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AAFD: Conventional Radiographs are not Enough! I Need the Third Dimension

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Abstract: There is an increasing amount of literature suggesting that 3-dimensional (3D) weight-bearing computed tomography (WBCT) imaging overcomes the inherent limits of traditional bidimensional imaging in foot and ankle surgery. This seems to have a significant impact on the study and on the clinical management of adult acquired flatfooot deformity (AAFD) that by definition is a 3D complex deformity. In this study, we reviewed the recent literature about the use of WBCT in AAFD, starting from a critical analysis about the biases related to conventional radiography and to non-standing CT. Then, we focused on the effects of load on the 3D architecture of the foot and ankle in AAFD. Finally, we discussed the benefits and future perspectives for the use of WBCT in the management of this condition and as a surgical planning tool as well.

Level of Evidence: Diagnostic Level V, expert opinion. See Instructions for Authors for a complete description of levels of evidence.

Key Words: adult acquired flatfoot, pes planovalgus, weight-bearing CT, cone beam, 3D biometrics

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Weight-bearing computed tomography (WBCT) is still too often considered as a 3-dimensional (3D) computed tomography (CT) scan "only nicer because it's weight bearing." Because of our training, we are used to extracting relevant information by intellectually combining the 3D aspect from conventional CT and the weight-bearing (WB) aspect from conventional radiographs in complex foot and ankle deformities. In more standard cases such as most forefoot pathologies, the 3D aspect goes most of the time unseen. And therefore the indications for WBCT do not seem so obvious and undermined by the fact that the conventional radiographic sequence, which is available in most places worldwide, is thought to provide for roughly the same amount of information, in keeping with our training.

However, that is a wrong assumption. Recently, a number of investigations have shown the superiority of WBCT in assessing any kind of angle or measurement in the foot and ankle[1] but also that conventional standing radiographs and non–standing CT underestimate anatomy alteration in severe deformities, particularly in adult acquired flatfoot deformity (AAFD).[2] In general terms, WBCT is important not only because it emphasizes some conditions such as joint space narrowing and impingement syndromes "because it's weight bearing," but mostly because it prevents biases related to the non-WBCT conventional-radiography sequence "because it's 3D and Weight Bearing." In this new and revolutionizing technology, the single most important aspect is that measurements can be made in 3D.

Bearing this in mind, AAFD is one of the conditions that benefit the most from the advances of WBCT. As a 3D deformity, it is very difficult to assess using conventional modalities. This explains the great number of existing measurements for AAFD, none of which has become a Gold Standard because it was not possible to capture in a single measurement the 3D aspect of AAFD. Now, WBCT is already changing this paradigm and the future looks even more promising using innovative image processing software.

DOWNFALLS RELATED TO THE CONVENTIONAL RADIOGRAPHY-CONVENTIONAL CT SEQUENCE IN AAFD

AAFD is no different from any other foot and ankle condition in terms of downfalls related to the conventional radiography CT sequence. As a complex of 28 bones and 34 joints structure, the foot and ankle assessed using conventional radiographs are pictured as an altered 2D image, in many ways different to reality. The 2 main alterations known are superimposition of the bones and joints and projection biases.[3] Superimposition is the stacking up of the spatially distributed individual bones and joints on a single 2D plane, resulting in difficulties in analyzing the exact positions of each bone. This requires mentally back projecting the resulting image, which is a time consuming and unreliable process. Among projection biases, the most discussed are rotational distortion and fan effect. Rotational bias is the equivalent of shadows changing shapes depending on how

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the object is rotated relatively to the source of light. The same effect is observed when the source and/or the target film are displaced relative to the object (this is known as setup or operator-related bias). Fan effect is related to the fact that incident x-rays are not parallel. They diverge from each other, spreading the object's inner features, thus resulting in a magnified and distorted picture. A recent study demonstrated how the rotation of the foot relative to the incident x-rays affects hindfoot alignment measurement both a cadaver limb and a mathematical model[3] (Fig. 1). In the first 30 degrees in either direction, the hindfoot alignment value changed by 30%. This fact may be particularly impairing in the management of AAFD where choosing the different osteotomy modalities dramatically affects reduction or translation power. It is thus possible, based on conventional radiographic measurements only to choose an underpowered or overpowered osteotomy to treat our patients. The main advantage in this setting advocating for the use of WBCT as a standard in the management of AAFD is the test-retest reproducibility. In this imaging modality, the stability of the volume in which the patient anatomy is acquired is regularly checked as a standard procedure (Quality Assurance Testing, Q&A) using phantoms of known density and dimensions. This ensures that operational WBCT's accurately reproduce reality.

In the dental arena, cone-beam CT was introduced in the late 1990s by Mozzo et al.[4] Over the last 20 years, this has allowed developing personalized surgery using custom surgical guides. In the foot and ankle and particularly in AAFD, this just was not a possibility using the conventional sequence. WBCT might be the first step to enabling this mutation also in our specialty. Another major downfall in the conventional setup is the radiation dosage, taken into account that AAFD typically is a pathology in which both measurements and 3D analysis are warranted. It was recently shown that WB 3D extremity cone-beam CT outperforms conventional CT for evaluation of the foot and ankle, with less radiation exposure[2] (Figs. 2–4).

