



Tibiocalcaneal Arthrodesis for Ankle Arthropathy Using Patient-Matched Modular 3D-Printed Porous Titanium Implants and Locked Intramedullary Fixation

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Purpose: To evaluate the clinical and radiographic outcomes of tibiocalcaneal arthrodesis using patient-matched modular 3D-printed porous titanium implants combined with locked intramedullary nails for advanced ankle arthropathy with substantial bone loss.

Methods: This prospective cohort study included seven consecutive patients who underwent tibiocalcaneal arthrodesis using patient-matched modular 3D-printed porous titanium implants between January 2024 and December 2025. Functional outcomes were assessed using the Foot and Ankle Ability Measure (FAAM). Osseous union, alignment, and implant position were evaluated using radiographs and computed tomography at 1 year.

Results: The mean patient age was 58.4 years (71.4% female). Mean follow-up was 12 months. Median reconstruction volume was 9,862 mm³ (interquartile range, 4,049–11,118 mm³). The median FAAM score improved from 60 preoperatively to 80 at 1 year ($p = 0.018$). At 1 year, complete osseous union was observed in two patients (28.6%), partial union in four (57.1%), and nonunion in one (14.3%). Complications occurred in three patients (42.9%): persistent nonunion with mechanical instability ($n = 1$), transient instability requiring supplemental fixation ($n = 1$), and superficial wound maceration that resolved with conservative care ($n = 1$). No major complications were reported.

Conclusions: Patient-matched modular 3D-printed porous titanium implants combined with locked intramedullary nails may offer a limb-salvage option for advanced ankle arthropathy with massive bone loss. However, the high complication rate (42.9%) and low complete union rate (28.6%) at 1 year highlight the limitations of this approach. Long-term postoperative mechanical protection and regular monitoring are essential to prevent late structural failure.

Keywords: Ankle arthropathy, tibiocalcaneal arthrodesis, patient-matched modular, 3D-printed implant, limb salvage

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Tibiocalcaneal arthrodesis is an important salvage procedure for patients with severe foot and ankle pathology presenting with large osseous defects. This challenging surgical intervention is typically indicated for failed prior arthrodesis, avascular necrosis (AVN), chronic osteomyelitis, recalcitrant nonunion, post-traumatic disability, and Charcot neuroarthropathy. Traditional reconstruction methods for managing these bone defects include end-to-end arthrodesis, autogenous struc-

tural bone grafts, femoral head allografts, bone transport, the Masquelet induced-membrane technique, and free vascularized osteomyocutaneous flaps. However, these conventional techniques have substantial limitations. Autografts may cause donor-site morbidity, chronic pain, and graft collapse, whereas femoral head allografts carry substantial risks of infection, nonunion, and progressive bone resorption under structural loads^(1–3). In cases involving extensive segmental defects, standard bone-graft-augmented fusion often fails to provide sufficient immediate structural support, leading to premature hardware failure or significant limb shortening.

Recent advances in 3D printing, particularly patient-specific porous titanium implants, offer a promising alternative by providing rigid metallic scaffolds tailored to individual defect morphology. These implants eliminate the risks of graft resorption and structural collapse, restore multiplanar limb alignment, and provide predictable structural support while their graded porous architecture accelerates biological osseointegration^(1–6).

Therefore, this prospective study aimed to evaluate the clinical and radiographic outcomes of tibiocalcaneal arthrodesis using a combination of a patient-matched modular 3D-printed porous titanium implant and locked intramedullary nails (IMNs). Specifically, we assessed fusion rates, postoperative complications, and functional outcomes in patients undergoing complex hindfoot reconstruction.

METHODS

This prospective cohort study included seven consecutive patients who underwent tibiocalcaneal arthrodesis using a patient-matched modular 3D-printed porous titanium implant at Trang Hospital, Thailand. The study evaluated the clinical, radiographic, and functional outcomes of this surgical technique in patients undergoing hindfoot salvage reconstruction.

Patients were prospectively enrolled between January 2024 and December 2025. The inclusion criteria were an indication for tibiocalcaneal arthrodesis because of severe bone loss,

Charcot arthropathy, postinfectious bone defects following infection control, or traumatic bone loss. Patients with active infection, severe comorbidities precluding surgery, or an inability to comply with follow-up were excluded.

