The Journal of Foot & Ankle Surgery 57 (2018) 972–981

Contents lists available at ScienceDirect

The Journal of Foot & Ankle Surgery

journal homepage: www.jfas.org

Review Articles

Triplane Hallux Abducto Valgus Classification

Daniel J. Hatch, DPM, FACFAS [1,2], Robert D. Santrock, MD [3], Bret Smith, DO, MSc [4,5], Paul Dayton, DPM, MS, FACFAS [6,7], Lowell Weil Jr., DPM, MBA, FACFAS [8]

[1]*Surgical Director, Northern Colorado Podiatric Medicine & Surgery Residency, Greeley, CO*
[2]*Clinical Instructor, Dr William M Scholl College of Podiatric Medicine, North Chicago, IL*
[3]*Assistant Professor and Chief of Foot & Ankle Surgery, Department of Orthopaedics, West Virginia University School of Medicine, Morgantown, WV*
[4]*Director, Foot & Ankle Division, Palmetto Health-USC Orthopedic Center, Columbia, SC*
[5]*Assistant Professor, Orthopedics, University of South Carolina, Columbia, SC*
[6]*Attending Staff, UnityPoint Clinic, Fort Dodge, IA*
[7]*Assistant Professor, College of Podiatric Medicine and Surgery, Des Moines University, Des Moines, IA*
[8]*President and Fellowship Director, Weil Foot and Ankle Institute, Des Plaines, IL*

ARTICLE INFO

Level of Clinical Evidence: 5

Keywords:
bunion correction
CORA
first metatarsal
frontal plane rotation
hallux abducto valgus
hallux valgus
3-dimensional

ABSTRACT

One of the most common procedures performed in the foot and ankle is correction of hallux abducto valgus deformity or "bunion surgery." Most foot and ankle surgeons recognize the challenges associated with defining each patient's individual deformity and selecting the optimal procedure for the best long-term results. Using current 2-dimensional algorithms that focus on the severity of the transverse plane deformity, surgical outcomes have varied. In the past 10 years, high recurrence and complication rates for popular procedures have been reported. In the same period, the reported data have elucidated an evolving anatomic understanding of the bunion deformity, with an expansion to 3 dimensions, including the frontal/coronal plane. We present a new classification and approach for the evaluation and procedure selection for bunion surgery. We hope this conceptual treatise on hallux abducto valgus based on clinical consensus and current data will stimulate academic discussion and further research. This anatomic classification is based on the 3-dimensional anatomy of the first ray.

Medical classification systems are most useful if they provide an understanding of the deformity/pathology and then provide some useful insights into the predictable correction of the deformity. The optimal long-term results for bunion surgery have been elusive as demonstrated by the poorer than expected outcomes reported in recent studies (1–5). Bock et al (2) reported a 30% recurrence rate after the scarf procedure. Chong et al (4) discussed a 25.9% patient dissatisfaction rate after 5.2 years of follow-up for patients who had undergone bunion repair. Jeuken et al (5) performed a randomized controlled trial in 2016 and found a 75% recurrence rate in patients who had undergone a chevron or scarf procedure. These studies also reported radiographic recurrence rates ranging from 25% to as high as 78%. Although many bunion repair patients do well and have satisfactory results, the critical scrutiny of these results shows they could be improved. The evaluative parameters should include, not only patient satisfaction and other patient-reported outcome measures, but also anatomic realignment and recurrence of deformity, in particular, because patients are living longer and having more productive lives.

Currently, the most common classification used to determine procedure selection is a severity-based system that relies primarily on the first intermetatarsal angle (IMA) and other transverse plane angular measurements taken from an anteroposterior (AP) radiograph (6). Condon et al (7), in 2002, described the classic considerations in hallux abducto valgus (HAV), referencing the first IMA as normal (<9°), mild (9° to 11°), moderate (11° to 16°), and severe (>16°). Using classification, mild to moderate deformities would require a distal first metatarsal osteotomy, and more "severe" deformities would require more proximal osteotomies or first tarsometatarsal (TMT) fusions. Using this historic 2-dimensional framework, well over 100 procedures have been proposed to treat the HAV deformity with a primary focus on a transverse-plane metatarsal osteotomy at various levels combined with soft tissue balancing procedures at the first metatarsophalangeal (MTP) joint. Deenik et al (8) systematically reviewed the reported data to better understand the evidence basis for classifying HAV deformities according to angular measurements. They concluded that "treatment algorithms for HAV are primarily based on expert opinions and

Financial Disclosure: The authors are consultants for Treace Medical Concepts.
Conflict of Interest: None reported.
Address correspondence to: Daniel James Hatch, DPM, Medical Center of the Rockies, 2500 Rocky Mountain Avenue, Loveland, CO 80538.
E-mail address: dhatch@footandanklecolorado.com (D.J. Hatch).

