Anatomy and Terminology

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Merrell Kauwe

Osseous Segment Descriptions

The Medial Cuneiform

The medial cuneiform has five surfaces and articulates with the navicular, the intermediate cuneiform, the second metatarsal, and the first metatarsal. The posterior surface articulates with the navicular. It is triangular or pear shaped, as is the corresponding facet on the navicular. The lateral surface is concave with two articular facets. The facet located superior and anterior is small and oval and articulates with the base of the second metatarsal. The superior and posterior facet is in the shape of an inverted L with the long vertical portion posterior and the shorter arm superior. Two ligaments attach to the lateral surface, the lisfranc ligament and the intercuneiform ligament. The medial surface is roughly pentagonal. The anterior-inferior aspect has a small smooth oval surface covered by a bursa that interfaces between the bone and a cartilaginous sesamoid of the tibialis anterior tendon. The tendon attachment begins just posterior to this facet and continues to the base of the first metatarsal. The medial surface also provides attachment for the dorsal and medial cuneonavicular ligaments, the dorsal intercuneiform ligaments, and the dorsal cuneometatarsal ligaments to both the first and second metatarsals. The plantar surface is rectangular and convex medial to lateral. It provides attachment for the peroneus longus at the lateral half of the distal portion just anterior to a tubercle located on the plantar surface. Additional attachments at this surface include the plantar cuneonavicular ligament, plantar intercuneiform ligament, and plantar cuneometatarsal ligaments to both the first and the second metatarsals [31]. The anterior surface of the medial cuneiform articulates with the base of the first metatarsal. It is kidney or reniform in shape. The surface has an average height of 28.3 mm and an average width of 13.1 mm, and both continuous and bilobed facets are common anatomical variants [5]. See Fig. 2.1 for pictorial osteology. All osteology figures were 3D scanned and digitally reconstructed from human skeletal remains (Fig. 2.1).

The First Metatarsal

The first metatarsal is the shortest and strongest of the five metatarsal. It has two articular surfaces. Proximally it articulates with the medial cuneiform and distally with the base of the first proximal phalanx. It is best described using three anatomic segments, the base, the shaft, and the head. There are numerous ligamentous and tendinous attachments. The base is roughly triangular with an inferior, lateral, and medial boarder. The

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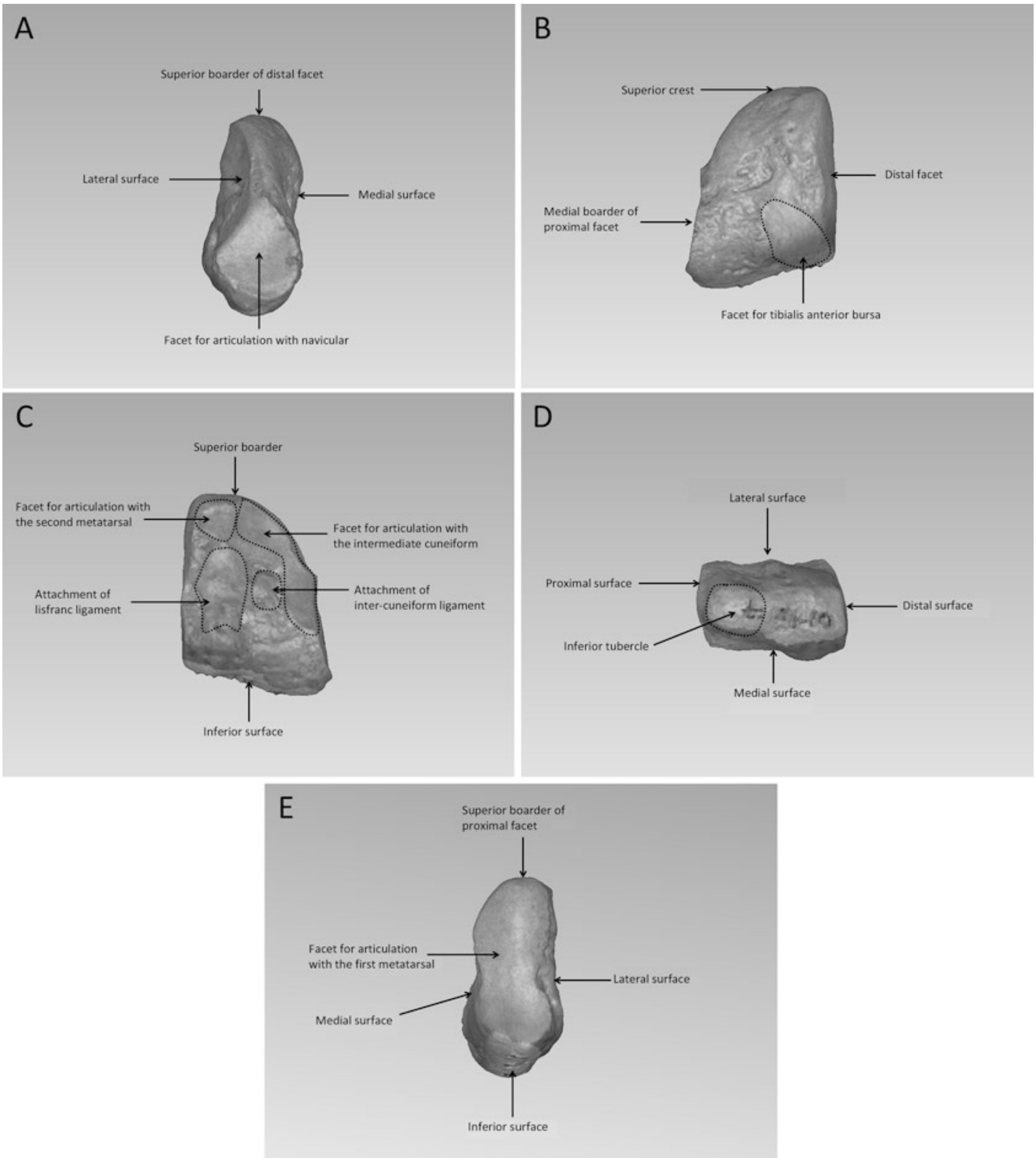