Clinical outcomes included ambulatory status and functional outcomes measured using the Foot and Ankle Ability Measure (FAAM)⁽⁷⁾. Postoperative radiographs were obtained at 1, 2, 4, and 6 months and at 1 year. Computed tomography (CT) was performed at 1 year to evaluate implant integration and bony union in all patients using a standardized protocol. Earlier CT scans were obtained only when clinically indicated to assess the stability of high-risk constructs. Radiographic outcomes included alignment and implant position. A radiologist evaluated fusion outcomes using standard radiographs and CT scans. Consolidation was categorized into three groups: nonunion ($\leq 33\%$), partial fusion (34%–66%), and complete fusion ($\geq 76\%$)⁽⁸⁾. Complications, including infection, wound problems, implant failure, nonunion, malalignment, and the need for revision surgery, were prospectively recorded⁽⁹⁾.

The primary outcome was the safety of the patient-matched modular 3D-printed porous titanium implant. Secondary outcomes included time to union, complication rate, reoperation rate, limb-salvage rate, and functional improvement over time. The reoperation rate was defined as any unplanned secondary surgical intervention required to manage postoperative mechanical instability, hardware failure, or soft-tissue complications. This definition excluded preplanned intraoperative structural augmentations implemented during the primary index surgery.

Descriptive statistics were used to summarize patient characteristics. Continuous variables are presented as means $\pm$ standard deviations and medians with interquartile ranges (IQRs).

Preoperative and postoperative FAAM activities of daily living (ADL) scores were compared using the Wilcoxon signed-rank test.

A p-value of <0.05 was considered statistically significant. Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 26.0

Implant Design

A patient-matched modular 3D-printed porous titanium implant was developed to reconstruct the talus and restore ankle function⁽¹⁰⁾. The implant has a spherical external geometry with variable diameters to accommodate different defect sizes and patient anatomies. Its internal graded porous structure is designed to promote osseointegration while maintaining mechanical stability. Higher-density regions are positioned near load-bearing interfaces, such as the IMN contact region, whereas lower-density regions reduce implant weight and facilitate bone ingrowth, potentially improving integration and long-term performance.

The implant design and porous-based talus reconstruction concept are also described in a United States patent application entitled “Porous-Based Talus Reconstruction Prosthesis and Associated Method” (US 2025/0339282 A1), which covers the implant geometry, graded porous

architecture, and osseointegration-oriented design principles used in this study⁽¹¹⁾.

To evaluate the structural integrity and cyclic endurance of the patented design before clinical implementation, a preclinical finite element analysis framework utilizing CT-derived heterogeneous bone modeling was executed under a peak mid-stance physiological load of 3433.5 N⁽¹²⁾. Structural analysis showed that the maximum von Mises stress in the retrograde IMN ranged from 114.8 to 120.0 MPa, remaining safely below the material fatigue threshold of approximately 300 MPa. Previous studies indicate that additively manufactured Ti-6Al-4V components subjected to cyclic stresses below this threshold may resist microcrack nucleation and withstand more than 10^8 loading cycles⁽¹³⁾. Accordingly, the graded architecture is intended to optimize load transfer and reduce the theoretical fatigue failure risk during long-term cyclic weight-bearing conditions (Fig. 1).

