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New Sagittal Plane Reference Parameters for Foot Deformity Correction Planning: The Vitruvian Foot

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ABSTRACT

Currently available methods for analysis and planning of post-traumatic or congenital deformity correction of the foot have some limitations. The aim of this retrospective study was to establish reference lines and angles (RLAs), and the resulting ratios, based on reproducible anatomic points on sagittal feet radiographs. The key starting point of our evaluation was the previously undescribed length and position of the talus joint line (TJL), from the border of the articular surface of the talus and the posterior process of talus. First, we calculated the relationships between the TJL and the axes of the foot, particularly the anatomic and mechanical lateral talometatarsal angle axes of the first metatarsal. Then, we assessed the relationships with the calcaneus, particularly the lateral heel angle. Finally, we calculated the parameters (angles and coefficients k) derived from the TJL and the foot-bearing points (foot quadrilateral). A total of 64 normal radiographs from 55 patients were analyzed. The values that resulted are as follows: anatomic lateral talometatarsal angle = 28.5° ± 4.5°, mechanical lateral talometatarsal angle = 23.6° ± 3.2°, lateral heel angle = 15.2° ± 3.4°, foot quadrilateral: abc = 144.6° ± 9.4°, bcd = 31.3° ± 2.6°, cda = 79.2° ± 9.8°, dab = 105.0° ± 8.3°, $k1$ = 3.09 ± 0.4, $k2$ = 3.77 ± 0.78, and $k3$ = 1.56 ± 0.24. Sagittal plane reference lines and angles are proposed, providing quantitative values for reference. These parameters have the potential to be easily implemented in foot deformity analysis and correction planning.

Accurate preoperative planning in midfoot and hindfoot deformities is possible only with a thorough understanding of reference lines and angles (RLAs) of the foot, which are the basis for planning surgical correction and ensuring a predictable treatment outcome (1,2). In the case of calcaneus fracture after a fall from a height, the intact talus breaks the calcaneus, pushing its articular surfaces (3). This change in the subtalar joint alters the form of the heel because of the medial and proximal displacement of the body of the calcaneus (4). This in turn leads to anterior impingement of the ankle joint (5) and overloads the cortical layer of the calcaneus (6), which ultimately leads to a limp, affecting the entire lower limb (7–9).

Re-creating the correct spatial relationships between the calcaneus and talus after such trauma is a key factor for the restoration of normal lower limb function, and ultimately for improving the quality of life of patients (10). This same argument can be applied to congenital deformities of the hindfoot (3). Many authors have dealt with the definition of RLAs of the hindfoot and midfoot (1,11–14). The most commonly mentioned measurements are Böhler's angle (5,15) for the calcaneus, the talometatarsal angle (Meary's angle) (10), the lateral talocalcaneal angle, the first metatarsal declination angle, the tibiometatarsal angle (16), and the calcaneal-fifth metatarsal angle (17). However, the use of these RLAs provides the measurement of the angles of the deformity without considering the length of the bones. Additionally, deformities of the talus and calcaneus associated with the primary injury or deformity can lead to a significant measurement error. The correction planning technique, specifically the determination of the center of rotation of angulation, or the apex of the deformity, has been described for the foot only with respect to the anterior frontal plane (16) or for correction of ankle joint malalignment (17). Methods of determining the center of rotation of angulation or apex of deformity for hindfoot and midfoot deformities have not entered into the clinical routine. Another significant drawback of the known methods of analysis and planning for deformity correction of the hindfoot is the complexity or impossibility of such analysis in the presence of concomitant deformities of the midfoot,

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ankle joint contractures, or presence of ankylosis of the ankle joint in a nonanatomic position.

