6 Clinical and Surgical Implications of First Ray Triplane Deformity

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In a bunion deformity, the fundamental problem is a deviation of the hallux at the metatarsophalangeal joint (MTPJ) and deviation of the first metatarsal at the tarsometatarsal joint (TMTJ) from their normal positions. While one plane, namely, the transverse plane, may appear to dominate, there is typically at least some degree of movement in all three planes: the transverse, sagittal, and frontal. This observation is very important when one considers that the most prevalent methods recommended to correct the deformity (metatarsal osteotomy) are in fact altering a deviated but intrinsically straight metatarsal. The starting point for understanding hallux abducto valgus (HAV) deformity, like any bone deformity, is a definition of the point of misalignment of the bone segments, which has been described by many surgeons and researchers [5, 9, 26, 36, 39, 49, 51].

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The apex of the deformity can be defined using the center of rotation angulation (CORA) concept described by Paley [40]. Using this accepted deformity mapping concept, the level of deformity is determined to be at the first TMTJ, and we consider the TMTJ to be the starting point for understanding the pathomechanics of the deformity. Mapping the deformity at the anatomic CORA requires bisection of the mid diaphysis of the first and second metatarsals and comparison of these anatomic axes to the medial cuneiform and proximal phalanx of the hallux. Others [30] have suggested a mechanical axis for the deformity that can be mathematically mapped to a location proximal to the TMTJ. Whether the CORA is anatomically at the TMTJ or defined mechanically at a point proximal is currently a subject of study, however, it is clear that the deformity does not reside distally within the metatarsal (Fig. 6.1).

The next important consideration when describing the anatomy of the deformity is understanding the individual planar components of the deformity. Typically surgeons rely on an anterior-posterior (AP) radiograph almost entirely to define the deformity by measuring the intermetatarsal angle (IMA), hallux valgus angle (HVA), tibial sesamoid position (TSP), and the joint surface angle known both as distal metatarsal articular angle (DMAA) and proximal articular set angle (PASA). It must be pointed out that these are all two-dimensional observations which define only the transverse plane components of the deformity. To identify and characterize the

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Fig. 6.1 (**a**) Mapping of the *CORA* for first metatarsal transverse plane deviation component of HAV deformity. The metatarsal has no intrinsic angular deformity but is deviated from its normal orientation relative to other first ray components. Although this may not represent the true mechanical axis definition for the first ray, it represents the anatomic axis definition of the deformity and the site of correction to realign the first metatarsal. (**b**) The degree of IMA does not change the actual level of the deformity and in reality does not define the deformity despite the common convention of assigning procedure choice based on IMA

other planar components of the deformity (frontal and sagittal), we must look at different landmarks, and it is very helpful to look at the anatomy on axial radiographic projection as well as the lateral radiographic view. Though it's also important to understand that since the AP radiograph is a two-dimensional projection of the three-dimensional anatomy, an out-of-plane deformation, such as frontal plane rotation of the first metatarsal, can substantially change several visible cues on the AP radiograph, and we will discuss the effect rotation has on each of the common radiographic findings.

The practice of preferentially considering the transverse plane of the deformity by relying primarily on AP radiographic measurements gives an incomplete understanding of the deformity and in our opinion is one of the main factors driving poor outcomes and recurrence. If we analyze the majority of the most popular osteotomy procedures, it is clear that correction priority is in a single plane (transverse) with most procedures either angulating or sliding the first metatarsal in the transverse plane while failing to address either the frontal or sagittal planes to a meaningful degree. Despite the published description of the frontal plane component of the first ray deformity dating to the 1950s [35], it has not been common to address this component of the deformity in a bunion operation. Recently there is a renewed interest in the frontal plane position of the first metatarsal and sesamoid alignment, and there are many current publications illustrating the effect frontal plane rotation has on common paradigms of preoperative bunion evaluation and the selection of the corrective procedure. In these studies frontal plane rotation has consistently been observed to be in the direction of eversion (valgus or pronation are equivalent) and has a significant and dramatic effect on the alignment of the first MTPJ including the sesamoids (Fig. 6.2).

Scranton and Rutkowski [47] presented a series of sesamoid axial radiographs to observe the position of the metatarsal. They found feet with bunions had a mean of 14.5° of metatarsal pronation (valgus orientation), while normal feet had a mean of 3.1° of valgus metatarsal orientation. They concluded that the three structural deformities present in a bunion must be corrected: the abducted hallux, the adducted metatarsal, and the pronated or valgus metatarsal position. Mortier et al. [36] also used sesamoid axial radiographs to observe the position of the