Fig. 2.1 Medial cuneiform. (**a**) Posterior surface. (**b**) Medial surface. (**c**) Lateral surface. (**d**) Inferior surface. (**e**) Superior surface

articular surface of the base is reniform with the hilum facing laterally and a transversely oriented concavity. The tibialis anterior tendon inserts at a tubercle present to the medial-inferior boarder junction. The peroneus longus inserts at a tuberosity present at the junction of the inferior and lateral surfaces. The dorsal and plantar cuneometatarsal ligaments attach to the medial and inferior surfaces, respectively. The lateral surface of the base has an inconsistent articulation with the second metatarsal [29, 33, 37]. The shaft of the first metatarsal has three surfaces: dorsal-medial, lateral, and inferior. The first dorsal interossei inserts into the lateral surface. The plantar surface is concave in a longitudinal direction and its concavity exaggerated by the inferior plantar tubercle. There are three boarders present, the superolateral, inferolateral, and the inferomedial.

The head of the first metatarsal is wider than it is tall, unlike the lesser metatarsals whose vertical diameter is greater than their transverse diameter. The distal surface is covered in cartilage that articulates with the first proximal phalanx. This distal surface is contiguous with the inferior surface that articulates with the sesamoid bones of the first metatarsal phalangeal joint. There are two facets on this surface separated by a ridge or crest called the media crista (Fig. 2.2).

The Great Toe

The proximal phalanx has two articular surfaces. Proximally it articulates with the first metatarsal