Overall, in the authors'experience about over 8000 WBCT scans, total radiation exposure has been estimated to have dropped by 6000 mSV and allocated time by 15,800 hours per year. This confirms prior literature and the experience in the dental field. These savings are explained by the ability to perform both alignment assessment and fine 3D bony and joint space analysis with a single examination. Richter et al[1] also published studies reporting on the ability of a bilateral standing WBCT system to perform better measurements than conventional CT or radiography. Similar conclusions were obtained by Carrino et al[5] and Demehri et al[6] confirming that WBCT outperforms multidetector CT for evaluation of the foot and ankle, with less radiation exposure and that cone-beam CT scans were better for evaluating bone anatomy, with good interobserver reliability. To sum up, systematic use of WBCT imaging in the evaluation of AAFD may avoid projection bias resulting in more precise surgical planning using reliable 3D and WB measurements, with less radiation impact on patients and significant time savings.

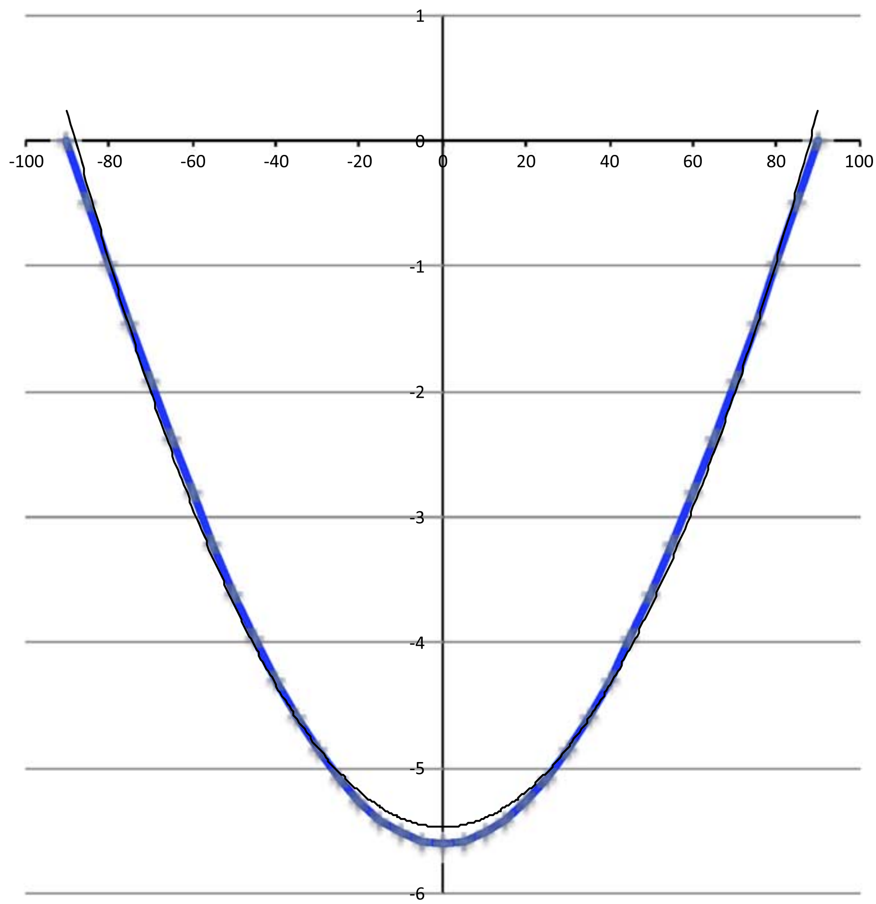

FIGURE 1. Variations of hindfoot alignment during foot rotation according to the study from Baverel et al.[3]

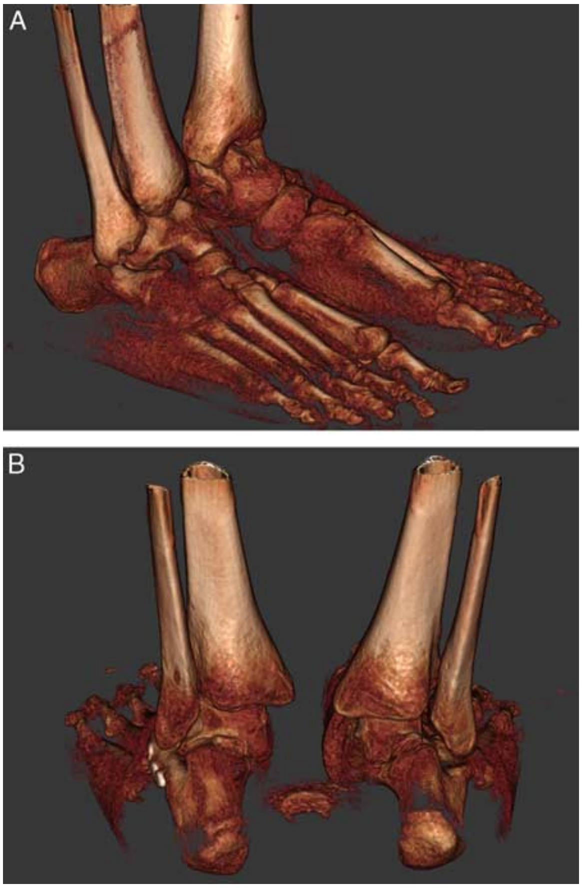

FIGURE 2. Tridimensional reconstruction of both feet during stance from weight-bearing computed tomography scans, with an overall overview from dorsolateral (A) and from posterior (B).