1067-2516/$ - see front matter © 2018 by the American College of Foot and Ankle Surgeons. All rights reserved.
https://doi.org/10.1053/j.jfas.2018.02.008

Table
Triplane hallux valgus classification and treatment algorithm

Class	Anatomic Findings	MTP Joint Status	Treatment Recommendation
1	Increased HVA and IMA No first metatarsal pronation evident on AP or sesamoid axial radiograph Sesamoids might be subluxed	No clinical or radiographic evidence of DJD	Metatarsal osteotomy or TMT correction; sesamoid release to help realign complex
2A	Increased HVA and IMA First metatarsal pronation evident on AP and sesamoid axial radiographs No sesamoid subluxation on Axial	No clinical or radiographic evidence of DJD	Triplane correction, including first metatarsal inversion, with or without lateral capsulotomy
2B	Increased HVA and IMA First metatarsal pronation evident on AP and sesamoid axial radiographs With sesamoid subluxation on Axial	No clinical or radiographic evidence of DJD	Triplane correction, including first metatarsal inversion plus conservative lateral capsular release before correction
3	Increased HVA and IMA; >20° MTA	No clinical or radiographic evidence of DJD	Metatarsal 2 and 3 transverse plane correction; metatarsal osteotomy or TMT correction per class 1 and 2 recommendations
4	Increased HVA and IMA with or without first metatarsal pronation	Clinical and or radiographic evidence of DJD	First MTP arthrodesis preferred; joint arthroplasty

Abbreviations: AP, anteroposterior; DJD, degenerative joint disease; HVA, hallux valgus angle; IMA, intermetatarsal angle; MTA, metatarsus adductus; MTP, metatarsophalangeal; TMT, tarsometatarsal.

are not supported by level 1 and 2 evidence." Of the parameters used to define the deformity in algorithms, the hallux valgus angle (HVA) was found to be the "single predictive parameter." Historically, the reported data support the HVA and metatarsal 1-2 angle as predictive radiographic indicators of the bunion deformity.

The search for consistent and effective methods for evaluation and management of the bunion deformity has continued for decades with elusive results, and attempts to classify the HAV deformity are numerous. This has resulted in part because the first metatarsal is not usually intrinsically deformed, despite a multitude of "corrective" osteotomies that have been used (9,10). Mizuno et al (11), in 1956, reported that a detorsional osteotomy should be performed for hallux valgus repair to address the valgus rotation of the first metatarsal. Scranton and Rutkowski (12), in 1980, studied 35 cadaveric specimens and found a significant valgus rotation in the bunion group (14.5°) versus the normal group (3.1°). The current data have demonstrated that the HAV deformity is a 3-dimensional condition of the first ray with the anatomic center of rotation angulation (CORA) at the first TMT joint (TMTJ) (13–20). Specifically, it has been consistently demonstrated that frontal/coronal plane rotation of the metatarsal is commonly associated with a HAV deformity, making it a 3-plane deformity. Three-dimensional imaging by Kim et al (18) demonstrated that ≤87% of HAV patients will have a frontal/coronal plane metatarsal rotational component to the deformity. Furthermore, the lack of consideration and treatment of all 3 planes of the deformity have been implicated as potential factors for deformity recurrence (21). With the new information highlighting the existence of frontal/coronal plane rotation of the first ray, it is necessary to consider a new classification system that will clarify both the deformity and a logical triplane anatomic algorithm for treatment. In creating this new classification, an attempt was made, not only to identify the key components of the HAV deformity in all 3 anatomic planes, but also to highlight the key deformities that can significantly affect the outcome of procedures on the first ray.

We present this classification specifically to initiate academic discussion and to generate scientific interest regarding the shortcomings of the common severity-based methods (Table). We hope the use of this system will spark interest in further research and higher levels of evidence. The individual classes are designated by identification and understanding of the key pathologic alignments in all 3 anatomic planes. Therefore, this classification is intended to make surgical interventions more comprehensive for all contributing pathologies. The assessments needed to implement this classification include both clinical assessment of MTP joint health and mobility and radiographic assessment of all 3 planes of metatarsal alignment (transverse, sagittal, frontal/coronal). At a minimum, this radiographic assessment of the foot will require AP, lateral, and axial sesamoid weightbearing radiographs.

Triplane HAV Classification

Class 1

In the class 1 deformity, HAV is present and the IMA is increased only in the transverse plane. No frontal/coronal plane rotational deformity of the first metatarsal will be present in class 1 deformities. Also, no clinical or radiographic indicators of MTP joint degenerative joint disease should be present. Sesamoid subluxation might or might not be present. From semi-weightbearing computed tomographic (CT) scan results, this less common type of deformity might occur in 12.7% of HAV cases (Fig. 1) (19).

Class 1 deformities can be treated using a number of transverse plane corrective procedures, including distal and midshaft first metatarsal osteotomies, because no frontal plane rotational component is present. Additional distal soft tissue procedures might or might not be necessary, depending on the presence of sesamoid subluxation.

Class 2

Class 2 HAV is subdivided into class 2A and class 2B and is defined by an increased HVA and increased IMA with the concurrent presence of frontal/coronal plane pronation/eversion of the first metatarsal. This can be best appreciated on sesamoid axial views. Kim et al (18) described the α-angle to measure pronation in their study. This is the angle formed by the line crossing the plantar condyles of the first metatarsal with respect to the horizontal surface (Fig. 2). They defined pronation as an angle >15.8° (18). Puccinelli et al (20) found in their CT study that the normal pronation observed was 0.8°. As such, when pronation is observed on axial views and correlates with the "apparent" sesamoid subluxation on the AP radiographic projection, rotational deformity correction in the frontal plane should be considered. Just as with class 1, no clinical or radiographic indicators of MTP joint degenerative joint disease should be present. Class 2 might represent

Fig. 1. Radiographs showing class 1 hallux abducto valgus, with no rotation observed on the axial view.

~87.3% of HAV deformities (18). A subdivision of this group is necessary to describe those cases in which sesamoid subluxation is present. For the purposes of this classification, sesamoid subluxation has been defined by the medial sesamoid appearing on or lateral to the central crista of the first metatarsal on a sesamoid axial view.

Fig. 2. Axial sesamoid radiograph showing observation and method of evaluating frontal plane rotation; any angle >0 is deemed pronated for surgical planning.