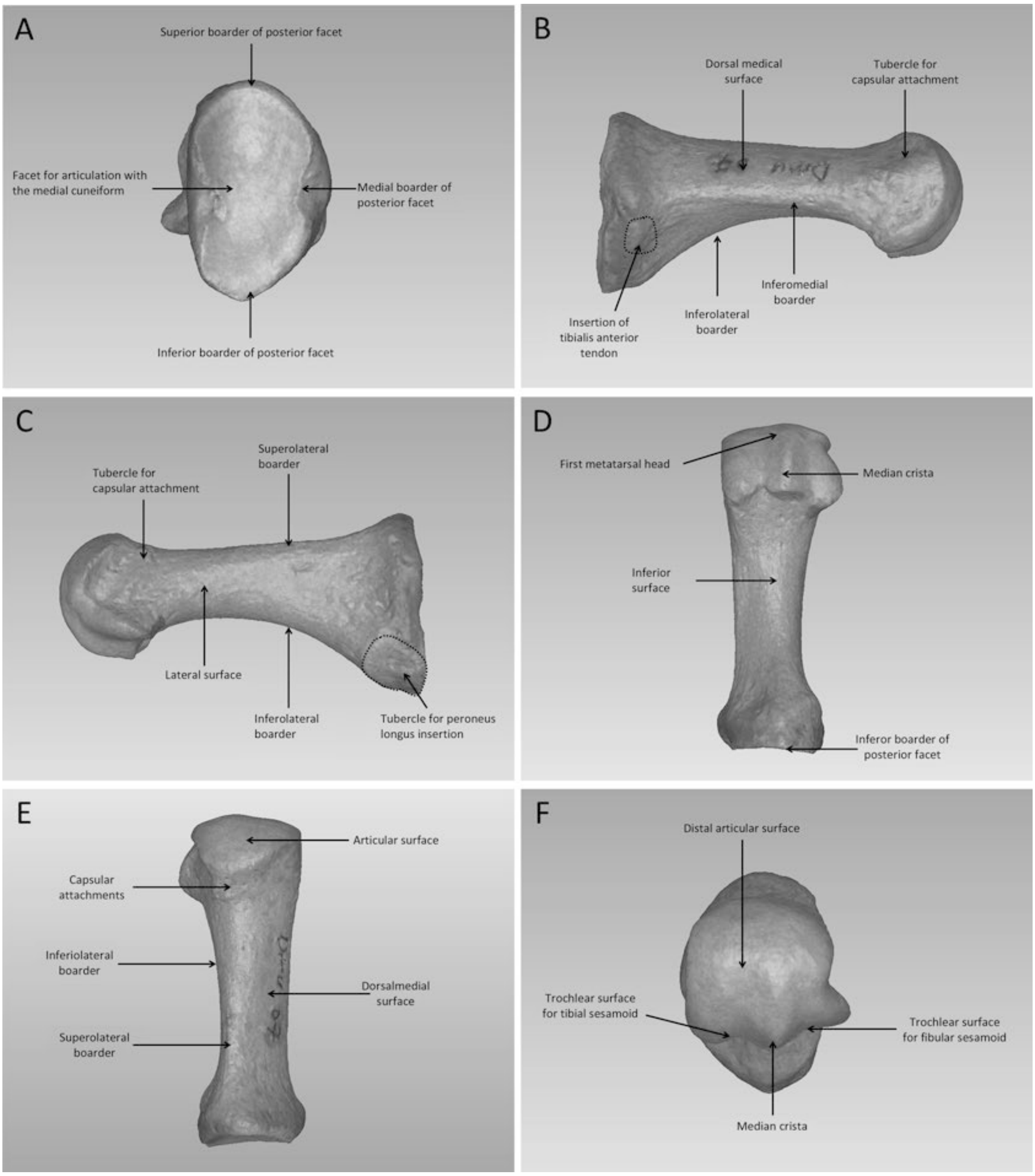

Fig. 2.2 First metatarsal. (**a**) Posterior surface. (**b**) Medial surface. (**c**) Lateral surface. (**d**) Inferior surface. (**e**) Anterior surface. (**f**) Anterior surface

head and distally with the distal phalanx. The base is oriented transversely with an oval posterior facet that is smaller than the metatarsal head it articulates with. This surface is called the glenoid cavity [31]. The dorsal surface provides attachment for the first metatarsal phalangeal joint capsule and the flexor hallucis brevis tendon at a ridge just distal to the proximal articular surface. The plantar surface provides attachments for the abductor hallucis and the adductor hallucis as well as the flexor hallucis brevis and the plantar plate. The shaft is flat plantar with a small groove for the flexor hallucis longus. The dorsal surface is convex. The head is flat with a trochlear articular surface extending more plantar than dorsal. It articulates with the first distal phalanx (Fig. 2.3).

The distal phalanx has a transversely oriented base. The dorsal transverse tubercle just distal to the articular surface serves for attachment of the joint capsule as well as the extensor hallucis longus. The plantar surface has an obliquely oriented ridge from the base to the distal tuberosity providing attachment for the flexor hallucis longus tendon. The distal phalanx deviates laterally approximately 15° from the proximal phalanx [38] (Fig. 2.4).

The Sesamoids of the First Metatarsal Phalangeal Joint

The non-articular surface is convex in both bones. These surfaces provide multiple attachments including medial and lateral attachments for the flexor hallucis brevis and medial and lateral suspensory metatarsosesamoid ligaments. Laterally there is attachment for the transvers and oblique portions of the adductor hallucis and the deep transverse intermetatarsal ligament. Medially there is attachment for the abductor hallucis tendon. The sesamoids are

