The Journal of Foot & Ankle Surgery 000 (2020) 1−8

Contents lists available at ScienceDirect

The Journal of Foot & Ankle Surgery

journal homepage: www.jfas.org

Case Reports and Series

Computer-Assisted Gradual Correction of Charcot Foot Deformities: An In-Depth Evaluation of Stage One of a Planned Two-Stage Approach to Charcot Reconstruction

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A R T I C L E I N F O

Level of Clinical Evidence: 4

Keywords:
Charcot
deformity
external fixation
Hexapod
peripheral neuropathy
rocker bottom foot
surgery

A B S T R A C T

The surgical treatment of Charcot foot is a widely debated topic, with issues ranging from when to operate to how to properly correct a deformity. Historically, correction of a severe deformity was attempted in 1 acute surgical procedure that frequently required open reduction and internal fixation through large incisions. This 1-time procedure would often result in complications including under- or overcorrection of the deformity, neurovascular injury, or incision dehiscence leading to possible soft-tissue infection or osteomyelitis. This retrospective case series aims to evaluate stage 1 of a planned 2-stage approach to Charcot deformity correction, consisting of gradual modification with the use of computer-assisted external fixation. The purpose of using gradual correction was to safely and accurately correct the Meary and calcaneal inclination angles, which were measured using preoperative and postoperative digital radiographs. The procedure was performed on 18 Charcot foot deformities in 18 patients. Each of the feet had a notably significant rocker bottom deformity and most contained an ulceration. Complete ulcer healing was noted in 100% (13/13) of feet with an ulcer, and a statistically significant corrected Meary's ($p < .05$) and calcaneal inclination angle ($p < .05$) to within a normal range was achieved in all deformity corrections with few postoperative problems and complications noted. Average patient follow-up was 39.6 months with a minimum of at least 12 months necessary for inclusion in the study. Therefore, gradual Charcot deformity correction through the use of computer-assisted hexapod external fixation, demonstrates safe, accurate, and reproducible characteristics that adequately prepares the lower extremity for stage 2, the implantation of rigid internal fixation.

Charcot neuroarthropathy (CN), also known as Charcot foot, is a progressive condition typically seen in diabetic patients with peripheral neuropathy. It affects the bones, joints, and soft tissues of the foot and ankle. There are several different theories regarding the origin of CN, notably neuropathic, repetitive microtrauma or increased blood flow causing bone to washout and breakdown (1,2). Progression of CN can lead to the collapse of weightbearing joints in the lower extremity resulting in a red, hot, swollen foot or ankle. Subsequent deformities from fractures and soft-tissue injuries often follow (3). If left untreated, CN can be a limb-threatening condition because the resulting deformities frequently lead to ulcerations that can cause cellulitis or osteomyelitis, leading to possible future amputations (3).

The optimal surgical treatment for CN has been a popular topic of debate in recent years because it has been reported that as high as 50% to 80% of Charcot reconstructions fail (4). Most of the foot and ankle literature has centered around different techniques for acute correction; however, multiple authors have now described a 2-stage approach to Charcot reconstruction that involves gradual correction of large, complex deformities followed by internal fixation (5−7). This staged method allows for a more accurate deformity correction while providing less risk to neurovascular and soft-tissue structures, especially in light of recent literature that describes a roughly 40% prevalence of peripheral arterial disease in patients with CN (8). Therefore, protecting these vital arterial structures along with preventing venous congestion, skin stretching, and nerve irritation has become even more paramount.

Deformity correction en masse usually entails the removal of truncated wedges of bone and implantation of hardware through large,

Financial Disclosure: None reported.
Conflict of Interest: None reported.

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https://doi.org/10.1053/j.jfas.2019.06.008

open incisions. In severe disfigurements, it can be challenging to preoperatively plan for this type of correction because CN usually presents as a multiplanar deformity accompanied by equinus, foot shortening or subluxation, and rotational and angular irregularities with multiple centers of rotation of angulation. This often requires surgeons to make estimations and intraoperative judgments on the fly, which is a nearly impossible task given the complex combination of deformity factors. Furthermore, once a position has been obtained and fixated following acute correction, there is no room for postsurgical adjustment or manipulation if the foot was fixed in an unacceptable position (i.e., varus forefoot or ankle) (9−11).

In CN, insufficiency within the medial column of the foot contributes to lateral column failure and often plantar dislocation of the cuboid, forming a “rocker bottom” deformity. This can ultimately lead to shortening of the foot because of subluxation of the forefoot on the rearfoot, and it frequently causes plantar lateral ulcerations. The talar-first metatarsal (Meary’s) angle, and to a lesser extent the calcaneal inclination angle, serves as a sagittal plane measurement of the deformity within the medial column, and there is often a large “break” in this angle (12−14). Therefore, correction of Meary’s angle in the sagittal plane is reportedly the most significant reconstruction principle that produces the best long-term outcomes if corrected properly. Correction of this multifaceted type of deformity usually requires either relengthening of the foot or removal of bone to reduce the subluxation (15). Once again, it is extremely challenging to attempt to calculate intraoperatively the exact amount of bone to eliminate in order to safely achieve acute deformity correction without placing any tension on the soft-tissue or neurovascular structures, which may lead to local ischemia and soft-tissue failure (5-7). By applying a Hexapod computer-assisted gradual correction technique to a collapsed, subluxed, angulated, rotated, translated, and shortened foot, we are enabling a more accurate deformity correction, providing less risk to neurovascular and soft-tissue structures, preserving more bone, and allowing for potential postoperative manipulation of the deformity.