Class 2A

A class 2A deformity is defined as an increase in the HVA and IMA with pronation/eversion of the first metatarsal in the frontal/coronal plane without any signs of sesamoid subluxation. The sesamoids should remain anatomically positioned within their respective grooves on either side of the crista. The AP radiograph could give the appearance of a “lateral or “pseudosubluxation” of the sesamoids”; however, the axial radiograph will show that the metatarsal is pronated/everted, with the sesamoids located in their respective grooves. This group might represent 25.9% of HAV deformities (18) (Fig. 3).

The recommended surgical treatment should be a triplane correction to address the deformity at or as near to the CORA as possible. The triplane correction should incorporate supination/inversion of the first metatarsal in the frontal/coronal plane to realign the entire segment, including the sesamoids, regardless of the degree of HVA and IMA increase.

Class 2B

Similar to class 2A, the class 2B deformity has an increased HVA and IMA with pronation/eversion of the first metatarsal in the frontal/coronal plane. However, in class 2B, the sesamoids will have subluxed relative to the transverse and frontal plane deviation metatarsal head. The change in position can range from subtle to complete subluxation of 1 or both sesamoids toward the lateral plane compared with the anatomic position on either side of the crista. The theory behind this pathologic subluxation of the sesamoids is that the longstanding frontal/coronal plane rotation and transverse plane deviation of the first metatarsal has subluxed the sesamoids from the metatarsal head. After subluxation, the lateral soft tissues become contracted and, therefore, require release. Class 2B might represent most of HAV deformities at 61.4% (18) (Fig. 4).

The treatment considerations are the same as for class 2A, with a triplane correction required to address the deformity at or as near to the CORA as possible. Because sesamoid subluxation exists class 2B deformities, a distal soft tissue procedure (release) will often be needed to allow the sesamoids to be relocated into their anatomic positions. This release is to relieve any lateral ankylosis and allow for concurrent repositioning of the first metatarsal and hallux. We recommend that the surgeon assess sesamoid subluxation and lateral capsule ankylosis clinically and radiographically at the beginning of the HAV procedure with an axial radiograph. This assessment can be a semi-weightbearing sesamoid axial or an intraoperative axial fluoroscopic view. If subluxation of the sesamoids is present, or if any associated lateral capsular ankylosis is found, a lateral soft tissue release procedure could be necessary.

Class 3

Class 3 is a unique HAV condition associated with the much more global foot deformity of metatarsus adductus (MTA) (22). The rationale for placing MTA into its own class rests on the understanding that this classification relies on not only restoring the foot to a more anatomically stable condition but also to improving biomechanical function. In this unique HAV deformity, the IMA is not often severe and often lacks significant rotation. The MTA should be measured according to the method described by Domínguez and Munuera (23). The HAV condition can therefore be treated in a similar fashion as those for class 1. However, when MTA exists, the traditional angular relationship between the first and second metatarsals does not adequately define the deformity. This deformity should be approached as a global midfoot deformity and not just as a HAV correction. The pathology is not isolated to the first metatarsal and usually has little to no frontal/coronal rotation in this condition. Corrective procedures isolated to

Fig. 3. Radiographs of class 2A hallux abducto valgus showing eversion of the first metatarsal and the sesamoid still in the groove with intact crista.

the first metatarsal will not comprehensively address the deformities of this type of foot abnormality; therefore, a separate algorithm of treatment is necessary (Fig. 5).

Aiyer et al (24) studied the recurrence of hallux valgus in 587 cases, comparing patients who had had underlying MTA to those who had not. Recurrence was defined as an HVA of >20°. The HVA, IMA, and MTA angle (MAA) were all measured, with the MAA considered abnormal if >20°. The recurrence rate was 15% for patients without MTA compared with 29.6% for patients with MTA. The rate of recurrence for the patients with MTA did not vary by procedure (Lapidus 28.5%, distal first metatarsal osteotomy 29.4%, proximal first metatarsal osteotomy 28.9%). Also, patients with less severe MTA (<31°) were shown to have a greater rate of recurrence than those with more severe MTA (82% versus 18%). A previous study reported MTA was associated with HAV in 30% of the cases reviewed (24). Demonstrating the uniqueness of this deformity, Fleischer et al (25) found a relationship between metatarsal adductus and the incidence of Jones fractures. We have noted that the presence of MTA clearly changes the ability to adequately and consistently correct the deformity in the long term, necessitating the inclusion of treatment of this condition as a separate algorithm.

The recommended treatment plan for a class 3 HAV deformity with an MTA >20° is to address the lesser metatarsal adduction first, as described by Sharma and Aydogan (26). The first metatarsal correction can be performed using various described methods. It is possible that a contributing deformity will be present even more proximal than the first TMTJ; therefore, careful evaluation of the transverse tarsal joints and hindfoot is recommended as part of a comprehensive approach to this unique foot pathology.

Class 4

Class 4 is characterized by degenerative health of the MTP joint, often referred to as the "degenerative bunion." The importance of including this class is to be certain that the surgeon recognizes that the clinical and/or radiographic evidence of MTP degeneration should not be ignored (Fig. 6). Although our preferred recommended treatment for this class is a first MTP arthrodesis, surgeons could elect other available arthroplasty techniques, including joint resection and implant arthroplasty. We believe arthrodesis consistently addresses the degenerative pain at the first MTP joint and also provides an adequate and consistent level of HVA and IMA deformity correction. Dayton et

Fig. 4. Radiographs of class 2B hallux abducto valgus showing rotation of the first metatarsal with subluxation of the sesamoid complex.

