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Special Article

Progressive collapsing foot deformity: how to use new knowledge in developing countries

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Abstract

The 2019 progressive collapsing foot deformity (PCFD) consensus did not only change the disease nomenclature and provided a new classification for the condition formerly known as flatfoot deformity. It was also the pinnacle of a revolution in the field in terms of knowledge and clinical perspectives. The use of advanced imaging, such as weight-bearing computed tomography, three-dimensional algorithms, and magnetic resonance, expanded the way we understand peritalar subluxation and how we can address it. However, much of these improvements felt short in terms of global reproducibility due to economic restraints. The objective of this review study is to present PCFD new concepts through the lens and realities of developing countries, considering their potentially limited access to novel technologies.

Level of Evidence V; Expert opinion.

Keywords: Flatfoot; Tomography; Cone-Beam Computed Tomography; Disruptive Technology; Low Cost Technology; Developing Countries.

Introduction

Progressive collapsing foot deformity (PCFD) was the name chosen to better describe what was previously termed flatfoot by a consensus of world specialists in the disease through a series of articles, in 2020[1,2]. The nomenclature would solve some of the problems associated with adult acquired flatfoot deformity, such as the fact it might occur outside the adult scope and present congenital features, besides not being a variation of normality[1,3,4]. Setting these concepts and establishing the posterior tibial tendon acquitting as the main driver of the disease was only possible due to an ocean of knowledge produced in the years previous to the consensus[5,6]. What was produced in the following years substantiated and expanded these principles around PCFD[7,8], and much of this new knowledge was possible with the advent of the weight-bearing computed tomography (WBCT)[9,10]. By assessing the foot and ankle under physiological stress, relations among structures and their environment were redefined due to this clearer portray of the local anatomy, including coronal and three-dimensional (3D) assessments[11-13]. This technology allowed further development of bone segmentation and 3D mappings, increasing our understanding on how components interact in the normal and PCFD scenarios[14,15]. Lately, the clinical applicability of these findings has been putted into test, and results are encouraging[16].

Contrary to what is expected from a scientific product, many of the treatment plans elaborated were not able to reach practice globally, especially in developing countries with economic restraints. This review study aims to report the scientific advancements made in PCFD over the last years while trying to implement these ideas in locations with limited access to technology.

Study performed at the Medstar Orthopedic Institute, MedStar Union Memorial Hospital, Baltimore, United States.

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The Concept of Peritalar Subluxation (PTS)

The concept is not new, being introduced by Sangeorzan et al. more than two decades ago and using conventional weight-bearing radiographs (WBRs) and non-weightbearing computed tomography (CT)[5,17.]. In PCFD/flatfoot, the talus would stay in a fixed position while the structures around it would progressively subluxate, moving in external rotation, eversion, and dorsiflexion (Figure 1)[6]. Although intuitively being an ongoing aspect of a pathological process, PTS was also found to be extremely accurate in diagnosing PCFD, also being reliable for assessment of treatment success[16,18].

Ananthakrisnan et al. used the overlap of posterior facets of the talus and calcaneus as a marker of PTS to demonstrate the difference between flatfeet and controls (0.92 vs. 0.68; $p = 0.0066$)[17]. Later, de Cesar et al. explored the middle facet of the subtalar joint and found this subluxation has a high accuracy (>17.9%, with 100% specificity and 96.7% sensitivity; AUC = 0.99) and presents as an earlier mark (middle vs. posterior difference: 17.7%) for PCFD diagnosis (Figure 2)[18,19]. Whilst most of these findings were established by WBCT, which could be of limited access in developing countries, concepts can still be appreciated in simulated WBCT and WBR[20,21].

Sinus tarsi impingement (STI) and subfibular impingement (SFI) are also important clinical and radiographic manifestations of PTS[14,22]. They probably represent prognostic factors too, STI being a sign of symptom onset and SFI, an indication of more pronounced and advanced PTS[16]. Several studies demonstrated a correlation between impingement and PCFD diagnosis, function, pain, deformity severity, and soft tissue impairment[15,16,22,23]. Recognizing an STI or SFI in the clinical setting is crucial and does not require advanced imaging[23,24]. Physical examination and conventional WBR, including a hindfoot alignment view, are adequate and inexpensive[25,26].