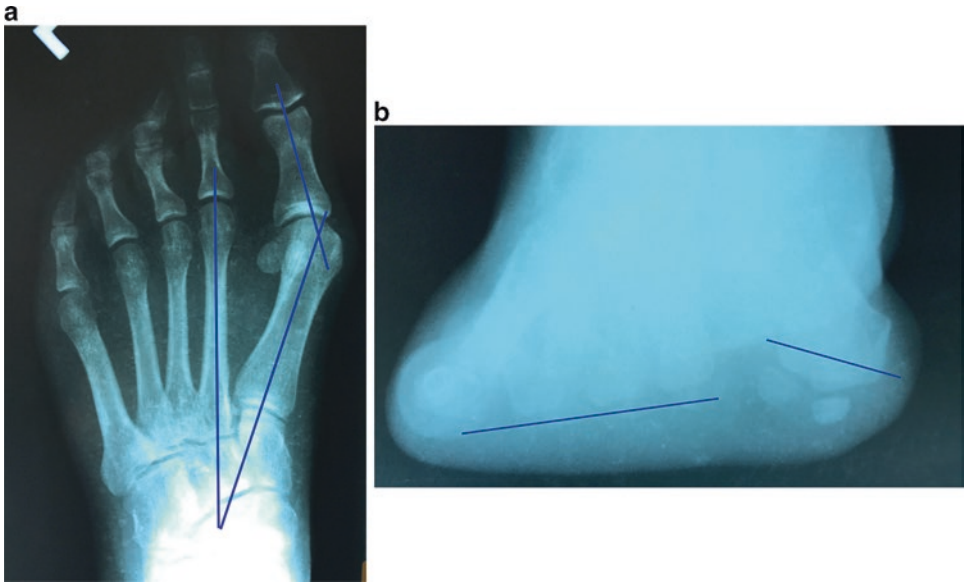

Fig. 6.2 (**a**) The AP radiograph shows typical transverse plane angular findings commonly used for decision-making regarding procedure choice (IMA, HVA, TSP). This view shows a TSP of V. (**b**) Semi-weight-bearing sesamoid axial view clearly showing the sesamoids in their normal anatomic location medial and lateral to the crista. Frontal plane eversion of the first metatarsal relative to the plane of the lesser metatarsals gives the appearance of sesamoid subluxation on the AP view when the sesamoids are in reality in normal alignment relative to the metatarsal head

metatarsal in a bunion deformity. Their novel method of both patient position and measurement showed a mean of 12.7° of metatarsal pronation in feet with bunion deformities. They concluded this rotation was due to metatarsal cuneiform instability rather than torsion of the metatarsal shaft and that valgus metatarsal rotation in bunion deformities is systematic. Eustace et al. [13] devised a way to measure pronation of the first metatarsal based on the observation of the location of the inferior proximal tuberosity of the first metatarsal base. The lateral translation of the tuberosity that takes place with metatarsal pronation or valgus position was established in a cadaveric study. They found that the degree of first metatarsal pronation has a linear relationship to the amount of medial deviation of the first metatarsal. They concluded that derotational surgical procedures should be further explored (Fig. 6.3).

Recent computed tomography studies have clarified the position of the first metatarsal in the frontal plane then in normal and bunion feet. Collan et al. [3] first reported on the use of weight-bearing 3-D CT on hallux valgus patients and found that pronation (valgus position) of the first metatarsal and proximal phalanx existed in all ten patients with hallux valgus. While not found to be statistically significant, they found that the amount of first metatarsal rotation of the hallux valgus group was 8° everted versus the control group of 2°. They found that the cuneiform was rotated into valgus to a greater degree than the first metatarsal although they were both rotated. One methodological issue that may confuse their findings is the fact that while the scans were taken weight bearing, the patient was in single leg stance, not in functional angle and base of gait. This fact alters the overall kinematic relationships because in single leg stance, the weight-bearing extremity is externally rotated inducing supination of the foot. Kim et al. [25] evaluated 166 ft with hallux valgus versus 19 normal control feet utilizing semi-weight-bearing 3-D CT analysis and measured the amount of first metatarsal rotation, which they referred to as the α angle. This angle, representing first metatarsal pronation, averaged 21.9° in their hallux valgus group versus 13.8° in the control

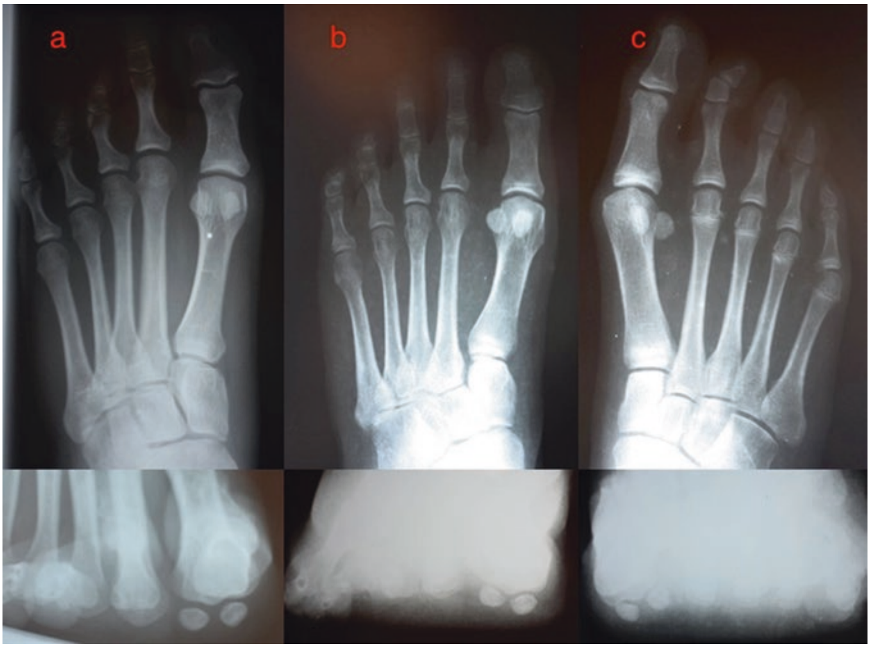

Fig. 6.3 AP and sesamoid axial views of three patients. (**a**) Normal alignment of bone segments used to diagnose HAV and corresponding normal frontal plane rotation of the first metatarsal. (**b**, **c**) Patients with HAV showing the AP and sesamoid axial alignment. Note the easily visible eversion of the first metatarsal in the frontal plane relative to the lesser metatarsal plane

group. They concluded that the first metatarsal pronation in subjects without hallux valgus is typically less than 15.8°, and that pronation higher than 15.8° is abnormal (Fig. 6.4). Kim and colleagues [25] further identified four groups based on the presence of either pronation of the first ray (87.3% of patients) and/or subluxation of the sesamoid (71.7% of patients) (Fig. 6.5). We also have data to suggest that in a foot without HAV, the first metatarsal and/or the first ray are neither pronated or supinated. Lamo-Espinosa et al. [29] found that in normal subjects, the CT appearance of the sesamoid complex showed no subluxation and minimal metatarsal rotation. The utilization of computerized tomography will provide further three-dimensional information to help elucidate the pathomechanics of hallux valgus. A more detailed analysis of CT studies is discussed in Chap. 5.