Fig. 5. Radiographs of class 3 hallux abducto valgus associated with metatarsus adductus, with no first metatarsal frontal/coronal plane rotation seen on sesamoid axial view.

al (27) performed a systematic review to identify deformity correction outcomes after first MTP joint fusion for HAV. The review identified 15 studies that had specifically considered deformity correction of HAV/IMA after isolated primary first MTP joint fusion. Eight studies reported an average preoperative IMA of <15° and had a pooled mean IMA reduction of 3.7°. The remaining 7 studies reported a pooled mean IMA >15° and a mean IMA reduction of 5.42°. Individual studies have shown that the correction expected will be proportional to the preoperative IMA, with a larger degree of correction expected with a larger IMA. This correction obviates the need for additional osteotomy procedures to correct the IMA when MTP joint fusion is used as the index procedure for most bunions.

Fig. 6. Radiographs of class 4 hallux abducto valgus showing arthrosis of the first metatarsal phalangeal sesamoid complex.

Discussion

It is most likely that the first metatarsal in a bunion is not intrinsically deformed but that it and the hallux have deviated from their normal anatomic alignment (10,28). When a single osteotomy procedure or, in some cases, >1 osteotomy in the first metatarsal is chosen, new deformities in the metatarsal can be created, with, at the same time, the original deviation of the metatarsal not being corrected (13,29,30). The practice of creating a surgical deformity of the metatarsal, rather than restoring the normal anatomic alignment of the first ray has been elucidated in deformity correction principles described by Paley (30). This could be one of the reasons for the greater than expected rates of recurrence. Recent studies have shown anatomic recurrence rates ranging from 25% to 78% depending on the procedure studied and, in some cases, the method of measurement used (2–5,31–33). The question is whether these outcomes resulted from poor execution of the procedures or a failure in the basic anatomic definition and preoperative classification of the deformities.

The common transverse plane radiographic parameters do not consider the frontal/coronal plane. The reported data have revealed the consistent presence of a net metatarsal frontal/coronal plane rotation associated with a hallux valgus deformity, making it a triplane deformity (14–19). Therefore, it stands to reason that procedure selection and the classifications used to direct decisions must consider the frontal/coronal plane component of the metatarsal position. Frontal/coronal plane pronation or valgus position of the hallux in a bunion deformity is readily observable clinically. However, it can be difficult to observe the frontal/coronal plane position of the metatarsal during clinical and radiographic examination unless the surgeon understands the specific findings associated with the rotational component of the deformity. In 1980, Scranton and Rutkowski (12) reported a study in which they had used sesamoid axial radiographs to observe the position of the metatarsal and found that feet with bunions had a mean of 14.5° of metatarsal pronation, or valgus position, and normal feet had a mean of 3.1° of valgus position. Mortier et al (14) also used sesamoid axial radiographs to observe the position of the metatarsal in a bunion deformity, reporting a mean 12.7° of metatarsal pronation in feet with bunion deformities. They concluded that this rotation resulted from metatarsal cuneiform instability rather than torsion of the metatarsal shaft and that valgus metatarsal rotation in bunion deformities is systematic (14). Grode and McCarthy (10) studied cadaveric feet in multiple planes and at multiple levels with varying degrees of bunion severity and observed that the position of 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/coronal plane sections confirmed a metatarsal head in eversion, a term synonymous with both pronation and valgus in the reported data. Eustace et al (34) found that the degree of first metatarsal pronation has a linear relationship with the amount of medial deviation of the first metatarsal. They concluded that derotational surgical procedures should be further explored (34).

Recurrence has been related to failure to correct the deformity in all 3 dimensions (21,35). A 3-dimensional (3D) framework will allow surgeons to perform a more complete assessment of the deformity and therefore choose the procedures that will optimally provide the best correction and lead to improved long-term outcomes. The framework incorporates the use of semi-weightbearing axial sesamoid views, in addition to weightbearing AP radiographs to provide a representation of each planar component of the deformity. At present, we do not recommend the need for weightbearing CT evaluations owing to the relatively limited availability of this technology. The use of AP and axial views in combination gives a useful and meaningful representation of the 3D position of the first ray relative to the plane of the lesser metatarsal (36).

Recent CT studies have clarified the relationship of the sesamoids and the first metatarsal in normal and bunion feet. Although earlier 2-dimensional studies by Scranton and Rutkowski (12), Mortier et al (14), and Eustace et al (34) have provided insight into the 3D aspects of the first ray, it was not until the use of CT studies that the pathomechanics of the first ray with HAV could be fully appreciated. In 2015, Geng et al (37) focused on 20 feet in their evaluation of the first metatarsal cuneiform joint with weightbearing CT scans. They found that the medial cuneiform and the first metatarsal were pronated in the HAV group. Kim et al (18), in 2015, evaluated 19 control feet versus 166 feet with HAV (average age 54.5 years) using semi-weightbearing 3D CT analysis. They supported the classification of sesamoid subluxation from 0 to 3 of Smith et al (38). They found a high incidence (87.3%) of pronation of the first metatarsal in the HAV group (>15.8°) (18). They concluded that the candidates could be categorized into 4 groups that included either pronation of the first ray and/or subluxation of the sesamoid, as indicated by Smith et al (38). The net results were as follows. Group 1 had no pronation of the first metatarsal and no sesamoid subluxation (incidence 2.4%). Group 2 had no pronation and positive subluxation of the sesamoids (incidence 10.3%). Group 3 had positive pronation and a negative sesamoid subluxation (incidence 25.9%). Finally, the largest group, group 4, had both pronation and positive sesamoid subluxation (incidence 61.4%). Overall, sesamoid subluxation occurred in 71.7% of the feet and pronation of the first metatarsal was found in 87.3% of the feet in the study group. Again, the first metatarsal might not be intrinsically rotated and that might be the summation of the first ray mechanics. The net effect at the level of the metatarsals when viewed on axial radiographs or CT scans is that of pronation/eversion (20). In 2013, Collan et al (16) first reported on the findings from weightbearing 3D CT for HAV patients compared with a control group. They found that pronation (eversion) of the first metatarsal and proximal phalanx existed in 10 patients with HAV compared with 5 in the control group. Although the difference was not statistically significant, they found that the amount of first metatarsal rotation of the hallux valgus group was 8° everted compared with 2° in the control group (16). They also found that the cuneiform was rotated into valgus to a greater degree than the first metatarsal, although both were pronated. One methodologic issue that might confuse their findings is that although the scans were taken weightbearing, the patient was in single leg stance, not at a functional angle and base of gait. This could have altered the overall kinematic relationships because, in a single leg stance, the weightbearing extremity is externally rotated, inducing supination of the foot. Katsui et al (39) found a direct correlation between sesamoid displacement and increased HAV severity and arthritic changes. Additionally, the study by Lamo-Espinosa et al (40) of normal subjects found the CT appearance of the sesamoid complex was zero using the classification of Yildirim et al (41). Most recently, Campbell et al (42) found greater pronation of the first metatarsal relative to the second metatarsal in the hallux valgus group in their CT study of 10 normal and 10 with hallux valgus. The future usage of CT will likely provide further information to help elucidate the pathomechanics of HAV.