It is important to differentiate STI from subtalar arthritis, since they can determine distinct treatments (joint sparing vs. fusion)[27-29]. In STI, alongside with localized pain at the sinus tarsi, radiographs show a direct contact between the lateral process of the talus and the Gissane angle in the calcaneus[22]. If available, a magnetic resonance imaging can show indirect signs, such as bone edema, subchondral cysts, or erosion of the lateral process and Gissane[23]. Arthritis has a more diffuse clinical pattern and also significant loss of subtalar joint space,

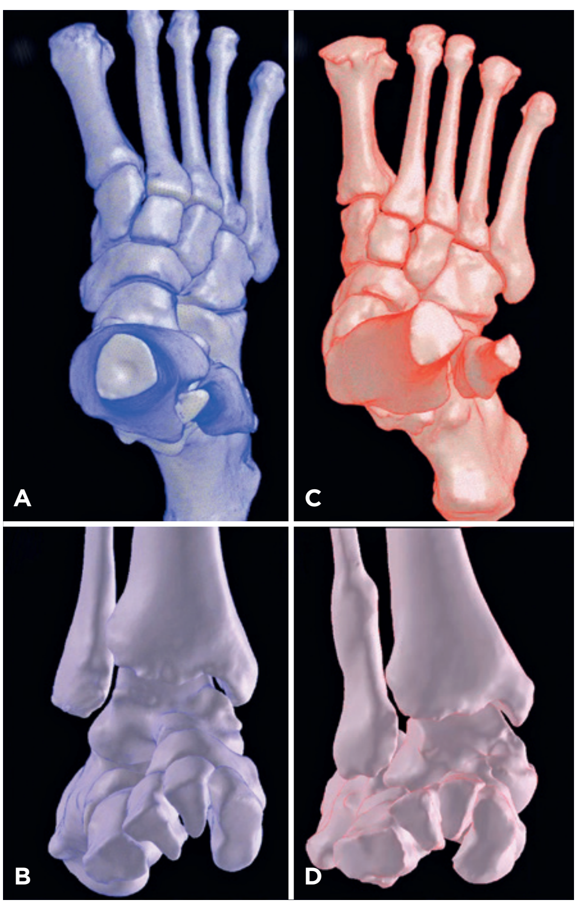

Figure 1. Three-dimensional weight-bearing computed tomography reconstruction from a patient with neutral/physiological alignment (blue; A and B) and progressive collapsing foot deformity (red; C and D). Axial (A and C) and coronal (B and D) views show signs of peritalar subluxation, such as external rotation and eversion of the subtalar joint, midtarsal external rotation and translation, and subtalar and subfibular impingement.

Figure 2. Coronal weight-bearing computed tomography images showing middle facet subluxation (A) and posterior facet subluxation (B) in patients with progressive collapsing foot deformity. The red circle highlights the area of interest and where the subluxation is measured.

which might be not so easy to assess with the overlapping of bones (Figure 3)[24,30]. A combination of diagnostic modalities might provide answers in challenging cases[4,28].

Weight-bearing Computed Tomography (WBCT)

The development of WBCT changed the PCFD understanding substantially[21]. Not only PTS and joint interaction became clearer, but other aspects of the disease were also highlighted[1,11,31]. The new consensus classification incorporated the idea of different deformity patterns combining into a PCFD presentation (Table 1)[1,32]. Much of the classes are easily recognizable clinically and radiographically, such as A (hindfoot valgus) and E (ankle instability). However, as previously stated, class D (PTS) is better appreciated by WBCT[31]. The identification of classes B (midfoot abduction) and C (medial column instability), in particular, can be incremented with the technology due to its multiplane capability[31]. Instability of the tarsometatatarsal or naviculocuneiform joints, in the form of plantar gapping, dorsal subluxation, or arthritis, can change the therapeutic approach of PCFD[33-35]. Foot tripod reestablishment through a medial longitudinal arch stabilization procedure directed to the apex of the deformity is a fundamental step of the reconstruction plan[36-38]. Again, the rational use of a careful clinical assessment combined with WBR (and, eventually, simulated WBCT) to assess classes B and C can bring plentiful information for the decision making[39,40].

Multiple imaging acquisition by WBCT also allowed the development of different software to analyze the obtained data[20,41,42]. One of the first and most impactful of these is the Foot and Ankle Offset (FAO)[43]. The 3D relation between the center of the ankle and the foot tripod was introduced by Lintz et al. with the use of WBR, at first[44]. The Torque Ankle Lever Arm System (TALAS®; CurveBeam™, LLC, Warrington,

Figure 3. Progressive collapsing foot deformity patient with sinus tarsi impingement. Lateral weight-bearing radiograph (A) shows the lateral facet of the talus touching the crucial angle of Gissane in the calcaneus. Assessment of the joint space is significantly hindered by the apposition of bones. The technique illustrates the contact between bones as well as cystic changes (B) and sclerosis secondary to the impingement. Other indirect signs of STI can be seen in the magnetic resonance imaging, such as bone edema, subchondral cysts, and local synovitis (D).