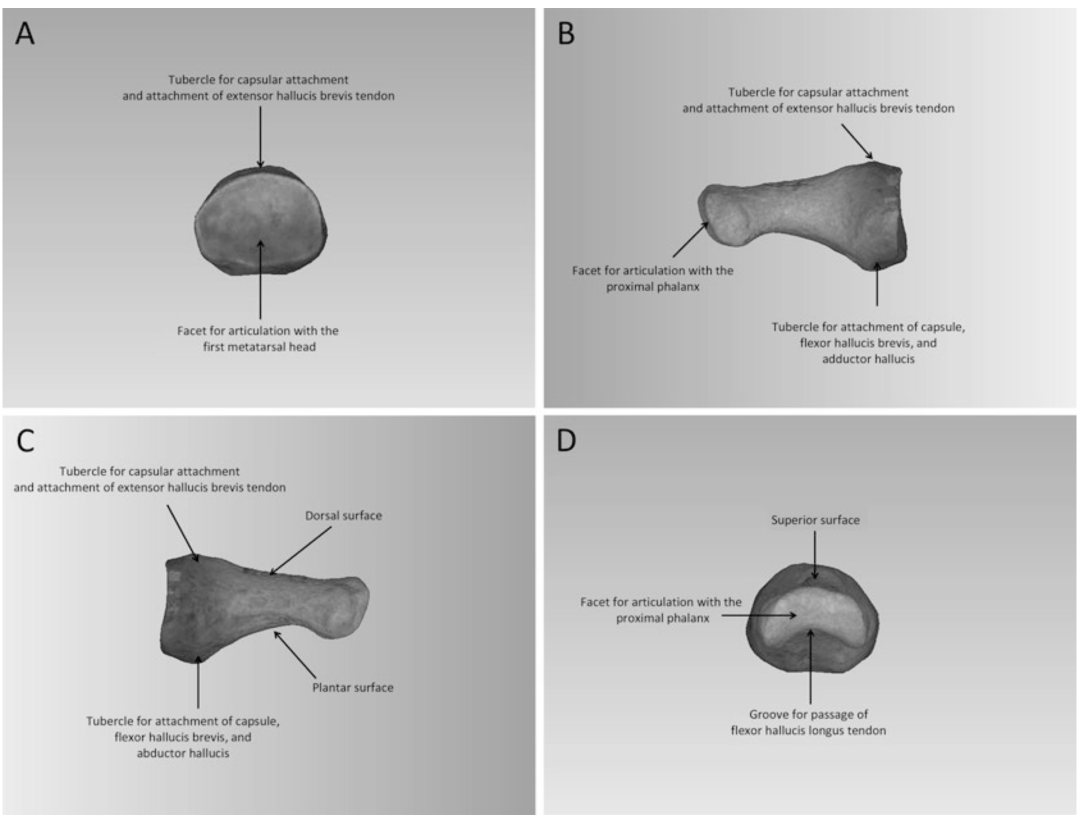

Fig. 2.3 Proximal phalanx. (**a**) Posterior surface. (**b**) Medial surface. (**c**) Lateral surface. (**d**) Anterior surface

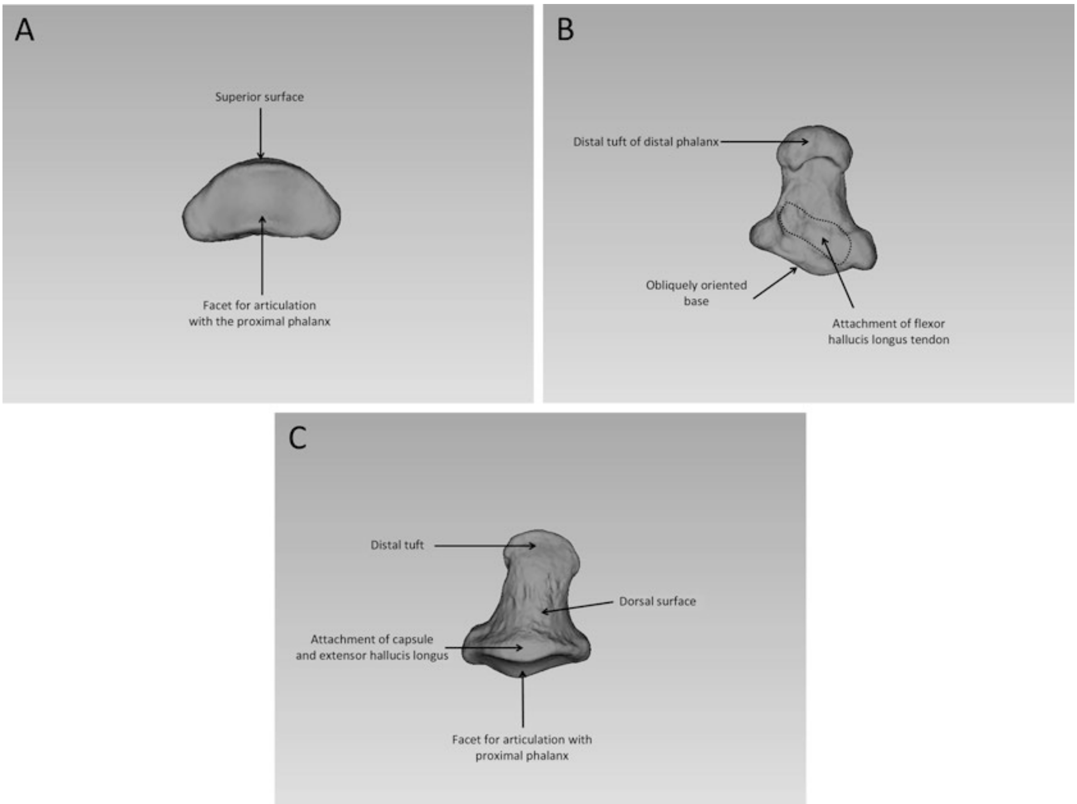

Fig. 2.4 Distal phalanx. (**a**) Posterior surface. (**b**) Inferior surface. (**c**) Superior surface

embedded into the thick plantar plate and within the flexor hallucis brevis tendon. There are two surfaces, articular and non-articular. The shape and size of these are variable [31], though the medial or tibial sesamoid is consistently larger than the lateral or fibular sesamoid. The articular surface interfaces with the inferior portion of the first metatarsal head. The sesamoids are concave longitudinally and slightly convex transversely. The sesamoids are primarily connected to each other via the plantar plate, but there is a thin fibrous band also noted termed the intersesamoidal ligament. They have intracapsular connections to the base of the proximal phalanx at the plantar tubercles and attachment to the metatarsal head via the metatarsosesamoidal ligaments. The sesamoids normally move with the phalanx relative to the first metatarsal head.

