoot. Larger angles will be associated with a more medially placed talar head and hence a more adducted medial column.

Multiple points were added around the edge of the talar head facet on the dorsal and plantar edges, and a plane through these points was created (Fig. 4). Three points were selected to represent the plane (points S, T, and U). Angle DEF:STU formed the proximal articular set angle measurement.

The Navicular

When measuring this bone from the anterior and posterior views, the plantar surface was kept in the horizontal plane. On the anterior view, the nonarticular "shelf" under the lateral cuneiform facet was just evident.

Ratio of the Maximum Talar Facet Length Dimension to the Maximum Talar Facet Width Dimension

This measurement was applied in a similar way as the measurement of the shape of the talar head as described by Kidd et al,[1] who referenced Lisowski.[22] The long talar facet dimension (the maximum dimension of the talar facet) and the short talar facet dimension (the minimum dimension of the talar facet) were found. The index created by length/width was used to describe the direction of movement, with values greater than 1 indicating increased length of the articular facet and the potential for increased movement in the direction of abduction/adduction.

The edges of the proximal surface of the navicular were found at points A, B, C, and D. The values of the straight-line distances A-B/C-D were calculated to represent the shape of the articular surface (Fig. 5).

Functional Angle of the Curve of the Talar Facet

This angle was measured along the midline of the facet. Undertaken in a similar way as that described for the talar head, a best-fit curve through points A, E, and B was applied, and the functional angle was calculated using the formula of Latimer and Love-

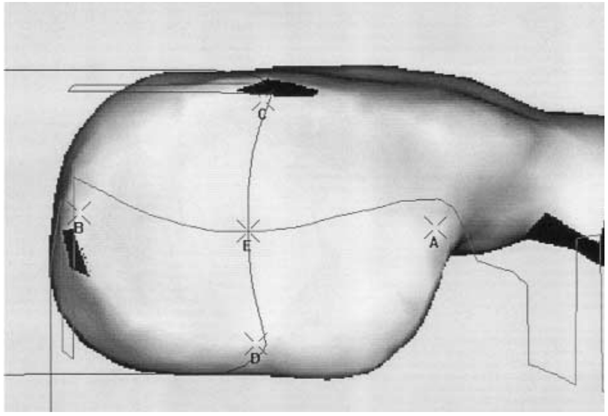

Figure 5. View of the talar head facet on the navicular.

joy.[26] The center of the articular facet (point E) was found at the point of maximum vertical and horizontal curves. An increased angle will relate to a greater range of movement and thus an increased ability of the navicular to move medially and laterally on the talus, suggesting an ability to adduct the first ray.

Ratio of the Medial Bone Width to the Lateral Bone Width

This ratio was described by Kidd.[28] In this study, the index is used to give an indication of the wedged shape of the bone.

With the anterior surface of the bone facing, the most medial edge of the articular facet of the medial cuneiform and the most lateral edge of the articular facet of the lateral cuneiform were marked (points F and G, respectively) (Fig. 6). The medial width was measured between medial marks A-F, the lateral width was measured between marks B-G, and a value of A-F/B-G was calculated. A value of 1 would indicate that the medial and lateral edges of the bone are equal and that the bone was not wedge-shaped. Values less than 1 would suggest reduced medial width of the bone, leading to a more adducted position of the cuneiforms when articulated.

Medial Cuneiform Facet Angle

This angle is formed between the tangential line across the intermediate cuneiform facet and the tangential line across the medial cuneiform facet. This measurement was described in the capitate bone for the hand using line bisections.[29] An increased angle would indicate a more medially facing medial facet.

Two planes were created representing the plane of the medial facet and a plane that combines the intermediate and lateral cuneiform facets. Using the points that identified the medial and lateral edges of the anterior face (points F and G, respectively), the angle between planes FHI and GHI was found (Fig. 6).

Functional Angle of the Curve of the Medial Cuneiform Facet

This measurement was taken along the midline of the medial cuneiform facet (Fig. 7). It was found in a similar way as the functional curve of the talar head. With the dorsal surface of the navicular being viewed, the best-fit curve to the joint surface was applied, and the calculation for the functional angle was made using the previous formula. An increased functional angle will be related to increased movement in

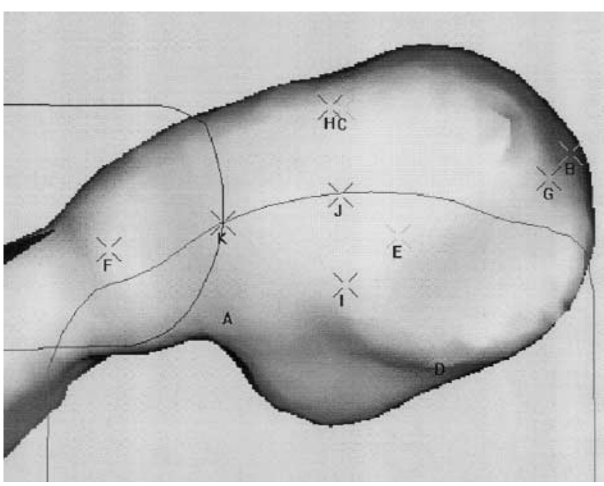

Figure 6. Anterior view of the navicular.

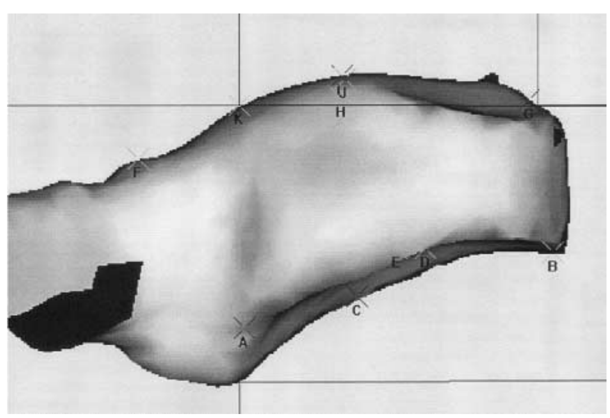

Figure 7. Plantar view of the navicular.

the direction of abduction/adduction of the first ray. The midpoint of H-I was marked (point J). The midpoint of J-F was found (point K). When viewed from the medial side, JKL must form a straight line. The radius of the curve through FJK was found. The distance between points F and J formed the chord length. The functional angle could then be calculated. A subjective description of the facet was given using the following terms: convex, flat, and concavoconvex.

The Medial Cuneiform

When measuring the cuneiform, the anterior and posterior surfaces were viewed with the medial surface of the bone placed on the horizontal plane.