EFFECTS OF LOAD ON THE 3D ARCHITECTURE OF THE FOOT AND ANKLE IN AAFD

The literature production on the use of WBCT in AAFD has been increasing ever since the introduction of cone-beam CT technology in the upright position in 2008.[7] In an updated pubmed search (November 2018) using the search terms "weight bearing," "standing," "CT," "cone-beam," and "cone beam," 13/73 papers concerned AAFD, a pathology in which, through a combination of pathologic alignment and soft tissue laxity the architecture of the foot and ankle is known to be deeply affected by load bearing.[8]

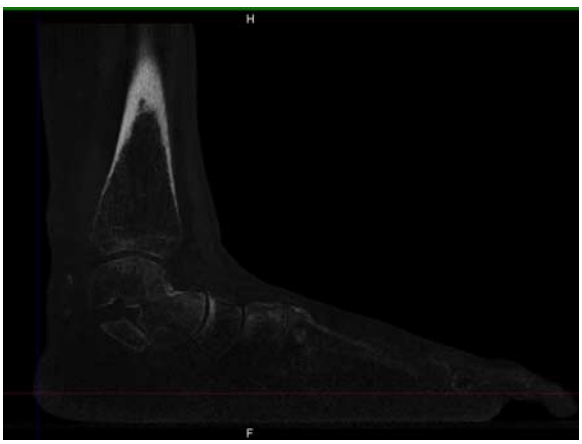

FIGURE 3. Particular of a sagittal cut with view of the talonavicular joint.

FIGURE 4. Visual assessment of the hindfoot with reconstruction of soft tissue (superiorly), then evaluation of the tibiotalar and subtalar joints and possibility to detect a calcaneofibular impingement (inferiorly).

Initially described as a consequence of isolated dysfunction of the posterior tibial tendon (PTT), AAFD is a common and complex disorder characterized by a diverse combination of deformities. It can differ in severity and location along the entire medial longitudinal arch of the foot and is associated with failure of multiple soft tissue structures, including the talonavicular joint capsule, deltoid ligament, and other arch support ligaments, with the spring ligament being the most important.[8] Deficiency of these structures can occur before or after the failure of the PTT. The resultant deformity is a combination of flattening, plantar and medial migration of the talar head, foot abduction at the talonavicular joint, midfoot joint displacement, and hindfoot valgus.[8] WB radiographs are the standard imaging modality, and different measurements have been described as tools for assessing the deformity.[9] However, the use of WBCT is rapidly expanding and may allow for a more detailed understanding of this complex, 3D deformity that has been challenging to characterize using 2D radiographs or conventional non-WBCT.

This intuitively known fact that the 3D configuration of the foot, particularly in a condition like AAFD where soft tissue laxity is involved, changes under load has been known and investigated in the past literature using simulated WBCT. Ananthakrisnan et al[10] in 1999 investigated 4 healthy controls and 8 AAFD patients with rupture of the PTT using 750 N axial force applied with a custom loading frame in the supine position and found a decreased contact surface in the talocalcaneal joint. Greisberg et al,[11] in 2003, observed decreased talonavicular and naviculocuneiform angles, and increased tarsometatarsal subluxation in 37 patients with AAFD. Ferri et al,[7] in 2008, compared 8 healthy controls with 15 AAFD subjects and found that controls had a 29% lower forefoot arch angle during WB, while this value AAFD patient was 52%. Kido and colleagues, using also a custom spatial frame but with close to full patient WB compared about 20 patients and controls in 2 seperate studies (2011 and 2013) and found more talus plantarflexion and eversion, while calcaneus were more dorsiflexed and everted, naviculars more rotated and everted and first tarsometatarsals more dorsiflexed.[12,13] Apostle et al[14] studied peritalar subluxation on 22 symptomatic feet via simulated WBCT, concluding that the valgus orientation of the subtalar joint might play a role in the etiology of this condition. Other than by demonstrating the changes in bone positioning and conventional angles and distances traditionally used in AAFD-related literature, the introduction of simulated weight bearing in conventional CT also demonstrated the importance of using WB to unveil bony impingements. For instance Malicky et al[15] in 2002 using a 750 N spatial frame, found the prevalence of sinus tarsi talocalcaneal impingement to be 92% in 19 AAFD patients versus 0% in 8 healthy controls, and subfibular calcaneal impingement was present in 66% of the AAFD versus 5% in the controls. Subsequent authors published similar results. Barg et al[16] summarized this abundant literature in 2017 in an emerging technology topical review. However, in the same paper, the authors commented on the disadvantages of "simulated WB," namely, by comparison with cone-beam CT, the radiation dose, which is 5 to 10 times less in WBCT than conventional CT. Also, the fact that the simulated WB setup obviously does not correspond to a natural, bilateral, full WB stance, explains that the normal soft tissue baseline response to stance, in particular muscular and tendon tensions, which way have an impact on the 3D architecture of the foot and ankle complex, is not accurately taken into account by these modalities. The cost and absence of standardization of the spatial loading frames used in these modalities should also be mentioned.