To solve these problems, surgeons have tried computer modeling (18,19) and 3-dimensional printing in an attempt to develop surgical simulation technologies for preoperative planning of foot deformity correction (20). However, these models fail to fully capture foot and ankle deformities. Moreover, such efforts have the disadvantage of increased cost of diagnostics (computed tomography and magnetic resonance imaging). They also require very specialized hardware and software. The purpose of our study was to develop a simple method for evaluating and planning deformity correction of the hindfoot, midfoot, and forefoot in the sagittal plane based on standard plain radiographs and measured RLAs.

Patients and Methods

To obtain the desired reference line values, lateral view weightbearing radiographs of feet of living patients were retrospectively analyzed by 2 experienced orthopedic surgeons (L.N.S. and K.A.U.). Inclusion criteria were availability of lateral view weightbearing radiographs at the Vreden Russian Research Institute of Traumatology and Orthopedics and indication for radiography including soft tissue injury and exclusion of fractures. Exclusion criteria were age <18 years, being a professional athlete, or presence of deformity as determined using known reference line schemes and angles (13,16,21). Specifically, after drawing the lines and angles on each of the radiographs, they were checked and compared with RLAs described in the literature, thus confirming absence of pathology. Applying the preceding criteria, a total of 64 normal radiographs from 55 randomly chosen patients (24 of 55 [44%] males and 31 of 55 [56%] females), mean age 36.1 ± 6.6 (range 23 to 54) years, acquired from April to July 2016, were included in the analysis.

Similar to the Roman and Renaissance thought leaders, a human structure was used as the unit of measurement. Vitruvius, for example, said that 4 finger widths equal a palm. We propose the talus joint line (TJL) as the unit of measurement for the foot (Fig. 1). The talar dome is the equivalent to a keystone in an arch, hence an essential part of the arch structure of the foot (Fig. 2).

The TJL is defined by 2 points: the posterior point of the TJL is the border of the articular surface of the talus and the posterior process of talus. The anterior point is the border of the articular surface of the talus and neck of the talus. The length of TJL in millimeters is considered a basic unit of length for the foot, normalized to be equal to 1.

To develop a method for analyzing midfoot corrections for deformity planning, we developed an RLA scheme based on the anatomic axis of the first metatarsal bone, which is the mid-diaphyseal line (Fig. 3), and the mechanical axis, defined as the line that conjoins the midpoints of the proximal and distal articular surfaces, respectively (Fig. 4). All of the RLAs subsequently defined are based on these reference axes.

Based on the anatomic axis, first, it was necessary to understand and measure where and at which angle the TJL is intersected by the anatomic axis of the first metatarsal. Second, it was necessary to determine how far from the intersection point of these 2 lines the head of the first metatarsal lies.

Fig. 1. The talus joint line connecting the posterior border of the articular surface and anterior border of the articular surface of the neck of the talus.

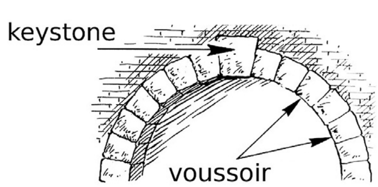

Fig. 2. The keystone of an arch is analogous to the talus in the foot. The other bones of the arch are analogous to the wedge-shaped “voussoirs” of the architectural arch.

