

## Review

# Tibiototalcaneal Arthrodesis With 3D-Titanium Implants for Management of Critical-Sized Osseous Defects of the Hindfoot and Ankle

## A Systematic Review and Meta-Analysis

Zachary Hill, DPM ,  
Andrew Regal, DPM,  
Meghan Roby, DPM, Griffin Van, DPM,  
Brian Elliott, DPM,  
Douglas Blackledge, DPM,  
and John Michael Miller, DPM

**Abstract:** Background. Managing critically sized osseous defects of the hindfoot and ankle remains challenging, particularly in the setting of failed arthrodesis, trauma, Charcot, or failed total ankle arthroplasty. Custom 3D-printed titanium implants have emerged as a potential alternative to structural allografts, offering mechanical stability and biologic incorporation through patient-specific geometry and engineered porosity. Methods. A systematic review and meta-analysis were conducted in accordance with PRISMA guidelines. A search of major databases identified studies reporting outcomes of tibiototalcaneal (TTC) arthrodesis using 3D-printed titanium implants for critical-sized defects. Union rates, complications, and limb-salvage outcomes were

extracted and synthesized. A random-effects model was used to calculate pooled rates. Results. Fifteen studies comprising 142 patients met the inclusion criteria. Indications included segmental bone loss ( $n = 32$ ), failed total ankle replacement ( $n = 31$ ), avascular necrosis ( $n = 21$ ), and nonunion ( $n = 20$ ). The pooled union rate was 88.2% (95% CI: 82.0%-94.5%), and the limb-salvage rate was 92.3% (95% CI: 87.3%-97.3%). The complication rate was 16.9%, with infection and nonunion being the most frequent types. Functional outcome scores

improved significantly in multiple studies. Only 6.3% of patients required below-knee amputation. Conclusion. Custom 3D-printed titanium implants demonstrate high union and limb-salvage rates with acceptable complication profiles in the treatment

“A growing body of evidence has shown that tibiototalcaneal (TTC) arthrodesis with 3D-printed titanium structural implants can lead to favorable outcomes in patients with otherwise unsalvageable hindfoot and ankle pathology.”

DOI: 10.1177/19386400261420376. From Indy Foot and Ankle Reconstructive Surgery Fellowship, Indianapolis, Indiana (ZH, AR, MR, GV, BE, DB, JMM). Address correspondence to: Zachary Hill, DPM, AACFAS, 1230B Clark St. Cambridge, OH 43725; e-mail: Zph1582@gmail.com.

For reprints and permissions queries, please visit <http://www.sagepub.com/journalsPermissions.nav>.

Copyright © 2026 The Author(s)

*of large osseous hindfoot and ankle defects. These implants may offer a favorable alternative to traditional grafting in complex salvage scenarios.*

**Keywords:** reconstructive foot and ankle surgery; diagnostic & therapeutic techniques, complex foot and ankle conditions; general disorders, implant arthroplasty; diagnostic & therapeutic techniques, arthritis and joint disease; comorbid conditions, joint replacement; diagnostic & therapeutic techniques, trauma; general disorders, ankle injuries; heel—rearfoot—ankle, Charcot's disease; neurological problems

## Introduction

Managing critically sized osseous defects of the hindfoot and ankle remains a formidable challenge in reconstructive foot and ankle surgery, particularly in cases involving failed arthrodesis, trauma, Charcot, tumor resection, infection, or failed total ankle arthroplasty. These large bony voids, often defined as defects greater than 2 cm, compromise mechanical stability and osseous integration, rendering conventional fixation methods inadequate.<sup>1</sup>

Historically, structural bone grafts such as femoral head allografts have been utilized for limb salvage in these settings, with Cifaldi et al<sup>2</sup> demonstrating their utility in providing both structural support and osteoconductive potential for large talar or hindfoot voids. However, limitations such as graft resorption, nonunion, and delayed incorporation have prompted the exploration of alternative solutions.

In recent years, custom 3D-printed porous titanium implants have emerged as a promising option for addressing these complex defects. Their design allows for patient-specific geometry, immediate mechanical stability, and enhanced biologic incorporation due to engineered porosity that promotes osseointegration. A growing body of evidence has shown that tibiotalocalcaneal (TTC) arthrodesis with

3D-printed titanium structural implants can lead to favorable outcomes in patients with otherwise unsalvageable hindfoot and ankle pathology.<sup>3,4</sup>

Hutchison et al,<sup>5</sup> in their work on revision surgery following failed total ankle arthroplasty, recommended the use of custom metallic implants for osseous defects larger than 2 cm, particularly when traditional structural grafting is unlikely to succeed. Their findings support a broader application of additive manufacturing technologies in reconstructive surgery of the distal tibia and hindfoot.

The purpose of this systematic review and meta-analysis is to critically evaluate the available literature on the use of 3D-printed titanium implants in TTC arthrodesis for the management of critical-sized osseous defects of the hindfoot and ankle. By synthesizing outcomes data, complication rates, and implant survivorship, this study aims to clarify the role of custom implants in this demanding clinical scenario.

## Methods

A comprehensive literature review of electronic databases, including PubMed, Embase, Cochrane Library, OvidSP, and Google Scholar, as well as a general search engine, was performed without restriction on publication date. The review followed standard systematic review methodology in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. No date or language restrictions were applied; however, articles not written in English were excluded. The search was performed by the authors from March through July of 2025, utilizing the following terms: “tibiotalocalcaneal arthrodesis,” “ankle fusion,” “retrograde intramedullary nail,” and “talar avascular necrosis,” combined with Boolean operators “AND” and “OR” to include “3D titanium implant.” Titles identified through the search were screened for relevance, followed by a review of abstracts and, when appropriate, full-text articles.