This study focuses solely on stage 1, the gradual correction phase, of a 2-stage approach to Charcot foot reconstruction. The use of computer-assisted external fixation is an imperative element for proper gradual correction, and currently, there are few studies that describe this. We sought to demonstrate significant correction of severe medial column deformities using computer-assisted software to calculate the rate of correction while limiting risk to paramount soft-tissue and neurovascular structures (5). The primary aim of the investigation was to evaluate the ability to correct the Meary’s and calcaneal inclination angles radiographically to within a normal range with few postoperative complications using gradual correction. The secondary goal was to evaluate ulceration healing in patients that had an ulcer before surgical intervention. We hypothesized that opting for gradual correction with the use of computer-assisted external fixation during stage 1 of a 2-stage approach to Charcot reconstruction is an effective method of achieving safe, accurate, and reproducible deformity correction.

Case Series

Patients and Methods

A retrospective chart review was performed in order to obtain patient information as well as radiographic data from digital x-rays (20/20 Imaging®, Konica Minolta Healthcare, Tokyo, Japan). Eighteen patients and a total of 18 feet underwent a planned, 2-stage surgical Charcot reconstruction. The use of computer-assisted external fixation for gradual correction was used in stage 1 followed by the implementation of rigid internal fixation during stage 2. All procedures were performed by the senior author and took place from November 2011 through January 2018.

Patient age was determined at the time of the initial surgery. The presence of ulceration was noted upon clinical examination by the senior author and included any full-thickness neuropathic ulcerations as well as ulcerations secondary to surgical dehiscence from prior procedures. History of osteomyelitis was determined by chart review and included any diagnosis of osteomyelitis of the operative foot at any time before surgical intervention. The type of deformity was determined by both clinical and radiographic examination, and the presence and nature of equinus was ascertained using the Silversköld test (16). CN stage was defined by the Eichenholz classification (17).

Digital radiographic measurements of the Meary’s and calcaneal inclination angles were performed by the senior author using preoperative lateral weightbearing x-rays that were taken in the angle and base of gait (18). Postoperative radiographs contained external fixation devices holding the foot in a static position with no ability to obtain a standard weightbearing radiograph; however, measurements were able to be taken appropriately following adequate correction in preparation for stage 2 of the reconstruction (Fig. 1).

Using the Paley classification system, postoperative complications were defined as any issue that caused additional surgery during stage 1 such as broken hardware, fractures, or deep infections. Superficial pin tract infections that did not cause a true bone infection were defined only as a problem, not a complication. A pin tract infection was only considered a complication if it progressed to osteomyelitis (19).