Table 1. Progressive collapsing foot deformity consensus classification enabling a combination of classes with flexible (stage I) or rigid (stage II) presentations

Types	Stage I: Flexible Deformity type/location	Stage II: Rigid Consistent clinical/radiographic findings
Class A	Hindfoot valgus	Hindfoot valgus alignment Increased HMA, HAA, and FAO
Class B	Midfoot/forefoot abduction	Decreased talar head coverage Increased TNCA Presence of STI
Class C	Forefoot varus/medial column instability	Increased TFMA Plantar gapping at first TMT/NC joints Clinical forefoot varus
Class D	Peritalar subluxation/dislocation	Significant subtalar joint subluxation SFI
Class E	Ankle instability	Valgus tilting of the ankle

HMA: hindfoot moment arm; HAA: hindfoot alignment angle; FAO: foot and ankle offset; TNCA: talonavicular coverage angle; STI: sinus tarsi impingement; TFMA: talus-first metatarsal angle; TMT: tarsometatarsal joint; NC: naviculocuneiform joint; SFI: subfibular impingement.

PA) program allowed FAO to be obtained in a semi-automatic manner, by clicking at the most distal voxel (aspect) of the first metatarsal head, followed by the most distal voxel of the fifth metatarsal head and the most distal voxel of the calcaneus posterior tuberosity[(45,46)]. Those three points generate the foot tripod[(44,46)]. Finally, the most central point of the talar body is obtained and the amount of this point deviation considering the center of the tripod is automatically measured by a percentage (Figure 4)[(47)]. Normal values range between -0.6% and 5.2% (mean: 2.3%), as positive values above 5.2% indicate valgus, and negative values below -0.6%, varus[(45,46)]. The FAO has been demonstrating high reliability rates (>0.97), diagnostic values (>4.6%: 100% specificity and 89.2% sensitivity), and clinical correlations as a surrogate for overall foot and ankle alignment[(13,48-50)]. Manual measurement using simulated WBCT or even WBR is possible in situations where a WBCT or the software are not available (Figure 4)[(44-46)].

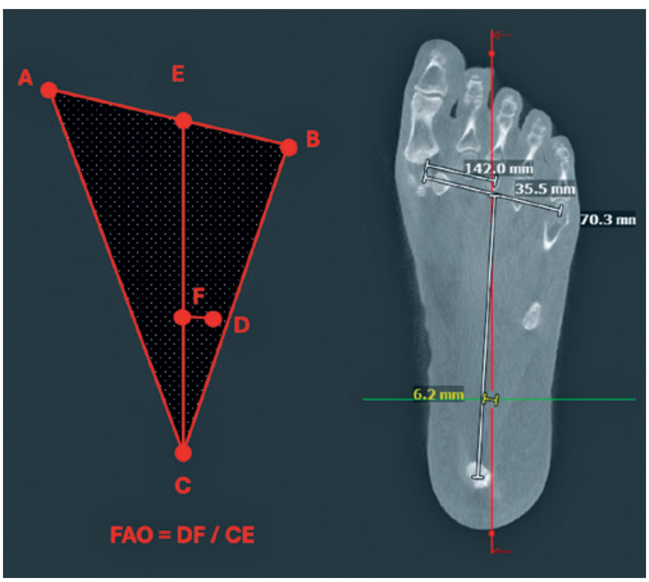

Figure 4. Measuring the foot and ankle offset without semi-automatic software. In this case, a conventional computed tomography with simulated weightbearing was used. The most distal aspect of the first metatarsal is determined in the three computed tomography planes and marked (point A). Using the three planes, the most distal aspect of the fifth metatarsal is obtained (point B). Next, the most distal aspect of the calcaneus is found (point C). The mid-distance between points A and B (70/2 = 35) is marked as point E. A line is drawn between points E and C and the distance is measured (142 mm). The projection of the center of the talus to the tripod plane is established as point D. A perpendicular line connecting point D with the CE line (point F at the line) represents the DF distance (6.2 mm). Line F would be a perfect alignment of the talus over the center of the tripod. The FAO can be obtained by dividing DF (6.2) by CE (142); in the represented case, 0.0436, or 4.36%, of talar deviation from the point F or the central tripod line.