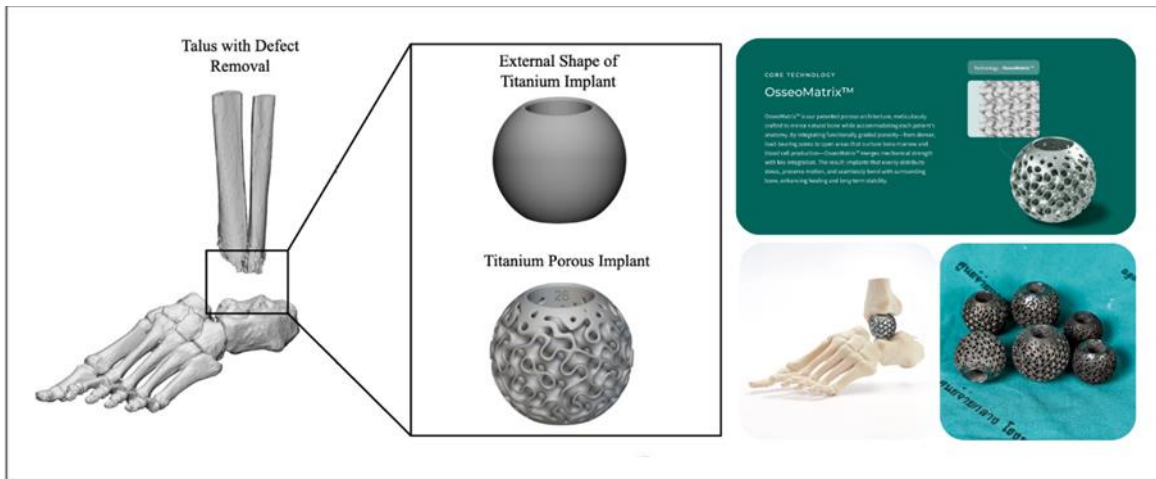


Fig. 1 Talus defect after removal and design of a Titanium Porous Implant showing external geometry and internal graded porous structure.

Laser Powder Bed Fusion Manufacturing

The prosthesis was fabricated using Laser Powder Bed Fusion with Ti-6Al-4V (Grade 23) powder. A high-energy laser selectively melted successive powder layers according to the digital design, using a laser power of 90 W, a scan speed of 905 mm/s, a hatch spacing of 0.1 mm, and a layer thickness of 0.03 mm⁽¹⁴⁾. This process enabled the precise fabrication of complex external geometries

and internal porous architectures. Postprocessing involved removing supports and residual powder, particularly from porous regions, followed by heat treatment to relieve residual stress and improve mechanical properties. No surface finishing was performed to preserve surface roughness and promote bone integration. The implants were then cleaned and sterilized by autoclaving before implantation⁽¹⁵⁾.

Surgical Technique

All surgical procedures were performed under general anesthesia with patients positioned supine on a radiolucent operating table. A bump was placed under the ipsilateral hip to optimize access to the lateral hindfoot, and a thigh tourniquet was routinely applied.

A standard transfibular approach was used⁽¹⁶⁾. A distal fibular osteotomy was performed approximately 5 cm proximal to the ankle joint line to maximize surgical exposure of the deep hindfoot defect and facilitate thorough debridement of all necrotic tissue. Subsequently, the distal tibial articular surface and superior aspect of the calcaneus were meticulously prepared using acetabular reamers to create congruent, bleeding bony beds capable of accommodating the patient-matched modular 3D-printed porous titanium implant. Trial implants were inserted under fluoroscopic

guidance to confirm the appropriate prosthesis size, multiplanar alignment, and joint congruity.

For definitive internal fixation, a retrograde guide pin was introduced through the plantar aspect of the calcaneus and advanced proximally into the tibial medullary canal. The tibia was sequentially reamed to a diameter 1 mm larger than that of the planned retrograde IMN. The patient-matched modular 3D-printed porous titanium implant was then impacted into the defect, with its central canal aligned with the reamed tract. The retrograde IMN was advanced through the calcaneus, the implant's central sleeve, and into the distal tibia. Alignment was maintained in a functional position, with neutral dorsiflexion (0°), 5° of hindfoot valgus, and external rotation matching that of the contralateral limb. Two distal locking screws were inserted through the nail into the calcaneus to maximize rotational and axial