The following inclusion criteria were applied to include studies reporting on (1) TTC arthrodesis utilizing a custom 3D titanium structural implant and retrograde intramedullary nail (IM) to manage critically sized hindfoot and ankle defects (>2 centimeters), (2) documented outcomes including union rate, salvage rate, fixation construct employed, and complications, and (3) at least 1 year follow-up. In studies that included both TTC arthrodesis with the use of a structural allograft and 3D spherical implant, data had to be reported in a manner that allowed the extraction of results specific to patients treated with a structural allograft. Union was defined as radiographic evidence of osseous fusion at both the tibiotalar and subtalar joints. Studies that did not meet all inclusion criteria were automatically excluded.

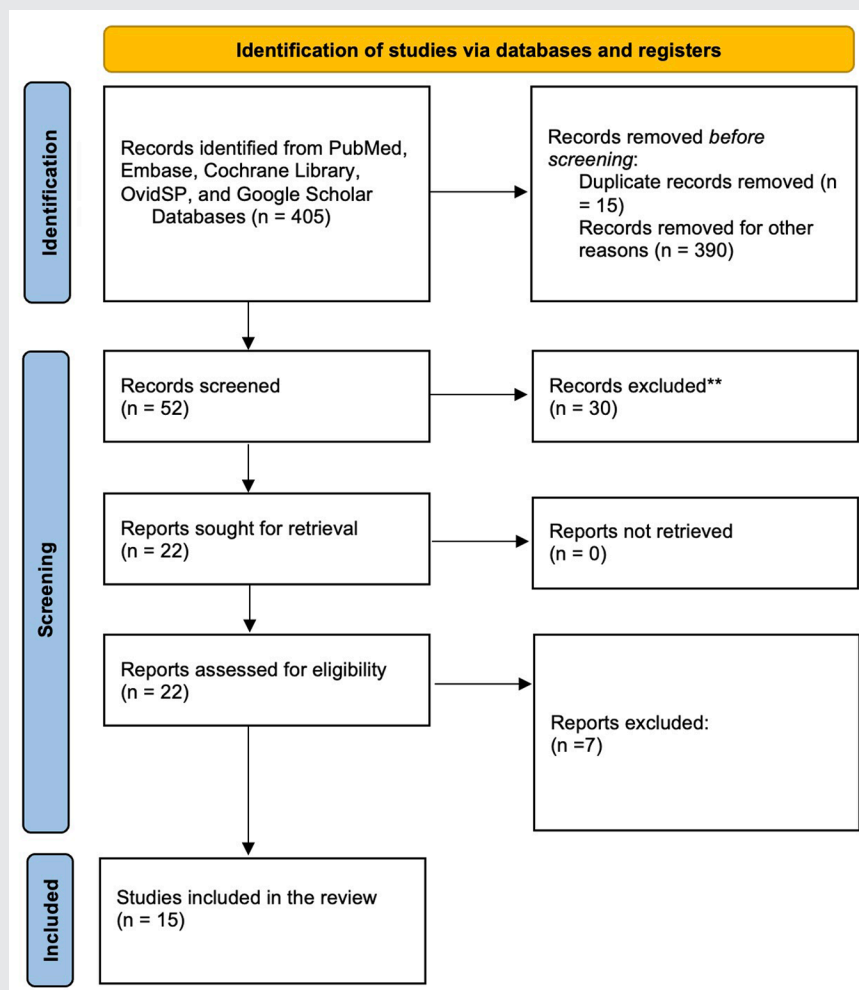
A meta-analysis of the results was conducted to evaluate the pooled union and limb-salvage rates following TTC arthrodesis to address critically sized osseous defects of the hindfoot and ankle using patient-specific 3D-printed titanium implants. A random-effects model (Der Simonian-Laird method) was applied to account for between-study heterogeneity. To address the presence of zero-variance outcomes from studies reporting 100% success, a continuity correction of 0.5 was incorporated for each variable.

## Results

A total of 405 articles were identified through the initial search. After removing duplicates and screening titles and abstracts, 52 full-text articles were reviewed in detail. Ultimately, 15 studies met the inclusion criteria and were included in this systematic review. Figure 1. The 15 included studies represented a combined total of 142 patients undergoing TTC arthrodesis using a custom or patient-specific 3D-printed titanium implant for reconstruction of critical-sized hindfoot and ankle osseous defects. Studies included 3 Level III, 8 Level IV, and 4 Level V articles, with publication dates ranging from 2015 to

**Figure 1.**

PRISMA 2020 flow diagram illustrating the study-selection process.



A total of 405 records were identified through database searching. After removal of duplicates and title/abstract screening, 52 full-text articles were assessed for eligibility. Of these, 37 were excluded (reasons detailed in text), leaving 15 studies that met inclusion criteria and were incorporated into the systematic review and meta-analysis.

2024. The mean patient age was approximately 55 years, and the mean follow-up duration was 25 months.

Table 1

The most common surgical indications included: segmental bone loss (n = 32), failed total ankle replacement (n = 31), avascular necrosis of the talus or distal tibia (n = 21), nonunion (n = 20), Charcot neuroarthropathy (n = 13), failed prior hindfoot surgery (n = 5), infection, congenital deformity, or other pathology (n = 5). Many patients had

multiple contributing indications, reflecting the complexity and salvage nature of the cases.