South America currently holds only two WBCT equipment in operation, while it is still scarce in Africa and Asia. Nonetheless, much of the PCFD concepts developed or expanded with WBCT have strong clinical and radiographic correspondence[(20)]. Classes, stages, and presentations can be clearly identified using traditional approaches. As many of the ideas and advancements brought by these apparatuses, FAO can be employed with creativity, using the concepts introduced by the original authors.

Three-dimensional (3D) Algorithms

Segmentation is not a novelty when it comes to imaging assessment and medical applications[(51,52)]. Image acquisition and software developments were fundamental to the thriving of this technology, allowing 3D WBCT mapping algorithms to be established[(53,54)]. The software captures the images from the WBCT file, creating a 3D isosurface of the bone tissue[(55)]. In order to obtain a patient-specific shape, deformable shape models are used by the program, which also automatically generates landmarks and bone axis[(56)]. Bone segmentation can then be used to perform simple, automatic angular and linear measurements reliably (ICCs: >0.972) and faster (97%)[(53,57)]. Mostly, a more comprehensive assessment of structural interaction in a 3D approach is possible using distance and coverage mapping[(15,56,58)].

Many of the PCFD concepts proposed in the last decades were substantiated using this advanced technology[(58,59)]. Studies were able to fully characterize PTS through changes on joint coverage, bone positioning, and distancing[(57,60)]. Middle facet subluxation (46.6% of uncoverage), sinus tarsi impingement (98% increase in coverage), and subfibular impingement (17 of 20 patients) were more objectively and extensively appreciated using maps of coverage and distance for the specific areas[(15)]. A direct clinical application of the same concepts was later demonstrated by de Cesar et al. when showing changes in coverage and distance by 3D mapping in patients operated for PCFD joint-sparing procedures (Figure 5)[(16)]. A direct correlation among improvement in patient reported outcomes (PROs), improvement in facet coverage (middle facet and PCS; $p = 0.030$), and impingement (SFI and PROMIS; $p = 0.020$) was established. In this study, the FAO improvement also affected PROs significantly (i.e., $R^2 = 0.35$ for VAS), showing that the correction of overall alignment, joint coverage, and extra-articular impingements (STI and SFI) have a positive effect on clinical results.

Although challenging to be obtained in low economic environments, 3D WBCT mapping algorithm conceptions help not only by driving innovation in the field, but also allows a more contemplative metric[(16,59)]. Many of the software being developed for segmentation and 3D analysis are able to get data from simulated WBCT and, in some extent, WBR. Imaging from normal, pathological, and cadaveric samples are feeding artificial neural networks that might be able to translate data from different modalities. As the orthopedic industry evolves and invests in this technology, more are the chances of these software being offered freely to providers around the globe.

Surgical Planning and Interventions

Application of basic concepts in segmentation and 3D WBCT algorithms allowed researchers and engineers to develop surgical planning tools in programs[(61-63)]. It is possible to feed the software with preoperative WBCT images and simulate the effect of isolated or combined osteotomies on specific measurements and on the overall foot alignment (Figure 6)[(64-66)]. As discussed, artificial intelligence is supplied with cases and studies, making 3D preoperative plans increasingly more consistent[(63,67)]. Although this technology will not replace the surgeon's insights and experience, it will potentially add good information when making intraoperative decisions, such as the desired amount of displacement in a calcaneal osteotomy, the size of an wedge for a midfoot osteotomy, or the need for additional soft tissue procedures[(63,67)]. Again, these are not indispensable steps when planning PCFD reconstruction, but there is hope that these software become widely available in the future, with the ability to translate data from simulated WBCT and WBR[(68)].

Technical surgical aspects have not changed much in the last decades, even though advancements in soft tissue reconstruction are promising[(69,70)]. There is a tendency of leaving the posterior tibial tendon intact whenever possible[(23,71,72)]. Placing the calcaneus under the tibial axis and reestablishing the foot tripod are still the main goals of PCFD bone reconstruction, while avoiding hypercorrection[(4,28,37,73)]. The importance of the first ray and medial column in regaining triple foot support has been highlighted in the last years (Figure 7)[(24,34-36)]. A short or insufficiently plantarflexed first ray/medial column might not be enough to derotate the hindfoot, helping to correct PTS[(74,75)]. On the other spectrum of the disease – rigid deformities –, well-aligned triple arthrodesis is still found to be mandatory for good outcomes and to protect the ankle joint[(39,76)]. Moreover, as total ankle replacements continue to evolve, they became a viable option when treating class E deformities in a PCFD setting[(77,78)].