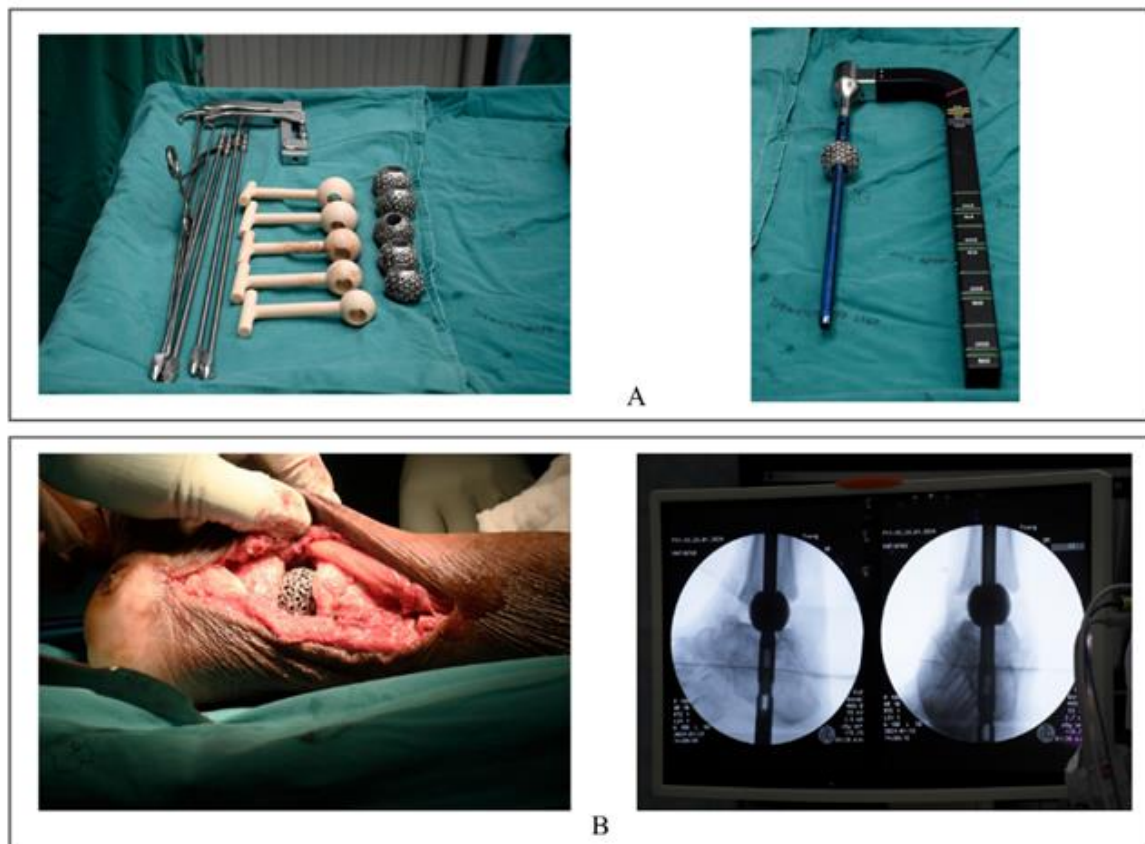


Fig. 2 Detailed surgical instrumentation, pre-assembly, and intraoperative execution of the patient-matched modular 3D-printed titanium porous implant. (A) Preoperative preparation. (B) Intraoperative implantation and fluoroscopic verification.

stability. Previously harvested morselized autologous bone graft, occasionally supplemented with iliac crest bone graft depending on the defect size, was packed circumferentially within and around the porous implant to promote osseointegration. In patients with severe multiplanar instability and compromised regional bone quality due to advanced Charcot changes or extensive postinfectious bone loss, the fixation construct was augmented intraoperatively with a supplemental anatomical locking plate⁽¹⁷⁾. The surgical wound was closed in anatomical layers, and a negative-pressure wound therapy (NPWT) dressing was applied postoperatively (Fig. 2).

Staged Treatment Protocol for Infection-Related Defects

For patients with active or previous infection-related bone destruction, a standardized two-stage protocol was implemented. This protocol was designed to control infection before implantation of the definitive patient-matched modular 3D-printed porous titanium implant, thereby minimizing the risk of infection recurrence^(18–21).

Stage 1 (Infection Control and Screening Preparation):

The initial stage involved aggressive surgical debridement of infected and nonviable bone and soft tissue. Multiple deep-tissue biopsies were systematically harvested for aerobic, anaerobic, and mycobacterial (tuberculosis) cultures, and histopathological examination. After thorough joint

irrigation with normal saline, a polymethylmethacrylate (PMMA) bone cement spacer impregnated with vancomycin and gentamicin was inserted into the defect to maintain anatomical alignment and limb length. The wound was managed postoperatively with a NPWT dressing.

Targeted antimicrobial therapy was immediately initiated in collaboration with an infectious disease specialist. For bacterial infections, tailored intravenous antibiotic therapy was administered for approximately 8 weeks. For *Mycobacterium tuberculosis* infections, a comprehensive antituberculosis regimen was continued for up to 1 year to eradicate the pathogen, prevent drug resistance, and minimize relapse risk. During treatment, patient compliance was monitored, and serum inflammatory markers, including the white blood cell count, erythrocyte sedimentation rate, and C-reactive protein level, were measured serially to objectively evaluate treatment response.