Distal Joint Angle

This measurement is of the angle formed from the line joining the medial and lateral edges of the distal facet to the line joining the proximal and distal edges of the lateral facet of the intermediate cuneiform. Schultz[30] described the line bisections used to create the angle. In the present study, the angle between the planes forming each surface was measured. With the anterior surface facing, the most dorsal point and the most plantar point of the facet were marked points A and B, respectively. To create the plane, a third point (point C) was found at the medial surface approximately at the center of the bone (Fig. 8). With the posterolateral surface facing, the apex of the facet for the navicular was marked (point D), and the plantar proximal edge of the facet for the second cuneiform was found (point E). To create the plane, the third point at the anterodorsal edge of the facet for the second cuneiform was marked (point F) (Fig. 9). The angle between planes ABC and DEF was found and represented the angle measured by Schultz.[30] A second measurement, ABC:ABI, was tested for improved accuracy.

Functional Angle of the Curve of the Navicular Facet

This measurement was similar to the measurements taken of other curves. It was taken along the midline from the dorsal apex of the facet to the midpoint of the plantar surface of the facet. The curve from medial to lateral was also calculated. For the mediolateral curve, points G, H, and I were created. When the bone is present in an articulated foot, this curve allows abduction/adduction of the cuneiform on the navicular. For the dorsoplantar curve, points D, I, and J were found. When the bone is articulated, this curve allows dorsiflexion/plantarflexion of the cuneiform. The radii of curves DIJ and GHI were found. The functional angle for each curve was found using chord lengths DJ and GH, respectively (Fig. 10).

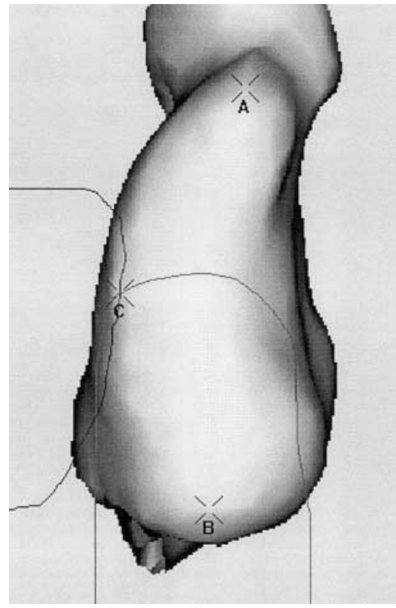

Figure 8. Anterior surface of the medial cuneiform.

Functional Curve of the Metatarsal Facet

As mentioned previously, Schultz[30] described the importance of this measurement with respect to adduc-

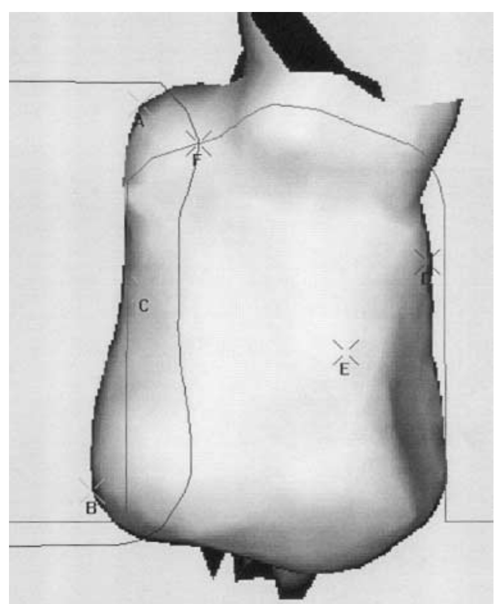

Figure 9. Lateral surface of the medial cuneiform.

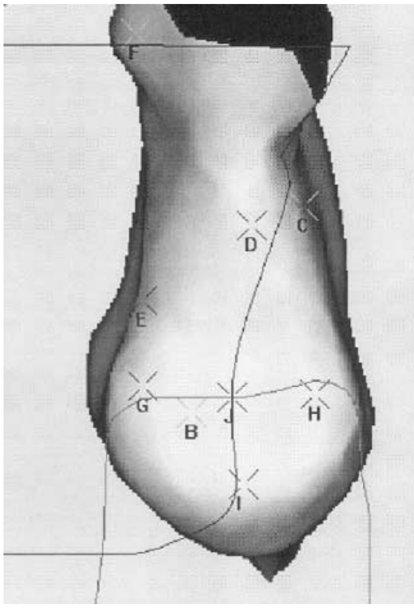

Figure 10. Posterior view of the medial cuneiform.

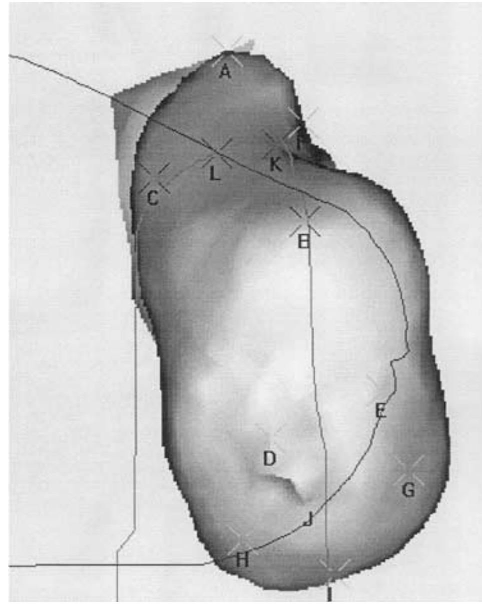

Figure 11. Plantar view of the medial cuneiform showing the curve of the anterior surface.

tion of the first ray. The cuneiform was placed with the anterior surface facing. The functional curve across the center of the metatarsal facet running from lateral to medial was calculated.

Points C, L, and K were found. Point K represented the most lateral point of the anterior facet, and point L was found at the center of the bone, in line with points C and K. The functional angle was found using the radius of curve CLK and chord length CK (Fig. 11).

The First Metatarsal

When the metatarsal was measured, it was positioned so that the plantar projection on the basal facet was pointing directly plantar. When the anterior surface (metatarsal head) was viewed, the crista was placed plantarly, and the metatarsal base could be seen equally around the edge of the metatarsal head. On the lateral views, the base of the metatarsal appeared flat and was perpendicular to the viewing screen.

Metatarsal Length and Metatarsal Head Width

Metatarsal length is the measurement from the apex of the capitulum (head) to the midpoint of the articular surface of the base parallel to the longitudinal axis of the bone. Metatarsal head width is the measurement of the distance between the medial and lateral epicondyles.[3, 5]

With the metatarsal head facing, the point was found by locating the center of the horizontal and vertical curves of the facet (point A). The central point of the cuneiform facet was found with the base of the bone facing by locating the center of the horizontal and vertical curves of the facet (point B). With the medial surface facing, the highest point of the medial epicondyle was found (point C) using the maximum points of curvature of the horizontal and vertical projections. With the lateral surface facing, the highest point of the lateral epicondyle was found using the maximum points of curvature of the horizontal and vertical projections (point D). The straight-line distances between A-B and C-D represent the maximum length and width, respectively (Figs. 12 and 13).