Cone-beam CT scans were recently found better for evaluating bone anatomy, with good interobserver reliability.[17,18] Cody et al[19] used WBCT to analyze the talar anatomy and subtalar joint alignment in patients with AAFD. In total, 45 patients with stage II flatfoot deformity and 17 control patients were enrolled in this study. The subtalar joint alignment was assessed using 2 angles: (1) angle between the inferior facet of the talus and the horizontal line and (2) angle between the inferior and superior facets of the talus. Both angles were significantly different in both groups. Specifically, it was demonstrated that patients with flatfoot deformity had more innate valgus in their talar anatomy and more valgus alignment of the subtalar joint. This information might potentially be used to identify patients who have a higher risk of underlying deformity progression. Krahenbähl et al[20] analyzed the orientation of the subtalar joint in 40 patients with tibiotalar osteoarthritis and 20 healthy controls. The subtalar joint was assessed by measurement of the subtalar vertical angle using WBCT. Comparison of the varus and valgus joint between healthy controls and affected joints revealed significant differences in the subtalar vertical angle measurements. The findings of this study suggest that the orientation of the subtalar joint may be an important factor in the development of ankle joint osteoarthritis in patients with AAFD. Similarly, focusing on peritalar subluxation in AAFD, both Probasco et al[21] and Kunas et al[22] confirmed how the coronal assessment of the posterior subtalar joint on WBCT images helped to identify an increased valgus orientation in some patients with an associated higher risk for developing AAFD. Of note, studies are ongoing to evaluate the role of the middle subtalar facet as a marker for peritalar subluxation and to assess whether the middle facet uncoverage may be diagnostic for AAFD. Furthermore, in a recent prospective level 2 clinical study, de Cesar Netto et al[2] investigated the reliability of AAFD measurements in 3D WBCT foot and ankle data sets. In this study, 20 feet in 20 patients were assessed while sitting then while standing, using 19 well known AAFD measurements, which were adapted to the 3D WBCT setting. All the measurements were repeated by 3 independent observers and tested for intraobserver and interobserver reliability. Although the reliability of the measurements was good in both settings, it was found that 18 of the 19 measurements differed with WB, with non-WBCT underestimating the importance of the deformities. The most reliable measurements were found to be medial cuneiform-to-floor distance, which averaged 29 mm [95% confidence interval (CI) = 28-31 mm] on the non-WB images and 18 mm (95% CI = 17-19 mm) on the WB images, and the forefoot arch angle [mean, 13 degrees (95% CI = 12-15) vs. 3 degrees (95% CI = 1.4-4.6), respectively] in the coronal view and the cuboid-to-floor distance [mean, 22 mm (95% CI = 21-23 mm) vs. 17 mm (95% CI = 16-18 mm), respectively] and the navicular-to-floor distance [mean, 38 mm (95% CI = 36-40 mm) vs. 23 mm (95% CI = 22-25 mm), respectively] in the sagittal view (Fig. 5). In 2 other level 2 prospective studies, de Cesar Netto and collegaues also investigated the intraobserver and interobserver reliability of hindfoot alignment measurements in WBCT, which were found to be substantial to almost perfect and much better than clinical assessments, being not impacted by investigator experience.[18,23] Also, in 2018 Jeng and colleagues investigated the talocalcaneal and calcaneofibular impingement in flatfoot patients, reporting a prevalence of 38% and 35%, respectively. Interestingly, they also assessed the sinus tarsi volume in healthy controls, demostrating how this significantly reduces when moving the foot from varus to valgus, thus potentially causing lateral pain and soft tissue impingement.[24] In light of all these data, and also considering our own experience, there seems to be an increasing consensus on the superiority of WBCT over all other means of investigation regarding bony anatomy of the foot and ankle complex in AAFD. We advocate that WBCT should become the new gold standard for measurements and preoperative planning in this setting

BENEFITS AND FUTURE PERSPECTIVES FOR THE USE OF WBCT AS A SURGICAL PLANNING TOOL

As explained previously, WBCT combines the advantages of WB and 3D imaging. This statement, however, contains the seed of a whole new challenge regarding surgical planning, especially with AAFD, where taking into account the 3D is so essential to the success of surgical procedures. Therefore, WBCT is both a solution and a new problem. In the previous configuration using conventional radiography and CT, the problem was being blind to either the volume or the effects of weight and having to bridge the gap through our own interpretation, which is only so good as our experience or ability to "see in 3D." With WBCT this no longer goes, however, the new problem is the wealth of information provided. This generated 3 major questions which future research will have to answer.