Stage 2 (Infection Clearance Verification and Definitive Fusion):

Definitive second-stage reconstruction was undertaken only after clinical signs of infection had resolved and inflammatory markers had normalized. To assess infection clearance before implant placement, the PMMA spacer was removed, and repeat tissue specimens were sampled from multiple sites, including the distal tibia, residual talus, calcaneus, and surrounding soft tissues, for confirmatory cultures.

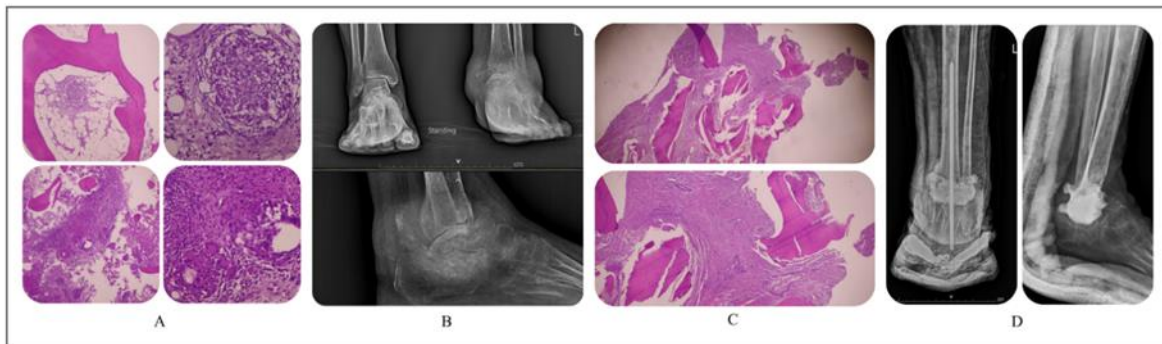


Fig. 3 Staged Surgical Approach: (A) Granulomatous inflammation observed in the biopsy tissue specimen. (B) Preoperative X-ray image of the affected ankle. (C) Histopathological findings of the biopsy specimen after one year of anti-tuberculosis therapy. (D) Cement spacer was implanted in the ankle joint.

The surgical site was then thoroughly irrigated with normal saline. Histopathological section examination was performed before definitive implantation to ensure a safe, pathogen-free environment for permanent implantation. Tibiocalcaneal arthrodesis using the patient-matched modular 3D-printed porous titanium implant and retrograde IMN was performed only after biopsy confirmed fewer than five polymer-phonuclear leukocytes per high-power field, indicating zero active infection (Fig. 3).

Postoperative Care

Patients were kept non-weight-bearing in a short-leg splint. At the 3-month follow-up, they transitioned to weight-bearing as tolerated in a removable boot⁽²²⁾.

Ethical Considerations

The Human Research Ethics Committee of our Hospital approved this study (protocol number: ID 053/11-2023).

RESULTS

A total of seven patients were included in the study. The mean age was 58.4 years (range, 41–68 years), and most patients were female ($n = 5$, 71.4%). The mean follow-up duration was 12 months.

• Operative and Perioperative Data

The mean operative time was 185.6 ± 62.3 minutes (median, 180 minutes; range, 109–300 minutes). The mean length of hospital stay was 20.1 ± 6.3 days (median, 19 days; range, 11–28 days).

• Implant Characteristics

The median implant volume was 9,862 mm³ (IQR, 4,049–11,118 mm³)

• Functional Outcomes

The median FAAM score improved from 60 (range, 20–70) preoperatively to 80 (range, 70–90) at the 1-year follow-up. The Wilcoxon signed-rank test showed a statistically significant improvement after surgery ($Z = -2.375$, $p = 0.018$).

• Radiographic Outcomes

Radiographic assessment showed complete union in two patients (28.6%), partial union in four (57.1%), and nonunion in one (14.3%). Thus, although complete osseous union was achieved in a minority of patients, most demonstrated at least partial fusion. Postoperative CT imaging showed satisfactory alignment in all patients. Although clinical follow-up extended up to 18 months for longitudinal monitoring, definitive radiographic fusion outcomes were assessed uniformly using CT scans obtained 12 months after surgery. This standardized assessment time point effectively minimized potential chronological evaluation bias and strictly maintained the primary study protocol (Fig. 4).

• Complications

Postoperative complications occurred in three patients (42.9%). One patient (14.3%; case 5) developed persistent nonunion associated with mechanical instability. Another patient (case 3) experienced transient instability that was managed with supplemental fixation. One patient (case 7) developed a superficial wound complication involving minor skin maceration, which resolved with conservative wound care. No major complications, such as deep infection, implant failure, or catastrophic hardware breakage requiring revision surgery, were observed in this cohort.

