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3D printing technology: Rethinking the approach to talar surgery; a literature review

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Talar fractures account for less than 1% of all fractures, yet despite this low occurrence they represent a major reconstruction challenge for surgeons. While total talar replacements are seldom used, there are very few procedures that can simultaneously repair a damaged talus and allow the patient to retain adequate range of motion, joint stability, function and satisfaction. These factors have become the impetus for exploring the role of 3D printing as a relatively novel surgical intervention for reconstructing the talus. Specific indications for a 3D printed total talar replacement include severe osteoarthritis, avascular necrosis, osteomyelitis, and trauma especially in the setting of a juvenile patient. As a relatively new approach, there is still much to be explored in regards to creating a 3D printed talar prosthesis, and the utility of the technology would greatly benefit from further research and development. Based upon our initial review of seven different studies, the use of 3D printed talar implants, when surgically indicated, demonstrates promising results in increasing patient satisfaction and improving postsurgical outcomes when compared to more conventional methods of repair. Thus, 3D printed talar implants represent a potentially viable tool to be considered by surgeons for a more precise and patient outcome-driven solution following talar injury.

Keywords: ankle, arthritis, bone, implant, replacement, tarsal

With its irregular shape and complex role in movements of the foot and ankle, the talus poses several concerns when it comes to surgery. First and foremost, the talus serves as the bridge between the foot and the leg playing a major functional role in ankle and subtalar motion. Consequently, surgical procedures such as arthrodesis significantly limit ankle and subtalar joint mobility and thus affect a patient's normal gait. The importance of this is highlighted by the classic article by Ramsey and Hamilton which showed that with just 1 mm of lateral talar displacement there is a 42% decrease in tibiotalar contact area [1]. Furthermore, the tenuous blood supply of the talus makes it particularly susceptible to avascular necrosis (AVN) with upwards of 50% of talar neck fractures resulting in avascular necrosis, thus necessitating precise anatomic reduction of fracture fragments and delicate handling of soft tissue during the surgical approach [2]. Patients who have undergone surgical repair of severe talar neck and body fractures often endure lengthened convalescence periods and may even require secondary procedures resultant to sequelae [3]. In a long-term follow-up of surgical treatment of talar neck and body fractures, Ohl, et al. reported a long-term reintervention in 35% of patients, post-traumatic osteoarthritis in 94% of patients, and only 59% of patients having normal rearfoot alignment at final follow-up [3]. This inspired our interest in the outcomes of 3D printing for treatment of fractures of this nature. Finally, one must assess preoperative aspects of the patient such as age, severity of deformity, and expected post-injury level of activity when considering using a 3D printed total talar prosthesis. With the advent and advancement of

3D printing technology, an opportunity exists to redefine the surgical approach to the damaged talus, reduce the length of postoperative recovery periods, and improve patient outcomes. The aim of this study is to review contemporary research on the use of 3D printing in talar surgery with respect to surgical outcomes and patient satisfaction.

Methods

In order to answer the research question, articles concerning patient recovery and outcomes were searched for through the online database, PubMed. The keywords searched on the database included "3D printing" or "three-dimensional printing" in combination with "talus" or "talar." The phrase "American Orthopedic Foot and Ankle Society Score" was also searched for, and sorted by best match. Only quantitative articles were included in the review so that there was objective data to properly compare whether the use of 3D printed prostheses improved treatment and healing of talar injuries (Table 1). All but one of the articles used to review and compare data were published after 2016 to keep the data relevant.

Results

In a study conducted by Chiu, et al., a 3D printed talar spacer was implemented to counteract issues pertaining to joint instability caused by the absence of the talus [4]. With the insertion of the custom cement spacer, 5° of dorsiflexion and 10° of plantarflexion were able to be retained, along with minimal subtalar joint (STJ) motion [4]. Its capability of maintaining these criteria while also combating severe infections versus a normal non-anatomical cement spacer has scarcely been reported in the literature. Serum C-reactive protein level (CRP) decreased from 47 mg/L to <5 mg/L; showing no signs of erosion with the surrounding articulation between the tibia, navicular and calcaneus [4].

In one particular case study by Fang, et al., a patient who presented with malignancy of the talus was surgically operated on using a novel approach: modular total talar prosthesis [5]. A modular prosthesis for the affected talus was made using 3D printing technology to replicate a mirror image of the contralateral talus [5]. The aim of the study was to determine if 3D printed modular talar prostheses are more effective at preserving ankle motion and function than conventional arthrodesis procedures [5]. Fang, et al., reported that following the surgery, the patient had normal range of motion in regards to ankle dorsiflexion and plantarflexion, scoring 26/30 and 91/100 according to the Musculoskeletal Tumor Society and AOFAS score, respectively [5].