All procedures utilized a custom 3D-printed titanium cage, truss, or spherical implant as the primary structural support, in combination with a retrograde intramedullary nail. Figure 2. In select cases, additional fixation (e.g., plates or screws) and bone grafts were used as adjuncts. The overall union rate across studies was 94%, based on radiographic evidence of fusion at both

the tibiotalar and subtalar joints when reported. However, because this figure represents a descriptive mean rather than a statistically pooled estimate, it does not account for between-study variability or differences in sample size. To provide a more rigorous assessment, a random-effects meta-analysis (DerSimonian-Laird method) was performed, incorporating variance across studies and applying a continuity correction for studies reporting perfect outcomes. This yielded a pooled union rate of 88.2% (95% CI:

**Table 1.**  
Included Studies.

Study	Author (Year)	Level of Evidence	Patients (#)	Mean Age (years)	Mean Follow-up (months)	Indication	Construct	Union Rate (%)	Complications	Salvage Rate (%)	Functional Scores	Notes
Comparison of 3D Printed Spherical Implants vs Femoral Head Allografts for Tibiotalocalcaneal Arthrodesis	Sheet et al <sup>6</sup>	III	8	56	23	Trauma with segmental bone loss (3), AVN of talus (5)	3D spherical implant with TTC retrograde nail (8)	92%	Revision surgery 1/8 (12%)	100%	NR	
Outcomes of Surgical Reconstruction Using Custom 3D-Printed Porous Titanium Implants for Critical-Sized Bone Defects of the Foot and Ankle	Abur et al <sup>7</sup>	III	39	NR	27	Nonunion (13), Failed TAR (2), Charcot (3), AVN of talus (4), Trauma (15), Debridement following osteomyelitis (1), Correction of congenital deformity (1)	3D printed cage (2), spherical implant (12), tibial and talar replacement lower (8), tibial replacement lower (5), all with TTC retrograde nail	74%	Septic nonunion 6/39 (15%), aseptic nonunion 4/39 (10%)	87%	NR	5 BKAs
The Use of 3D-Printed Titanium Implants for Arthrodesis in the Management of Large Osseous Defects in the Ankle	Strydom et al <sup>8</sup>	III	13	63	20	Failed TAR (8), AVN of talus (2), failed total talus (1), segmental bone loss (1), Charcot (1)	3D printed prosthesis with TTC retrograde nail (13)	85%	Infection 2/13 (15%), revision surgery 1/13 (7%)	100%	NR	
Midterm outcomes of lower limb salvage with 3D printed ankle cages	Kim et al <sup>9</sup>	IV	13	63	38	Failed TAR (10), AVN of talus (3)	3D printed cage with retrograde TTC nail (13)	100%	Infection 2/13 (15%)	85%	NR	2 BKAs
Improved pain and function after TTC fusion with Custom Cage	Rakin et al <sup>10</sup>	IV	21	59.3	32	Failed TAR (10), AVN of talus (6), Trauma with segmental bone loss (4), Nonunion (2)	3D printed cage with TTC nail (21)	90%	Nonunion 1/21 (4%), infection 1/21 (4%)	95%	VAS: FAAM, 12-Item Short-Form health survey significantly improved	1 BKA
Three-Dimensional Printed Cage in Patients with Tibiotalocalcaneal Arthrodesis Using a Retrograde Intramedullary Nail: Early Outcomes	Bejranco-Pineda et al <sup>11</sup>	IV	7	57	21	Segmental bone loss (7)	3D printed cage with TTC retrograde nail (7)	88%	Osteomyelitis 1/7 (14%)	88%	Pre-operative AOPAS = 35, post-operative AOPAS = 68 (range, 55-78), $P = .004$ . Pre-operative VAS pain = 80.4 vs 26.8 post-operative $P = .002$ .	1 BKA
Custom Patient-Specific 3D-Printed Titanium Truss Tibiotalocalcaneal Arthrodesis Implants for Failed Total Ankle Replacements: Classification, Technical Tips, and Treatment Algorithm	Lewis et al <sup>12</sup>	IV	6	72.1	36	Failed TAR (6)	3D printed truss with TTC retrograde nail (6)	100%	Prosthetic joint infection secondary to hematogenous spread 1/6 (16%), surgical wound dehiscence 1/6 (16%)	100%	MOXFQ index post-operative $P = .002$ . The mean EQ-5D-5L index improved from 0.366 to 0.743 ( $P = .05$ ) and the EQ-VAS also improved from 53.0 to 63.3 ( $P = .36$ ). The mean VAS-Pain score at final follow-up was 27.5.	
Salvage of Failed Total Ankle Replacement Using a Custom Titanium Truss	Mulhern et al <sup>13</sup>	IV	1	56	12	Failed TAR (1)	3D printed truss with TTC retrograde nail (1)	100%	No complications reported 0/1 (0%)	100%	NR	
Outcomes of Tibiotalocalcaneal Arthrodesis using a Custom Three-Dimensional Printed Titanium Truss Implant	Carr et al <sup>3</sup>	IV	18	58.7	12	NR	3D printed truss implant with TTC nail	94%	Infection 1/18 (5%), nonunion 1/18 (5%)	94%	FAAM ADL scores improved from 33.23 prior to surgery to 59.56 ( $P = .023$ ), while VAS pain scores decreased from 59.07 to 34.22 ( $P = .001$ ), SF-12 Mental Health scores increased from 45.45 to 56.42 ( $P = .031$ ), while Physical Health scores improved mildly from 28.78 to 31.75 ( $P = .110$ ).	