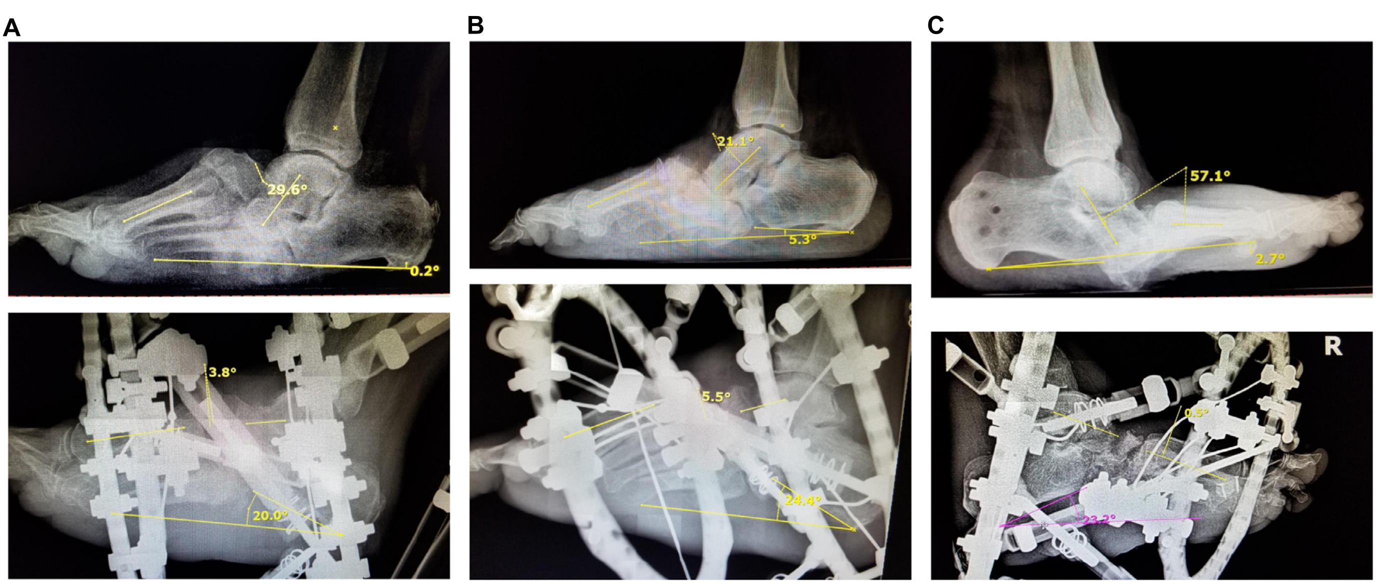

Fig. 1. Preoperative and postcorrection angular measurements on digital lateral radiographs (20/20 Imaging®, Konica Minolta Healthcare, Tokyo, Japan). (*A*−*C*) Preoperative and postcorrection Meary’s and calcaneal inclination angle measurements before and after computer-assisted gradual Charcot deformity correction was employed using external fixation.

All of the data obtained were recorded using a Microsoft Excel spreadsheet (Microsoft Office, 2011; Microsoft, Redmond, WA). All statistical analyses were performed using the statistical software StatPlus (AnalystSoft Inc., Walnut, CA). Detailed descriptive statistics were calculated for each angle measurement, and a 2-tailed *t*-test was performed to evaluate for possible statistical significance regarding the mean change of the Meary's and calcaneal inclination angles preoperatively compared with postoperatively. Statistical significance was defined as $p < .05$.

Surgical Technique

The senior author performed the planned, 2-stage reconstruction procedures as previously described by Lamm et al. (5), with stage 1 consisting of the application of a Hexapod external fixation device (Taylor spatial frame, Smith & Nephew, Memphis TN, or TL-Hex TrueLok Hexapod System, Orthofix Inc., Lewisville, TX) for gradual correction. The frame constructs were built intraoperatively specifically to each patient's deformity. Moderate to severe deformities limited to the midfoot received a Butt frame configuration; more complex deformities with multiple rearfoot and/or midfoot irregularities received a miter frame construct (Fig. 2).

All patients were placed in the supine position and underwent general anesthesia for the procedure. A tourniquet was not used during any of the procedures. Posterior heel cord lengthening was achieved by