Functional Angle of the Curve of the Metatarsal Head

This functional angle was found using the formula, described previously, of Latimer and Lovejoy.[26] Increased angles are associated with increased abduction of the hallux.[17] The midpoint of the articular facet medially (point E) and the midpoint of the articular facet laterally (point F) were found. The center of the metatarsal head was located (point A) and the radius of the curvature through the three points was calculated, and chord length EF was used.

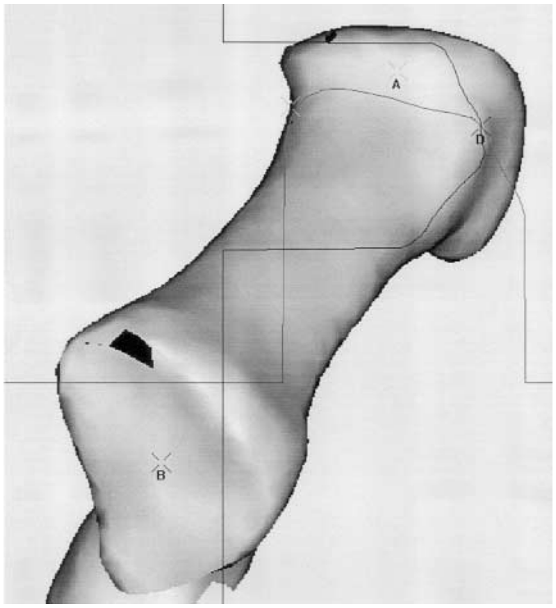

Figure 12. Dorsomedial view of the first metatarsal.

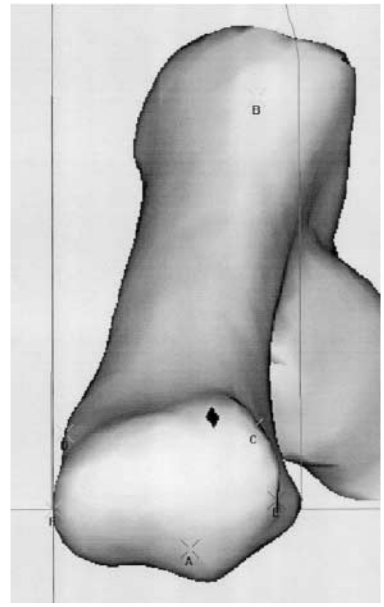

Figure 13. Anterodorsal view of the first metatarsal.

Proximal Articular Set Angle

This functional measurement describes the position of the metatarsal head articular facet relative to the bisection of the metatarsal shaft.[27] With the metatarsal head facing, the medial and lateral edges of the facet were joined across the midline of the joint surface. The bone was then viewed from the dorsal direction, and the shaft was bisected longitudinally with plane ABG. The angle between the shaft and the head was measured (Fig. 14).

Tarsometatarsal Joint Angle

This angle is formed between the bisection of the medial and lateral sides of the first metatarsal base and the longitudinal bisection of the bone. Increased angulation of the base facet would be associated with adduction of the metatarsal when articulated with the medial cuneiform. On a view of the base of the metatarsal, the plantar edge of the metatarsal plantar projection was marked (point G). The widest point of the base was marked on the edge of the facet medially (point H) and laterally (point I). The angle between planes ABG and GHI was found.

The Use of Indices (Ratios)

The use of ratios or indices in anthropometric data has been subject to severe criticism[31, 32] because dividing one measurement by another has usually been undertaken to account for the effect of size. Creating a ratio does not account for the effect of size, and it alters the distribution of the data, making statistical analysis difficult. In this study, the use of indices has been undertaken using the guidelines of Kidd et al[1] when they have been used to describe the biomechanical aspects of the facet morphology. This is

Figure 14. Posterodorsal view showing angle of base of the first metatarsal.

stated as acceptable by Albrecht et al[31] and Atchley et al.[32] The distribution of the ratio data was tested to apply suitable statistical analysis.

Repeatability and Validity

Initial pilot studies were undertaken to test the intraobserver repeatability and the validity of the measurement system. One bone of each type was scanned ten times to test for differences in the scanning process. A two-way analysis of variance showed no difference between the scans ($P > .1$). Ten bones of each type were measured five times to test for repeatability of the measurements. Two-way analyses of variance for each measurement showed a significant difference between the bones ($P < .01$) but no significant difference between the repeated measurements ($P > .07$). In the main study, to improve accuracy, each measurement was taken five times, and the mean value was included in further analysis of the data.

The validity of the measurement system was tested by comparing linear measurements taken by handheld calipers with the measurement taken from the digitized image. No significant differences between the methods were found. The differences between the measurements were no greater than 4 mm.

Results

A total of 107 individuals were measured (53 men and 54 women aged 18 to 84 years). The numbers of each bone used are given in Table 1. The data were analyzed using SPSS for Windows (SPSS Science, Chicago, Illinois).

The distributions for each measurement were tested using a one-sample Kolmogorov-Smirnov test prior to comparison of the sexes. All measurements were normally distributed ($P \geq .06$), allowing for parametric tests to be applied for continuous data.

Bones from either left or right feet were used. To test for no difference between sides, left and right bones from the same individuals were compared. The null hypothesis of no difference between sides was tested using paired *t*-tests. There was no significant difference in any of the measurements for the 13 pairs of metatarsal bones, 10 pairs of cuneiforms, and 6 pairs of naviculae. The 11 pairs of tali showed a significant difference between the left and right talar body-neck angles (ABC:DEF), talar head torsion angles (ABC:GHI), and length measurements. A nonparametric sign test was applied because of the small sample size, and only the talar body-neck angle continued to show significant left-to-right differences ($P = .02$).

Table 1. Number of Foot Bones Analyzed

Bone	Men (No.) (n = 53)	Women (No.) (n = 54)
Tali	52	54
Naviculae	49	53
Cuneiforms	52	54
Metatarsals	53	52

The Talus

Table 2 gives the data for the male and female tali. A *t*-test was used to test for differences in the male and female talar measurements. The talar head torsion angle was found to have a small but statistically significant difference between the sexes ($P = .03$), with men having a greater angle than women (mean difference, 3.01°, 95% confidence interval [CI], 0.23° to 5.79°). The maximum functional length and width of the bone were significantly different between the sexes, as would be expected ($P < .001$). The value of facet length/width was calculated for the head facet to describe the shape of the facet, with a value of 1 indicating a round surface and a value greater than 1 indicating an oval surface with increased length in the direction of abduction/adduction. No significant difference was found between male and female bones ($P = .36$). The radius of the talar head facet was greater in men (mean difference, 2.36°). When the functional angle was calculated using the chord length (OP), a statistically significant difference between the sexes was found, with women demonstrating a greater functional angle (mean difference, –4.91°; 95% CI, –9.24° to –0.56°), indicative of a more curved facet ($P = .027$) (Fig. 15).