(continued)

**Table 1. (continued)**

Study	Author (Year)	Level of Evidence	Patients (#)	Mean Age (years)	Mean Follow-up (months)	Indication	Construct	Union Rate (%)	Complications	Salvage Rate (%)	Functional Scores	Notes
Use of patient-specific 3D Printed titanium implants for Complex Foot and Ankle Limb Salvage, deformities and arthrodesis procedures.	Dekker et al <sup>14</sup>	IV	11	54	24	Failed TAR (2), Segmental bone loss (1), AVN (3), Nonunion (5)	3D printed truss with TTC retrograde nail (1)	91%	Nonunion 1/11 (9%)	100%	Pre-operative FAAM ADL score = 23.5-62.8 at most recent follow-up. AOFAS improved from 28.4 prior to surgery to 64.8 at most recent follow-up. VAS scores significantly decreased, showing improvement from 89.0 prior to surgery to 23.9 at most recent follow-up.	
Large Osseous Defect Reconstruction using a Custom Three-Dimensional Printed Titanium Truss Implant	So et al <sup>15</sup>	IV	1	38	21	Failed TAR (1)	3D printed truss with TTC retrograde nail (1)	100%	Superficial Infection 1/1 (100%)	100%	NR	
Patient-Specific 3-Dimensional Printed Titanium Truss Cage with Tibiofibular Arthrodesis for Salvage of Persistent Distal Tibia Nonunion	Hsu et al <sup>4</sup>	V	1	63	12	AVN of distal tibia (1)	3D printed truss with TTC retrograde nail (1)	100%	No complications reported 0/1 (0%)	100%	NR	
Lower Limb Salvage Using Patient-Specific 3D-Printed Titanium Cage Following Severe Left Ankle Traumatic Partial Amputation: A Pediatric Case Report	Dow et al <sup>16</sup>	V	1	16	24	Trauma with segmental bone loss (1)	3D printed cage with TTC retrograde nail (1)	100%	No complications reported 0/1 (0%)	100%	NR	
Salvage arthrodesis of a failed total ankle replacement using a custom 3D-printed cage implant: A case report and review of the literature	Preston et al <sup>17</sup>	V	1	66	12	Failed TAR (1)	3D printed cage with TTC retrograde nail (1)	100%	No complications reported 0/1 (0%)	100%	NR	
Five-Year Follow-Up of Distal Tibia Bone and Foot and Ankle Trauma Treated with a 3D-Printed Titanium Cage	Nwankwo et al <sup>18</sup>	V	1	46	60	Trauma with segmental bone loss (1)	3D printed cage with TTC retrograde nail (1)	100%	No complications reported 0/1 (0%)	100%	FAAM ADL subscale score was 79 post-operatively, FAAM sports subscale score was 46 post-operatively. AOFAS ankle-hindfoot scale score was 71/100.	
<b>Totals</b>		<b>Level III (3), Level IV (9), Level V (4)</b>	<b>142</b>	<b>54.86</b>	<b>24.9</b>	<b>Charcot (13), Failed TAR (3), Failed Prior Hindfoot Surgery (5), segmental bone loss (32), AVN (21), Congenital Deformity (1), Nonunion (20), Infection (1), Not Reported (18)</b>		<b>94%</b>			<b>96%</b>	<b>9 BKAs</b>
Key:	a) AVN = avascular necrosis, b) TTC = tibiofibular canal, c) TAR = Total Ankle Replacement, d) BKA = below-knee amputation, e) NR = not reported											

**Figure 2.**

Lateral radiograph of the ankle demonstrating tibiotalocalcaneal (TTC) arthrodesis construct using a custom 3D-printed titanium spherical implant combined with a retrograde intramedullary nail in a 45-year-old male with Charcot neuroarthropathy and a critical bone defect of the talus.



82.0%-94.5%), which more accurately reflects the expected clinical performance of 3D-printed implants across heterogeneous populations. Thus, while the 94% value illustrates consistency among the 15 included reports, the 88.2% pooled rate should be interpreted as the principal quantitative finding with a 95% confidence interval (CI) ranging from 82.0% to 94.5%.

#### Figure 3

A similar random-effects meta-analysis was performed to evaluate limb-salvage outcomes, defined as avoidance of below-knee amputation. The limb-salvage rate was 96% across the studies, with 9 reported below-knee amputations (BKAs) among the 142 patients. After applying continuity correction to studies reporting perfect outcomes, the pooled salvage rate was calculated at 92.3% (95% CI: 87.3%-97.3%) across the same cohort of 142 patients. Figure 4. These results highlight the effectiveness of 3D-printed titanium implants in achieving durable limb preservation, even in complex salvage scenarios involving failed total ankle replacement, avascular

necrosis, or severe post-traumatic bone loss.

Complications varied across studies and included: Infection, nonunion or persistent radiographic failure in approximately 12 patients, wound complications, revision surgery in several cases due to hardware issues or infection, and, ultimately, below-knee amputation in 9 patients (6.3%). Overall, complications were reported in 24/142 (16.9%) of the included patients, with infection and nonunion as the most frequent types. Despite these complications, most studies reported low rates of implant failure, and very few required removal of the titanium construct.