New implants are constantly developed to treat the different aspects and presentations of PCFD. Still, they lack clinical superiority over the traditional implants available in developing places[(79-81)]. Allograft pre-molded wedges can be substituted by metal or autograft[(81)]. Free tendon graft or suture material might replace expensive suture tapes and anchors[(77,78,82,83)]. The creativity of the developing world surgeon in specific situations is also an important factor when operating specific cases.

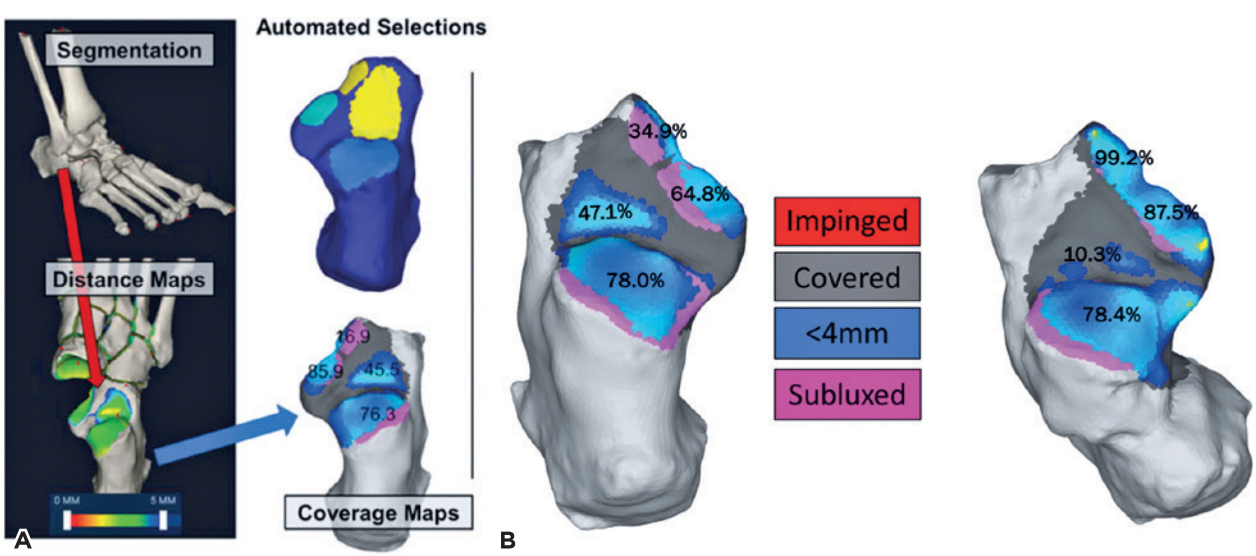

Figure 5. Three-dimensional weight-bearing computed tomography algorithms starts with bone segmentation (A), providing anatomical displays of the desired interaction – in this case, the subtalar joint. Vertical vectors between talus and calcaneus are obtained, portraying distance and coverage maps. Distance is portrayed in millimeters, red colors representing areas with smaller distances (arthritis or impingement) and green/blue, greater distances. Coverage is displayed using color diagrams for these vectors that characterize how much the structures are close to or with no contact with each other. Red represents contact between bones (impingement), blue symbolizes distances bellow 4 mm (physiological coverage), gray denotes coverage with distances over 4 mm, and pink indicates no coverage (subluxation). Example of a Three-dimensional weight-bearing computed tomography coverage map (B) in progressive collapsing foot deformity preoperatively and postoperatively. Before surgery, sinus tarsi have signs of impingement (more coverage: 47%, less distance) and medial and anterior facets have a significant subluxation (34% and 64% of coverage, respectively). After joint-sparing procedures, facets recover much of the coverage (99% and 87%) and sinus tarsi impingement is considerably improved (10%).