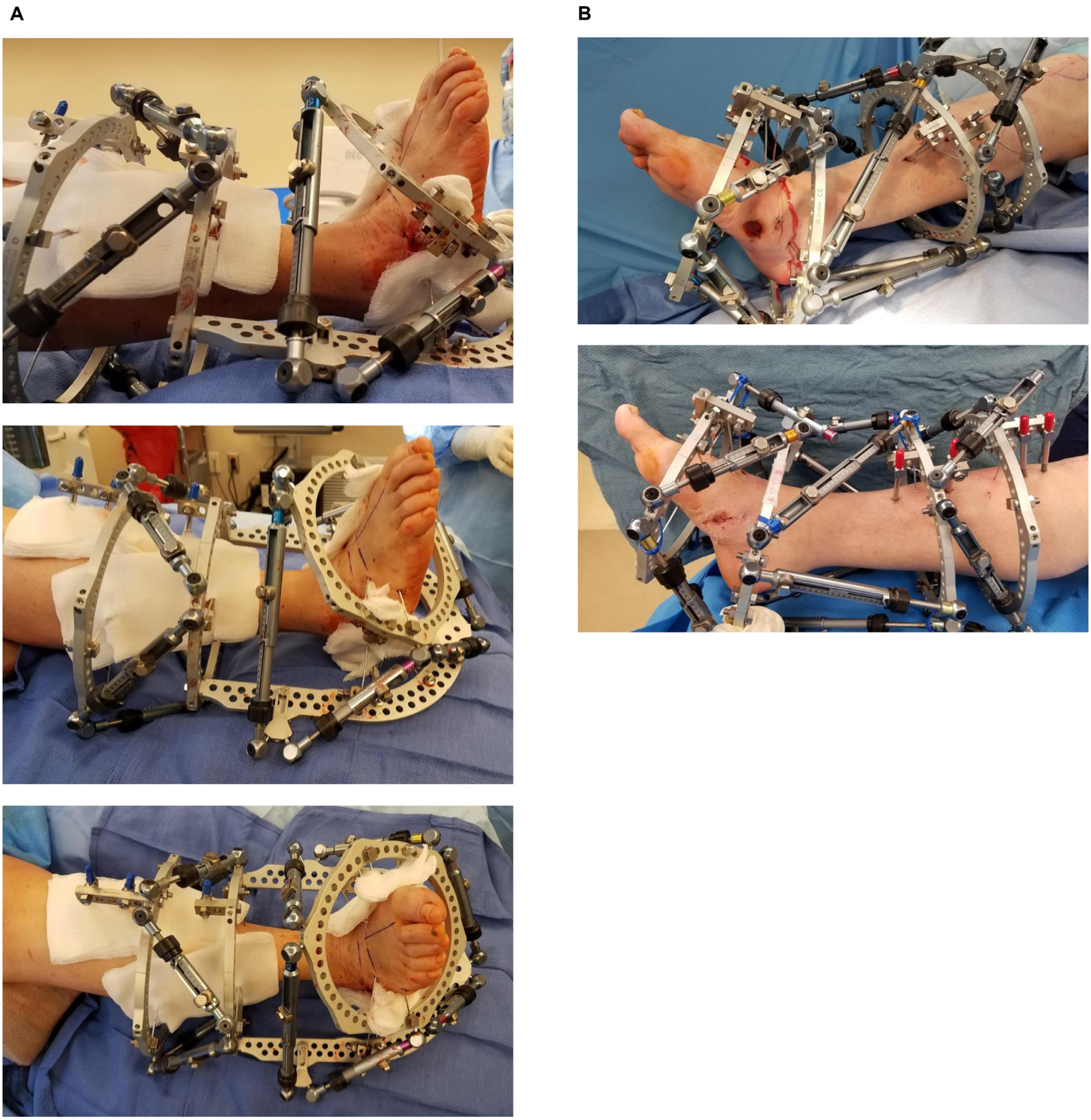

Fig. 2. External fixation constructs. (*A*) Example of a Butt frame configuration and correction. (*B*) Example of a miter frame configuration and correction with notable ulceration healing.

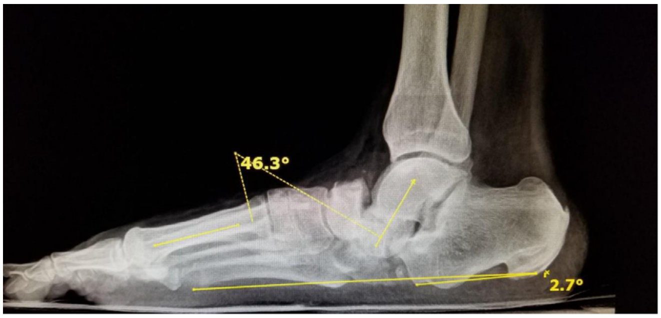

Fig. 3. Preoperative digital lateral weightbearing radiograph (20/20 Imaging®, Konica Minolta Healthcare, Tokyo, Japan) that shows severe, rigid joint subluxation and foot shortening.

performing percutaneous triple hemi-section tendo-Achilles lengthening on all patients, secondary to gastrocnemius-soleal equinus. The tendo-Achilles lengthening was performed before the application of the external fixation device as previously described by Hatt and Lamphier (20). Resection of any osteomyelitic bone was then executed as needed, and any deficits were packed with antibiotic-impregnated calcium sulfate beads to provide local antibiosis. The external fixation device was then applied in either a miter or butt configuration depending on the deformity that was present (21).

Most patients presented with a severely coalesced deformity that required a midfoot osteotomy to allow for distraction osteogenesis to occur secondary to a rigid, shortened, or subluxed foot (Fig. 3). Patients that did not require an osteotomy allowed for gradual correction through ligamentotaxis. The bone cut was performed following stabilization of the limb with the external fixation device (22). A Gigli saw had been percutaneously inserted through 4 1-cm incisions around the midfoot before application of the external fixation device (Fig. 4). Following the osteotomy, the Gigli saw was removed, and the external fixation device was left in place. Adequate gradual correction of the deformity was aided by the use of an internet-based software program that allowed the surgeon to decide on and calculate an accurate rate of correction (http://www.tlhex.com/ and https://www.spatialframe.com/myCases.action).

The use of a hexapod designed external fixation device consisted of a stationary base connected to a moving platform equipped with 6 struts. The unique design enables adjustments to be made in all 3 axes (x, y, and z) simultaneously. This allowed for accurate correction of a complex deformity that may require any combination of angulation, translational, rotational, or lengthening considerations. The software program uses the intricate concept of predictive geometry. The surgeon inputs the deformity parameters, the relationship of the Hexapod to the deformity or osteotomy, and the size of the hexapod and struts into the web-based software program. The surgeon is then able to decide on the speed of correction based on the structures at risk. Understanding which structures were potentially at risk in relationship to the centers of rotation of angulation was of paramount importance during this period. The software program was then able to calculate the necessary daily strut adjustments required for accurate correction (Fig. 5).

Complete correction was defined as Meary's and calcaneal inclination angles that were within a normal range. For Meary's angle, this range was defined as 0 to 15 degrees, and for the calcaneal inclination angle, the range was 8.5 to 30 degrees (23). All other measurements were performed during the preoperative and postoperative periods using digital anteroposterior and lateral radiographs. These included correctional measures for abductus, adductus, forefoot or rearfoot varus or valgus, frontal plane misalignment, and lengthening considerations for subluxations that resulted in shortening. The patient, a family member, or a home health nurse was then responsible for adjusting the struts daily, providing pin tract care, and performing wound care as needed. Patients were allowed to be partial weightbearing as tolerated on the external fixation device. Weekly follow-up visits to the senior author's clinic and serial x-rays were necessary to monitor the progress of the gradual deformity correction.

Following sufficient correction, the external fixation device was left in place for an additional 4 to 6 weeks for the bone to coalesce and for the soft tissues to acclimate to their new position. The device was then removed, and rigid internal fixation was implanted in stage 2 of the 2-stage approach. Determination of which internal hardware to use and further discussion of the stage 2 fixation methods is warranted in a follow-up manuscript because it is a separate and complex topic within itself.

