3-D Printing for Surgical Planning of Complex Foot and Ankle Deformity

[1]Joseph Brown BS, [1]Ryan Larsen BS, [1]Jonathan Nigro BS, [2]Connor Reed BS, [2]Travis Anderson BS, [2]Tobee Gunter BS, [2]Anthony Smaldino BS

[1]CPMS-III, College of Podiatric Medicine and Surgery, Des Moines University, Des Moines, IA

[2]CPMS-II, College of Podiatric Medicine and Surgery, Des Moines University, Des Moines, IA

ACFAS STUDENT CLUB DMU

DES MOINES UNIVERSITY

Statement of Purpose

Revision surgery for patients with Charcot neuroarthropathy in the hindfoot and ankle present a challenge for foot and ankle surgeons. Traditional imaging limits preoperative planning and an appreciation of spatial relationships in complex foot and ankle deformities. The purpose of this case study is to document the utility of three-dimensional (3-D) reconstructed models for perioperative planning of complex foot and ankle surgeries.

Literature Review

Patients with diabetic neuropathy have a high rate of complications.[1] Charcot deformity renders patients at risk for plantar and ankle ulcerations leading to amputation.[2-5] Malunion of the ankle in varus also predisposes patients to increased stress under the fifth metatarsal.[6] In addition, peripheral neuropathy and increased surgery duration have been associated with increased bone healing complications in diabetic patients undergoing foot and ankle surgery.[7]

Focal dome supramalleolar osteotomies have been described for restoring congruency of the malunited ankle while preserving hindfoot alignment.[6,8] The Osteotomy Rules state that when the rotation of angulation passes through the apex, the bone realigns if the osteotomy is done at a different level than the deformity.[9,10] Hence, the surgeon must be able to make the correction in multiple planes which requires extensive preoperative planning to be successful.[6,11] Comprehensive radiographic evaluation is required to optimize the accuracy of the osteotomy.[12]

Two-dimensional radiographs are limited by superimposition and rotational distortion.[13-15] Traditional imaging limits the planning of complex rotational deformities as well as intra-articular malunions because the osteotomy must be performed in multiple planes to correct the deformity.[12] This limits the preoperative planning, leading the surgeon to make decisions based on clinical experience and real time assessment of the situation.[16]

3-D anatomical models can address the multiplanar nature of complex deformities by improving spatial anatomical recognition.[12,17] Since the development of the first 3-D printer in the early 1980s,[18] technological advancements have revolutionized the utilization of 3-D printing for multiple uses in medicine.[19,20] Various advantages of 3-D models have been cited in the literature, including (1) better preoperative planning,[12,19,21-26] (2) decreased operating time,[16,21,27-29] (3) improved patient education,[16,19,21] (4) decreased intraoperative radiation exposure,[27,28,30] and (5) decreased intraoperative blood loss.[16,21,29] 3-D printing is particularly advantageous when 3-D spatial relationships are critical to surgical decision making.[12,17,21,22,24]

Case Study

A 59-year-old type II diabetic male with peripheral neuropathy presented with a non-union of the left ankle status post Charcot reconstruction surgery. A bone stimulator was utilized to facilitate healing of the non-union. The non-union healed malunited in a varus position [Figure 1]. The residual deformity resulted in a plantar-lateral ulceration [Figure 2]. The wound healed using serial total contact casts over a period of 2 months. However, the diabetic foot ulcer re-occurred in 5 months once the patient resumed weightbearing due to the mal-aligned ankle. Advanced skin substitute grafts were applied to the lesions without resolution. As a final option, the patient was offered a below knee amputation versus additional limb salvage surgery.

To better understand the deformity, a CT scan was obtained. A 3-D anatomical model was constructed of the left foot and ankle [Figure 3]. The 3-D model was

Case Study Cont.

utilized to educate the patient on their deformity and for surgical planning. To address the varus deformity, based on information provided by the 3-D model, a left tibial supramalleolar osteotomy with application of an external fixator was performed [Figure 4]. The outcome of the surgical procedure was a rectus ankle with plantigrade foot [Figure 5].