All postoperative CT findings and osseous consolidation percentages in Table 2 correspond to the standardized 12-month postoperative time point for all seven patients, irrespective of the total duration of total clinical ambulatory follow-up^(1, 4).

Table 1 Preoperative and 1-year FAAM score.

FAAM score	Preoperative	1 year	p-value
Median (Q1–Q3)	60 (20–70)	80 (70–90)	0.018

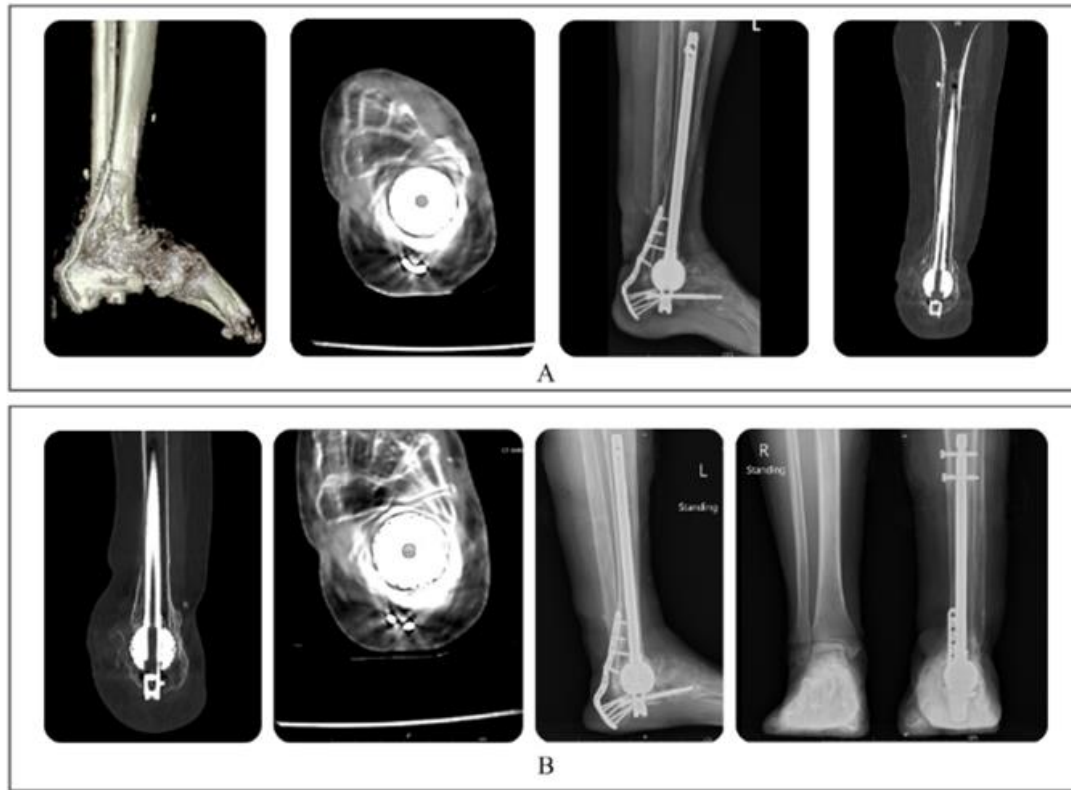


Fig. 4 Radiographic Outcomes. (A) Representative 6-month post-operative CT scan performed exclusively for Case 3 due to high-risk clinical necessity (active tuberculous arthritis with profound structural bone loss) to monitor early construct stability and rule out subsidence, demonstrating partial consolidation (75%). (B) Standardized 1-year post-operative X-ray and CT scan demonstrating complete bony consolidation (90%) according to the core study protocol ^(4, 5).

Table 2 Summary of patients demographics, procedures, and outcomes.