One difficulty in explaining the rotational component or third plane of the metatarsal position in a bunion deformity is terminology. This terminology shortfall was discussed and clarified by Dayton et al (43) in 2014, with the universal description of the deformity defined as "hallux abducto valgus with metatarsus primus adducto valgus." This recommendation considers all 3 planar positions of the hallux and the first metatarsal and describes it from the anatomic perspective of the adult foot. We agree with the investigators that, in the foot, the equivalent frontal/coronal plane positional descriptors are varus/valgus, inversion/eversion, and supination/pronation (44). Although pronation and supination in the hindfoot are multiplanar motions, in the case of the isolated first ray position, supination and pronation are uniplanar frontal/coronal plane positions similar to the open kinetic chain movements of supination and pronation of the wrist. Also, for clarity in communication, the frontal and coronal planes are equivalent terms. Throughout our description, we have used this basic anatomic understanding and terminology to describe the triplane anatomy. “Metatarsus primus varus” has been specifically avoided in favor of “metatarsus primus adductus” to describe the increase in 1-2 IMA and pronation/valgus/eversion has been used to describe the frontal/coronal plane deviation. Similarly, hallux valgus has been abandoned for the more complete triplane designator of HAV.

Similar to the IMA and HVA, evaluation of the sesamoid position is a common radiographic consideration and is one way we attempt to define the deformity. Most investigators have referenced the AP projection evaluation of the sesamoid position as reported by Hardy and Clapman (45). However, the appearance of the sesamoids on an AP radiograph might not be indicative of their actual position in relation to the median crista and the bisection of the metatarsal shaft. In some cases, the sesamoid position seen on the AP radiograph will be a product of the radiographic projection of a pronated/everted metatarsal, with the sesamoids appearing laterally displaced. The sesamoids might be anatomically located in their respective grooves medial and lateral to the crista. Consideration of this artifact caused by the frontal/coronal position of the metatarsal is necessary when classifying the deformity. Recurrence of the deformity has been attributed to failure to completely and consistently correct the sesamoid position (35). This is a vital distinction, and metatarsal rotation must be considered for proper evaluation and management. Frontal/coronal plane rotation of the first metatarsal alters what is perceived on the AP radiographic projection (Fig. 7*A*,*B*). The pronated or valgus position of the metatarsal gives the appearance that

Fig. 7. (*A*) Effect of coronal rotation of the first metatarsal on the perceived position of the sesamoids on anteroposterior radiograph. The sesamoids appear displaced but are, in fact, in normal anatomic position relative to the crista. (*B*) Osteotomy with residual coronal valgus rotation, which was uncorrected during the procedure, with apparent sesamoid subluxation on anteroposterior radiograph but normal position on the axial view.

the metatarsal head has migrated off the sesamoid complex and that the fibular sesamoid resides in the interspace. Inman (46) used a combination of models and radiographs to show that in a valgus or pronated metatarsal the sesamoids will appear to deviate laterally on an AP radiograph. However, a comparison of sesamoid axial radiographs against their AP counterparts will show the sesamoids often are still their anatomic positions (in their grooves and separated by the median crista) despite their appearance of lateral translocation. Catanese et al (47) concluded that the axial view is especially needed when the sesamoid position is ≥4 to 5. Boberg and Judge (48) made an observation on the sesamoid position in a study of bunion correction without interspace release. In most of the cases they reviewed, the preoperative AP radiographs showed apparent deviation of the sesamoids, although the sesamoid axial radiographs failed to confirm sesamoid displacement (48). One possible explanation is that the apparent subluxation of the sesamoids is due to an oblique rotation of the metatarsal head much the same that an oblique radiograph shifts the perspective making structures appear more laterally than is the case. Talbot and Saltzman (49) came to the same conclusion regarding the use of AP radiographs to evaluate sesamoid subluxation. They found that the sesamoid position estimated using AP radiographs did not correlate with the actual sesamoid position when viewed using a tangential view, a term synonymous with sesamoid axial. The difference between the observations could not be accounted for by changes in MTP joint positioning while obtaining the sesamoid axial view. Because of the valgus (pronated) position of the metatarsal, AP radiograph-based measurement models will not be reliable in assessing the true sesamoid position. These studies have been corroborated by multiple published works (17,21,41).