Orientation and Motion of the First Tarsal Metatarsal Joint

The first tarsometatarsal joint has been identified as the apex or center of rotational angulation (CORA) of a bunion [20, 25, 27, 35, 39] with the shape of the distal aspect of the cuneiform described as one of the predisposing features in the development of the deformity. Some have argued that the oblique shape of the cuneiform in bunion-affected feet is an inherited atavistic or ancestral trait. A similar obliquity is noted in human fetal development that decreases as the fetus progresses but is retained in other primates. This ancestral trait remains expressed in individuals with bunions. Others argue that the biomechanical flaws cause stress and strain and the obliquity observed is a result of the Wolf and Davis law as the bone remodels in response

[1, 8, 24]. One investigator found that the appearance of an atavistic cuneiform was a function of radiographic projection rather than actual intrinsic deformity and x-ray tube angle, foot position, and metatarsal declination angle affected the relative appearance of atavism [40]. They concluded that radiographic measurement of obliquity did not indicate true anatomic structure and that one should look to a source besides cuneiform shape in understanding bunion development. This finding is corroborated by Dayton et al. [4] in a study on the effect of a first metatarsal phalangeal joint fusion on cuneiform obliquity. They found that the one-to-two intermetatarsal angle decreased with the fusion as did the measureable cuneiform obliquity on standard anterior posterior radiograph. Not only did they both decrease, but they did so with a linear relationship. They suggested the metatarsal and cuneiform moved together in multiple planes as the deformity was reduced to change the perspective of the cuneiform, thereby altering what is observed on radiograph. The problem two-dimensional imaging poses to a three-dimensional deformity is a recurring conversation in the discussion of bunion evaluation and treatment.

The findings discussed above suggest the first ray, defined as both the first metatarsal and medial cuneiform, is moving as a unit; that motion or position applied to the first metatarsal is translated to movement of the cuneiform and in a linear fashion. For this to happen there would need to be very little motion available at the first metatarsal cuneiform joint. Just how much motion takes place at the first metatarsal cuneiform joint (TMTJ1) is debatable, and while there have been multiple studies that attempt to answer this question, many questions remain. First, there is poor reproducibility and validity with subjective evaluations. Second, measurements of mobility with assistive devices are unable to effectively isolate the metatarsocuneiform joint from the first ray as a whole. An extensive review of the literature on first ray mobility was performed by Roukis in 2003 highlighting an additional problem when finding and answer to how much motion takes place at the first tarsometatarsal joint: the fact that no clear consensus exists regarding direction and range of motion [30]. Additional inquiries into the question of hypermobility have been performed since Roukis' review. One such study, performed by Martin et al. [23], used dynamic fluoroscopic assessment of the foot through gait with full weight bearing. They observed 14 healthy feet and compared these to 8 ft that demonstrated clinical hypermobility and were scheduled for surgical correction of their bunion. The investigators found that maximum dorsal displacement of the first ray was 13.63 mm and 13.06 mm in the normal and bunion-affected patients, respectively, with a mean of 5.27° and 5.56°in the same groups. These values did not show statistical difference in the first ray motion. They also looked at relative translations of the osseous segments and found an average of only 2.61° of sagittal motion at the first metatarsal cuneiform articulation. An average of 5.63 and 4.83° of sagittal motion were observed at the cuneonavicular (CN) articulation and the talonavicular (TN) articulation, respectively. Maximum sagittal plane motion was found at the CN and TN articulations with comparatively little TMT1 motion observed.

Proximal motion may be the reason that persistent instability in multiple planes is retained at the first ray following first tarsal metatarsal joint arthrodesis. Galli et al. [11] performed a cadaveric study in which sagittal plane motion of the first ray was assessed before and after TMTJ1 joint fixation. They found the sagittal motion of the first ray was 7.45 mm prior to fixation and 4.41 mm following fixation. It was only after addition of intermediate cuneiform fixation from the base of the first metatarsal that they found significantly enhanced sagittal plane stability of the first ray. Fleming et al. noted intraoperative transverse plane instability of the first ray as evidenced by their hook test following TMTJ1 fusion. They showed transverse deviation of the first metatarsal with widening of the one-to-two IMA as they transversely stressed the fixated first ray and hypothesized that intercuneiform instability was the cause of retained instability. They proposed routing "spot welding" of the bases of the first two metatarsals to combat this instability [10]. Feilmeier et al. performed a cadaveric study to assess instability following TMTJ1 fusion [42].

After fixating the TMTJ1, they placed screws from the first ray into lateral osseous structures with in varying configurations and measured changes to the common hallux valgus measurements with transverse and frontal plane forces applied. Fixation of the TMTJ1 did not stabilize the first ray in the transverse or frontal plane. They also found that neither a screw from the medial to the intermediate cuneiform nor a screw from the base of the first metatarsal to the intermediate cuneiform stabilized the transverse or frontal plane to a significant degree. Only a screw from the base of the first to the base of the second metatarsal was able to significantly diminish multiplanar motion of the first ray. In all of these studies, it is clear that instability in multiple planes continues following TMTJ1 fusion indicating that motion of the first ray is not primarily at the TMTJ but comes from other intertarsal joints.