Although not consistently reported, multiple studies showed significant improvements in validated patient-reported outcomes. Reported FAAM ADL scores significantly improved from pre-operative to post-operative in 5 studies.<sup>3,10,11,14,18</sup> VAS pain scores decreased by more than 50% in studies reporting it.<sup>10-12,14,18</sup> MOXFQ, SF-12, AOFAS, and other quality-of-life

instruments also demonstrated meaningful improvements.<sup>3,10-12,14,18</sup>

## Discussion

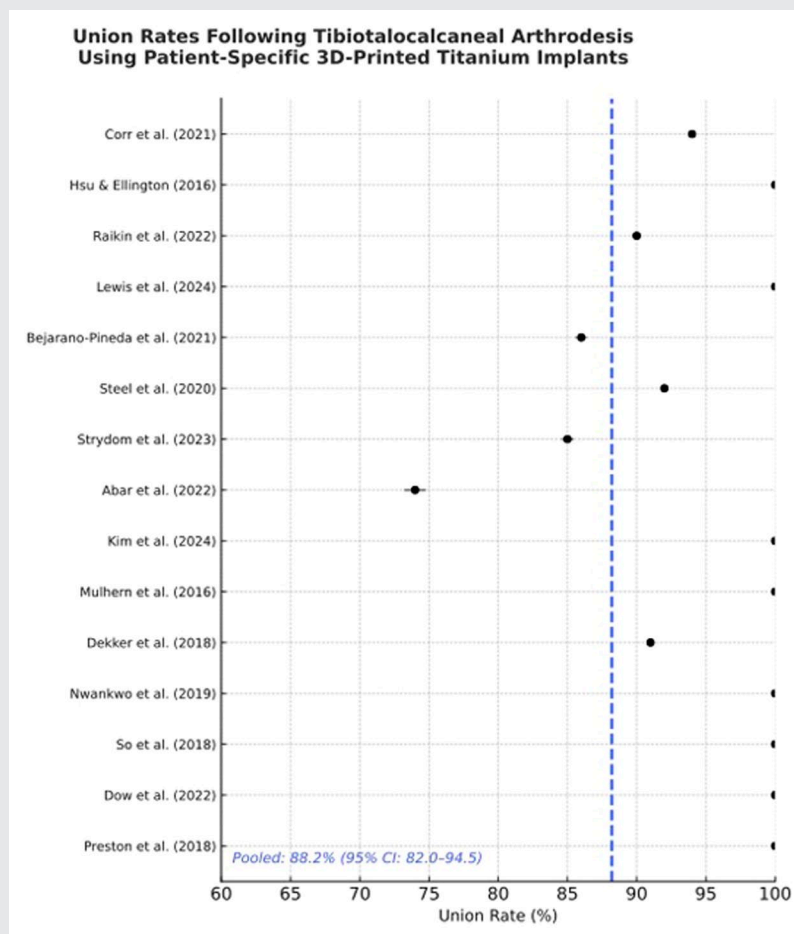
Reconstructing large segmental defects of the hindfoot and ankle remains a formidable challenge, particularly in cases of avascular necrosis, Charcot, or failed TAR. The design of custom 3D titanium implants plays a critical role in managing critically sized osseous defects of the hindfoot and ankle, and their use has gained popularity in reconstructive foot and ankle surgery.<sup>14</sup> Their custom geometry allows for precise anatomical replacement of the talus or distal tibia, while controlled porosity facilitates biologic incorporation. In our included studies, constructs ranged from spherical implants and cages to full tibial-talar towers, with fixation most commonly using retrograde intramedullary nails.<sup>3-18</sup> Several studies of these reported successful fusion with these constructs and pain relief despite large segmental voids and prior failed surgery.<sup>3-18</sup>

These advantages of 3D titanium implants are supported by biomechanical and preclinical studies demonstrating improved load sharing and early weight-bearing potential with porous titanium truss designs.<sup>19,20</sup> Additionally, finite-element analysis has shown favorable stress distribution with patient-specific 3D-printed titanium implants compared to bulk allografts, likely contributing to the reduced mechanical failure rates seen in clinical series.<sup>20</sup> These trends reflect the broader expansion of 3D-truss titanium implants beyond TTC arthrodesis, with increasing use in procedures like custom talus replacements, subtalar fusion cages, and revision ankle constructs, underscoring their growing role in foot and ankle reconstructive surgery.<sup>21</sup>

This systematic review and meta-analysis included 15 studies comprising 142 patients who underwent TTC arthrodesis using patient-specific 3D-printed titanium implants for critical-sized hindfoot and ankle defects. Our pooled analysis revealed a union rate of 88.2% (95% CI: 82.0%-94.5%) and

**Figure 3.**

Forest plot showing union rates (%) from individual studies evaluating tibiotalocalcaneal (TTC) arthrodesis performed with patient-specific 3D-printed titanium implants for reconstruction of critical-sized hindfoot and ankle defects.



Each circle represents a single study, with horizontal lines indicating 95% confidence intervals. The blue dashed line denotes the pooled estimate, demonstrating an overall union rate of 88.2% (95% CI, 82.0-94.5), calculated using a random-effects model (DerSimonian-Laird method). This figure highlights the consistently high fusion success across heterogeneous studies encompassing diverse indications and implant designs.

a limb-salvage rate of 92.3% (95% CI: 87.3%-97.3%), underscoring the high efficacy of these implants in complex salvage scenarios.