The direction of the talar head facet calculated using the proximal articular set angle showed no significant difference between men and women ($P = .3$).

The Navicular

Table 3 gives the data for male and female naviculae. The naviculae showed significant differences between men and women in the length and width of the talar head facet (AB and CD, respectively). The value of length/width (AB/CD) was used to describe the shape of the facet. Women showed a larger value (mean, 1.44) than men (mean, 1.39), indicating that the female facet was more oval in shape, having a greater length than width measurement. However, the difference was not large enough to reject the null hypothesis of no difference between the sexes ($P = .08$), and the differences were probably too small to be of interest.

Table 2. Tali Results

Measurement	Mean (SD) Men	Women	Mean Difference (95% CI)	*P* Value
ABC:DEF (°)	18.74 (4.42)	18.98 (4.18)	–0.25 (–1.89 to 1.40)	.77
ABC:GHI (°)	38.09 (7.87)	35.08 (6.47)	3.01 (0.23 to 5.79)	.03
Length (mm)	52.59 (3.14)	46.85 (2.72)	5.74 (4.61 to 6.87)	<.001
Width (mm)	38.03 (2.42)	34.36 (1.78)	3.77 (2.95 to 4.59)	<.001
Head facet length (mm)	29.52 (2.53)	26.13 (2.05)	3.38 (2.50 to 4.27)	<.001
Head facet width (mm)	19.23 (2.25)	17.26 (1.54)	1.96 (1.21 to 2.70)	<.001
Ratio length/width	1.55 (0.16)	1.52 (0.14)	0.03 (–0.031 to 0.044)	.36
Functional angle of head (°)	117.45 (11.07)	122.35 (11.58)	–4.91 (–9.24 to –0.56)	.03
Proximal articular set angle (°)	101.70 (4.84)	102.67 (4.71)	–0.97 (–2.80 to 0.86)	.30

Abbreviation: CI, confidence interval.

The medial and lateral width of the navicular was significantly greater in men than in women ($P < .001$), but when the value of medial width/lateral width was calculated to indicate the degree of wedging of the bone, no significant difference between the sexes was found ($P = .61$).

The radius of the curve of the talar head facet (AEB) was significantly greater in men, but when the functional angle was calculated using AB as the chord length, it showed no statistically significant difference between men and women ($P = .81$).

The alignment of the medial cuneiform facet compared with that of the lateral and intermediate cuneiform facets combined (FHI:GHI) was measured across the center of the facets. No significant difference in angle was found between the sexes ($P = .81$).

The medial cuneiform facet was classified through direct observation. The facet was described as concavoconvex in 6 men and 12 women, as flat in 5 men and 4 women, and as rounded in 38 men and 37 women. A χ^2 test showed that there was no significant difference in facet shape between the sexes ($P = .39$). The functional angle of the round facets only was calculated because the radii of the curvatures of the flat and concavoconvex surfaces could not be measured. The functional angle of the curvature (radius FJK, chord FK) showed no significant difference between men and women ($P = .33$).

The Medial Cuneiform

The results for the medial cuneiform are given in Table 4. The medial cuneiform showed no differences in the angle of the navicular facet as measured

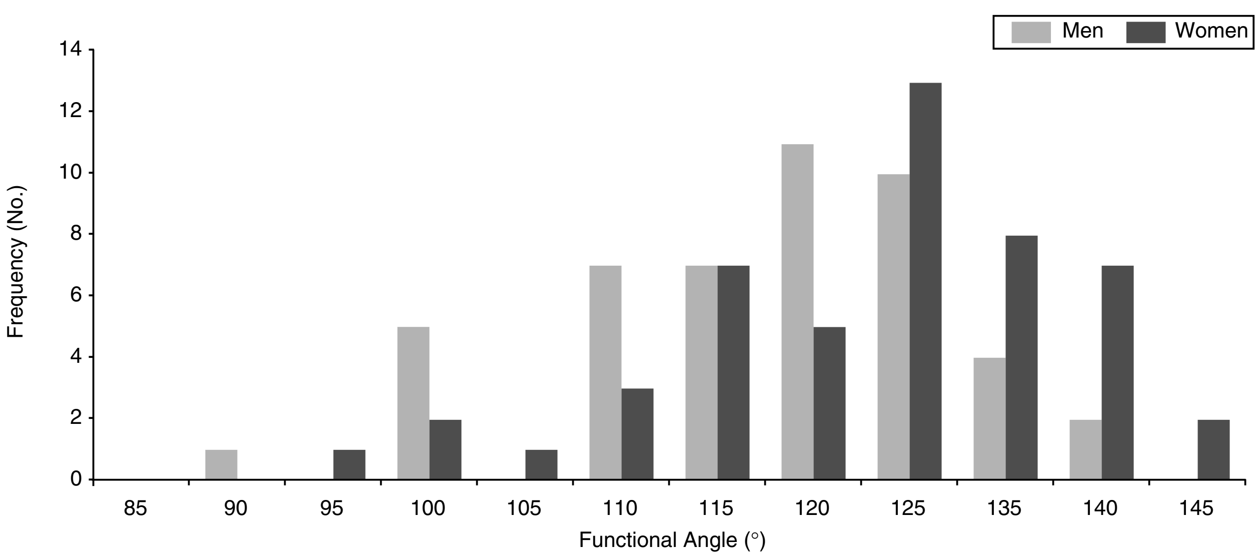

Figure 15. Histogram showing the functional angle of the talar head facet in men and women.