What is a 3D Measurement?

As today's surgeons have been trained to plan AAFD surgery using the current 2D technology for measurements, the first step of any attempt to use a novel modality was to validate the use of these measurements. Looking at the existing literature, it seems safe to affirm that this is the case as we have seen in the previous chapter. However, angles and distances are not fully adapted to the WBCT environment in that they are time consuming and blinded too much of the information contained in a WBCT data set. Time consumption is related to the fact that drawing an angle on a 2D projection involves just determining 3 points and drawing 2 lines. In the 3D environment, a single plane in which to do this also has to be found in a reproducible manner using surface anatomic

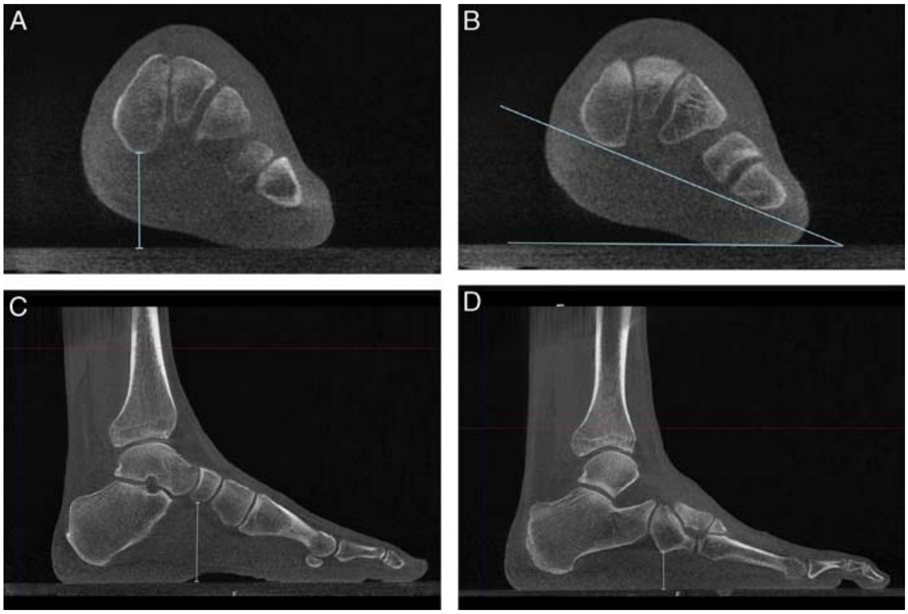

FIGURE 5. Some examples of adult acquired flatfooot deformity measurements perfomed on weight-bearing computed tomography images from patients diagnosed with adult acquired flatfooot deformity. A, Medial cuneiform-to-floor distance (coronal plane). B, Forefoot arch angle (coronal plane). C, Navicular-to-floor distance (sagittal plane). D, Cuboid-to-floor distance (sagittal plane).

markers. Furthermore, this plane can be tilted in the 3D space. In 2017, de Cesar Netto and colleagues stated that 5 minutes were required to perform measurements on conventional radiographs versus 25 minutes on WBCT data sets.[2] Being blinded to much of the information contained in the volume is related to the fact that the 3 landmarks defining an angle can only be contained in a plane and therefore can only picture the information contained in the same unique plane. The rest of the information contained in the volume is therefore not available and requires multiple measurements in other planes, which is all the more time consuming, therefore not practical in the clinical setting.

Are 3D Measurements Only the Tip of the Iceberg?

Three-dimensional measurements are only the beginning of the impressive series of challenges ahead. The fact that WBCT output is a full model of the 3D WB foot and ankle with its inner structure theoretically allows to investigate every possible aspect of anatomy, diagnostic, treatment planning, and prognostic. By comparison with a standard radiograph, where the information contained was only as important as the number of measurements that could be carried out on a single plain film in pixel (units of surface), a single WBCT data set may contain up to a million voxels (units of volume) containing each 4 pieces of information (*x*, *y*, and *z* coordinates + HU or bone density). When technology will be developed to extract efficiently every piece of information available and clinically useful, the possibilities for new fields of research and clinical applications in AAFD will be endless. However, in such a situation, it will be very difficult to make the most out of this wealth of new data without the help of a practical WBCT/Surgeon interface. In the author's experience, this is the most important challenge that WBCT manufacturers face today. In practice, the use first step is to obtain full, automatic recognition of the bones by intelligent software, in order to be able to calculate axes. This task is rendered immensely difficult by the presence of arthritis, which accounts for bony contacts in joints, and of metalwork. However, once this will be achieved, each bone position can be defined with its own center of gravity and single set of coordinates (*x*, *y*, *z*), its mean and density including automatic detection of fracture lines, cysts and other ruptures in normal patterns of density.