The post-operative course included an anterior ankle incision dehiscence and a pin tract infection. Both complications were treated and resolved without further complication. Upon removal of the external fixator, 4 months after application, rectus alignment of the ankle and a plantigrade foot were maintained. 15 months post-operatively, the foot remained plantigrade with acceptable ankle alignment [Figure 6]. Additionally, the distal tibial osteotomy site healed in good alignment without further osseous or wound complications [Figure 7].

Case Study Figures

Figure 1. Pre-revision malunited ankle in varus position.

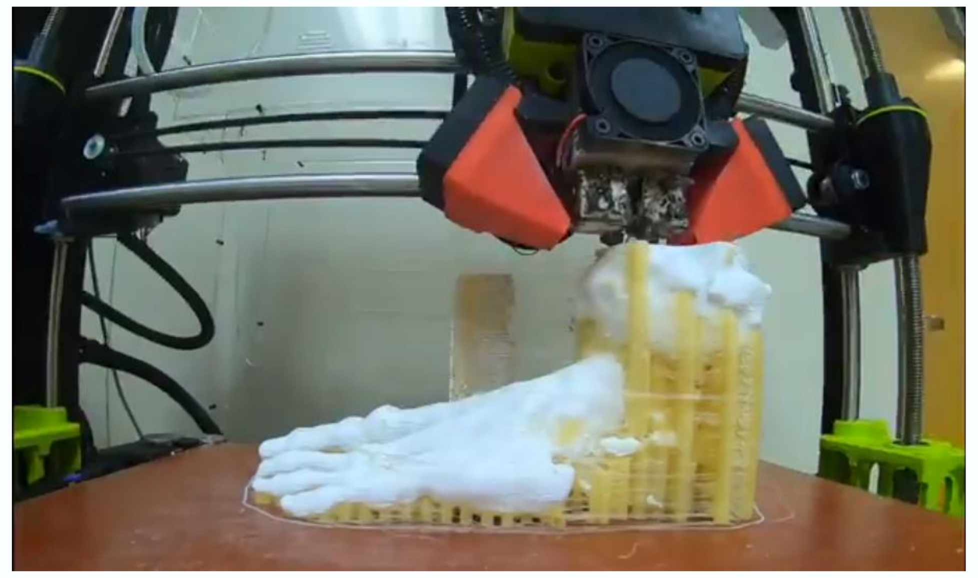

Figure 3. 3-D printing of reconstructed anatomical foot and ankle model.

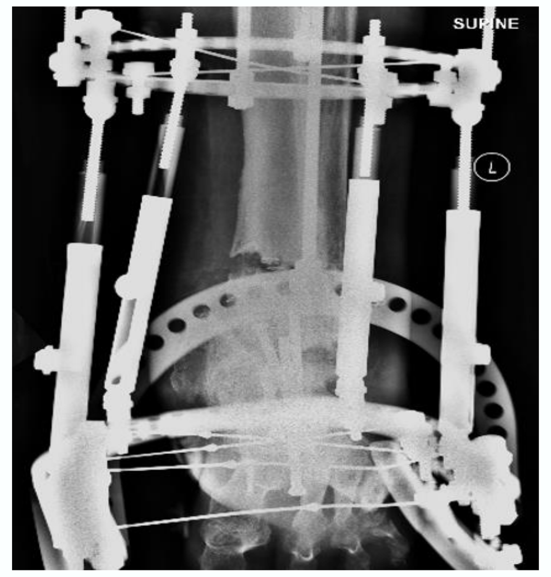

Figure 5. Rectus ankle alignment after left tibial supramalleolar osteotomy with external fixator application.

Figure 6. Rectus ankle alignment at final follow-up.

Figure 2. Plantar-lateral ulceration of left foot.

Figure 4. Utilization of 3-D anatomical model intra-operatively.

Figure 7. Fully healed and functional limb 15 months after revision.