Table 3. Naviculae Results

Measurement	Mean (SD) Men	Women	Mean Difference (95% CI)	*P* Value
AB (mm)	26.20 (2.18)	23.66 (1.70)	2.54 (1.76 to 3.31)	<.001
CD (mm)	19.03 (2.25)	16.49 (1.43)	2.54 (1.79 to 3.29)	<.001
Ratio AB/CD	1.39 (0.16)	1.44 (0.14)	–0.05 (–0.11 to 0.0069)	.08
Functional angle of head (°)	87.59 (10.98)	87.16 (6.34)	0.43 (–3.14 to 4.00)	.81
AF (mm)	16.81 (1.85)	15.11 (1.38)	1.70 (1.07 to 2.34)	<.001
BG (mm)	11.39 (1.85)	10.32 (1.37)	1.07 (0.43 to 1.72)	<.001
Ratio AF/BG	1.50 (0.23)	1.48 (0.19)	0.21 (–0.061 to 0.10)	.61
FHI:GHI (°)	151.14 (6.30)	150.87 (4.67)	0.26 (–1.93 to 2.46)	.81
FKJ (°)	31.26 (11.86)	28.92 (9.36)	2.34 (–1.89 to 6.56)	.27
FJ chord (mm)	18.22 (1.80)	17.00 (1.62)	1.22 (0.54 to 1.89)	.001
Functional angle (°)	41.84 (6.49)	40.18 (7.86)	1.65 (–1.60 to 4.99)	.33

Abbreviation: CI, confidence interval.

using Schultz's method (ABC:DEF) or the new method (ABC:ABI). A good correlation existed between the measurement techniques (R = 0.76, R^2 = 0.58), although the measurement error calculated using the square root of (sum of variance/n)[33] was lower with the new method (2.57° *versus* 3.89°).

The radii of the curvatures of the navicular facet, GHI (allowing abduction/adduction) and DIJ (allowing dorsiflexion/plantarflexion), showed no differences between the sexes despite the chord lengths for both joint surfaces (GH and DJ) being significantly greater in men (P < .001). The functional angle of the navicular facet in the direction GHI was greater in men but was not found to be significantly different between men and women, although the 95% CI for the mean was large, with the upper level for the mean difference value being as great as 8.7°. However, functional angle DIJ was significantly different (P = .002), with men showing a greater functional angle in the direction of abduction/adduction of the cuneiform on the navicular (Fig. 16). In both directions of movement, the male bones showed greater functional angles.

The radius of the curve at the center of the facet for the first metatarsal base showed a significant difference, with men having a larger radius of curvature (P = .003) and greater chord length (P < .001). When the functional angle of the curvature of the first metatarsal base was measured, women were shown to have a greater curvature, but the result was not significant (P = .15).

The First Metatarsal

Table 5 gives the results for each metatarsal measurement taken. The first metatarsal showed size differences in length and width, as expected (Fig. 17),

Table 4. Medial Cuneiform Results

Measurement	Mean (SD) Men	Women	Mean Difference (95% CI)	*P* Value
ABC:DEF (°)	135.80 (6.76)	135.93 (6.47)	–0.13 (–2.64 to 2.41)	.92
ABC:ABI (°)	105.41 (7.65)	104.35 (7.80)	–1.06 (–4.03 to 1.92)	.48
GHI radius (°)	15.83 (4.83)	15.81 (5.70)	0.02 (–2.03 to 2.07)	.98
GH chord (mm)	10.20 (1.54)	8.84 (1.05)	1.36 (0.85 to 1.87)	<.001
Functional angle GHI (°)	40.33 (12.58)	36.29 (11.60)	4.04 (–0.63 to 8.70)	.09
DIJ radius (°)	17.65 (3.71)	17.29 (3.83)	0.36 (–1.12 to 1.84)	.63
DJ chord (mm)	14.58 (1.94)	12.27 (1.62)	2.31 (1.61 to 3.00)	<.001
Functional angle DIJ (°)	50.38 (12.65)	42.41 (12.65)	7.97 (3.10 to 12.85)	.002
CLK radius (°)	16.60 (7.93)	12.50 (5.49)	4.10 (1.42 to 6.78)	.003
CL chord (mm)	7.83 (1.50)	6.61 (1.13)	1.22 (0.71 to 1.73)	<.001
Functional angle CLK (°)	31.49 (14.14)	35.27 (12.85)	–3.78 (–9.00 to 1.43)	.15

Abbreviation: CI, confidence interval.

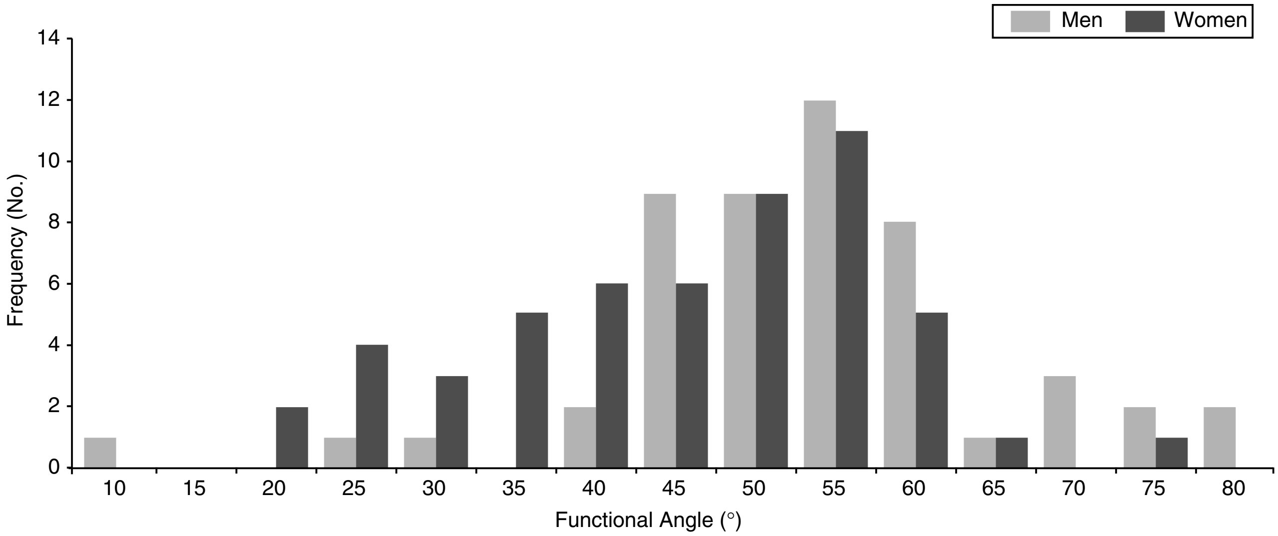

Figure 16. Histogram showing the functional angle of the cuneiform base facet (DIJ), which allows movement in abduction/adduction, in men and women.

with the male metatarsals being significantly larger ($P < .001$).

The alignment of the tarsometatarsal joint facet (MC plane) was shown to have an increased angle in women, indicating a more adducted position when articulated on the cuneiform. The mean difference between men and women was small, with the 95% CI showing a maximum difference of –3.2°. The difference between men and women was just at the chosen level of probability for the study ($P = .055$).

The metatarsal head was shown to have a greater radius of curvature and chord length in men compared with women ($P < .001$). However, when the functional angle of the head of the metatarsal was calculated, it was found to be significantly greater in women ($P = .047$), with the mean difference having an upper level for the 95% CI as great as –11.0° (Fig. 18).