Furthermore, another retrospective study by Tracey, et al., was directed on patients both preoperatively and postoperatively undergoing implantation of a custom total talar replacement. Both talar dimensions, such as talar height, talar arc length, and talar width, and talar alignment, such as tibiotalar alignment, talar tilt angle, declination angle, Boehler's angle, and Meary's angle, were analyzed and t-tests were used to identify significance ($p \leq 0.05$) [6]. As a result of the data analysis between talar arc length, talar height and talar width, only talar height was noted to be statistically significantly different ($P < 0.001$). The mean pre-talar height was 24.73mm whereas the mean post-talar height was 29.06mm indicating a significant increase in total talar height using Total Talar replacements (TTP) ($p < 0.01$) [6]. Out of the 5 alignment dimensions that were measured, talar tilt angle significantly decreased from $2.84° \pm 2.26°$ to $1.15° \pm 1.31°$ ($p < 0.03$) [6]. This highlighted that with the ability to synthetically re-create a talus through 3D printing, two dimensions (talar height and talar tilt angle) were corrected while maintaining the other six dimensions [6].

This data supports another similar study conducted by Hamid, et al regarding the success of 3D printing in which custom printed titanium scaffolds replaced the fractured talus. This study involved a patient who had distal tibia bone loss but the talus needed to be replaced due to the talar dome being highly sclerotic.

Title	Author (s) & Year	Purpose	Procedures Discussed
Use of Three-Dimensional Printing Techniques in the Management of a Patient Suffering From Traumatic Loss of the Talus	Chiu SY, Wan KW 2019	Explore the use of 3D anatomical printed spacers to allow increased ROM, stability and bilateral limb length to help facilitate walking in the patient compared to conventional spacers, while combating infection.	3D printed Talar cement spacer (pre-treatment), total talar replacement, AOFAS Scoring
Total talar replacement with a novel 3D printed modular prosthesis for tumors	Fang X, Lie H, et al. 2018	Use a modular 3D printed prosthesis, as an alternative to arthrodesis, for talar repair in order to increase post surgery ROM and joint longevity.	Total talar replacement, in place of an arthrodesis
Custom 3D-Printed Total Talar Prostheses Restore Normal Joint Anatomy Throughout the Hindfoot	Tracey J, Arora D, et al. 2019	To determine the accuracy of 3D printing by reproducing a synthetic talus and if this method will restore normal alignment of the ankle, subtalar and forefoot joints.	Total talar prostheses for Talar avascular necrosis, radiographic analysis of talar dimensions and alignment pre and postoperatively, t-tests identified significance
Salvage of Severe Foot and Ankle Trauma With a 3D Printed Scaffold	Hamid KS, Parekh SG, et al. 2016	To describe successful limb salvage through using a patient-specific custom 3D printed titanium scaffold to replace segmental bone loss of the distal tibia and complete talus.	Studied on one patient and was followed closely by routine radiographs and CT scans
Use of Patient-Specific 3D-Printed Titanium Implants for Complex Foot and Ankle Limb Salvage, Deformity Correction, and Arthrodesis Procedures	Dekker TJ, Steele JR, et al. 2018	To utilize 3D-printed titanium implants to correct multiple bone defects and lower extremity deformities by increasing successful limb salvage, long-term function, and patient satisfaction.	A total of 15 patients underwent either a tibio-talo-calcaneal arthrodesis, spanned tibia defect, tibia osteotomy, or an ankle fusion
3D Printed Total Talar Replacement: A Promising Treatment Option for Advanced Arthritis, Avascular Osteonecrosis, and Osteomyelitis of the Ankle	Shnol H, Laporta GA 2018	To determine if total talar replacement utilizing a prosthetic total talar implant may provide the best option for younger patients with end-stage ankle pathology.	Total talar replacement, total talectomy, ankle arthrodesis

Table 1 Brief overview of current literature regarding3D printing in talar surgery.

Post-implantation, the patient was examined closely through radiographs and CT scans and this method resulted in successful incorporation of bone of the talus [7]. Using 3D printed titanium truss structure resulted in successful limb salvage from foot fractures such as an unreconstructable talus fracture compared to other techniques, such as allograft and autograft, which this study invalidates [7].

Similarly, a retrospective study by Dekker, et al., was a consecutive case series using fifteen patients who underwent a custom-made 3D titanium implant to correct a tibial, ankle or hindfoot deformity [8]. The results show that the custom-made 3D printed titanium implants were successful in 87% of patients (13/15 patients). There was an average fusion time of 5 months with a range of 2.6-8.2 months, which was detected utilizing CT scan results [8]. There were two failures of the implant; one secondary to an early deep infection two weeks after implantation, the other due to nonunion of a prior attempted ankle arthrodesis which resulted in continued pain and sclerotic tibia bone. Both patients elected to have an amputation [8]. All patients were administered a 100-mm visual analog scale for pain using the AOFAS scale, and the Foot and Ankle Ability Measure Activities of Daily Living score (FAAM ADL). All scores demonstrated significant improvement with a p-level of $p<0.05$. Both the FAAM ADL and AOFAS significantly increased, while the 100-mm Visual Analog Scale (VAS) significantly decreased. With the exception of the two failed procedures, all patients reported they would choose to undergo the same procedure if presented with the same situation in the future [8].