Results

Of the 18 patients involved in this case series, the average age at the time of initial surgery was 60 years (range 34 to 81 years), and the average follow-up was 39.6 months (range 12 to 84 months) with a minimum of at least 12 months necessary for inclusion in the study. The patients were 77.8% (14/18) males and the laterality was 55.6% (10/18) right feet. The deformities present included Charcot of the midfoot, which made up 88.9% (16/18) of the patients, whereas 11.1% (2/18) of the patients exhibited Charcot of the rearfoot. The deformities were classified using Eichenholz staging, and 83.3% (15/18) of patients underwent gradual correction during stage 3, whereas the remaining 16.7% (3/18) of deformities were noted to be in stage 2 before the procedure. A gastrocnemius-soleal equinus deformity was found to be present in 100% (18/18) of patients, and therefore each patient underwent a percutaneous tendo-Achilles lengthening. Before surgical intervention, it was noted that 22.2% (4/18) of the patients had a history of previously diagnosed osteomyelitis. An ulceration was present on the operative foot at the time of initial surgery in 72.2% (13/18) of patients. Plantar cuboid ulcerations comprised 61.5% (8/13) of the patients that presented with an ulcer, 23.1% (3/13) had an ulcer located on the plantar medial aspect of their foot, and 15.4% (2/13) had an ulcer located on the dorsal aspect of their foot (Table 1).

The external fixation device was placed in a miter configuration in 88.9% (16/18) of patients and in a butt configuration in 11.1% (2/18) of patients. The mean time that the external fixation device was in place was 66 days (range 21 to 98). The ulcerations that were present preoperatively in patients were 100% (13/13) healed by the time the external fixation device was removed. Superficial pin tract infections occurred in 22.2% (4/18) of patients but none of these progressed to true bone infections; therefore, they were categorized as problems and not complications as previously described. One proximal tibial pin was also removed in a patient secondary to pain but not infection (Table 2).

The mean preoperative Meary's angle was −27.9 degrees, whereas the mean postoperative Meary's angle was shown to be 2.4 degrees. This was a mean change of 30.3 degrees, which was statistically significant ($p < .05$). The mean preoperative calcaneal inclination angle was 4.5 degrees, whereas the mean postoperative calcaneal inclination angle was 23.1 degrees. This was a mean change of 18.6 degrees, which was statistically significant as well ($p < .05$) (Table 3). Each of the corrected angular measurements fell within the previously described goal range.

Discussion

The overall goal of surgical treatment of severe Charcot deformities is to achieve a stable, plantigrade, weightbearing foot while decreasing the risk of further breakdown. Most previous publications have focused on acute reconstruction procedures that entail open reduction with internal fixation, with possible osteotomies, exostectomies, and hardware implantation through large, open incisions. However, these operations often put patients at an increased risk of osteomyelitis secondary