Also, recent evolutions in digital image analysis have enabled distance mapping, where a color code renders the 3D layout of joint space narrowing, which could be particularly useful in AAFD when investigating the states of the subtalar joints and sinus tarsi[25] (Fig. 6). Its position in space can then be defined relative to every other bone and to the WB plane through another set of spatial coordinates. At this stage, there is no doubt that an efficient interface will be instrumental in order to make the most of a plethoric set of data for each AAFD patient. Also, this will help to detect efficiently early forms of AAFD and discriminate between cases with a high or low risk of collapse. The surgical planning could potentially be improved, by deciding which procedure in more indicated depending on where the sagging takes place within the 3D anatomy. It is also likely that new photon detection modalities will be able to differentiate between ligament, tendon and bone tissues, helping surgeons to include this information in the treatment algorithms.

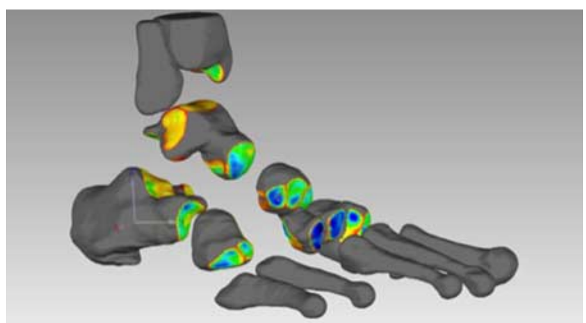

FIGURE 6. Example of distance mapping analysis of the foot from weight-bearing computed tomography images.

Is Personalized Surgery for AAFD Possible (Like for Dental Implants)?

Personalized surgery is already available and widely used in the lower limb in the form of custom cut guides for total knee replacements[26] and for femoral and tibial osteotomy.[27,28] However, these are based on the use of non-WB imaging, coupled with WB plain films. They should certainly benefit from the recent upcoming of new versions of WBCT machines which will likely include the possibility for a WBCT scan of the knee.[29]

In the foot and ankle realm, cases have been published using surgeon-conceived guides to correct complex 3D deformities in posttraumatic or congenital situations.[30] The experience with custom guided total ankle replacements remains limited but promising.[31] As in the knee, this experience remains confined to the conventional imaging sequence of WB radiographs and CT. In the author's opinion, it is no doubt that in such a highly demanding procedure in terms of realignment, the benefits of WBCT should be investigated by the industry.

Fortunately, many advances have been made which already, in the authors' experience make a significant and positive difference in the daily clinical use of WBCT in AAFD patients. In particular, significant advances have been made with regards to redefining hindfoot alignment measurements. Burssens et al[32] have recently published a study describing a clinically relevant and reproducible method to measure hindfoot alignment using WBCT. Sixty patients were enrolled in this prospective study, including 2 groups: 30 patients with varus alignment and 30 patients with valgus alignment. Hindfoot alignment was measured using 3 different angles: by the bisector of the Achilles tendon and the calcaneus (HAACL), by standard method using an inclination set at 45 degrees (to simulate the long axial view) (HAALA), and by a novel method that combines the inclination of the tibia (anatomic axis) and inclination of the talus and calcaneus (talocalcaneal angle) (HAANOV). The novel hindfoot angle assessment demonstrated a positive correlation with previous hindfoot angles, a high correlation with clinical alignment assessment, and excellent reliability. The authors concluded that WBCT can be used to objectively measure hindfoot alignment similar to plain films.

Using a different approach, Lintz et al[17] diffused in 2017 the concept of 3D biometrics in WBCT measurements, based on a volumetric analysis of hindfoot alignement, defined by 4 anatomical landmarks rather than 3 points defining a plane. The principles of 3D biometrics for hindfoot alignment are based on defining the latter by an offset, as Saltzman and Khoury had described,[33] between the ankle joint and the foot WB surface, which had shown better qualities as a landmark than the tibia. The result is given as the foot ankle offset (FAO) (Fig. 7). In practice, this measurement is semiautomatic through dedicated software, which calculates the FAO from landmarks selected by the surgeon. This technique has demonstrated excellent intra and interobserver reliability (0.99 and 0.97, respectively), a Gaussian distribution of values and high discriminative power between normal and pathologic cases for both cavovarus and planovalgus cases.[17] Specifically, data sets from 135 patients were analyzed: 57 with normal hindfoot alignment, 38 with varus hindfoot alignment, and 40 with valgus hindfoot alignment. FAO was described as the lever arm of the torque generated in the ankle from the combined actions of body weight and ground reaction force. In