It is clear that a bunion is in reality a triplane deformity with components in the transverse, sagittal, and frontal planes. Despite this anatomical fact, the most commonly accepted paradigm for the correction of a bunion employs transverse plane metatarsal and, to a lesser extent, hallux osteotomies to reposition the metatarsal in the transverse plane only. Osteotomies must almost universally be combined with lateral capsular release and medial plication to reposition the sesamoids under the metatarsal head which cannot be achieved with osteotomy alone in most cases. The common practice of transverse plane metatarsal osteotomy does not fully address the deformity, and it is not performed at the CORA (which is proximal to the metatarsal), both of which are believed to be principal factors in the high recurrence rates that have been identified with metatarsal osteotomy as discussed in the next chapter (Fig. 6.6).

At this time, we do not know the exact anatomic site of the frontal plane rotation. That is, whether it is occurring at the TMTJ or at a site proximal. Most likely it is occurring at a combination of joints similar to sagittal plane mobility of the medial column which is well known to occur at multiple joints along first ray including the naviculocuneiform joints, talonavicular joint, and to a lesser extent the TMTJ. Studies by

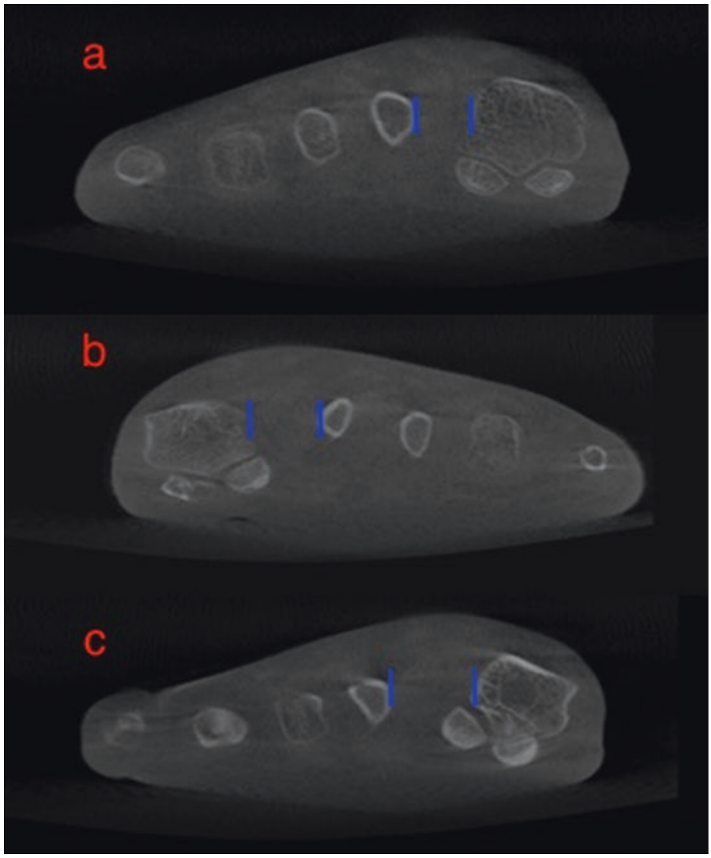

Fig. 6.4 Weight-bearing CT scan views of three patients with hallux valgus deformity (**a**) Patient with small increase in IMA with minimal to no eversion of the first metatarsals. (**b**) Patient with moderate increase in IMA with notable eversion of the first metatarsal relative to the lesser metatarsals. (**c**) Patient with a large increase in IMA again clearly showing eversion of the first metatarsal relative to the lesser metatarsal plane

Johnson and Christensen [20] and Dullaert et al. [11] provide insights into both the frontal plane position of the medial column and the mobility present. Using different models both groups showed in a weight-bearing foot, activation of the peroneus longus tendon pulls the first ray into eversion. Dullaert et al. [11] further stated that if this frontal plane mobility was not controlled through TMTJ fusion for correction of HAV that there is a concern for persistent frontal plane deformity. This phenomenon is a potential cause for poor results and recurrence as discussed in Chap. 7.

Effect of Rotation on Sesamoid Position

From our observations and from available literature, it is clear that radiographic tibial sesamoid position can largely be influenced by metatarsal frontal plane rotation rather than solely an observation of the metatarsal moving off of the sesamoids in the transverse plane [1, 6, 7, 19, 48]. In reality, both frontal plane rotation and transverse plane deviation of the first metatarsal produce the positional components of the bunion deformity. Two-dimensional radiographic findings are directly influenced by the three-dimensional deformity.

Several studies have demonstrated a correlation between the degree of sesamoid displacement observed on AP radiographs and the transverse plane severity of the bunion deformity [22, 34]. Discussion of this correlation often includes the observation that there is a constant position of the sesamoids in relationship to the second metatarsal [16, 17, 22, 42, 46] as well as the proximal phalanx to the second metatarsal [26]. The constant relationship of the sesamoid position in the transverse plane lends itself to a proposed process where the first metatarsal slides medially off of a stable and stationary sesamoid apparatus that is tethered in place via ligamen-

Fig. 6.5 Two patients with HAV and eversion of the first metatarsal relative to the plane of the lesser metatarsals. (**a**) No sesamoid subluxation from the normal position medial and lateral to the crista. (**b**) Everted first metatarsal starting to sublux medially off of the sesamoids with the medial sesamoid now partially on the crista

tous and tendon attachments. However, it is important to understand that the appearance of the sesamoids on AP radiograph is not always indicative of their actual position in relation to the median crista and the bisection of the metatarsal shaft through the median crista. Frontal plane rotation of the first metatarsal can significantly alter what is seen on the AP radiographic projection. The pronated or valgus position of the metatarsal can give the false appearance that the metatarsal head has migrated off of the sesamoid complex and that the fibular sesamoid resides in the interspace when in many cases the sesamoids are still positioned correctly medial and lateral to the median crista of the rotated plantar first metatarsal head (Figs. 6.3 and 6.4).