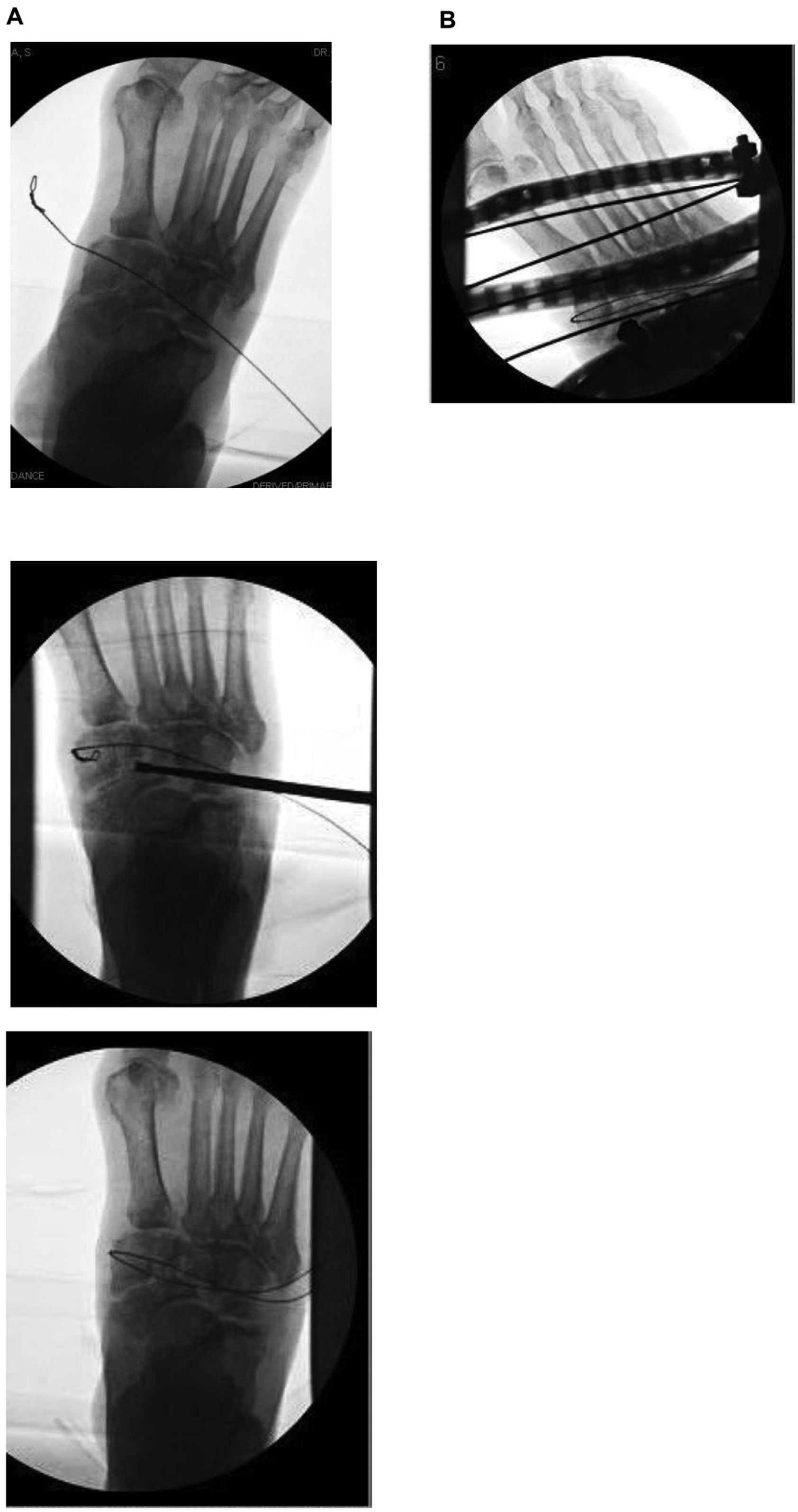

Fig. 4. Percutaneous Gigli saw setup. (*A*) The saw is percutaneously inserted through 4 1-cm incisions around the midfoot before application of the external fixation device. (*B*) The osteotomy is about to be performed following stabilization of the limb with external fixation.

to dehiscence, place severe stress on patients' neurovascular and soft-tissue structures, and often require a very long recovery time of which most is spent non-weightbearing. Furthermore, these operations may require further surgical intervention, which is made nearly impossible because of previously implanted hardware (24). There does seem to be a place for these types of acute corrections, which can be advantageous

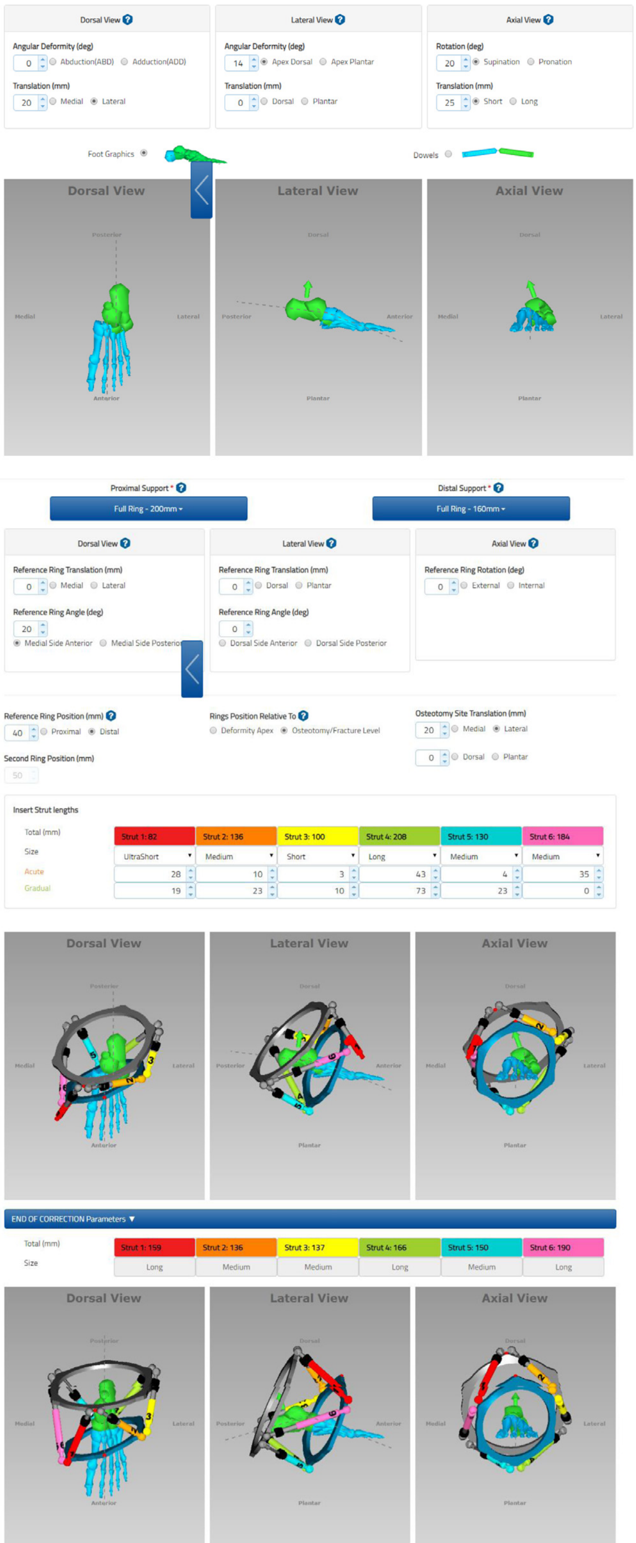

Fig. 5. Computer-assisted gradual correction. Example of internet-based software program that allows the surgeon to calculate an accurate rate of correction for each specific deformity (http://www.tlhex.com/ and https://www.spatialframe.com/myCases.action).