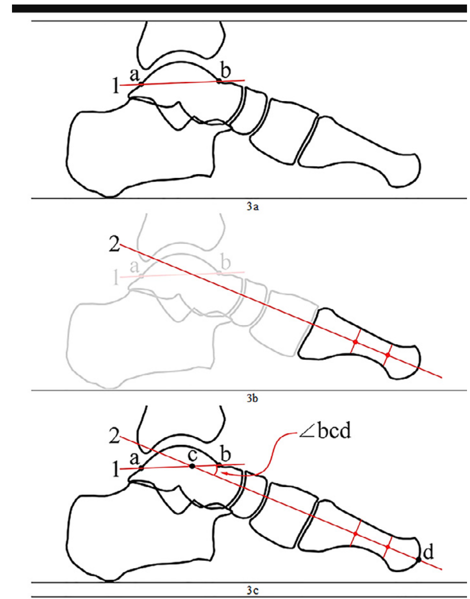

Fig. 3. Identification of the reference lines and angles of the midfoot using the mid-diaphyseal line (anatomic axis) of the first metatarsal bone. (*A*) Line (1) is an extension of the edges of the talus joint line. (*B*) Line (2) is the continuation of the mid-diaphyseal line of the first metatarsal bone. (*C*) determination of the intersection point of line (1) and line (2), for instance, point (c), and the magnitude of the intersection angle of these lines (∠*bcd*). The angle ∠*bcd* is the anatomic lateral talometatarsal angle. Point (d) is located at the intersection of line (2) with the anterior margin of the first metatarsal head. Used with permission, Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore.

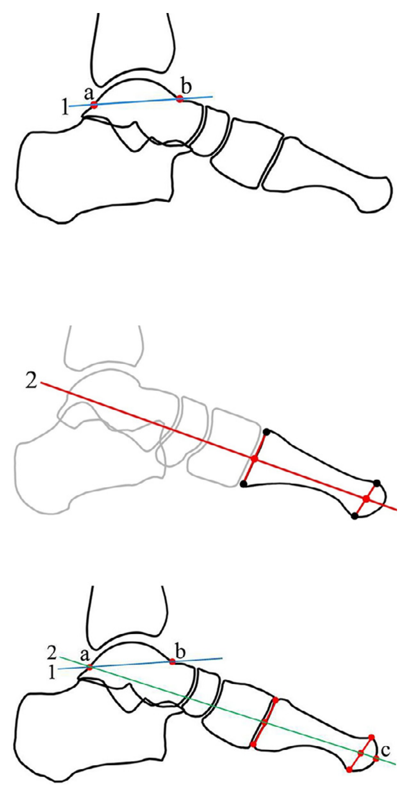

Fig. 4. Reference lines and angles of the midfoot using the mechanical axis of the first metatarsal bone. (*A*) Line (1) is the talus joint line. (*B*) Line (2) is a continuation of the mechanical axis of the first metatarsal. (*C*) The angle ∠bac is the mechanical lateral talometatarsal angle. Point (c) is located at the intersection of line (2) with the anterior margin of the first metatarsal head. Used with permission, Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore.

The following measurements were made on the radiographs included in the study: the TJL, based on points (a) and (b), was designated as line (1) (Fig. 3*A*). Then, a second line, line (2), was marked as the continuation of the mid-diaphyseal (anatomic) axis of the first metatarsal bone (Fig. 3*B*). The point of intersection of line (2) with line (1) was designated point (c). The angle of intersection of line (1) and line (2) (∠bcd) was also determined and denoted as the anatomic lateral talometatarsal angle (aLTMA) (Fig. 3*C*). The intersection of the mid-diaphyseal line of the first metatarsal bone [line (2)] with the anterior edge of the head of the first metatarsal bone was designated point (d). Finally, we determined the distance from point (c) to point (d).

Because the length of the segment |ab| was taken as the conventional unit of measurement (in millimeters), the required distances |ac| and |cd| were related to |ab| as ratios (coefficients, *k*). Thus, the following parameters were identified:

- the intersection angle of line (1) and line (2): ∠bcd = aLTMA
- the ratio of the length of |ac| to the length of |ab|: *k*1 = ac/ab
- the ratio of length |cd| to length |ab|: *k*2 = cd/ab

Based on the mechanical axis, an RLA scheme of the first metatarsal bone was elucidated for midfoot deformity planning (Fig. 4). We studied where and at what angle the TJL intersected the mechanical axis of the first metatarsal and the distance from this intersection point to the head of the first metatarsal.