Case	Age	Sex	Side	Diagnosis	Comorbidities	HbA1C (%)	Weight (kg)	BMI (kg/m ²)	Bone graft source	Fixation
1	68	M	Lt	Neuropathic foot	HT, spinal stenosis	6.2	63	24.6	local	IMN
2	41	M	Rt	Post-trauma	None	5.8	115.5	39.79	local+iliac	IMN
3	55	F	Lt	TB ankle	TB	5.6	52	23.11	local+iliac	IMN+plate
4	56	F	Rt	Charcot	T2DM	6.5	105	41.01	local+iliac	IMN
5	61	F	Rt	Charcot	T2DM	6.9	110	42.96	local	IMN+plate
6	70	F	Lt	Charcot	T2DM	7.7	41	16.05	local	IMN
7	58	F	Lt	Charcot	T2DM	10.6	78	28.65	local+iliac	IMN+plate
Case	Implant		Surgical stage	Complications	Outcome at 1 year	Post-op CT scan	FAAM ADL			
	Size (mm)	Volume (mm ³)					Pre-Op (%)	1 year (%)		
1	30	9,862	1-stage	None	Stable	Partial	15	80		
2	32	11,118	1-stage	None	Stable	Partial	37	80		
3	30	9,862	2-stage	Mechanical instability	Stable	Fusion	77	90		
4	32	11,118	2-stage	None	Stable	Partial	62	70		
5	22	3,078	1-stage	Mechanical instability	Stable	Nonunion	2	70		
6	20	4,049	1-stage	None	Stable	Fusion	83	95		
7	30	9,862	1-stage	Skin maceration	Stable	Partial	73 %	90 %		

DISCUSSION

Surgical reconstruction of ankle arthropathy associated with large osseous defects remains challenging for orthopedic surgeons, particularly in patients with Charcot neuroarthropathy secondary to trauma, AVN, failed arthrodesis, or osteomyelitis. When limb salvage is indicated, several techniques are available to address substantial bone defects. However, autologous and allogeneic bone grafts may be associated with complications, including graft collapse, donor-site morbidity, delayed union, and nonunion. 3D printing has emerged as a promising technology in orthopedic surgery, particularly for fabricating patient-specific implants to address complex bone loss. Therefore, patient-matched modular 3D-printed porous titanium implants represent a potential option for ankle reconstruction.

These implants offer several potential advantages, including the ability to fill bone defects and restore anatomical structures with osteoconductive properties. When combined with a retrograde IMN, they may provide rigid fixation. Strydom et al. reported satisfactory limb salvage and fusion outcomes using porous titanium cages for complex ankle reconstruction ⁽⁵⁾, while Abar et al. demonstrated that custom 3D-printed implants provide reliable structural support in critical-sized foot and ankle defects ⁽⁴⁾. Hill et al. reported union rates approaching 88% and limb-salvage rates exceeding 90% following tibiototalcalcaneal arthrodesis using 3D-printed titanium implants ⁽²³⁾.

To address these biological and mechanical limitations, three-dimensional (3D) printing technology has emerged as a promising option in orthopedic surgery, particularly through the fabrication of patient-matched modular 3D-printed porous titanium implants. The potential benefits of this technology can be attributed to several design features:

- **Patient-specific design:** Advanced additive manufacturing allows the design of custom implants tailored to the patient's unique defect morphology. This customization may facilitate multiplanar alignment correction and restoration of anatomical limb length.

- **Porous architecture and osseointegration:** The implants incorporate a porous scaffold designed to support bone ingrowth. This architecture maximizes the surface area available for bone-implant contact and may promote biological integration and long-term implant-bone interface stability.

- **Mechanical support and load distribution:** The structural properties of 3D-printed titanium provide immediate mechanical support in critical-sized defects. Appropriate implant design may help distribute loads across the hindfoot and reduce excessive mechanical stress on the surrounding host bone.

- **Compatibility with fixation constructs:** These implants are engineered to seamlessly interface with standard orthopedic hardware, such as retrograde IMNs, to provide construct stability. Future iterations could incorporate predefined screw trajectories, peripheral locking holes, or plate-compatible surfaces directly into the manufacturing phase to enhance fixation versatility and construct rigidity.

- **Favorable clinical efficacy:** Previous studies have reported that utilizing custom 3D-printed titanium implants yields high clinical success, with osseous union rates approaching 88% and limb-salvage rates exceeding 90% even in highly complex reconstructions.

At the 12-month follow-up, complete radiographic bridging remained uncommon (28.6%), whereas most patients demonstrated partial fusion (57.1%). In complex advanced arthropathy with massive bone loss, achieving complete osseous fusion is challenging because of compromised regional bone turnover. Nevertheless, the clinical efficacy of this reconstructive alternative is underscored by a 100% limb-salvage rate and a statistically significant improvement in median FAAM scores from 60 preoperatively to 80 at 1 year ($p = 0.018$). These findings suggest that satisfactory short-term function may be achieved despite incomplete radiographic union.