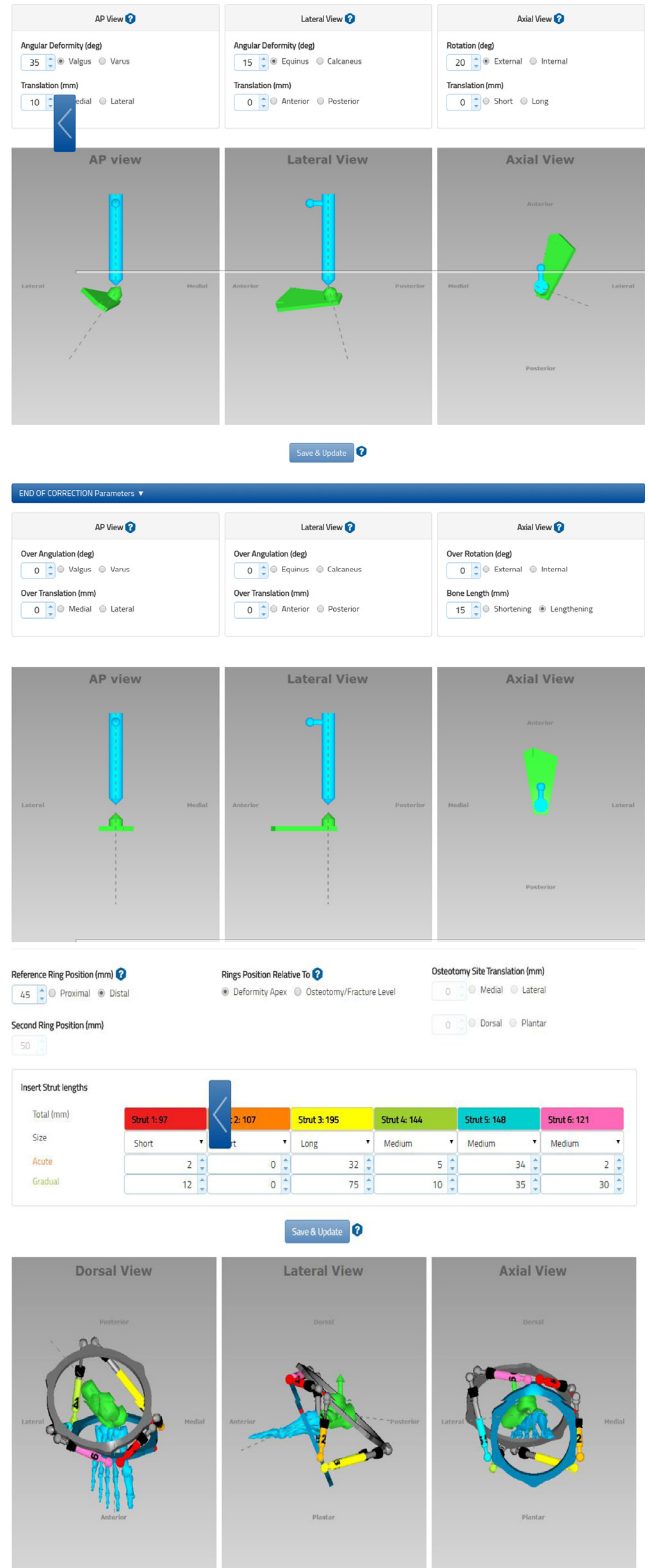

Fig. 5. Continued

Table 1
Patient demographics and information (N = 18 feet in 18 patients)

Patient	Age	Sex	Foot Laterality	Charcot Deformity Location	Eichenholz Classification Stage	Ulceration Location	Preoperative Gastrocnemius-Soleal Equinus	History of Osteomyelitis
1	61	M	Left	Midfoot	3	Plantar cuboid	Yes	Yes
2	69	M	Right	Midfoot	2	Plantar medial foot	Yes	Yes
3	49	M	Left	Midfoot	2	Plantar cuboid	Yes	Yes
4	71	M	Left	Midfoot	3	None	Yes	No
5	53	M	Left	Midfoot	2	Dorsal foot	Yes	No
6	69	M	Right	Midfoot	3	Plantar cuboid	Yes	No
7	66	F	Right	Midfoot	3	Plantar cuboid	Yes	No
8	72	M	Left	Midfoot	3	Plantar cuboid	Yes	No
9	69	M	Right	Midfoot	3	Dorsal foot	Yes	Yes
10	81	M	Right	Midfoot	3	Plantar cuboid	Yes	No
11	67	F	Right	Midfoot	3	Plantar cuboid	Yes	No
12	56	M	Left	Midfoot	3	None	Yes	No
13	39	M	Right	Midfoot	3	None	Yes	No
14	60	F	Right	Rearfoot	3	Plantar cuboid	Yes	No
15	34	M	Right	Midfoot	3	Plantar medial foot	Yes	No
16	65	F	Right	Rearfoot	3	Plantar medial foot	Yes	No
17	45	M	Left	Midfoot	3	None	Yes	No
18	54	M	Left	Midfoot	3	None	Yes	No

Abbreviations: F, female; M, male.