The following measurements were made on the radiographs included in the study. The TJL, based on points (a) and (b), was adopted as line (1) (Fig. 4*A*). After this, line (2) was drawn, defined as the proximal continuation of the mechanical axis of the first metatarsal bone (Fig. 4*B*). In all cases, the intersection point of line (1) and line (2) was point (a). The point of intersection of line (2) with the distal cortex of the head of the first metatarsal was designated point (c) (Fig. 4*C*). The angle of intersection of line (1) and line (2) (∠bac) was designated the mechanical lateral talometatarsal angle (mLTMA). Thus, the following parameters were identified:

- the angle between line (1) and line (2): ∠bac = mLTMA
- the ratio of the length of |ac| to the length of |ab|: *k* = ac/ab

For hindfoot correction deformity planning, we used an RLA scheme based on the TJL and an axis of calcaneus. First, it was necessary to understand where and at what angle the TJL intersects with the axis of the calcaneus. Second, it was necessary to determine the distance from the intersection point of these 2 lines to the posterior cortex of the calcaneus.

To answer these questions, the following measurements were made: the TJL, based on points (a) and (b), was adopted as line (1) (Fig. 5*A*). Then we drew line (2), the calcaneal axis line. This line starts at the back of the calcaneal tuberosity, point (d), and is drawn perpendicular to a line from top point (e) to the bottom point (f) of the calcaneal tuberosity (Fig. 5*B*). The intersection of the calcaneal line and the TJL is denoted as point (c) (Fig. 5*C*). The angle ∠acd was designated the lateral heel angle (LHA). The following parameters were thus identified:

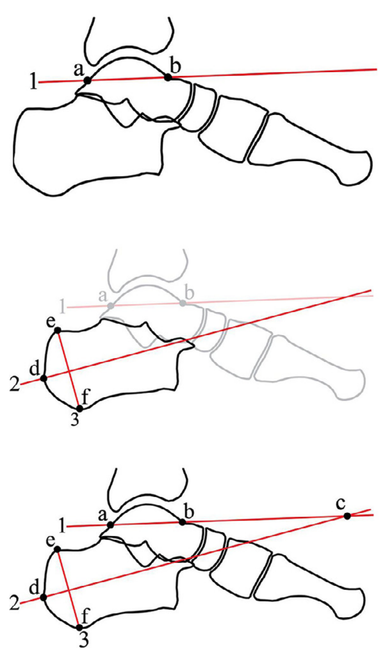

Fig. 5. Reference lines and angles of the hindfoot. (*A*) Line (1) is the talus joint line. (*B*) Line (2) is the calcaneal axis line. (*C*) Point (c) is the intersection point between line (1) and line (2). The angle ∠acd is the lateral heel angle. Point (d) is the posterior cortex of the calcaneus. Used with permission, Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore.

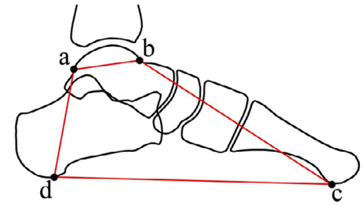

Fig. 6. Four reference points and 4 sides of the foot quadrilateral. Used with permission, Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore.

- magnitude of the angle between line (1) and line (2): ∠acd = LHA
- the ratio of the distance |bc| to the distance |ab|: *k*1 = bc/ab
- the ratio of length |cd| to length |ab|: *k*2 = cd/ab

For the evaluation of the entire foot and the combined deformities of the hindfoot, midfoot, and forefoot, the foot quadrilateral (FQ) was developed (Fig. 6). (This may be considered analogous to the da Vinci "Vitruvian Man" concept of ideal proportions of the entire body.) Points (a) and (b) are the ends of the TJL. Point (c) is the weightbearing (the most plantar) point of the first metatarsal head. Point (d) is the most plantar point of the calcaneus. The following measurements were made to characterize the reference parameters of the FQ:

- value of angles ∠dab, ∠abc, ∠bcd, and ∠cda
- the ratio of the distance |bc| (anterior side) to the distance |ab|: *k*1 = bc/ab
- the ratio of the distance |cd| (bottom side) to the distance |ab|: *k*2 = cd/ab
- the ratio of the distance |ad| (posterior side) to the distance |ab|: *k*3 = ad/ab

The data array obtained from the analysis of the RLAs on the lateral radiographs was statistically processed using Statistica 6.0 software (Dell Inc; Round Rock, TX). We performed a descriptive statistic analysis, particularly reporting the mean ± standard deviation of the obtained values across feet. Considering the retrospective observational design of the study, a specific informed consent and ethics review board approval were not needed according to the local legal regulations.