The maximum position of adduction of the first metatarsal was calculated by adding the contribution of each significant measurement in men and women. When the means of the significant angles for all of the bones were added together, women had a possible angle of adduction of 12.06°. Men had a maximum possible angle of 7.97°. When the maximum difference was calculated from the upper limit of the 95% CI of the mean, the angle increased to 23.34° in women compared with 12.85° in men. Table 6 shows where the differences occurred.

Prediction of Sex

To investigate the usefulness of each measurement in determining the sex of each bone, logistic regression was applied. The measurements were entered in

Table 5. First Metatarsal Results

	Mean (SD)			
Measurement	Men	Women	Mean Difference (95% CI)	*P* Value
Length (mm)	58.58 (3.31)	53.71 (3.29)	4.86 (3.59 to 6.14)	<.001
Width (mm)	16.38 (1.59)	14.63 (1.47)	1.75 (1.16 to 2.35)	<.001
Head radius (°)	12.62 (2.24)	10.27 (1.46)	2.35 (1.62 to 3.08)	<.001
Chord (mm)	18.35 (1.62)	15.77 (1.53)	2.58 (1.97 to 3.19)	<.001
MC plane (°)	96.70 (3.94)	97.34 (5.87)	–1.59 (–3.20 to 0.034)	.055
Proximal articular set angle (°)	91.82 (5.95)	92.90 (5.01)	–1.08 (–3.21 to 1.05)	.97
Functional angle (°)	96.72 (15.97)	102.29 (12.13)	–5.56 (–11.00 to –0.075)	.047

Abbreviation: CI, confidence interval.

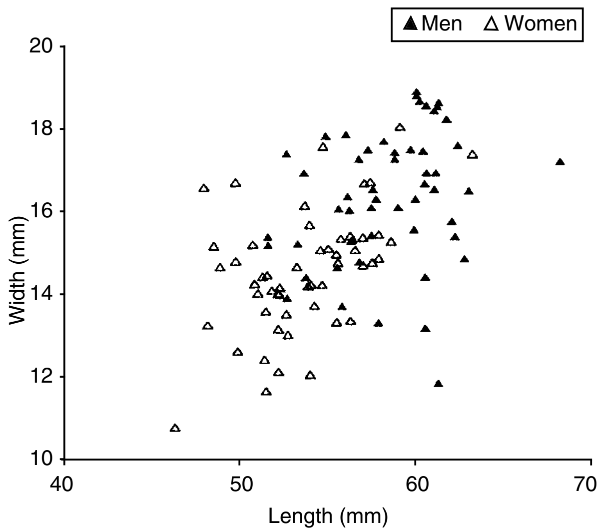

Figure 17. Scatterplot of length *versus* width for the first metatarsal in men and women.

a stepwise method to identify those that were important in the analysis. Table 7 shows the percentage accuracy of prediction for each of the bones measured for the final steps in the calculation. The talus had an 86.0% prediction accuracy, with length and width being the only two significant contributors (Table 8).

For the navicular, an 82.4% prediction accuracy was found, with the important measurements being the long (AB) and short (CD) talar facet dimensions and the medial width of the bone (AF). The medial cuneiform showed a prediction accuracy of 75.0%, with three measurements being important in the prediction: the chord lengths of the navicular facets (DJ and GH) and the radius of the curvature of the distal facet of the metatarsal (CLK). The first metatarsal showed an 83.8% prediction accuracy, with the bone length, proximal articular set angle, and radius of the curvature of the metatarsal head being important factors.

In all cases of logistic analysis, the Hosmer-Lemeshow χ^2 statistic showed a good fit for each model ($P \geq .21$).

Discussion

This study used a novel measurement technique. Despite some differences in the methods used, limited comparison was possible with other published results on human subjects and showed good comparability between this and traditional techniques (Table 9). This is the first study to use a handheld laser scanner for the measurement of foot bones. Although 3-D laser scanning was available for the measurement of bones previously, it has had limited application because the machines have been too large to take to the collections and it is impractical to move large numbers of bones to the scanners. The handheld scanner has the advantage of being portable, and, once the bones have been scanned, a permanent visual record of the bones is created that can be used on subsequent occasions for further measurement without the need to return to the collections. The software used to measure the bones allowed marker placement to be made visually, as would occur with other techniques, aided by the use of contour lines, which identify very small deviations in the bony surface.

The results showed no differences between left and right sides for most measurements, as would be expected. The exception was the talar body-neck

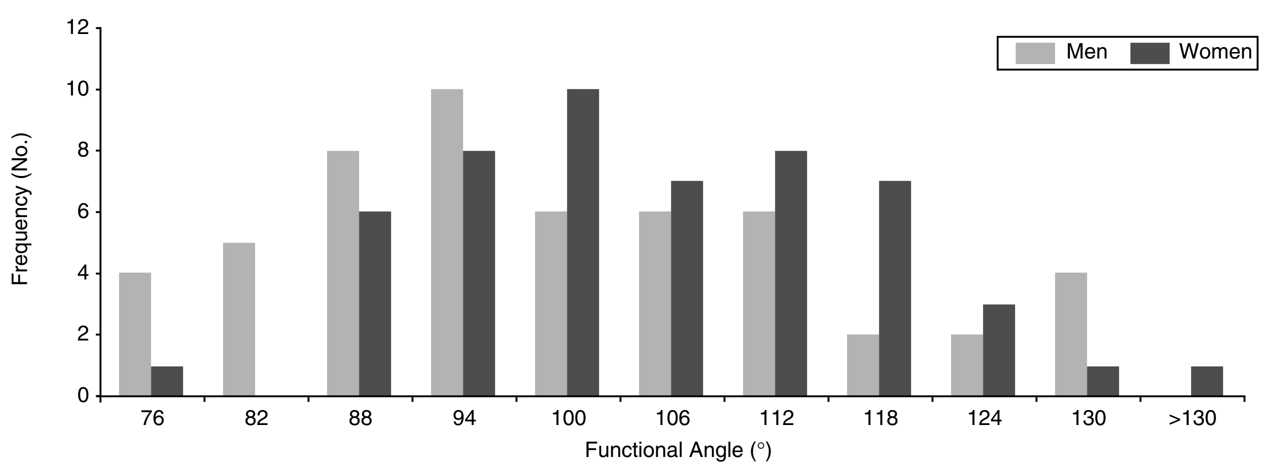

Figure 18. Histogram showing the functional angle of the metatarsal head in men and women.