The constant in our classification is an increase in the HVA and IMA as measured on the AP foot radiograph. However, HVA and IMA severity are not used in assigning the appropriate category in the classification or for determining the corrective procedure of choice. The philosophy of our approach is based on triplane deviation and a constant anatomic deformity apex (i.e., CORA), proximal to a nondeformed first metatarsal (29,50). Specifically, we do not use a high IMA and hypermobility of the medial column as necessary indications for a corrective procedure. Instead, we use the anatomic apex of the deformity to choose the level of correction. Because the metatarsal is not typically anatomically deformed, we believe that correction at a level proximal to the deviated metatarsal will result in the most anatomic result and that triplane correction is readily facilitated at the TMTJ. Additionally, we have not included a component of hypermobility in the classification. Although hypermobility might seem intuitive from traditional teaching and practice, the role of hypermobility has not been scientifically proved to either exist at the TMTJ or to be a consistent factor in the deformity or the correction (51). We agree that hypermobility of the first ray might be identifiable as a component of foot deformities, as indicated by King and Toolan (52); however, identification of the joint complex responsible for the hypermobility could also point to joints more proximal to the TMTJ in the first ray complex. Selection of the TMTJ as a preferred site of correction was based on this site being the anatomic CORA, the easiest site to facilitate stabilization between the first and second rays, the best site to establish a collinear effect in the first ray, and the most convenient surgical site to obtain triplane correction (50,53). The added benefit of this site is the ability of the first metatarsal to be stable in all 3 planes, allowing for improved loading and less transfer metatarsalgia by using the windlass mechanism (54).

Other clues to the rotational deformity can be seen on 2-dimensional radiographs in addition to the sesamoid position and proximal articular set angle/distal metatarsal articular angle. The presence of a round appearance of the lateral first metatarsal head has been associated with first metatarsal pronation/eversion and with an increased incidence of deformity recurrence when not addressed through supination/inversion as a part of the corrective procedure (21) (Fig. 8). Rounding of the lateral first metatarsal head represents the profile of the plantar lateral metatarsal head brought into profile by a pronated/everted first metatarsal. In addition to the “round sign,” other observations of metatarsal rotation can be realized by an apparent bowing and thickening of the lateral cortex of the first metatarsal (55) (Fig. 8). This appearance of a more concave and thicker lateral metatarsal shaft cortex is again a radiographic artifact resulting from the plantar cortex of the metatarsal being brought into view when the first ray is pronated/everted.

Fig. 8. Radiographic indicators of first metatarsal frontal/coronal rotation on anteroposterior radiograph: 1, lateral rounding of the metatarsal head, “lateral round sign”; 2, apparent lateral displacement of sesamoids; 3, bowing and cortical thickening of the lateral metatarsal shaft; 4, sesamoid axial view can be used to verify metatarsal rotation.

Fundamental to this new classification system is identification of associated pathologies that could lead to poor outcomes and compromise outcomes such as MTA. Although Shibuya et al (56) reported no correlation between the presence of metatarsal adductus and surgical outcomes, other investigators have reported that these cases are often highly complex and can result in less than favorable outcomes if the MTA is ignored and the bunion deformity alone is corrected (24,26). Therefore, the case of MTA illustrates the complexity of overall foot alignment and the contribution to foot mechanics. A key purpose of our classification system is to provide an anatomic basis to restore the foot to proper 3D alignment and to avoid the complications and deformity recurrence that can occur if triplane correction is not achieved.

The proposed classification of HAV has some shortcoming. First, we based our proposal based on a current review of the reported data and author consensus. The main goal was to provide a framework for discussion and more evidence-based research of this deformity. Second, this classification has not yet been validated. Deenik et al (8) noted that most classifications have been based on "expert opinion" and higher levels of evidence are required. We certainly agree with this finding. Finally, it is imperative that prospective cohort studies and randomized controlled trials be performed. These studies should compare the proposed triplane concepts to the more traditional HAV surgical approach to determine whether any differences occur in outcomes, especially regarding patient satisfaction and foot-related quality of life.

In conclusion, we believe the current paradigm for evaluation of HAV deformity is incomplete. Because it is now understood that recurrence rates with bunion procedures using traditional algorithms are greater than previously thought and have been linked to uncorrected frontal/coronal plane rotation, it is essential to increase the depth of understanding of this complex 3D deformity. We propose rethinking the current paradigm for evaluation and management to include all 3 planes of the deformity. Triplane correction of the first metatarsal position addresses the HAV deformity and could help to maintain the correction over time. Understanding the role that frontal/coronal rotation plays in the mechanics of the HAV deformity and in the radiographic appearance is vital. As we begin to understand the more complex 3D deformity, it will likely push our understanding further. We believe the classification system will provide a basis for improved and consistent surgical outcomes and hope that it will form the basis for further investigations and provide a framework for future research and higher levels of evidence on the HAV deformity.