Results

Fig. 7 summarizes the results for the assessed parameters. For the midfoot, the following RLAs and coefficients were determined. RLAs were as follows: aLTMA = 28.5° ± 4.5°, *k*1 = 0.7 ± 0.3, *k*2 = 3.6 ± 0.2; mLTMA = 23.6° ± 3.2°, *k* = 4.3 ± 0.9. For the hindfoot, the following RLAs and coefficients were determined: LHA = 15.2° ± 3.4°, *k*1 = 2.56 ± 1.1, *k*2 = 4.59 ± 1.0. The FQ reference values were abc = 144.6° ± 9.4°, bcd = 31.3° ± 2.6°, cda = 79.2° ± 9.8°, dab = 105.0° ± 8.3°, *k*1 = 3.09 ± 0.4, *k*2 = 3.77 ± 0.78, *k*3 = 1.56 ± 0.24.

Discussion

The 15th-century Italian Renaissance artist and scientist Leonardo da Vinci described the relative proportions and relationships of the human form in his iconic drawing of the Vitruvian Man (22). This approach credits the great Roman architect Marcus Vitruvius as being the originator of analytic descriptions of the human form (23); hence, his appellation pays homage to Vitruvius ("Le proporzioni del corpo umano secondo Vitruvio"). da Vinci was clearly familiar with the rediscovered work of Vitruvius "On architecture" (circa 30 BCE), albeit minus illustrations, particularly the third book (of 10 on the topic of architecture) in which Vitruvius discussed the principles of symmetry in architecture of temples and how it is analogous to the symmetry of the human form. In the text around his drawing, da Vinci copied the proportions described by Vitruvius and expanded on them. For example, da Vinci quoted Vitruvius: "A palm is four fingers, a foot is four palms, a cubit is six palms, and four cubits make a man." da Vinci expanded this analysis with his own measurements: "the length of the outspread arms is equal to the height of a man, . . . the foot is one