Inman [19] used a combination of models and radiographs to show that in a valgus or pronated metatarsal position, the sesamoids appear to deviate laterally in an AP radiograph. However, the comparison of sesamoid axial radiographs to their AP counterparts show the sesamoids are still found in their anatomic positions (in their grooves and separated by the median crista) despite their appearance of lateral translocation. Boberg and Judge [1] make the same observation after bunion correction without interspace release. In the majority of their cases, the preoperative AP radiographs showed apparent deviation of the sesamoids, and the sesamoid axial failed to confirm the sesamoid displacement. They explained that the apparent subluxation of the sesamoids is due to an oblique rotation of the metatarsal head much the way that a medial oblique radiograph shifts the perspective making structures appear more lateral. The authors called into question the use of AP radiographic sesamoid measurement as a tool of bunion assessment. Talbot and Saltzman [48] came to a similar conclusion regarding the use of AP radiographs to evaluate sesamoid subluxation. They found that sesamoid position as estimated from AP radiographs did not correlate to the actual sesamoid position when viewed using a tangential

Fig. 6.6 (**a**) Patient who had a sliding osteotomy without correction of frontal plane eversion. The sesamoids are not aligned in the sagittal plane, and therefore the forces exerted by pull of the long and short flexors on the everted sesamoids are angular and pull the hallux into valgus and abduction. There is a medial force exerted by the hallux on the first metatarsal driving increased IMA and recurrence. (**b**) In the normal state the movement of the sesamoids and the hallux are predominantly in the sagittal plane without abnormal angular forces induced by metatarsal and sesamoid rotation

view, a term synonymous with sesamoid axial. The difference between the observations could not be accounted for by changes in MTPJ positioning while obtaining the sesamoid axial view. Because of the valgus (pronated) position of the metatarsal, measurement models based on AP radiographs are not valid in assessing true sesamoid position. These studies are corroborated by a cadaveric study by Dayton et al. [6], in which the first TMTJ was freed and the metatarsal was moved into various degrees of inversion and eversion. With eversion (pronation) of the metatarsal, there was the appearance of lateral displacement of the sesamoids on AP radiograph. With inversion (supination) the apparent sesamoid position was corrected. In this study, the metatarsal clearly did not move off of the sesamoid apparatus, rather rotation altered what was observed on AP radiographs.

Because they recognized the difficulty in assessing sesamoid position from an AP radiograph, Kuwano et al. [28] devised a measurement used to observe sesamoid position on tangential or axial radiographs. Not only did they find a correlation to the degree of HAV and the valgus (pronated) position of the sesamoid apparatus, but they also found the AP assessment of sesamoid subluxation was inadequate to assess true sesamoid position. These results also support the observations from Dayton et al. [6], DiDomenico et al. [9], and Mizuno et al. [35] that varus (supination) rotation imparts correction of sesamoid position on AP radiographs when the coronal plane valgus (pronated) position of the metatarsal is addressed. Kim et al. [25] identified both rotation of the first metatarsal and sesamoid subluxation on CT scans of HAV patients. Both states can exist in isolation and in combination. The striking finding is that, in many cases, the AP radiographic views do not accurately define the position of the sesamoids and thus AP x-rays cannot be reliably used to identify sesamoid subluxation. Obtaining axial views of the sesamoid complex is a necessary and vital part of evaluation

Fig. 6.7 Progressive deviation of the hallux first metatarsal and sesamoids after correction with metatarsal osteotomy and capsular balancing. Note the increase in the HVA, IMA, and apparent re-subluxation of the sesamoids. The axial clearly shows the sesamoids have returned to their normal positions medial and lateral to the crista driving the recurrence

and management of the complex triplane deformity of HAV. Similarly, Katsui et al. [24] found a direct correlation of sesamoid displacement with increased severity of hallux valgus and arthritic changes.

If the pronated or valgus metatarsal is a consistent reason for perceived deviation of the sesamoids, what is really taking place with transverse plane translational osteotomies that produce the appearance of restored sesamoid position in AP radiographs immediately post procedure? In the case of a sliding osteotomy that corrects the IMA but cannot produce inversion (supination) rotation to correct frontal plane position of the metatarsal, we hypothesize that iatrogenic subluxation of the sesamoids medial to the median crista creates the perception that the sesamoids are correctly positioned under the metatarsal on the AP radiograph. This occurs after the lateral release and during the medial capsular plication. An additional explanation is that in some cases a degree of frontal plane correction takes place spontaneously when retrograde buckling forces of the hallux acting on the metatarsal are relieved. If the appearance of sesamoid correction is a result of iatrogenic medial subluxation, then the position on AP radiograph would not be maintained over time. The sesamoids would appear corrected on the postoperative film due solely to the lateral soft tissue release and medial soft tissue plication, but over the ensuing months, the sesamoids would find themselves returning to their anatomic position in the sesamoidal grooves, which are still rotated in a valgus (pronated) orientation. This lateral drift, which is in reality resumption of normal position relative to the metatarsal head, is due to the plantar soft tissues including the short and long flexor tendons resuming their linear orientation after joint motion resumes and therefore pulling the sesamoids back to their anatomic location under the metatarsal head, which is still in a rotated position. This sesamoid position relative to an everted metatarsal would mean recurrence of a displaced

Fig. 6.8 Pre- and postoperative AP and sesamoid axial radiographs of a patient who had correction with included inversion of the first metatarsal in addition to transverse plane angular correction completing triplane realignment and normalizing the forces exerted on the hallux and first metatarsal

appearance of sesamoids on an AP radiograph. Though immediately postop sesamoid position would be predictable and within control of the surgeon via soft tissue balancing, long-term maintenance of this position would not be predictable nor under control of the surgeon as the pathologic position of the metatarsal causing the appearance of subluxation has not been addressed. This would also produce deforming forces from the hallux proximal to the metatarsal because of the lateral position of the sesamoids and tendons as described by Mortier (2012) and can result in recurrence of both the HAV and increased IMA (Fig. 6.7). Thus, if frontal plane metatarsal pronation is present as a component of the deformity (PVB Class 2A or 2B, described in Chap. 5), it must be addressed by the corrective procedure to achieve full anatomical correction of the metatarsal sesamoid complex (Fig. 6.8).