References

1. Pentikainen I, Ojala R, Ohtonen P, Piippo J, Leppilahti J. Preoperative radiological factors correlated to long-term recurrence of hallux valgus following distal chevron osteotomy. Foot Ankle Int 35:1262–1267, 2014.
2. Bock P, Kluger R, Kristen KH, Mittlböck M, Schuh R, Trnka HJ. The scarf osteotomy with minimally invasive lateral release for treatment of hallux valgus deformity. J Bone Joint Surg Am 97:1238–1245, 2015.
3. Iyer S, Demetracopoulos CA, Sofka CM, Ellis SJ. High rate of recurrence following proximal medial opening wedge osteotomy for correction of moderate hallux valgus. Foot Ankle Int 36:756–763, 2015.
4. Chong A, Nazarian N, Chandrananth J, Tacey M, Shepherd D, Tran P. Surgery for the correction of hallux valgus: minimum five-year results with a validated patient-reported outcome tool and regression analysis. Bone Joint J 97-B:208–214, 2015.
5. Jeuken RM, Schotanus MGM, Kort NP, Deenik A, Jong B, Hendrickx RPM. Long-term follow-up of a randomized controlled trial comparing scarf to chevron osteotomy in hallux valgus correction. Foot Ankle Int 37:687–695, 2016.
6. Coughlin MJ, Freund E. The reliability of angular measurements in hallux valgus deformities. Foot Ankle Int 22:369–379, 2001.
7. Condon F, Kaliszer M, Conhyea D, O'Donnell T, Shaju A, Masterson E. The first intermetatarsal angle in hallux valgus: an analysis of measurement reliability and the error involved. Foot Ankle Int 23:717–721, 2002.
8. Deenik A, Verburg A, Louwerens JW, de Waal Malefijt M, de Bie R. Evidence of treatment algorithms for hallux valgus. JSM Foot Ankle 1:57–68, 2016.
9. Truslow W. Metatarsus primus varus or hallux valgus. J Bone Joint Surg 7:98–108, 1925.
10. Grode SE, McCarthy DJ. The anatomical implications of hallux abducto valgus: a cryomicrotomy study. J Am Podiatry Assoc 70:539–551, 1980.
11. Mizuno S, Sima Y, Yamazaki K. Detorsion osteotomy of the first metatarsal bone in hallux valgus. J Jpn Orthop Assoc 30:813–819, 1956.
12. Scranton PE Jr, Rutkowski R. Anatomic variations in the first ray: part I. Anatomic aspects related to bunion surgery. Clin Orthop Relat Res 151:244–255, 1980.
13. Tanaka Y, Takakura Y, Sugimoto K, Kumai T, Sakamoto T, Kadono K. Precise anatomic configuration changes in the first ray of the hallux valgus foot. Foot Ankle Int 21:651–656, 2000.
14. Mortier J-P, Bernard J-L, Maestro M. Axial rotation of the first metatarsal head in a normal population and hallux valgus patients. Orthop Traumatol Surg Res 98:677–683, 2012.
15. Dayton P, Feilmeier M, Kauwe M, Hirschi J. Relationship of frontal plane rotation of first metatarsal to proximal articular set angle and hallux alignment in patients undergoing tarsometatarsal arthrodesis for hallux abducto valgus: a case series and critical review of the literature. J Foot Ankle Surg 52:348–354, 2013.
16. Collan L, Kankare JA, Mattila K. The biomechanics of the first metatarsal bone in hallux valgus: a preliminary study utilizing a weight bearing extremity CT. Foot Ankle Surg 19:155–161, 2013.
17. DiDomenico LA, Fahim R, Rollandini J, Thomas ZM. Correction of frontal plane rotation of sesamoid apparatus during the Lapidus procedure: a novel approach. J Foot Ankle Surg 53:248–251, 2014.
18. Kim Y, Kim JS, Young KW, Naraghi R, Cho HK, Lee SY. A new measure of tibial sesamoid position in hallux valgus in relation to the coronal rotation of the first metatarsal in CT scans. Foot Ankle Int 36:944–952, 2015.
19. Kimura T, Kubota M, Taguchi T, Suzuki N, Hattori A, Marumo K. Evaluation of first-ray mobility in patients with hallux valgus using weight-bearing CT and a 3-D analysis system: a comparison with normal feet. J Bone Joint Surg Am 99:247–255, 2017.
20. Puccinelli A, Feldman K, Green D, Waalen J. Weight-bearing CT evaluation of first metatarsal frontal plane rotation in hallux abducto valgus deformity. In: *Update 2017: The Proceedings of the Annual Meeting of the Podiatry Institute*, The Podiatry Institute, Decatur, GA, 2017.
21. Okuda R, Kinoshita M, Yasuda T, Jotoku T, Kitano N, Shima H. The shape of the lateral edge of the first metatarsal head as a risk factor for recurrence of hallux valgus. J Bone Joint Surg Am 89:2163–2172, 2007.
22. Coughlin MJ, Jones CP. Hallux valgus: demographics, etiology, and radiographic assessment. Foot Ankle Int 28:759–777, 2007.
23. Domínguez G, Munuera PV. Metatarsus adductus angle in male and female feet: normal values with two measurement techniques. J Am Podiatr Med Assoc 98:364–369, 2008.
24. Aiyer A, Shub J, Shariff R, Ying L, Myerson M. Radiographic recurrence of deformity after hallux valgus surgery in patients with metatarsus adductus. Foot Ankle Int 37:165–171, 2016.
25. Fleischer A, Stack R, Klein E, Baker J, Weil L Jr, Weil LS Sr. Forefoot adduction is a risk factor for jones fracture. J Foot Ankle Surg 56:917–921, 2017.
26. Sharma J, Aydogan U. Algorithm for severe hallux valgus associated with metatarsus adductus. Foot Ankle Int 36:1499–1503, 2015.
27. Dayton P, Feilmeier M, Hunziker B, Nielsen T, Reimer RA. Reduction of the intermetatarsal angle after first metatarsal phalangeal joint arthrodesis: a systematic review. J Foot Ankle Surg 53:620–623, 2014.
28. Thordarson DB, Krewer P. Medial eminence thickness with and without hallux valgus. Foot Ankle Int 23:48–50, 2002.
29. Tanaka Y, Takakura Y, Kumai T, Samoto N, Tamai S. Radiographic analysis of hallux valgus. J Bone Joint Surg Am 77A:205–213, 1995.
30. Paley D. Radiographic assessment of lower limb deformities. In: *Principles of Deformity Correction*, pp. 31–60, Springer, Berlin, 2002.
31. Agrawal Y, Bajaj SK, Flowers MJ. Scarf–Akin osteotomy for hallux valgus in juvenile and adolescent patients. J Pediatr Orthop B 24:535–540, 2015.
32. Edmonds EW, Ek D, Bomar JD, Joffe A, Mubarak SJ. Preliminary radiographic outcomes of surgical correction in juvenile hallux valgus: single proximal, single distal versus double osteotomies. J Pediatr Orthop 35:307–313, 2015.
33. Shibuya N, Thorud JC, Martin LR, Plemmons BS, Jupiter DC. Evaluation of hallux valgus correction with versus without akin proximal phalanx osteotomy. J Foot Ankle Surg 55:910–914, 2016.
34. Eustace S, O'Byrne J, Stack J, Stephens MM. Radiographic features that enable assessment of first metatarsal rotation: the role of pronation in hallux valgus. Skeletal Radiol 22:153–156, 1993.
35. Okuda R, Kinoshita M, Yasuda T, Jotoku T, Kitano N, Shima H. Postoperative incomplete reduction of the sesamoids as a risk factor for recurrence of hallux valgus. J Bone Joint Surg Am 91:1637–1645, 2009.
36. Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. J Biomech Eng 128:604–609, 2006.
37. Geng X, Wang C, Ma X, Wang X, Huang J, Zhang C, Xu J, Yang J. Mobility of the first metatarsal-cuneiform joint in patients with and without hallux valgus: in vivo three-dimensional analysis using computerized tomography scan. J Orthop Surg Res 10:1–7, 2015.
38. Smith RW, Reynolds JC, Stewart MJ. Hallux valgus assessment: report of research committee of American Orthopaedic Foot and Ankle Society. Foot Ankle 5:92–103, 1984.
39. Katsui R, Samoto N, Taniguchi A, Akahane M, Isomoto S, Sugimoto K, Tanaka Y. Relationship between displacement and degenerative changes of the sesamoids in hallux valgus. Foot Ankle Int 37:1303–1309, 2016.
40. Lamo-Espinosa JM, Florez B, Villas C, Pons-Villanueva J, Bondia JM, Alfonso M. Sesamoid position in healthy volunteers without deformity: a computed tomography study. J Foot Ankle Surg 55:461–464, 2016.
41. Yildirim Y, Cabukoglu C, Erol B, Esemenli T. Effect of metatarsophalangeal joint position on the reliability of the tangential sesamoid view in determining sesamoid position. Foot Ankle Int 26:247–250, 2005.
42. Campbell BC, Miller MC, Conti SF. Pronation of the first metatarsal in hallux valgus: 3D clinical measurements, Presented at the 2017 Orthopaedic Research Society Annual Meeting in Poster Format, March 19 to 22, 2017, San Diego, CA. Available at: https://www.ors.org/Transactions/63/1189.pdf. Accessed March 19, 2017.