Table 6. Differences in the Potential Adduction of the First Metatarsal Between Men and Women

	Men	Women
Initial	0°	0°
Talar head functional angle (F>M)		4.91° (upper 95% CI = 9.24°)
Medial cuneiform DIJ angle (M>F)	7.97° (upper 95% CI = 12.85°)	
First metatarsal base angle (F>M)		1.59° (upper 95% CI = 3.20°)
First metatarsal head functional angle (F>M)		5.56° (upper 95% CI = 11.00°)
Final total	**7.97° (upper 95% CI = 12.85°)**	**12.06° (upper 95% CI = 23.34°)**

Abbreviations: CI, confidence interval; F>M, female measure greater than male measure; M>F, male measure greater than female measure.

Table 7. Classification Table

	Predicted Sex (No.)		
Bone	Male	Female	Percentage Correct
Talus			
Male	45	7	86.5
Female	8	47	85.5
Subtotal			**86.0**
Navicular			
Male	39	10	79.6
Female	8	45	84.9
Subtotal			**82.4**
Medial cuneiform			
Male	36	13	73.3
Female	12	39	76.5
Subtotal			**75.0**
First metatarsal			
Male	45	8	84.9
Female	7	43	82.7
Subtotal			**83.8**

angle. The measurement of the angle between planes is highly sensitive, and a small deviation in one of the two planes can greatly change the angle recorded. The mean value of five repeated measurements reduced some of the possible error, but it may have been necessary to increase the number of repeated measurements for certain measurements to show no difference between sides. This would be particularly relevant for the measurements that involved "eyeballing" the bisection line as opposed to locating a specific landmark. The sample size was also small for the left-to-right tests (n = 11). The mean difference between left and right talar neck angles was only 2° (95% CI, 0.74° to 3.4°), so the difference is probably not sufficiently great to be important in terms of changing function.

The foot bones displayed sexual dimorphism. Several differences between male and female foot bones were found, and these were principally due to size. As expected, in measurements involving length and width, the mean values of the male bones were always larger than those of the female bones, and this was also true of joint sizes, where chord lengths and radii were greater in men. Such information provides little evidence for a predisposition of the female foot to hallux abducto valgus deformity. The functional angles and angular measurements also showed some male-female differences. The functional angle of a joint surface provides an angular measurement of the possible movement at the joint. It will not provide the exact motion at the joint, as this will be influ-

Table 8. Variables in the Equation for Logistic Regression of the Talus

	B	SE	Wald	*df*	Significance	Exp(B)
Step 1[a]						
LENGTH	–0.654	0.119	30.434	1	.000	0.520
Constant	32.534	5.909	30.319	1	.000	1.3E+14
Step 2[b]						
LENGTH	–0.451	0.138	10.687	1	.001	0.637
WIDTH	–0.460	0.200	5.293	1	.021	0.631
Constant	38.985	7.357	28.082	1	.000	8.53E+16

[a]Variable(s) entered on step 1: LENGTH.
[b]Variable(s) entered on step 2: WIDTH.

Table 9. Comparison of Measurement Technique with Other Studies

	Rhoads and Trinkaus (1977)[34]	Kidd et al (1996)[1]	Steele (1976)[4]	Ferrari et al (present study)
Mean talar length (mm)	53.59–48.08	NA	Men: 55.3 Women: 49.7	Men: 52.59 Women: 46.85
Mean talar width (mm)	NA	NA	Men: 43 Women: 38.6	Men: 38.03 Women: 34.36
Talar neck angle (°)	25.76–24.06	Men: 18.56 Women: 18.94	NA	Men: 18.74 Women: 18.98
Talar neck torsion angle (°)	42.78–40.32	Men: 45.17 Women: 45.16	NA	Men: (90–38.09) = 51.91 Women: (90–35.08) = 54.92

Abbreviation: NA, not available.

enced by the surrounding soft-tissue structures and changes in position of the bones during movement. However, the functional angle does allow comparison of the bones. Differences in the functional angle between men and women were sought to investigate whether any of the movements could account for increased adduction of the first metatarsal in the female foot. Three significant differences in functional angles were found (Table 10). The functional angle of the metatarsal head was greater in women than in men. Although this was not related to the adduction of the metatarsal, it was considered a possible cause of bunion deformity because a greater curvature of the metatarsal head has been shown to be associated with increased abduction of the proximal phalanx of the hallux.[11, 17] This 3-D study confirmed the findings of an earlier 2-D study.[17]

The proximal articular set angle of the metatarsal head was not found to be significantly different between the sexes. This finding also concurs with the results of a radiographic study.[11, 35]

The functional angles of the joint facet in the medial cuneiform for the navicular showed sexual dimorphism. The functional angle of the facet of the navicular was significantly greater in men than in women in the direction of abduction/adduction (DIJ) and was greater in dorsiflexion/plantarflexion, although the difference did not reach statistical significance. This difference was unexpected, as it may be associated with an ability to adduct the medial cuneiform and, therefore, the metatarsal in men more than in women. However, the angles involved were small, suggesting that the joint surface was almost flat, so little movement would occur at this joint. The difference between men and women was 7.97°. The movement across the facet in the direction of DIJ was taken to represent abduction/adduction, but at this joint it is particularly difficult to confine the description to movement in one plane. The anatomical position of the cuneiform depends on the alignment of the navicular. In an articulated skeleton, the medial cuneiform is slightly tilted to the transverse plane so that movement through curve DIJ is in a direction of abduction with dorsiflexion and adduction with plantarflexion. If the navicular was more everted, the position of DIJ would change so that the movement becomes dorsiflexion/plantarflexion. Having said this, the measurement of the functional curve at the facet representing dorsiflexion/plantarflexion (GHI) was also increased in men, but it did not reach statistical significance ($P = .09$). With a change in alignment of the navicular, the curvature along GHI would provide abduction/adduction; in either case, then, it would seem that the movement is greater in men.

Table 10. Summary of Significant Findings for Functional Angle Measurements

	Mean (SD)			
Functional Angle	Men	Women	Mean Difference (95% CI)	*P* Value
Metatarsal head (°)	96.72 (15.92)	102.29 (12.15)	–5.56 (–11.00 to –0.075)	.047
Medial cuneiform DIJ (°)	50.38 (12.65)	42.41 (12.65)	7.97 (3.10 to 12.85)	.002
Talus (°)	117.45 (11.07)	122.35 (11.58)	–4.91 (–9.24 to –0.56)	.03

Abbreviation: CI, confidence interval.

At the talar head, the functional angle was significantly greater in women, indicating that the motion at that joint would be increased in women compared with in men if all other factors influencing movement at the joint were equal between the sexes. The movement would be increased in the direction of adduction with plantarflexion and abduction with dorsiflexion.