Lastly, Schnol, et al., explored 3D printed total talar replacement as a treatment option for advanced arthritis, avascular osteonecrosis, and osteomyelitis of the ankle [9]. 3D printed talar prostheses were custom made for each patient by measuring the talus with radiographs, MRI, and CT scans. The composition of the artificial talus was also made to match the bone's biological affinity [9]. The outcome of patients treated by the first-generation talar body prosthesis was in 1997; these patients were evaluated 11-15 years after the operation and eight out of nine of the patients had a satisfactory result [9].

Discussion

A thorough examination of the preoperative considerations and postoperative outcomes of 3D printed TTRs must be conducted in order to critically evaluate their utility in salvage procedures of the talus. It was found that both dorsiflexion and plantarflexion would allow enough range of motion for walking with the use of an implanted 3D talar spacer [4,5]. Fang, et al., concluded that a 3D printed modular prosthesis for a total talar replacement is an effective procedure leading to potential long-term ankle stability and function in patients with a large tumor in the talus [5]. The consecutive case series conducted by Dekker, et al., consisted of fifteen patients who had either a tibio-talo-calcaneal arthrodesis (TTC), spanned tibia defect, tibia osteotomy, or ankle fusion, where custom-made 3D printing titanium implants were utilized to correct their respective deformity. The results indicated successful outcomes with the use of the custom-made 3D printed titanium implants for difficult lower extremity limb salvage, correction of deformity and arthrodesis with early follow-up [8]. The study demonstrated effective use and incorporation of the custom-made implant via this 3D technology, and was shown to be a successful piece of surgical equipment. Because the implants are patient specific, this represents an efficient way to address, treat, and mimic the once healthy lower extremity by allowing for specific needs to be met and planned for preoperatively [8]. Moreover, the study by Tracey, et al., discovered that 3D printed total talar replacements were particularly effective in re-creating and correcting talar height and tilt angle [6].

These findings were also supported in a study conducted by Hamid, which used 3D reconstruction from CT scans for processing and implant creation [7]. The case study by Walley, et al., discovered that 3D reconstruction of MRI and CT scans were able to estimate the size of talar lesions much more accurately. These studies as a whole suggest that using 3D printing for talar replacements, either total replacements or for fractured bone, have shown better outcomes when used in addition to other techniques, such as MRI, CT scans, and in association with autografts and allografts.

However, some possible complications have also been brought up. Some of the issues faced with using the anatomical cement spacer were that the talar surface is not as smooth as a normal talus [4]. This could lead to complications such as cartilage damage of the tibial plafond, navicular, and calcaneus, cement spacer breakage if the ultimate tensile and compression strengths are surpassed, and generation of cement particles following cement mantle wear [4]. Wear of the cement spacer and the subsequent polymethyl-methacrylate (PMMA) particle debris could possibly trigger inflammation in the synovial cavity, granulomatous or nongranulomatous bony destruction, or lymphadenopathy [4]. However, none of the listed possible complications were reported, they were merely listed as possibilities therefore long-term effects are unknown [4]. A limitation of this review is the generalized nature of the research question, which includes many different types of surgical procedures involving the talus. Further research is needed, specifically randomized control trials related directly to the talus.

Conclusion

While many complications with the talus occur, whether traumatic, systemic, or iatrogenic, there are multiple surgical approaches that can be utilized to address damage to the talus. Utilizing 3D printed implants attempts to address many of the limitations with other surgical procedures, such as bone allograft and autograft reconstruction and osteomyocutaneous flaps. The studies included in this review found that 3D printed implants have shown to increase patient AOFAS scores, FAAM ADL, and specific talar dimensions post-total talar prosthesis. Additionally, 3D printed implants increased the accuracy of measuring osteochondral lesions for surgical planning as well as acceptable ankle range of motion. Based on these studies, there is substantial information to validate the continued use of 3D printing in talar procedures; however, further research should be introduced beyond the talus. Expanding research of 3D printing to other tarsal bones may assist in identifying if this method can further prevent amputations, limit patient dissatisfaction with alternative methods, and determine if any new complications arise. In addition, more research on the sustainability of 3D printed customized implants can be examined to verify the longevity of these custom-printed pieces. Application of 3D printing to customize the patient-specific implant utilized to correct the patient's deformity is a breakthrough in approaching anatomical bone implantation not only in the ankle, but in the lower extremity as a whole.

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Level of Clinical Evidence: 5, Literature Review

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