Effect of Rotation on the Appearance and Function of the First MTPJ

Grode and McCarthy [18] looked at an axial representation of the foot through cryomicrotomy rather than radiographs. They sectioned cadaveric feet in multiple planes and at multiple levels in varying degrees of bunion severity. They observed that the position in the medial eminence or "bump" actually represents the dorsomedial surface of the head of the first metatarsal that is "brought into prominence by rotation through eversion." The frontal plane sections of HAV deformities confirmed the metatarsal head is oriented in eversion, a term synonymous with both pronation and valgus in the literature. In a study looking at the medial eminence in bunion and non-bunion feet, Thordarson and Krewer [50] observed that when comparing bunion and normal feet, there was no statistically significant difference in the width of the medial eminence. Their finding was that the average medial eminence in bunions is 4.37 mm and in non-bunions is 4.14 mm concluding that if the goal of bunion surgery is to reconstruct normal anatomy, then medial eminence resection does little to help as there was no significant eminence present. This study was performed prior to the greater acknowledgment of frontal plane rotation, and they did not make an association with frontal plane rotation.

A similar study was performed by Lenz et al. [31], using the same measurement of medial eminence width, they analyzed bunion and non-bunion feet. They found the width of the medial eminence in bunions is statistically different with a mean of 4.40 mm in bunions and 3.28 mm without. Their measurement of medial eminence width of 4.40 mm in a bunion was nearly identical to Thordarson (4.37 mm). However the control group was 3.28 mm versus 4.14 mm measured by Thordarson. A possible explanation for this finding is the effect of metatarsal pronation making the medial head more prominent on AP radiograph. Assuming that the first metatarsal head is more square than circular, when the metatarsal rotates in the frontal plane, the width of the head would enlarge on the AP radiograph. While no study has measured the frontal plane rotation and compared it to medial eminence width, a linear correlation between the two could explain the difference between these two studies (Fig. 6.9).

DiDomenico et al. [9] described a procedural approach to multiplanar bunion correction using the hallux to drive derotation of the valgus metatarsal via ligamentotaxis. As the hallux was moved in a supinated or varus direction, the metatarsal followed. This in turn aligned the metatarsal phalangeal joint reducing the HVA, sesamoid position, and the proximal articular surface angle (PASA/DMAA). The authors noted the resolution of the medial prominence without resection of the medial eminence in their procedure.

We note a consistent reduction in the prominence of the medial first metatarsal prominence

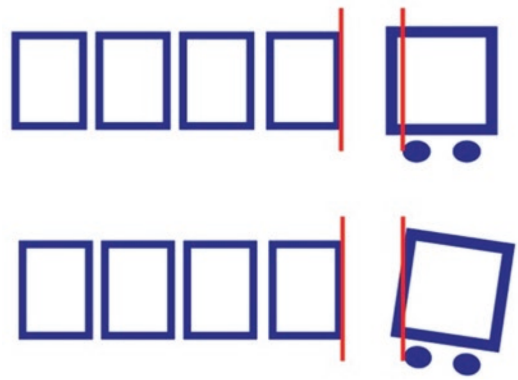

Fig. 6.9 Geometric effect of eversion of the first metatarsal bringing the dorsal medial corner of the first metatarsal into prominence which would show on the AP radiograph as an artificial enlargement of the medial eminence

following triplane correction as well, and we rarely resect any significant bone. The traditional eminence resection removing the section of bone medial to the sagittal groove is unnecessary and undesirable after the metatarsal is supinated into anatomical alignment because it can result in the removal of a large portion of normal joint surface. There are cases in which adventitious thickening of the medial capsule and other soft tissues occurs, and in these cases, capsular thinning reduced the visible medial prominence (Fig. 6.10).

The shape of the lateral first metatarsal head perceived on AP radiographs also changes with frontal plane rotation of the metatarsal. Studies have classified the lateral edge of the first metatarsal head into three shapes: round, square (angular), and chevron (intermediate). Okuda et al. [38] studied these shapes in female patients with moderate to severe bunions, pre- and postoperatively. These shapes were also compared to a control group. They found round metatarsal heads more prevalent in bunion feet than in the control group, while angular shapes were more prevalent in the control group than in the bunion group. They also found postoperatively that some bunions would change from round to either intermediate or angular. In their early follow-up, they noted that if a patient had a positive round sign on AP radiograph, there was a greater hallux valgus angle and a greater chance of recurrence. Their explanation is that as the bunion worsens and frontal plane rotation increases, the lateral first metatarsal head appears more round. When in its anatomic rectus position, the metatarsal head is flattened medially and laterally. With a pronated first metatarsal, the round plantar condyles lateral of the metatarsal head are brought into profile, and their projection appears quite convex on the AP radiograph. They concluded that this lateral round sign, a marker of frontal plane pronation, should be corrected intraoperatively and, if seen postoperatively, is a risk factor for bunion recurrence due to failure of complete derotation to neutral position (Fig. 6.11).