Geng et al. [12] performed an in vivo 3D CT study to assess the first ray hypermobility. Ten control and ten bunion-affected patients with a total of 20 ft in each group were observed. They found that during weight-bearing conditions of the foot, the first ray was pronated or everted from its non-weight-bearing position in all patients with the medial cuneiform more pronated than the first metatarsal. The degree of pronation was significantly larger in the bunion-affected feet. The TMTJ1 did show increased motion in bunion-affected feet in both the sagittal and frontal planes with 1.2° more sagittal motion and 1.19° more of frontal plane motion than the control feet. And, while the TMTJ1 joint did invert when compared to the medial cuneiform, the whole first ray was pronated. The findings are consistent with multiple other investigations that very little motion is present at TMTJ1 and that instability of the first ray in multiple planes exists at a proximal level. Their findings also confirm multiple observations of an everted or pronated first ray in a bunion-deformed foot compared with non-affected feet.

First Metatarsal Position

Despite findings such as Xiang's regarding pronation of the first ray in bunion-affected feet, evaluation of normal vs abnormal position of the first ray and first metatarsal has traditionally focused on the transverse plane aspect of the deformity. In 1951 Hardy and Clapham attempted to describe normal and abnormal positions of the various osseous segments involved in bunion-affected feet. The first metatarsal, hallux, and tibial sesamoid position were included in the assessment. They took weight-bearing anteroposterior (AP) radiographs of 252 control feet and 177 affected feet and performed angular evaluations of the various joint segments. They concluded that the transverse plane angular position of the first metatarsal relative to the second metatarsal in a normal foot averaged 8.5° and 13.0° in affected feet [14]. This deviation of the first metatarsal toward the midline of the body is a universally acknowledge component of a bunion, and the angle's severity is often used to define procedure selection. The position of the first metatarsal in a bunion is reflected in the term *metatarsus primus varus* coined by Truslow in 1925. The term as used by Truslow refers to the angulation of the first metatarsal toward the midline of the body in the transverse plane. He felt this term was more reflective of the deformity and intended to move the mind away from the lateral deviated hallux toward what he felt was the primary level of the deformity, the medially deviated first metatarsal.

While the transverse plane position of the metatarsal is easy to clinically and radiographically observe, the frontal plane position of the metatarsal is not. Because of the difficulty in observation of this position, Hick's axis of first ray motion has been used to presume the frontal plane position of the metatarsal in a bunion without actual observation. As described by Hicks [15] the orientation of the axis of the first ray produces a motion of dorsiflexion with concurrent inversion. Application of the Hick's normal range of motion of the first ray leads to the assumption that in a bunion, the first ray is dorsiflexed and inverted [15]; however, in investigations to date, the first ray has been shown to be everted in a bunion deformity. In 1980, Scranton and Rutkowski used axial radiographs of the first metatarsal phalangeal joint to observe the frontal plane position of the first metatarsal head in normal and bunion feet. They found that while normal feet had an average of 3.1° of pronation, feet with bunions had 14.5° of first metatarsal pronation with the conclusion that three structural components (the laterally deviated hallux, the medially deviated and pronated hallux) must be addressed when surgically addressing bunions [32]. Mortier et al. in 2012 also utilized axial radiographs to assess rotational position of the first metatarsal. They found that significant pronation occurred with 12.7° of metatarsal pronation in feet with bunion deformities. Their study conclude that it was not a structural torsion of the first metatarsal that produced pronation at the head, rather pronation of the entire metatarsal was responsible [25]. Grode and McCarthy in 1980 also observed an axial view, but rather than a radiographic image they viewed frozen frontal plane sections. They describe an everted position of the first metatarsal head in bunion feet as well as the observation that in a bunion, the medial eminence observed on radiograph represents the dorsal-medial surface of the first metatarsal head brought into prominence through rotational, not an actual medial structure. The term eversion used by Grode and McCarthy is synonymous with pronation [13]. A discussion of terminology is treated later in this chapter. Eustace et al., in 1993 [9], used AP radiographs to assess first metatarsal pronation. They observed the translocation of the inferior proximal tuberosity of the base of the first metatarsal. Lateral translocation of the tuberosity occurs with metatarsal pronation. After establishing the amount of translocation that occurs with specific degrees of pronation in a cadaveric model, they applied these quantified amounts to bunion and normal feet. They found significantly more metatarsal pronation in bunion feet than normal feet and concluded additional investigation should be performed regarding de-rotation of the frontal plane position during surgical correction (9).

In 2015 Kim et al. performed a partial weight-bearing CT examination of bunion and normal feet. Nineteen normal feet and 166 bunion-affected feet were studied. They found the transverse deviation of the metatarsal to be very consistent with what was reported by Hardy and Clapham, with normal feet exhibiting a mean 8.6° one-to-two IMA with bunion feet exhibiting a mean 15.0°. They found a mean of 13.8° of first metatarsal pronation in normal feet with bunion feet exhibiting a mean 21.9° of pronation. In total 87.3% of bunion-affected feet had pronated metatarsals. The Kim study also observed the metatarsal phalangeal joint, specifically the sesamoid/first metatarsal articulation. They found that the AP radiographic position of the sesamoids on a seven grade scale did not correlate to true sesamoid subluxation visualized on the CT scan [19]. This again illustrates the difficulty of assessing three-dimensional deformities with two-dimensional images. AP radiographic findings associated with a pronated metatarsal include the transposition of the inferior tuberosity as described by Eustace [9], increased lateral curvature of the first metatarsal as the plantar convexity is brought into view described by D'Amico [41], lateral rounding of the first metatarsal head described by Okuda [26], and an increased appearance of a medial eminence described by Grode and McCarthy [13]. Figure 2.5 highlights two-dimensional findings characteristic of the first metatarsal when it is pronated.