43. Dayton P, Kauwe M, Kauwe JSK, Feilmeier M, Hirschi J. Observed changes in first metatarsal and medial cuneiform positions after first metatarsophalangeal joint arthrodesis. J Foot Ankle Surg 53:32–35, 2014.
44. Dayton P, Kauwe M, Feilmeier M. Clarification of the anatomic definition of the bunion deformity. J Foot Ankle Surg 53:160–163, 2014.
45. Hardy RH, Clapham JCR. Observations on hallux valgus. Bone Joint J 33-B:376–391, 1951.
46. Inman VT. Hallux valgus: a review of etiologic factors. Orthop Clin North Am 5:59–66, 1974.
47. Catanese D, Popowitz D, Gladstein AZ. Measuring sesamoid position in hallux valgus: when is the sesamoid axial view necessary? Foot Ankle Spec 7:457–459, 2014.
48. Boberg JS, Judge MS. Follow-up of the isolated medial approach to hallux abducto valgus correction without interspace release. J Am Podiatr Med Assoc 92:555–562, 2002.
49. Talbot KD, Saltzman CL. Assessing sesamoid subluxation: how good is the AP radiograph? Foot Ankle Int 19:547–554, 1998.
50. Lapidus P. Operative correction of the metatarsal varus primus in hallux valgus. Surg Gynecol Obstet 58:183–191, 1934.
51. Roukis TS, Landsman AS. Hypermobility of the first ray: a critical review of the literature. J Foot Ankle Surg 42:377–390, 2003.
52. King DM, Toolan BC. Associated deformities and hypermobility in hallux valgus: an investigation with weightbearing radiographs. Foot Ankle Int 25:251–255, 2004.
53. Suzuki J, Tanaka Y, Takaoka T, Kadono K, Takakura Y. Axial radiographic evaluation in hallux valgus: evaluation of the transverse arch in the forefoot. J Orthop Sci 9:446–451, 2004.
54. Klemola T, Leppilahti J, Laine V, Pentikäinen I, Ojala R, Ohtonen P, Savola O. Effect of first tarsometatarsal joint derotational arthrodesis on first ray dynamic stability compared to distal chevron osteotomy. Foot Ankle Int 1–8, 2017.
55. D'Amico JC, Schuster RO. Motion of the first ray: clarification through investigation. J Am Podiatry Assoc 69:17–23, 1979.
56. Shibuya N, Jupiter DC, Plemmons BS, Martin L, Thorud JC. Correction of hallux valgus deformity in association with underlying metatarsus adductus deformity. Foot Ankle Spec 20:1–5, 2017.