When compared to structural allograft-based TTC arthrodesis, outcomes appear favorable. Previous reviews documented union rates around 67% with femoral head allografts, accompanied by complication rates exceeding 25%, while standard TTC fusion with intramedullary nails achieved approximately 87% union but faced hardware failure rates as high as 56%.<sup>1,2</sup> In contrast, 3D-printed titanium

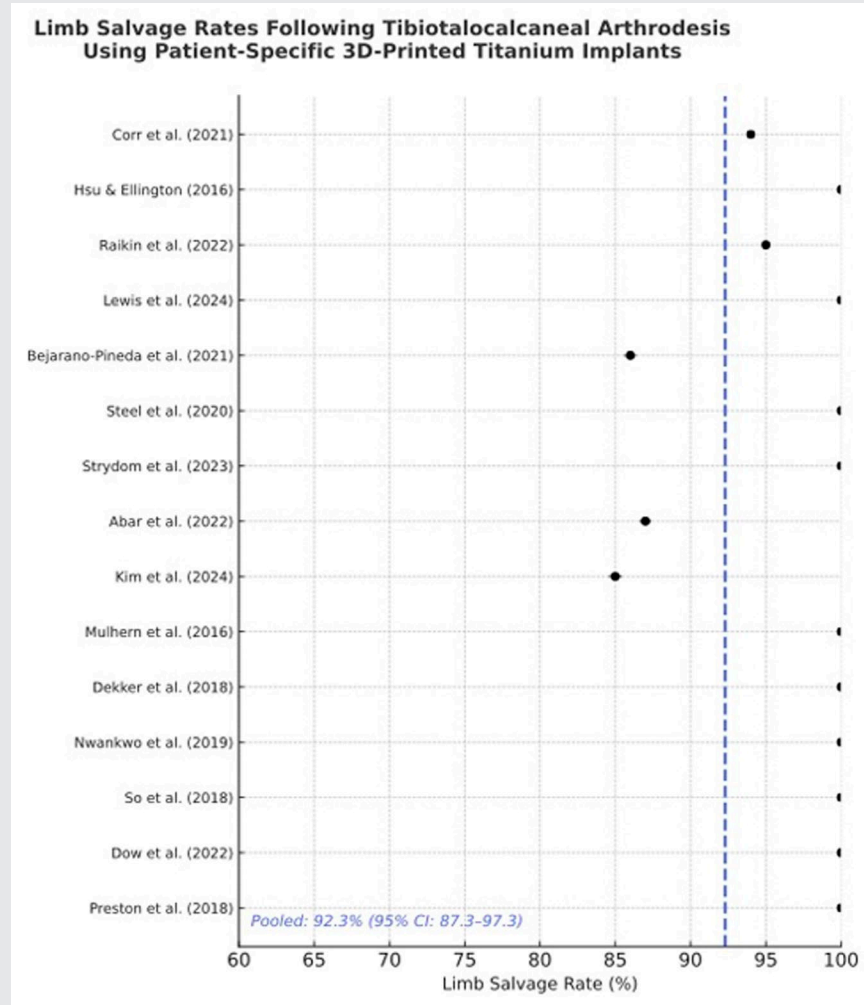
implants demonstrated equivalent or superior efficacy with fewer implant failures and comparable limb-salvage rates.<sup>1,2</sup>

Cost considerations further highlight key differences of allograft vs. 3D-printed implants. Structural allografts are typically less expensive (approximately \$1000-\$5000 per graft),<sup>22</sup> whereas patient-specific 3D-printed implants can generally range from \$8000-\$15000, depending on the manufacturer and geometry.<sup>14,23</sup> However, TTC nonunion and limb-salvage complications carry

substantial downstream costs. Economic analyses in orthopedic limb salvage have shown that revision nonunion surgery, prolonged immobilization, or conversion to below-knee amputation can generate total costs exceeding \$50000 to \$75000, making early mechanical success highly cost-dependent.<sup>24-26</sup> Modeling studies suggest that porous metallic implants become cost-advantageous when revision rates exceed 15%, a threshold commonly surpassed in large-defect TTC fusions using structural allografts.<sup>24-26</sup> Collectively, this data suggests that

**Figure 4.**

Forest plot illustrating limb-salvage rates (%) from individual studies reporting outcomes of tibiotalocalcaneal (TTC) arthrodesis using patient-specific 3D-printed titanium implants for reconstruction of critical-sized hindfoot and ankle defects.



Each plotted point represents a single study, with horizontal lines denoting the reported limb-salvage rate and associated 95% confidence interval when available. The vertical blue dashed line indicates the pooled limb-salvage estimate of 92.3% (95% CI, 87.3-97.3), calculated using a random-effects model (DerSimonian-Laird method) with continuity correction applied to studies reporting 100% salvage.

although custom 3D-printed implants incur a higher upfront cost, they may provide greater long-term economic value due to lower revision rates, enhanced mechanical reliability, and improved durability in the setting of limb salvage and critical-sized defect management.

Management of complex hindfoot deformities requiring TTC arthrodesis is often compounded by multiplanar instability and the interdependence between the hindfoot and medial

column. Many of the pathologies represented in this review, particularly Charcot neuroarthropathy, failed total ankle arthroplasty, and post-traumatic deformity, are characterized by hindfoot valgus combined with first ray insufficiency and medial column collapse, which disrupts weight-bearing alignment and joint congruency. Traditional reconstruction methods struggle to restore both the mechanical axis and load distribution in these cases. Recent biomechanical insights emphasize

the correlation between hindfoot valgus and medial column insufficiency, underscoring that deformities at the ankle and hindfoot cannot be corrected in isolation.<sup>27-29</sup> These multiplanar, interdependent deformities further justify the use of custom 3D-printed titanium implants, which can be tailored to restore anatomic height, alignment, and stability across the tibiotalar and subtalar joints in a single structural construct.