The First Metatarsal Phalangeal Joint and Hallux Position

The first metatarsal phalangeal joint (MTPJ1) is composed of the first metatarsal head, the proximal phalangeal base, the two sesamoid bones, and the joint capsule and ligaments. Normal motion is reported up to 65° of dorsiflexion and 10° of plantarflexion when using the first metatarsal shaft as a reference point (Valmassy). The normal transverse plane alignment of this joint is lateral deviation of the hallux from the first metatarsal by 12–13° [14, 19]. The sesamoids should be aligned under the first metatarsal head on their respective sides of the medial crista. The motion is roughly in the sagittal plane of the foot. Dorsiflexion of MTPJ1 in the sagittal plane allows proper mechanical function of the first ray.

In bunion-deformed feet, these normal relationships are affected. The hallux is laterally deviated in the transverse plane at the level of the

Fig. 2.5 Weight-bearing AP radiograph. Changes observed indicative of frontal plane valgus of the first metatarsal include translocation of the proximal inferior tubercle laterally, increased lateral curvature of the shaft, and lateral rounding of the first metatarsal head, and increased prominence of the medial first metatarsal head. Changes to the first metatarsal phalangeal joint indicating frontal plane valgus include appearance of subluxation of the sesamoid apparatus laterally and increased proximal articular set angle

MTPJ a mean of 30–32.0°. The whole joint complex including the metatarsal, proximal phalanx, and sesamoids are rotated in the frontal plane. This causes abnormal forces at the first metatarsal with force vectors aligned to press the metatarsal medially [25]. This rotational position also causes problems with radiographic interpretation of the joint. The pronated or valgus position of the joint gives the appearance that the metatarsal head has migrated off a stationary sesamoid apparatus when that is not always the case. Multiple investigators have found that the appearance of the lateral deviation of the sesamoids from under the metatarsal head visualized with standard AP radiograph does not correlate to the true position of subluxation because the alteration in perspective is imparted by the pronated position of the joint [2, 4, 18, 19, 21, 34]. Correction of the pronated position of the metatarsal improves sesamoid position and correlates to reduced recurrance (27). Pronation of the MTPJ1 is also purported to be responsible for the radiographic appearance of the proximal articular set angle (PASA) also termed the distal metatarsal articulation angle (DMAA). These equivalent terms are used depending on one's educational and training background. AP radiographic findings associated with a pronated first metatarsal phalangeal joint include the appearance of sesamoid deviation laterally as described by Kim and increased PASA described by Robinson and Lee [28, 22] (Fig. 2.5).

Clarification of Terminology

In both the Hardy and Clapham and the Kim studies, the word valgus refers to the hallux deviation away from the midline of the body and is a transverse plane descriptor. Valgus as used by these authors is defined differently than it is in the term hallux abducto valgus (HAV). HAV refers to the clinically present transverse and frontal plane deviation of the hallux, with abducto referring to the transverse plane deviation and valgus in this instance referring to the frontal plane. This discrepancy in terminology is a consistent finding in descriptions of the first ray and hallux in the bunion-deformed foot and can lead to confusion. One reason that a variety of terms exist in the description of the anatomic segments of a bunion is that knowledge regarding the position of the deformed segments and the etiology of the deformity has evolved over time. This evolution of understanding has progressed in parallel across different disciplines and educational backgrounds. As the understanding of etiology and treatment evolved, the terms used to describe the bunion did as well, though not with unified clarity. Durlacher [7] reported the bunion to be an enlarged first metatarsal phalangeal joint. Heuter [16] reported that it was not an enlargement of the joint; rather it was a lateral deviation of the hallux. He used the term hallux valgus to describe the great toe deviating away from the midline of the body. The term valgus, used by Heuter, is the same definition used by Hardy and Clapham. It describes a transverse plane position. In 1925 Truslow proposed a change in terminology from hallux valgus to metatarsus primus varus. He no longer retained the position of the hallux in his anatomic description. This was because he believed the primary deformity was the first metatarsal deviated toward the midline of the body. The term varus used by Truslow was not a frontal plane descriptor; rather it described the metatarsal deviating toward the midline of the body (37).