Of the three significant functional angles found, two showed greater movement in women compared with in men, and both of these could influence movement in the direction of adduction of the metatarsal or abduction of the hallux. Latimer and Lovejoy,[26] who first introduced the use of the functional angle, noted that female gorillas had a greater functional angle at their joints than male gorillas. Women are known to be more flexible than men.[7] Such hypermobility is thought to be due to ligament laxity, but the results of this study suggest that the articular surfaces of female joints tend to allow greater movement before the influence of the soft tissues is added.

Several significant differences in angular measurements were also found. The difference in the angle of the facet on the metatarsal base for the medial cuneiform between men and women was at the chosen level of significance for this study. Women had a greater angle of the metatarsocuneiform facet on the metatarsal base than men; when articulated, this would result in greater adduction of the metatarsal on the cuneiform in women compared with in men (Fig. 19). The reciprocal facet on the anterior surface of the medial cuneiform did not show a difference between the sexes.

The talar neck torsion angle was found to be significantly different between men and women, with men having a greater angle, which would indicate that the talar head was less everted and so more horizontal in men than in women. The difference was small, so again the clinical significance is questioned (mean difference, 3.01°), but the result suggests that the navicular will be more horizontally articulated on the talus in men, allowing more abduction/adduction at this joint, whereas women would have more dorsiflexion and plantarflexion available at the joint. The fact that the navicular is potentially more horizontal in men has an impact on the position of the medial cuneiform. The curve of the base facet of the medial cuneiform in the direction of adduction/abduction (DIJ) will change to represent dorsiflexion/plantarflexion. Thus the significant difference found between men and women for DIJ may not represent a difference in the degree of adduction available.

The facet for the medial cuneiform on the navicular is known to be quite variable, and this study confirmed this, identifying the existence of flat, round, and concavoconvex facets.[24, 30, 36] A rounded facet was most frequently seen, and no difference in the curvature was found between the sexes. The posterior facet on the navicular for the talus was greater in length and width in men, as would be expected. However, when the length was divided by the width to provide an index representing the direction of movement, a difference was found between men and women, but it was not statistically significant. Females had a higher length/width index, suggesting that the facet was more oval in shape. The movement at the facet would be abduction/adduction along the length of the bone and dorsiflexion/plantarflexion along the width, but this would depend on the position of the direction of the talar head. In this study, the measurements were taken with the navicular positioned with the plantar surface in the horizontal plane. When articulated, the navicular is tilted to the horizontal owing to the torsion in the talar neck. The movement along the length of the facet would not be pure abduction/adduction but a component of movement in several planes.

It is recognized that reference to the position of each bone to its neighbor in this study is based on the theoretical position of the bones when re-articulated. When the foot functions, the bones may change alignment considerably. Thus movements thought to be abduction/adduction may change to dorsiflexion/plantarflexion (or *vice versa*) when the foot is weightbearing. The function of an individual's feet depends on many factors, such as the biomechanical alignment of the lower limb. Throughout this study, an attempt was made to use standardized reference

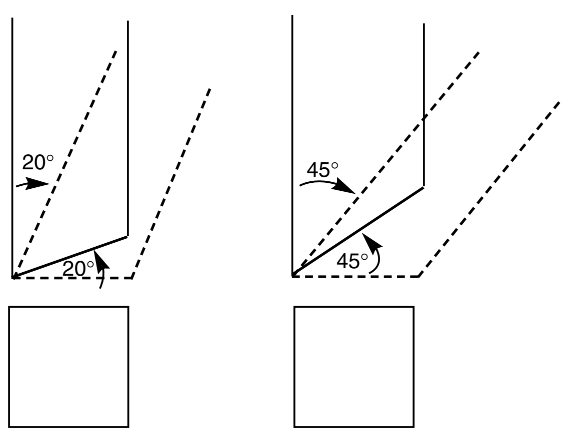

Figure 19. Diagram demonstrating how the increased angle of the metatarsal base facet (MC angle) will affect the angulation of the metatarsal when articulated.

positions so that comparisons can be made with other studies in the field. Further study is necessary to test the influence of the angles measured on the position of the first metatarsal. It was also noted that reciprocal joint surfaces often did not have matching curvatures. For example, the talar head functional angle of curvature was approximately 117°, whereas the curvature of the reciprocal facet on the navicular was 87°. To improve joint congruence, the depth of the joint is enhanced by the shape and thickness of the articular cartilage and by surrounding ligaments and joint capsule. Such structures may influence the degree and direction of movement at the joint.

Considering individual bones, sexual dimorphism did exist, and it allowed the sex of a bone to be predicted with an accuracy of up to 86%, which compares well with the forensic studies cited. This study found identification rates similar to those of other studies, such as that of Steele,[4] who had a prediction accuracy of 81% for the talus (compared with 86% in this study), and Smith,[5] who had an 84% prediction accuracy for the metatarsal (compared with 83.8% in this study). Interestingly, the measurements most important in discriminating between the sexes proved to be the linear dimensions rather than the significant functional and angular measurements identified.

Although the emphasis of this article is on the potential of the differences identified between male and female bones to cause hallux abducto valgus deformity, it is recognized that the differences between the bones may be the result of hallux abducto valgus deformity or due to differences in foot function or environmental factors. Because the skeletons in the collection were disarticulated, it was not possible to identify the prevalence of hallux abducto valgus deformity in this population. There are no references in the literature to the prevalence of hallux abducto valgus deformity at the time this group was living (1685–1885). References exist regarding the treatment of "bunions" from as early as the 13th century, with surgical treatments being developed in the 19th century.[37] It is therefore likely that some of the individuals measured would have had hallux abducto valgus deformity, but whether sufficient numbers would have had the deformity to influence the results of this study is not known. In the population measured, there would be a small chance of environmental conditions influencing the bone structure. The people who made up this collection were involved in the silk trade in London and were reasonably wealthy. However, there is little information available as to whether the occupations of men and women would have been sufficiently different to cause the difference in function or footwear being reflected in the bone shape.

Finally, although statistical analysis has been applied to determine whether a statistically significant difference exists between the measurements of male and female bones, some of the differences identified were small and therefore may not result in a clinically important difference. No studies exist to help with the interpretation of the differences described; thus the magnitude of a difference that would bring about a change in function or position of the foot bones is not known.

Conclusion

A new method for bone measurement has been introduced that uses the original planar measurements suggested by Lisowski[22] that have not been possible with earlier techniques. The method has produced results comparable to those of other studies and has found that sexual dimorphism exists in the foot bones such that the sex of an individual may be predicted with an accuracy of up to 86% using simple linear measurements and measurements of facet curvature.

Several measurements showed statistically significant differences between men and women and may lead to functional differences between male and female feet. Overall, there was a tendency for the measurements to show that increased adduction of the metatarsal and abduction of the hallux may occur in the female foot, thus suggesting that the female foot has an underlying anatomical predisposition to first metatarsal adduction and thus hallux abducto valgus formation.

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