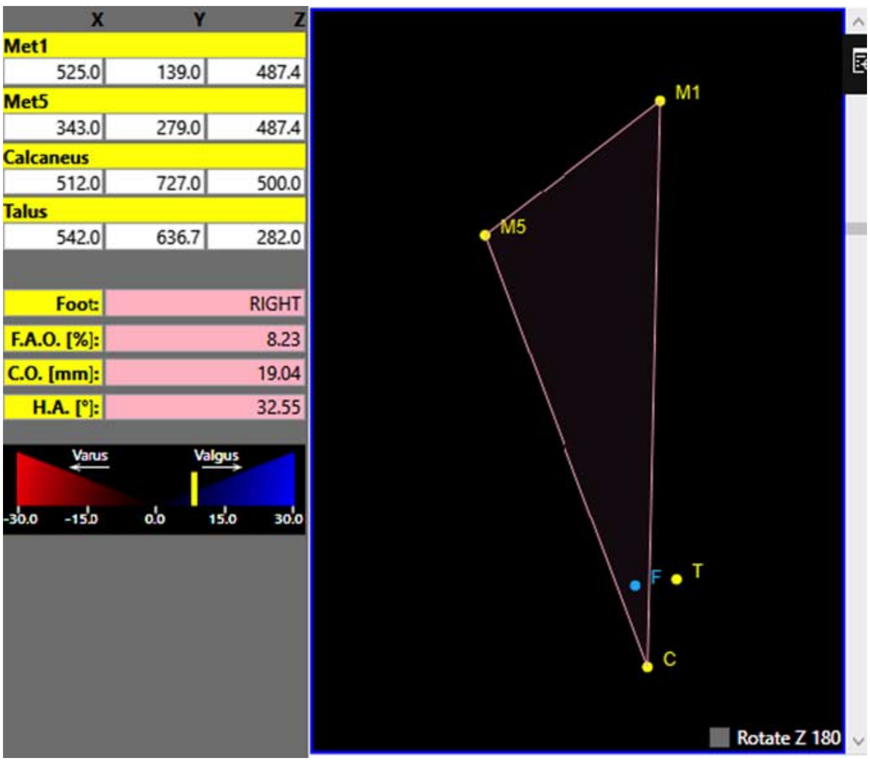

FIGURE 7. Example of semiautomatic measurement using TALAS, CubeVie (CurveBeam). Three-dimensional coordinates (*x*, *y*, *z* planes) were harvested for the first (met1), fifth (met5), calcaneus and talus. The tripod is represented by the triangle formed by the coordinates of M1 (first metatarsal), M5 (fifth metatarsal), and C (calcaneus). F represents the ideal position of the center of rotation of the ankle joint that lies on a bisecting line of the tripod. T represents the positioning of the most proximal and central aspect of the talus, center of the ankle joint, in this specific patient.

patients with neutral hindfoot alignment, the mean FAO value was 2.3% (SD: 2.9%). In patients with varus and valgus alignment, the offset was −11.6% (SD: 6.9%) and 11.4% (SD: 5.7%), respectively. The findings of this pilot study suggest that the measurement of the foot and ankle offset can be used as a tool for hindfoot alignment assessment.

In conclusion for what concerns perspectives and challenges, with the use of WBCT in AAFD, it is first and foremost required that software becomes available to automatically detect the relative positions of the bones. This will enable the development of new measurement and planning tools, which will have to be tested and validated in light of the experience gained today using previously known 2D measurements.

CONCLUSIONS

It appears clear after a few years of experience and past literature on the use of WBCT in AAFD, that the traditional sequence of conventional radiographs and conventional CT is less reliable (due to intrinsic projection biases) and responsible for more radiation. In particular in the management of AAFD as a 3D deformity, a 3D analysis is nowadays mandatory. This is why the use of the "third dimension" (in a physiological standing position) must be considered paramount in clinical practice. To achieve this, WBCT imaging should become the new standard for preoperative investigation, treatment planning, and postoperative follow-up.