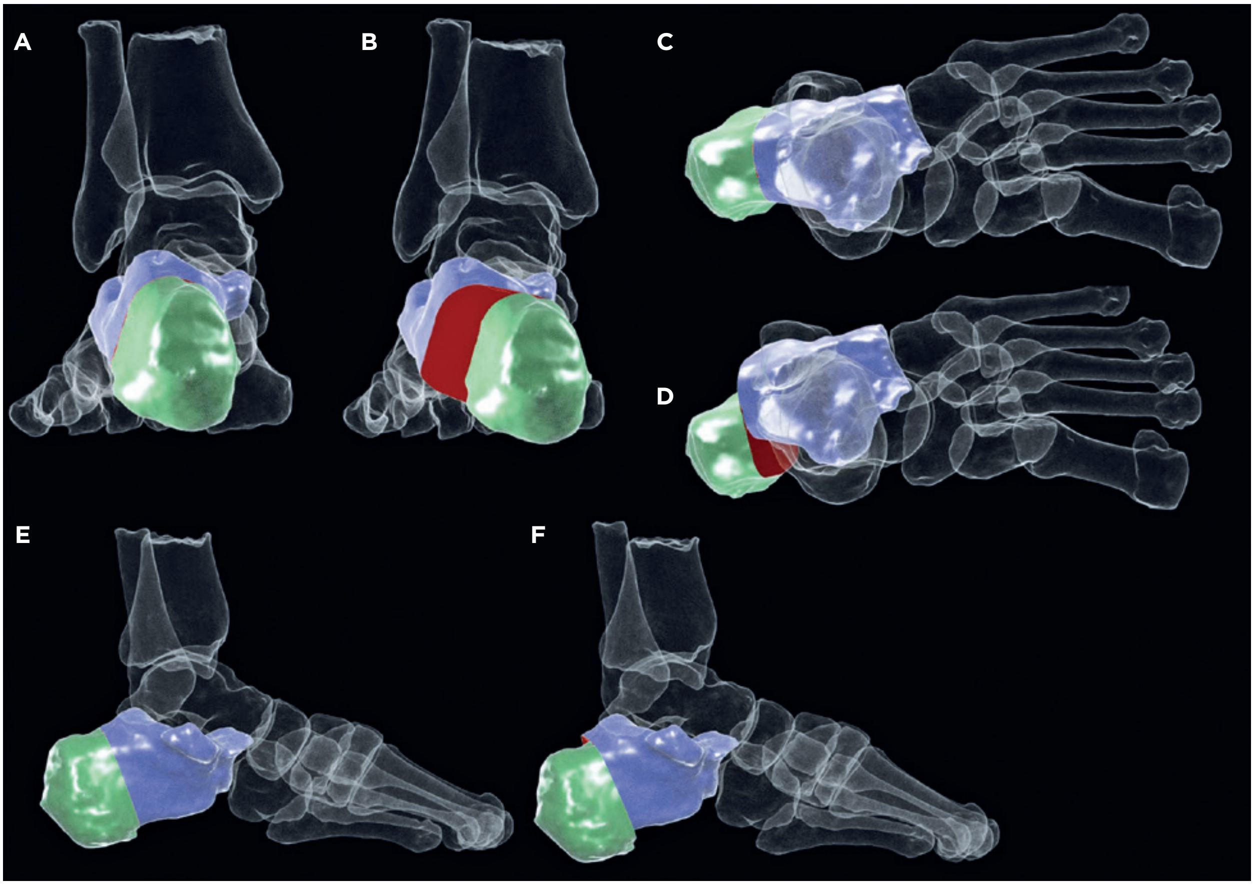

Figure 6. Example of preoperative planning of a medial displacement calcaneal osteotomy in a progressive collapsing foot deformity. Coronal (A; B), axial (C; D), and sagittal (E; F) reconstruction images comparing the overall alignment and specific angular and metric relations between bones. Semi-automatic angles can be easily measured in preoperative and postoperative assessments. Even an isolated hindfoot osteotomy can affect different aspects and areas of the foot and ankle.

Figure 7. Example of a progressive collapsing foot deformity patient classified as 1ABC presenting with significant posterior tibial tendon degeneration and a viable muscle unit that underwent surgical treatment. Preoperatively (A), sinus tarsi impingement, talonavicular uncoverage, and first tarsometatarsal joint instability are noted. At the two-year follow-up visit (B), after a 10 mm medial displacement calcaneal osteotomy, a 10 mm Lapicotton, posterior tibial tendon reconstruction using hamstring allograft, and a gastrocnemius recession. The capability of the first ray to derotate the hindfoot and correct the talonavicular uncoverage (midfoot abduction) is appreciated.

Conclusions

Scientific advancements drive humanity. Health sciences are not different, due to our continuous search to offer our patients the best treatment. Substantial information produced in the last decades was detrimental to the development of PCFD understanding. Technology has provided us with expanded perceptions on how the disease behaves and presents itself. Impact on treatment is also starting to be shown. Although much of these methods are not available in developing countries, concepts and produced data can be applied in clinical practice using existing and resourceful tools. Knowledge will always be the most reliable instrument in the hands of a surgeon and knowledge has no geographical or financial background.

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