Analysis & Discussion

Complex Charcot deformities present a significant challenge. The foot and ankle surgeon must be able to identify deformity parameters, which becomes increasingly difficult when the patient requires revisional surgery. Focal dome supramalleolar osteotomies can restore congruency of a malunited ankle and preserve hindfoot alignment,[6,8] but the outcome is dependent on proper preoperative planning.[11] Advances in medical technology have allowed physicians to provide patients with improved perioperative care and streamline their surgical outcomes. 3-D printed models have been shown to assist with preoperative planning,[12,19,21-26] improve patient understanding,[16,19,21] decrease operating time,[16,21,27-29] and increase postoperative functional scores.[16] 3-D printed models may be especially beneficial when considering spatial relationships[12,17,21,22,24] or performing a complex multiplanar osteotomy.[12]

One drawback to 3-D printing is concern over increased cost. Low-cost commercial 3-D printing software is now widely available,[24] and multiple studies have found the use of 3-D printing to be cost-effective.[22,23,28,31] Utilization of 3-D printed models for Charcot reconstruction is lacking in the literature. This case study demonstrates that anatomic models can be a vital tool to assist surgeons in complex foot and ankle revisions. With the assistance of 3-D printing for perioperative care, the patient in this case study was able to achieve a plantigrade functional foot.