We recently completed a retrospective review of pre- and postoperative AP and sesamoid axial radiographs of bunion patients that confirmed that the sesamoid position identified on the AP radiographic view and the lateral round sign are associated with a pronated position of the first metatarsal (Dayton and Feilmeier 2016 submitted for publication). Seventeen of the 21 feet (81%) included in this review displayed radiographic findings of metatarsal pronation preoperatively based on axial sesamoid views and a positive lateral round sign on AP radiograph. At a mean follow-up of 5.2 ± 1.6 months after triplane

Fig. 6.10 (**a**, **b**) Radiographs showing the dramatic change in the medial eminence prominence on the AP radiograph when inversion of the first metatarsal is included as part of the correction and without medial eminence resection

Fig. 6.11 Pre- and postoperative AP radiographs with corresponding sesamoid axial views showing the shape of the lateral metatarsal head going from rounded in the everted metatarsal position to angular after frontal plane inversion as part of the correction. The change in the appearance of the medial eminence and the joint surface alignment resulting from frontal plane inversion can also be seen

deformity correction, a significant improvement in tibial sesamoid position on both AP and axial radiographs was measured. A negative metatarsal round sign, indicating correction of frontal plane metatarsal rotation, was observed in 20 of the 21 feet (95.2%) on AP radiographic evaluation, and the same number exhibited complete reduction of metatarsal pronation as noted on axial radiograph. Sesamoid subluxation from the normal position with the tibial sesamoid on or lateral to the median crista was noted in 4 feet (19%) preoperatively. All of the patients (100%) had a resolution of sesamoid subluxation on sesamoid axial at final follow-up. The sesamoid axial position was consistently normal when the round sign was absent, and the TSP was in the normal range of 1–3 on AP radiograph.

An additional two-dimensional radiographic finding often used in the definition of the bunion deformity and used in decision-making regarding procedure choice is the PASA/DMAA. Coughlin et al. [4] concluded, "The interobserver reliability in the assessment of the DMAA is questioned." Coughlin further stated that the decreased reliability of this measurement between the different observers was due to the "difficulty in consistently determining the medial and lateral extent of the distal metatarsal articular surface." Robinson et al. [45] also confirmed the PASA/DMAA measurement to be unreliable between observers. In both of these studies, they radiographically measured cadaveric first metatarsals and found that with frontal plane rotation of the metatarsal, the PASA measurements changed. Martin [32] presented a different perspective on the changes at the head of the metatarsal in his critical analysis of PASA. Martin found that preoperative PASA is rarely visualized intraoperatively and often decreased postoperatively without any procedures to address the PASA or the head of the metatarsal. Chi et al. [2] questioned the accuracy and the validity of DMAA and noted in a series of patients that underwent proximal first ray procedures the finding of a consistent reduction in DMAA without distal procedures indicating that this two-dimensional parameter may be a radiographic artifact. This highlights one of the most striking deficiencies in the two-dimensional radiographic analysis. Measurements are made of the articular surface angle and osteotomies chosen to correct this deformity when in fact this measurement may be simply a radiographic artifact that is based on metatarsal frontal plane rotation. Naziri et al. [37] also cautioned against choosing procedures based on DMAA. Using cadaveric feet, a transverse first metatarsal osteotomy was created, and the first metatarsal head was rotated in the frontal plane. An AP radiograph was then obtained using fluoroscopy, and DMAA was measured at certain increments of frontal plane rotation. The measured DMAA was not constant as frontal plane rotation occurred and the rotation caused the DMAA to vary unpredictably. The authors concluded that surgical procedures should not be based on DMAA, as frontal plane rotation in the bunion deformity can cause variance in DMAA. This emphasizes the point that frontal plane rotation should be evaluated and an integral component in the workup for bunion correction.

If the PASA/DMAA is indeed a radiographic artifact, which is becoming more apparent, we have to question the wisdom of performing additional procedures aimed at changing the joint surface alignment. When a transverse plane sliding or angulation osteotomy is done without coronal supination the joint surface angle (PASA/DMAA) may appear worse. On the other hand, it is interesting to observe the degree of change that can be seen in the PASA/DMAA when the pronated position of the metatarsal is corrected. Dayton et al. (2012) measured the IMA, hallux abductus angle (HAA), PASA, and TSP on weight-bearing radiographs of 25 ft in 24 patients who underwent tarsal metatarsal corrective arthrodesis without lateral capsular release. Specific attention was given to the reduction of the frontal plane rotation of the first metatarsal during correction. Angular measurements observed by four investigators identified a mean change in IM angle of 10.1°, HAA of 17.8°, and a mean change in TSP of 3.8. A very interesting finding regarding apparent joint surface alignment was noted with a mean reduction in PASA of 18.7° without osteotomy of the metatarsal head or any soft tissue or bone joint balancing (Fig. 6.12).

This makes a strong argument for radiographic appearance of joint surface angulation being merely a product of the nonspherical head of the metatarsal casting a deviated radiographic image rather than a true anatomic deformity of the distal metatarsal. Considering this, the common practice of doing secondary wedge osteotomies to realign the joint surface may not be necessary. Triplane correction with the addition of metatarsal supination is an excellent alternative to secondary osteotomies to realign the joint surface. Additionally, we need to recognize that measured PASA/DMAA abnormalities are often a result of radiographic artifact, and we perform an osteotomy in an attempt to correct the artificial abnormal alignment; we have not only performed an unnecessary osteotomy but also created a new deformity and exposed the patient to further surgical morbidity, healing, and scarring.

Finally, the function of the first MTPJ is directly affected by frontal plane position of the metatarsal. Ebert et al. [12] presented a poster presentation at the American College of Foot and Ankle Surgeons Annual Scientific Conference 2016 in which they performed a cadaveric experimental study to better understand the impact that frontal plane rotation of the first metatarsal has on first MTPJ ROM. They noted a statistically significant relationship between frontal plane rotation and the first MTPJ ROM in a simulated first TMTJ arthrodesis positioned in 10° increments of increasing valgus position of the first metatarsal. As they increased the valgus position (pronation) of the first metatarsal, there was a resulting decrease in the first MTPJ ROM. Though they did not propose a reason for the decrease in MTPJ ROM, the work of Mortier et al. [36] lends some insight into the mechanism. They discuss the "drive belt" effect that occurs as the first metatarsal pronates in the frontal plane, and the sesamoid apparatus rotates along with it. The sesamoids no longer slide normally in their grooves, and the sagittal plane hallux movement is restricted, replaced by a transverse pull, displacing the hallux laterally. This biomechanical concept can then be extended to provide a potential explanation for the fact that the if the frontal plane malposition of the first metatarsal is not addressed with the bunion correction, there may still be reduction of joint movement because of

Fig. 6.12 (**a**, **b**) Two cases with pre- and postoperative AP radiographs with corresponding sesamoid axial views showing dramatic change in the metatarsal joint surface alignment (PASA/DMAA), TSP, and hallux position after inversion of the first metatarsal relative to the plane of the lesser metatarsals as part of correction without metatarsal osteotomy or capsular balancing

the tethering of the soft tissues that occur as the first MTPJ is not fully restored to its anatomic position and thus lead to joint degeneration over time.