REFERENCES

1. Richter M, Seidl B, Zech S, et al. PedCAT for 3D-imaging in standing position allows for more accurate bone position (angle) measurement than radiographs or CT. *Foot Ankle Surg*. 2014;20:201–207.
2. de Cesar Netto C, Schon LC, Thawait GK, et al. Flexible adult acquired flatfoot deformity. *J Bone Joint Surg*. 2017;99:e98.
3. Baverel L, Brilhault J, Odri G, et al. Influence of lower limb rotation on hindfoot alignment using a conventional two-dimensional radiographic technique. *Foot Ankle Surg*. 2017;23:44–49.
4. Mozzo P, Procacci C, Tacconi A, et al. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *Eur Radiol*. 1998;8:1558–1564.
5. Carrino JA, Al Muhit A, Zbijewski W, et al. Dedicated cone-beam CT system for extremity imaging. *Radiology*. 2014;270:816–824.
6. Demehri S, Hafezi-Nejad N, Carrino JA. Conventional and novel imaging modalities in osteoarthritis. *Curr Opin Rheumatol*. 2015;27:295–303.
7. Ferri M, Scharfenberger AV, Goplen G, et al. Weightbearing CT scan of severe flexible pes planus deformities. *Foot Ankle Int*. 2008;29:199–204.
8. Abousayed MM, Alley MC, Shakked R, et al. Adult-acquired flatfoot deformity. *JBJS Rev*. 2017;5:e7.
9. Aebi J, Horisberger M, Frigg A. Radiographic study of pes planovarus. *Foot Ankle Int*. 2017;38:526–531.
10. Ananthakrisnan D, Ching R, Tencer A, et al. Subluxation of the talocalcaneal joint in adults who have symptomatic flatfoot. *J Bone Joint Surg Am*. 1999;81:1147–1154.
11. Greisberg J, Hansen ST, Sangeorzan B. Deformity and degeneration in the hindfoot and midfoot joints of the adult acquired flatfoot. *Foot Ankle Int*. 2003;24:530–534.
12. Kido M, Ikoma K, Imai K, et al. Load response of the tarsal bones in patients with flatfoot deformity: in vivo 3D study. *Foot Ankle Int*. 2011;32:1017–1022.
13. Kido M, Ikoma K, Imai K, et al. Load response of the medial longitudinal arch in patients with flatfoot deformity: in vivo 3D study. *Clin Biomech*. 2013;28:568–573.
14. Apostle KL, Coleman NW, Sangeorzan BJ. Subtalar joint axis in patients with symptomatic peritalar subluxation compared to normal controls. *Foot Ankle Int*. 2014;35:1153–1158.
15. Malicky ES, Crary JL, Houghton MJ, et al. Talocalcaneal and subfibular impingement in symptomatic flatfoot in adults. *J Bone Joint Surg Am*. 2002;84-A:2005–2009.
16. Barg A, Bailey T, Richter M, et al. Weightbearing computed tomography of the foot and ankle: emerging technology topical review. *Foot Ankle Int*. 2018;39:376–386.
17. Lintz F, Welck M, Bernasconi A, et al. 3D biometrics for hindfoot alignment using weightbearing CT. *Foot Ankle Int*. 2017;38:684–689.
18. de Cesar Netto C, Shakoor D, Dein EJ, et al. Influence of investigator experience on reliability of adult acquired flatfoot deformity measurements using weightbearing computed tomography. *Foot Ankle Surg*. 2018. [Epub ahead of print].
19. Cody EA, Williamson ER, Burket JC, et al. Correlation of talar anatomy and subtalar joint alignment on weightbearing computed tomography with radiographic flatfoot parameters. *Foot Ankle Int*. 2016;37:874–881.
20. Krähenbühl N, Tschuck M, Bolliger L, et al. Orientation of the subtalar joint. *Foot Ankle Int*. 2016;37:109–114.
21. Probasco W, Haleem AM, Yu J, et al. Assessment of coronal plane subtalar joint alignment in peritalar subluxation via weight-bearing multiplanar imaging. *Foot Ankle Int*. 2015;36:302–309.
22. Kunas GC, Probasco W, Haleem AM, et al. Evaluation of peritalar subluxation in adult acquired flatfoot deformity using computed tomography and weightbearing multiplanar imaging. *Foot Ankle Surg*. 2018;24:495–500.
23. de Cesar Netto C, Shakoor D, Roberts L, et al. Hindfoot alignment of adult acquired flatfoot deformity: a comparison of clinical assessment and weightbearing cone beam CT examinations. *Foot Ankle Surg*. 2018. [Epub ahead of print].
24. Jeng CL, Rutherford T, Hull MG, et al. Assessment of bony subfibular impingement in flatfoot patients using weight-bearing CT scans. *Foot Ankle Int*. 2018;40:152–158.
25. Siegler S, Konow T, Belvedere C, et al. Analysis of surface-to-surface distance mapping during three-dimensional motion at the ankle and subtalar joints. *J Biomech*. 2018;76:204–211.
26. Seon J-K, Park H-W, Yoo S-H, et al. Assessing the accuracy of patient-specific guides for total knee arthroplasty. *Knee Surg Sport Traumatol Arthrosc*. 2016;24:3678–3683.
27. Munier M, Donnez M, Ollivier M, et al. Can three-dimensional patient-specific cutting guides be used to achieve optimal correction for high tibial osteotomy? Pilot study. *Orthop Traumatol Surg Res*. 2017;103:245–250.
28. Jacquet C, Chan-Yu-Kin J, Sharma A, et al. "More accurate correction using "patient-specific" cutting guides in opening wedge distal femur varization osteotomies. *Int Orthop*. 2018. [Epub ahead of print].
29. Hirschmann A, Buck FM, Fucentese SF, et al. Upright CT of the knee: the effect of weight-bearing on joint alignment. *Eur Radiol*. 2015;25:3398–3404.
30. Dekker TJ, Steele JR, Federer AE, et al. Use of patient-specific 3D-printed titanium implants for complex foot and ankle limb salvage, deformity correction, and arthrodesis procedures. *Foot Ankle Int*. 2018;39:916–921.
31. Berlet GC, Penner MJ, Lancianese S, et al. Total ankle arthroplasty accuracy and reproducibility using preoperative CT scan-derived, patient-specific guides. *Foot Ankle Int*. 2014;35:665–676.
32. Burssens A, Peeters J, Buedts K, et al. Measuring hindfoot alignment in weight bearing CT: a novel clinical relevant measurement method. *Foot Ankle Surg*. 2016;22:233–238.
33. Saltzman CL, El-Khoury GY. The hindfoot alignment view. *Foot Ankle Int*. 1995;16:572–576.