References

1. Stapleton JJ, Belczyk R, Zgonis T. Revisional Charcot foot and ankle surgery. Clin Podiatr Med Surg 26:127-39, 2009.
2. Burns PR, Wukich DK. Surgical reconstruction of the Charcot rearfoot and ankle. Clin Podiatr Med Surg 25:95-120, 2008.
3. Rogers LC, Frykberg RG, Armstrong DG, Boulton AJM, Edmonds M, Van GH, Hartemann A, Game F, Jeffcoate W, Jirkovska A, Jude E, Morbach S, Morrison WB, Pinzur M, Pitocco D, Sanders L, Wukich DK, Uccioli L. The Charcot foot in diabetes. Diabetes Care 34:2123-2129, 2011.
4. Schols RM, Davies WL, Mudge EJ, Harding KG. Persistent plantar ulceration associated with midfoot Charcot deformity. Int Wound J 9:72-79, 2013.
5. Hastings MK, Sinacore DR, Mercer-Bolton N, McCormick JJ, Hildebolt CF, Prior FW, Johnson JE. Precision of foot alignment measures in Charcot arthropathy. Foot Ankle Int 32:867-72, 2011.
6. Myerson MS. Reconstructive Foot and Ankle Surgery. Philadelphia, PA, Saunders, 2010.
7. Shibuya N, Humphers JM, Fluhman BL, Jupiter DC. Factors associated with nonunion, delayed union, and malunion in foot and ankle surgery in diabetic patients. J Foot Ankle Surg 52:207-11, 2013.
8. Benthien RA, Myerson MS. Supramalleolar osteotomy for ankle deformity and arthritis. Foot Ankle Clin 9:475-87, 2004.
9. Stasko PA, Hlad LM. Essentials of deformity planning. Clin Podiatr Med Surg 35:457-65, 2018.
10. Paley D. Principles of Deformity Correction. Singapore, Springer, 2002.
11. Mendicino RW, Catanzariti AR, Reeves CL. Percutaneous supramalleolar osteotomy for distal tibial (near articular) ankle deformities. J Am Podiatr Med Assoc 95:72-84, 2005.
12. de Muinck Keizer RJO, Lechner KM, Mulders MAM, Schep NWL, Eygendaal D, Goslings JC. Three-dimensional virtual planning of corrective osteotomies of distal radius malunions: a systematic review and meta-analysis. Strategies Trauma Limb Reconstr 12:77-89, 2017.
13. Lintz F, Netto CC, Barg A, Burssens A, Richter M. Weight-bearing cone beam CT scans in the foot and ankle. EFORT Open Rev 3:278-86, 2018.
14. Barg A, Amendola RL, Henninger HB, Kapron AL, Saltzman CL, Anderson AE. Influence of ankle position and radiographic projection angle on measurement of supramalleolar alignment on the anteroposterior and hindfoot alignment views. Foot Ankle Int 36:1352-61, 2015.
15. Willauer P, Sangeorzan BJ, Whittaker EC, Shofer JB, Ledoux WR. The sensitivity of standar radiographic foot measures to misalignment. Foot Ankle Int 35:1334-40, 2014.
16. Bai J, Wang Y, Zhang P, Liu M, Wang P, Wang J, Liang Y. Efficacy and safety of 3D print-assisted surgery for the treatment of pilon fractures: a meta-analysis of randomized controlled trials. J Orthop Surg Res 13:283, 2018.
17. Crossingham JL, Jenkinson J, Woolridge N, Gallinger S, Tait GA, Moulton CA. Interpreting three-dimensional structures from two-dimensional images: a web-based interactive 3D teaching model of surgical liver anatomy. HPB (Oxford) 11:523-8, 2009.
18. Hull C. Apparatus for Production of Three-Dimensional Object by Stereolithography. US Patent 4,575,330, 1986.
19. Zang CW, Zhang JL, Meng ZZ, Liu LF, Zhang WZ, Chen YX, Cong R. 3D printing technology in planning thumb reconstructions with second toe transplant. Orthop Surg 9:215-20, 2017.
20. Whitaker M. The history of 3D printing in healthcare. Ann R Coll Surg Engl 96:228-9, 2014.
21. Yang L, Shang XW, Fan JN, He ZX, Wang JJ, Liu M, Zhuang Y, Ye C. Application of 3D printing in the surgical planning of trimalleolar fracture and doctor-patient communication. Biomed Res Int 2016:1-5, 2016.
22. Giovinco NA, Dunn SP, Dowling L, Smith C, Trowell L, Ruch JA, Armstrong DG. A novel combination of printed 3-dimensional anatomic templates and computer-assisted surgical simulation for virtual preoperative planning in Charcot foot reconstruction. J Foot Ankle Surg 51:387-93, 2012.
23. Lal H, Patralekh MK. 3D printing and its applications in orthopaedic trauma: a technological marvel. J Clin Orthop Trauma 9:260-68, 2018.
24. Jastifier JR, Gustafson PA. Three-dimensional printing and surgical simulation for preoperative planning of deformity correction in foot and ankle surgery. J Foot Ankle Surg 56:191-95, 2017.
25. Martelli N, Serrano C, van den Brink H, Pineau J, Prognon P, Borget I, El Batti S. Advantages and disadvantage of 3-dimensional printing in surgery: a systematic review. Surgery 159:1485-1500, 2016.
26. Chung KJ, Hong DY, Kim YT, Yang I, Park YW, Kim HN. Preshaping plates for minimally invasive fixation of calcaneal fractures using a real-size 3D-printed model as a preoperative and intraoperative tool. Foot Ankle Int 35:1231-6, 2014.
27. Izatt MT, Thorpe PLPJ, Thompson RG, D'Urso PS, Adam CJ, Earwaker JWS, Labrom RD, Askin GN. The use of physical biomodelling in complex spinal surgery. Eur Spine J 16:1507-18, 2007.
28. Zhang YZ, Chen B, Lu S, Yang Y, Zhao JM, Liu R, Li YB, Pei GX. Preliminary application of computer-assisted patient-specific acetabular navigational template for total hip arthroplasty in adult single development dysplasia of the hip. Int J Med Robot 7:469-74, 2011.
29. Xie L, Chen C, Zhang Y, Zheng W, Chen H, Cai L. Three-dimensional printing assisted ORIF versus conventional ORIF for tibial plateau fractures: a systematic review and meta-analysis. Int J Surg 57:35-44, 2018.
30. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online 15:115, 2016.
31. Lethaus B, Poort L, Bockmann R, Smeets R, Tolba R, Kessler P. Additive manufacturing for microvascular reconstruction of the mandible in 20 patients. J Craniomaxillofac Surg 40:42-6, 2012.

Acknowledgements

Special thanks to Collin Pehde DPM, FACFAS (DMU SCACFAS faculty advisor) for his advisory role in this case study.

Additional thanks to Brad Peck BS and Logan Gull BS for their assistance with 3-D printing.