Myerson et al. [33] reported a decrease in the ROM of the first MTPJ in their cohort of 67 patients undergoing a first TMTJ arthrodesis, with ROM 85% of normal postoperatively. Of note is that they performed a closing wedge TMTJ arthrodesis and did not specifically address the frontal plane component of the deformity. If in their procedure the metatarsal was left everted, the previously described binding effect of the sesamoids described may have interfered with motion. This differs from the findings of Perez et al. [41] who noted an increase in first MTPJ ROM after TMTJ fixation. In a cadaveric study they confirmed an increase in the MTPJ ROM and a decreased resistance to dorsiflexion after the TMTJ was fixated with the first ray anatomically aligned in a cadaveric study. Although their model does not prove why the ROM improved, it is important to note that they did not find a reduced first MTPJ ROM after simulated TMTJ fusion in a non-deformed model. It is apparent from these studies, and readily intuitive, that having the first ray positioned in a neutrally rotated position and positioning the sesamoids and muscular and tendinous units purely in the sagittal plane can restore the normal functional MTPJ alignment and consequently preserves MTPJ ROM. Based on extensive study of the first ray anatomy, we believe restoring or maintaining neutral frontal plane rotation prevents binding of the sesamoids and joint surfaces during first MTPJ ROM. The normal motion of the first MTPJ requires dorsal sliding of the hallux with a concurrent plantarflexion of the metatarsal when it moves in the sagittal plane. Frontal plane malposition of the metatarsal and hallux unit disrupts this normal ginglymoarthrodial mechanism. This concept is corroborated by Rush et al. [44] who showed an improvement of first MTPJ ROM after the correction of HAV deformity in a cadaver model. They suggested that the windlass mechanism is more efficient when the first metatarsal, sesamoids, and the hallux are properly aligned with the orientation of the plantar aponeurosis. It is worth noting at this point that the TMTJ is not the source of the majority of motion in the first ray and that normal mechanics of the first ray are minimally affected by TMTJ fusion. Biomechanical analysis has shown that the majority of motion comes from the naviculocuneiform and intercuneiform joints, and this is discussed comprehensively in a review paper by Roukis [43] as well as a biomechanical analysis by Martin et al. [32]. This concept is also reinforced by multiple studies showing that significant transverse, sagittal, and frontal plane instability persist after the elimination of TMTJ motion through fixation [8, 14, 15]. If the TMTJ was the primary anatomic site providing motion of the first ray instability would be eliminated after fixation. The fact that motion persists after fusion and the windlass mechanism seems to be improved after triplane alignment at the TMTJ points to joints other than the TMTJ as prime sites of movement in the first ray. This concept also supports the concept that triplane correction can be carried out through the fusion of the TMTJ without detrimental effects on first ray mechanics including the first MTPJ [23].

We have noted an interesting protective effect on hallux position post correction when frontal plane pronation is corrected to neutral. In some cases, the hallux position and IMA actually improve over time with weight bearing. We believe that this occurs because the sesamoids and the long flexors have been realigned to function purely in the sagittal plane. The activation of the tendons and the normal windlass mechanism during walking no longer place deforming forces on the hallux to pull it laterally and secondarily push the first metatarsal medially. Theoretically and in our experience, this reduces recurrence and in some cases provides for the improvement of the correction over time (Fig. 6.13).

Another interesting effect of realignment procedures for HAV was discussed by Doty and Coughlin [10]. They reviewed multiple studies that indicated an improvement of first ray sagittal plane stability following the correction of HAV with first MTPJ fusion and metatarsal osteotomy correction. They attributed the improved stability to realignment restoring proper mechanics of the first ray. They further stated that this finding may indicate instability in the first ray is a result rather than the cause of HAV deformity. Further indication of abnormal first ray mechanics associated with HAV was reported by Koller et al. [27]. They measured decreased loading under the hallux and increased loading under the lateral metatarsals in patients with HAV and sesamoid subluxation. Looking at this data and the previously cited works, we speculate that this abnormal pressure phenomenon resulted from the alteration of the normal windlass mechanism compromising the plantar flexion effect on the first metatarsal and therefore decreasing the loading at the first and increasing lateral loading.

When looking at the effect of more common osteotomy procedures, a decrease in first MTPJ ROM has been reported. Jones [21] performed a cadaveric study using cadavers with bunions. Following proximal metatarsal osteotomy and distal soft tissue reconstruction, specimens lost 22.6° of dorsiflexion and only 0.6° of plantarflexion. They hypothesize that this selective loss of dorsiflexion is secondary to non-isometric capsular repair or tight intrinsic musculature but could not correlate the loss of motion with an amount of IM or HVA correction. They did not take into account frontal plane rotation or sesamoid position. In performing proximal metatarsal osteotomies, no frontal plane correction is performed; it is possible that the rotated metatarsal leaves the MTPJ out of normal functional alignment and explains the failure to increase first MTPJ ROM. Further, it is possible that the distal soft tissue reconstruction actually displaced the sesamoids from their grooves on the metatarsal, leading to a loss of dorsiflexion. If first MTPJ ROM is reduced in the bunion deformity, then corrective surgery should aim restore the normal functional anatomy of the MTPJ in order to increase first MTPJ ROM back to a nonpathologic state. Therefore, if frontal plane rotation is not addressed, at best, decreased first MTPJ ROM may persist as the sesamoids bind during dorsiflexion and, at worst, displaced sesamoids may lead to a loss of dorsiflexion, HAV recurrence, or hallux varus.