The median implant volume in this study was 9,862 mm³ (IQR, 4,049–11,118 mm³). Implant size varied according to the extent of bone loss due to bone destruction. The availability of multiple

implant sizes may help surgeons select an appropriate implant based on defect dimensions to restore limb length and provide fixation stability.

From a biomechanical perspective, larger implant volumes may enhance structural support and limb-length restoration; however, they may also increase mechanical demands on the fixation construct and potentially reduce the surface area available for host bone ingrowth. Conversely, smaller implants may offer better bone-implant contact but provide insufficient structural support for severe defects. Therefore, balancing implant volume, porous architecture, and fixation stability is important for optimizing biological integration and long-term construct durability. Despite the use of different implant sizes, all patients experienced favorable clinical outcomes^(5, 24–26).

Despite its potential biological advantages, this technology has notable clinical limitations, including a postoperative complication rate of 42.9% and a partial fusion rate of 57.1% at 12 months. Although no amputations or major hardware breakage occurred, mechanical instability (cases 3 and 5) and superficial wound maceration (case 7) underscore the challenges of treating this high-risk population. These complications may have been associated with baseline patient factors, specifically morbid obesity (BMIs >40 kg/m²) and severe metabolic impairment (preoperative HbA1c up to 10.6%), highlighting the need for strict preoperative patient optimization.

Importantly, stable short-term clinical function should not be equated with complete biological fusion. Without solid osseous bridging, load transmission remains heavily dependent on the hardware interface, leaving the construct vulnerable to late fatigue failure, cyclic hardware breakage, or progressive implant subsidence. To mitigate these long-term mechanical risks, rigorous postoperative surveillance and adherence to follow-up are essential. Clinicians must ensure strict postoperative weight management, glycemic control, and low-impact activity modifications. Furthermore, patients must be trained to self-monitor for early signs of instability, coupled with mandatory, continuous longitudinal radiographic surveillance to prevent premature construct failure.

Future implant development should focus not only on anatomical reconstruction and porous architecture but also on fixation versatility. Modified 3D-printed titanium implants incorporating preplanned screw trajectories, peripheral locking holes, or plate-compatible surfaces may facilitate supplemental fixation when intraoperative or postoperative instability occurs, potentially improving construct rigidity while preserving the biological advantages of porous titanium. Additionally, to optimize postoperative bone fusion rates and minimize nonunion risks in high-risk cohorts, future prospective investigations should explore the application of bone-forming biological adjuncts. Systemic administration of agents such as teriparatide represents a promising avenue for subsequent research to accelerate bone remodeling and enhance integration at the bone-implant interface^(27–31). Although teriparatide was not used in the present pilot study, its potential role warrants investigation in future trials of this 3D-printed reconstruction approach.

This study has some limitations, including its small sample size, relatively short follow-up, and lack of a control group for direct comparison with conventional reconstruction techniques. Additionally, heterogeneity in underlying pathologies and baseline comorbidities may have influenced osseous union and functional outcomes. Nevertheless, the findings suggest that tibiocalcaneal arthrodesis using patient-matched modular 3D-printed porous titanium implants combined with locked intramedullary fixation may represent a reconstructive option for advanced ankle arthropathy with massive bone loss. Although this approach provided immediate structural support and satisfactory short-term functional limb preservation, the substantial complication and sub-optimal complete union rates underscore that this porosity-based strategy demands critical patient selection, strict long-term mechanical protection, and rigorous longitudinal surveillance to mitigate late structural or fatigue failure.

CONCLUSION

Tibiocalcaneal arthrodesis utilizing patient-matched modular 3D-printed porous tita-

nium implants combined with locked intramedullary fixation serves as a challenging alternative reconstructive option for advanced ankle arthropathy with substantial bone loss. However, the high complication rate (42.9%) and low complete union rate (28.6%) at 1 year highlight critical limitations of this approach. Because most patients achieve only partial union at the short-term follow-up, strict long-term mechanical protection and rigorous longitudinal surveillance are essential to prevent late structural failure. Further randomized controlled trials with larger patient cohorts and extended follow-up are warranted to definitively establish the long-term structural durability and biological efficacy of this reconstructive approach.

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