Our findings also align with the clinical recommendations from Hutchison and

Schweitzer,<sup>1</sup> who advocate for metallic implant use in defects greater than 2 cm, a common scenario in failed total ankle arthroplasty. In our series, failed TAR was the indication in over 30 cases, and studies by *Strydom et al*,<sup>8</sup> *Lewis et al*,<sup>12</sup> and *Mulhern et al*.<sup>13</sup> demonstrated reliable outcomes even in severe bone loss and infection settings. The versatility of 3D-printed implants across indications—including AVN (21 cases), post-traumatic defects (32), Charcot arthropathy (13), and longstanding nonunions (20)—further supports their utility in complex reconstruction.

Importantly, functional improvements were observed in several studies. Bejarano-Pineda et al<sup>11</sup> reported a 51% increase in AOFAS scores, while Raikin et al,<sup>10</sup> Dekker et al,<sup>14</sup> and Lewis et al<sup>12</sup> all demonstrated significant reductions in VAS pain scores, often exceeding 50%. Corr et al<sup>2</sup> showed meaningful gains in FAAM and SF-12 scores, while Lewis et al<sup>12</sup> reported marked improvements in MOXFQ and EQ-5D indices. Although outcomes tools varied across studies, these findings consistently supported pain relief, improved function, and enhanced quality of life following TTC fusion with a 3D-printed titanium implant, particularly in patients who had previously failed other salvage options.

Despite these positive outcomes, a 16.9% overall complication rate was observed, including infection, persistent nonunion, wound breakdown, and revision surgery. Notably, limb salvage was achieved in 96% of patients, and very few required implant removal or conversion to amputation. Only 9 BKAs were reported across the entire cohort, most in patients with underlying Charcot or prior infection.<sup>9-11</sup> Complications such as graft resorption, structural collapse, or immune-mediated failure—often associated with structural allografts—are mitigated with 3D titanium implants. However, concerns remain regarding the long-term fatigue behavior of lattice constructs and the potential for late failure or stress shielding.<sup>20</sup>

The current evidence is limited by study heterogeneity, small cohort sizes (some single-patient reports), and lack of uniform outcome reporting. Only a subset of studies used validated tools such as FAAM, AOFAS, or MOXFQ,

making the quantitative synthesis of functional outcomes challenging. Most studies were Level IV evidence or case series, and very few had more than 2 years of follow-up. Nevertheless, midterm data from Kim et al<sup>9</sup> and Corr et al<sup>3</sup> demonstrate durable fusion and pain relief out to 3 years, with ongoing radiographic integration of the implant.

Future research should focus on prospective, controlled comparisons of 3D-printed implants versus traditional grafting techniques or modular metal blocks. Additionally, establishing registries for long-term follow-up and cost-effectiveness analysis may help clarify where these implants fit in the limb-salvage algorithm. Standardized reporting of union timing, complications, and functional scores will be essential for evidence-based adoption.

## Conclusion

Custom 3D-printed titanium implants, based on the predominantly low-level evidence (Level III-V), appear to be a safe and effective reconstructive option for TTC arthrodesis in patients with critical-sized hindfoot and ankle bone defects. With high union and salvage rates, favorable mechanical properties, and growing versatility across diverse indications, these implants represent a promising tool in complex limb salvage. Continued prospective research and long-term outcome tracking are needed to validate their durability, refine indications, and optimize cost-effective integration into reconstructive protocols.

## Author Contributions

**Zachary Hill, DPM:** Conceptualization; Methodology; Investigation; Formal analysis; Writing—Original Draft; Supervision; Project Administration.

**Andrew Regal, DPM:** Data Curation; Investigation; Writing—Review & Editing; Visualization.

**Meghan Roby, DPM:** Data Curation; Validation; Writing—Review & Editing.

**Griffin Van, DPM:** Data Curation; Investigation; Writing—Review & Editing

**Brian Elliott, DPM, FACFAS:** Resources; Supervision; Writing—Review & Editing.

**Douglas Blackledge, DPM, FACFAS:** Conceptualization; Supervision; Writing—Review & Editing.

**John Michael Miller, DPM, FACFAS:** Supervision; Writing—Review & Editing; Resources.

## Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

## ORCID iD

Zachary Hill  <https://orcid.org/0000-0001-5627-2580> 

## References

- Hutchinson B, Schweitzer MJ. Revision surgery for failed total ankle replacement. *Clin Podiatr Med Surg*. 2020;37(3):489-504. doi:10.1016/j.cpm.2020.03.004
- Cifaldi A, Thompson M, Abicht B. Tibiotalocalcaneal arthrodesis with structural allograft for management of large osseous defects of the hindfoot and ankle: a systematic review and meta-analysis. *J Foot Ankle Surg*. 2022;61(4):900-906. doi:10.1053/j.jfas.2022.01.003
- Corr DN, Raikin J, O'Neil JT, Raikin SM. Outcomes of tibiotalocalcaneal arthrodesis using a custom three-dimensional printed titanium truss implant. *Foot Ankle Orthop*. 2020;5:2473011420800177.
- Hsu AR, Ellington JK. Patient-specific 3D-printed titanium truss cage for distal tibia nonunion. *Foot Ankle Spec*. 2015;8:483-489.
- Hutchison RL, DeCamp CE, Myerson MS. Critical bone loss in failed total ankle arthroplasties: when to consider custom metallic implants? *Clin Orthop Relat Res*. 2019;477(8):1786-1794.
- Steel MW, Kadakia RJ, Cunningham DJ, Dekker TJ, Kildow BJ, Adams SB. Comparison of 3D-printed spherical implants vs. femoral head allografts for tibiotalocalcaneal arthrodesis. *Foot Ankle Int*. 2020;59:1167-1170.
- Abar B, Kwon N, Allen NB, et al. Outcomes of surgical reconstruction using custom 3D-printed porous titanium