Table 2
Perioperative findings (N = 18 feet in 18 patients)

Patient	External Fixation Frame Configuration	Days Spent in External Fixation Device	Percutaneous Tendo-Achilles Lengthening	Preoperative Meary's Angle	Postoperative Meary's Angle	Preoperative Calcaneal Inclination Angle	Postoperative Calcaneal Inclination Angle	Ulceration Healed	Problems or Complications	Follow-Up (Months)
1	Miter	48	Yes	−44	3	10	15	Yes	Superficial pin tract infection	84
2	Miter	60	Yes	−31	6	2	17	Yes	–	59
3	Miter	58	Yes	−9	0	−1	10	Yes	–	70
4	Miter	50	Yes	−43	5	11	18	–	–	80
5	Miter	86	Yes	−35	2	4	26	Yes	Superficial pin tract infection	50
6	Butt	85	Yes	−22	4	12.9	27	Yes	Superficial pin tract infection	28
7	Butt	90	Yes	−31	3	14.6	28	Yes	Superficial pin tract infection	25
8	Miter	82	Yes	−21	4	2.4	31	Yes	–	32
9	Miter	79	Yes	−28	0	7	27	Yes	–	35
10	Miter	98	Yes	−55	2	−10	28	Yes	–	29
11	Miter	79	Yes	−15	4	7.7	25	Yes	–	34
12	Miter	50	Yes	−26	3	5	25	–	–	44
13	Miter	88	Yes	−15	0	14	25	–	–	37
14	Miter	67	Yes	0	0	−19	24	Yes	–	46
15	Miter	21	Yes	−35	5	2	20	Yes	–	20
16	Miter	32	Yes	−30	0	10	24	Yes	Painful pin removed	14
17	Miter	55	Yes	−40.7	2	2.8	22	–	–	13
18	Miter	60	Yes	−21.6	1	4.7	23	–	–	12

Table 3
Mean comparison of preoperative vs. postoperative angles (N = 18 feet in 18 patients)

	Preoperative Meary's Angle	Postoperative Meary's Angle	Preoperative Calcaneal Inclination Angle	Postoperative Calcaneal Inclination Angle
Mean	−27.9	2.4	4.5	23.1
Standard deviation	13.5	2.0	8.4	5.3
Range	−55.0 to 0.0	0.0 to 6.0	−19.0 to 14.6	10.0 to 31.0
Median	−29.0	2.5	4.9	24.5
Two-tailed distribution	$p = < 0.05$		$p = < 0.05$	

when dealing with smaller, less severe deformities when not much correction is necessary to achieve a stable, plantigrade foot. However, when dealing with more complex, severe deformities, the described computer-assisted, gradual, minimally invasive approach could be used to help minimize these complications and achieve a more accurate correction.

To further evaluate this approach, the current study aimed to demonstrate reproducibility of Lamm's method where he used the 2-stage reconstruction approach to show correction of the Meary and calcaneal inclination angles to within a normal range, exhibit avoidance of further ulcerations, and reduce the amount of time that it took for patients to return to normal shoe gear (5). Outcomes were shown to be similar in regard to complete ulcer healing, few postoperative problems, and statistical significance of the mean correction of the Meary and calcaneal inclination angles to within a normal range. These results not only build on the work of Lamm et al., but they also indicate that gradual deformity correction may be the most safe and effective approach when it comes to Charcot reconstruction. As well, that external fixation is indicated even in the place of ulceration in the foot.

The present case series is the largest to date focusing on gradual Charcot deformity correction with the use of computer-assisted external fixation. The study is limited in that it is only focused on stage 1 of the previously described 2-stage approach; however, it is necessary to focus on each stage separately because of the complexity and nature of the condition itself, the surgical correction, and the many different variables at stake. Subsequent studies will need to be performed to determine if these corrections were maintained over time and the frequency in which limb salvage could be achieved. Additionally, the current study is limited by the inability to take a true standard weightbearing radiograph postoperatively. Even though the postoperative lateral radiographs were taken with external fixation devices holding the foot in a static or “loaded” position to simulate a weightbearing film, it is not completely comparable to the preoperative radiographs.

In conclusion, stage 1 of a 2-stage approach to Charcot reconstruction can be accomplished successfully by gradual deformity correction with the use of computer-assisted external fixation. We further hope to build upon this study to ultimately find a consensus gold standard method for correction of complex Charcot deformities.

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