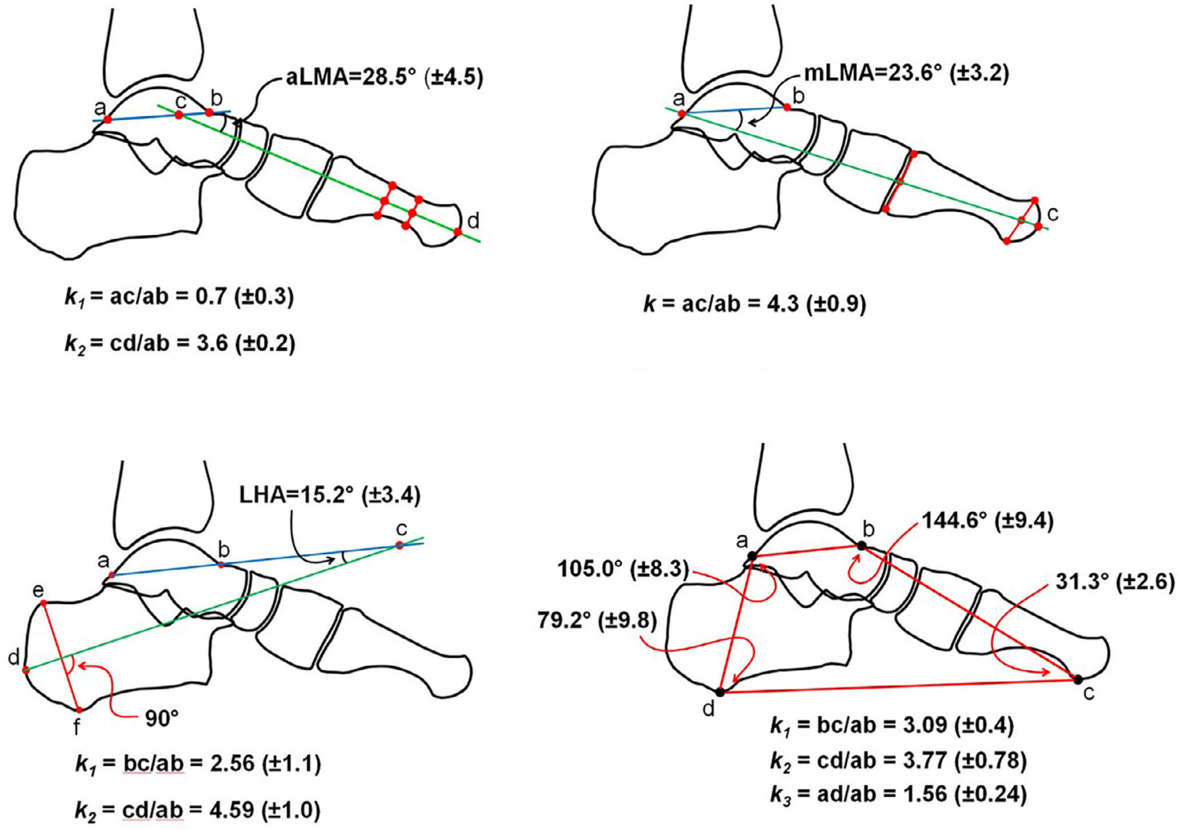

Fig. 7. Foot reference lines and angles (RLAs). (*A*) Midfoot RLAs based on the anatomic axis of the first metatarsal. (*B*) Midfoot RLAs based on the mechanical axis of the first metatarsal. (*C*) Hindfoot RLAs. (*D*) Foot quadrilateral RLAs. Used with permission, Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore.

seventh the height of a man." Just as he was inspired by Vitruvius, da Vinci's work inspired the German Renaissance painter and printmaker Albrecht Dürer to study human proportions, culminating in the posthumous publication (1528) of his "Four Books on Human Proportion" (24), which included Dürer's analysis of the proportions of the foot. In the spirit of da Vinci, Dürer, and other artists who have studied the proportions and relationships of the human body, we propose in this article an innovative description of the form of the human foot (in the sagittal view) with a purpose of using the data to help surgeons reconstruct normal foot anatomy and proportions after trauma, disease, and birth defects. We title our work "The Vitruvian Foot" in homage to the groundbreaking contributions of Marcus Vitruvius and Leonardo da Vinci.

The present study has some limitations. First, the interobserver variability in parameter measurements has not been assessed; however, the measurements were performed by 2 experienced orthopedic surgeons (L.N.S. and K.A.U.) in parallel, and the final measures were defined by consensus. Second, the measurements were performed in the sagittal plane only, not including the frontal and the transverse planes. This is related to the objective to provide a simple and easy-to-use method for deformity assessment.

In conclusion, the present study quantitatively described a normalized foot in terms of both angular and length measurements, analogous to the da Vinci concept of the Vitruvian Man's ideal proportions and angles. This approach for the analysis in the sagittal plane does not depend on the presence of the combined (midfoot + hindfoot) deformity, equinus of the ankle joint, or malpositioned ankle fusion. The methods, based on the proposed foot RLAs, not only can provide a solution for angular and transverse components of sagittal plane foot deformities but also can guide the restoration of the proper length of the middle and hind parts of the foot. Therefore, these are not only planning methods but foot modeling methods as well. The utility of the methods will be explored in future investigations on deformity correction planning.

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