- implants for critical-sized bone defects of the foot and ankle. *Foot Ankle Int.* 2022;43(6):750-761
8. Strydom B, Saragas NP, Ferrao PN. The use of 3D-printed titanium implants for arthrodesis in the management of large osseous defects in the ankle. *Foot Ankle Int.* 2023;44(7):576-583.
  9. Kim YJ, Mann T, Kelly C, et al. Midterm outcomes of lower limb salvage with 3D-printed ankle cages. *Foot Ankle Int.* 2024;45(2):100413.
  10. Raikin SM, Moncman TG, Raikin J. Improved pain and function after tibiototalcalcaneal fusion with custom cage. *Foot Ankle Int.* 2022;43(5):1410-1418.
  11. Bejarano-Pineda L, Sharma A, Adams SB, Parekh SG. Three-dimensional printed cage in patients with tibiototalcalcaneal arthrodesis using a retrograde intramedullary nail: early outcomes. *Foot Ankle Spec.* 2021;14(5):401-409.
  12. Lewis TL, Walker R, Alkhalfan Y, Latif A, Abbasian A. Custom patient-specific 3D-printed titanium truss tibiototalcalcaneal arthrodesis implants for failed total ankle replacements: classification, technical tips, and treatment algorithm. *Foot Ankle Int.* 2024;45(9):950-961.
  13. Mulhern BJ, Protzman NM, White AM, Brigido SA. Salvage of failed total ankle replacement using a custom titanium truss: a case report. *Foot Ankle Spec.* 2016;9(3):868-873.
  14. Dekker TJ, Steele JR, Federer AE, Hamid KS, Adams SB Jr. Use of patient-specific 3D-printed titanium implants for complex foot and ankle limb salvage, deformity correction, and arthrodesis procedures. *Foot Ankle Int.* 2018;39(8):916-921.
  15. So E, Mandas VH, Hlad L. Large osseous defect reconstruction using a custom three-dimensional printed titanium truss implant. *J Foot Ankle Surg.* 2018;57(1):196-204.
  16. Dow T, Lowe D, Morash J. Lower limb salvage using patient-specific 3D-printed titanium cage following severe left ankle traumatic partial amputation: a pediatric case report. *Foot Ankle Spec.* 2022;15(4):361-368.
  17. Preston CM, Wilson M, Hewitt EA, et al. Salvage arthrodesis of a failed total ankle replacement using a custom 3D-printed cage implant: a case report and review of the literature. *Foot Ankle Int.* 2018;39(12):277-281.
  18. Nwankwo EC, Chen F, Nettles DL, Adams SB. Five-year follow-up of distal tibia bone and foot and ankle trauma treated with a 3D-printed titanium cage. *Case Rep Orthop.* 2019;2019:7571013. doi:10.1016/j.fas.2017.11.011
  19. Thompson SM, Zhao L, Milner JS, Tung WL. Biomechanical modeling of porous 3D-printed titanium cages for tibiototalcalcaneal arthrodesis. *J Orthop Res.* 2021;39(6):1205-1214.
  20. Sun H, Lee JY, Park JH, et al. Enhanced osseointegration of porous titanium scaffolds in rabbit hindlimb defect models. *J Biomed Mater Res B.* 2022;110(5):879-889.
  21. McAnena AP, McClennen T, Zheng H. Patient-specific 3-dimensional-printed orthopedic implants and surgical devices are potential alternatives to conventional technology but require additional characterization. *Clin Orthop Surg.* 2025;17(1):1-15. doi:10.4055/cios23294
  22. Brown DA, Mallory GW, Higgins DM, et al. A cost-effective method for femoral head allograft procurement for spinal arthrodesis. *Spine.* 2014;39(15):E902-E906. doi:10.1097/brs.0000000000000395
  23. Hamid KS, Parekh SG, Adams SB. Salvage of severe foot and ankle trauma with a 3D printed scaffold. *Foot Ankle Int.* 2016;37(4):433-439.
  24. Chung KC, Saddawi-Konefka D, Haase SC. A cost-utility analysis of amputation versus salvage reconstruction for severe open tibial fractures. *Plast Reconstr Surg.* 2009;124(6):1965-1973.
  25. MacKenzie EJ. The LEAP study: economic impact of amputation vs salvage. *N Engl J Med.* 2002;347(24):1924-1931.
  26. Pinzur MS. Cost comparison of limb salvage versus amputation in diabetic foot infection. *J Foot Ankle Surg.* 2020;59(2):301-304.
  27. Colò G, Fusini F, Marcolli G, et al. Hindfoot valgus and first ray insufficiency: is there correlation? *Surgeries.* 2025;6(2): 26. doi:10.3390/surgeries6020026
  28. Lin Y, He P, Yang G, et al. Efficacy of 3D-printed customized titanium implants and its clinical validation in foot and ankle surgery. *Int J Bioprint.* 2024;10(1): 0125.
  29. Richards SR, Baldwin A, Tsai ST, Morgan SJ. Anatomical fit and early outcomes of patient-specific 3D-printed titanium cages in hindfoot reconstruction. *Foot Ankle Clin.* 2023;28(2):283-294.