Although not a commonplace in 2016, this concept of metatarsal triplane rotation to correct a

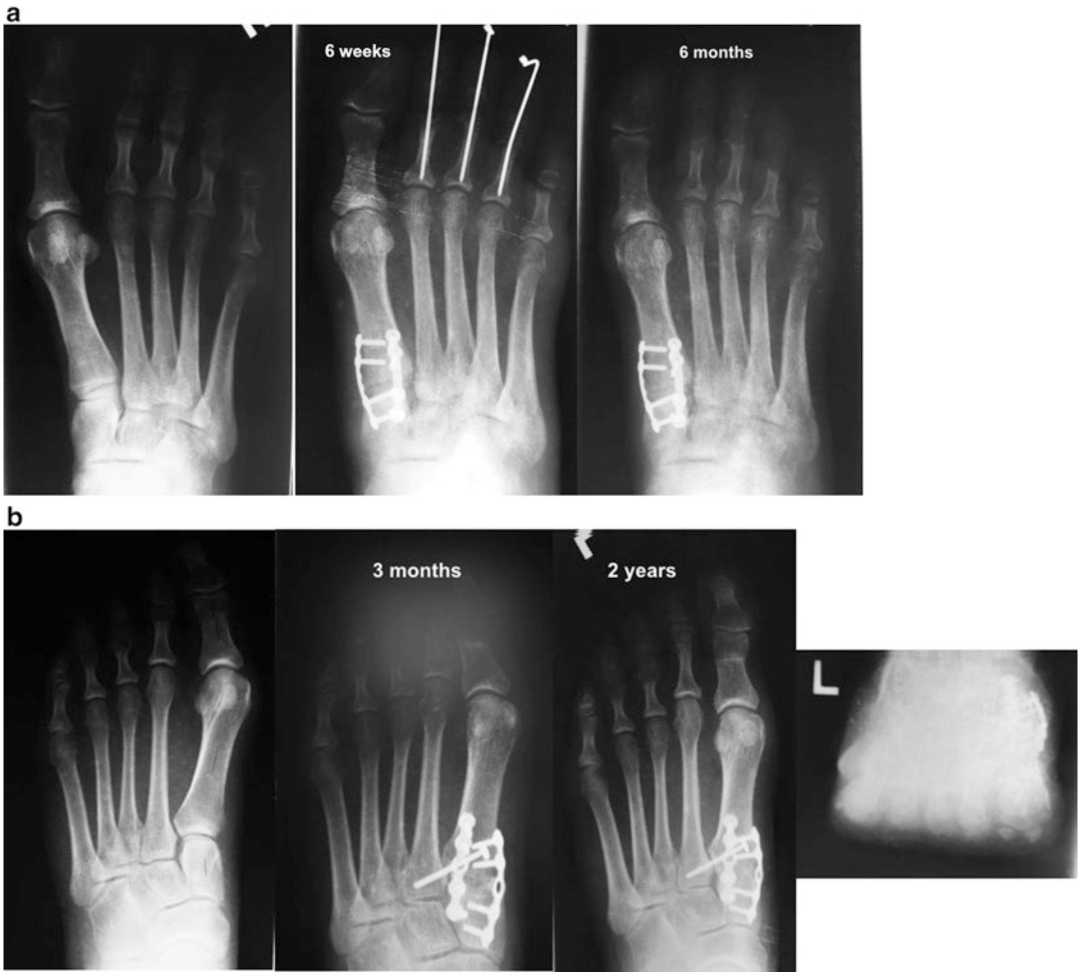

Fig. 6.13 (**a**, **b**) Two cases in which the hallux angle and first ray alignment improved over time. Frontal plane realignment resolved the angular forces on the hallux that occur with tendon pull during the windlass effort during gait. This allowed proper soft tissue alignment to improve the overall alignment. When frontal plane eversion of the first ray remains, the angular forces pull the hallux lateral during weight bearing and push the metatarsal medial resulting in recurrence. Removing rotation seems to protect against this effect

bunion was first described six decades ago. Mizuno [35] observed the frontal plane position of both the hallux and the metatarsal. He used the term torsion to describe the pronated position that the metatarsal assumed as it moved medially. He also proposed a derotational osteotomy of the first metatarsal, termed a "detorsional osteotomy" in his paper. Mizuno's paper highlights a difficulty found in reading about rotational position across the literature. This difficulty lies in the variety of terms used to describe the same pathologic position which can lead to confusion and misunderstanding. We presented an analysis of anatomic nomenclature in an attempt to overcome this semantic stumbling block [7]. With respect to metatarsal rotational position, one should read the terms pronation, valgus, and eversion as equivalent. Likewise, the terms supination, varus, and inversion are equivalent. The term hallux abducto valgus (HAV) with metatarsus primus adducto valgus (MPAV) is used to describe the multiplane deviation of both the hallux and the metatarsal segments within the deformity. This concept is discussed in detail in Chap. 2.

HAV with MPAV is a triplane deformity and correction of the valgus (pronated) position of the metatarsal with osteotomies or arthrodesis that imparts frontal plane mobility which allows the surgeon an ultimate flexibility in obtaining complete and consistent deformity correction. We typically choose a triplane first TMTJ arthrodesis as our preferred procedure because it addresses the deformity at the CORA, and it is at a level in which all components of the deformity can be reduced giving the surgeon complete control of positioning including the transverse, sagittal, and frontal plane. When the surgeon is aware of the rotational position of the metatarsal and understands the intraoperative assessment to observe anatomic alignment, all components of the deformity can be addressed without having to do multiple osteotomies, extensive joint releases, and soft tissue balancing at the MTPJ. The technical concepts for triplane correction will be discussed in detail in Chap. 13.

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