These early descriptions only included a single cardinal plane of the body. And though bunions are most easily clinically and radiographically observed in the transverse plane, the deformity exists in all three body planes. Recognizing that no current terminology was in place to describe the current understanding of the multiplanar position of both the hallux and the metatarsal in the bunion-deformed foot, Dayton et al. [3] proposed new terminology. Their publication justifies the new terminology by appealing to work by Huson [17], Sarrafian [31], and Draves [6]; that is, if one uses the tri-axial orthogonal coordinate plane system and transposes the planes used in the leg to the foot with the change in designation due to the foot position following embryologic development, then varus and valgus are more appropriate as frontal plane rather than transverse plane descriptors. This new term, *hallux abducto valgus with metatarsus primus adducto valgus*, captures "the multiplanar nature of the deformity along the entire segment of the first ray and great toe." They also highlight Sarrafian's work on equivalent terms about the axes of the foot. These are depicted in Fig. 2.6. Equivalent terms for the metatarsal and hallux frontal plane rotational position in a bunion are shown in Fig. 2.7.

Summary

Bunions are multiplanar deformities. Over time, observation of position of the osseous segments involved has increased our understanding of the deformity. Clearly, transverse plane deviation of both the hallux and metatarsal takes place, and mounting evidence points to a significant frontal plane component of both the first metatarsal and the

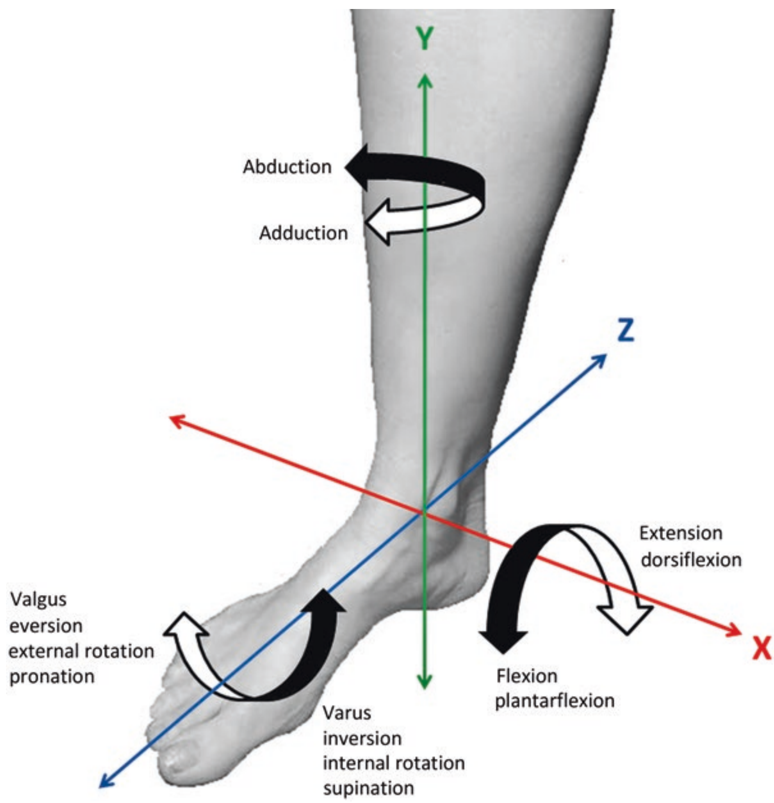

Fig. 2.6 Coordinate plane labeled with equivalent terminology for motion of the foot about each axis. The Y axis gives us motions of abduction and adduction in the foot. The X axis gives us motions of the foot known as flexion or plantarflexion in one direction and extension or dorsiflexion in the opposite. The Z axis gives us motions of the foot known as valgus, external rotation, eversion, or pronation in one direction and varus, inversion, internal rotation, or supination in the other

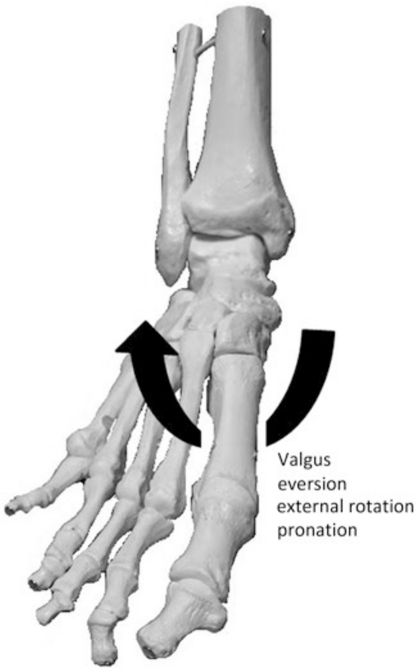

Fig. 2.7 Coordinate plane with Z axis motion about the first ray. The terms used to describe the position of the first metatarsal in a bunion deformity include valgus, eversion, external rotation, and pronation. Hallux abducto valgus with metatarsus primus adducto valgus should be used to describe the multiplanar deformity

hallux. By extension this frontal plane valgus position includes the first metatarsal phalangeal joints and its components, particularly the sesamoid apparatus. Our understanding of the deformity has evolved and accordingly the multiplanar position of the deformity should be reflected. Hallux abducto valgus with metatarsus primus adducto valgus is an appropriate and accurate anatomic term for the greater than 87% of bunion-affected feet that include a rotational component and should be used when a rotational component is present.

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