

Clinical Effect of Using a 3D-Printed Personalized Percutaneous Guide in Transverse Tibial Transport for Patients with Diabetic Foot versus Conventional Surgery

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Abstract

Background

Transverse tibial transport (TTT) has shown clinical potential in the treatment of diabetic foot by improving lower-limb microcirculation. With the development of digital technology, 3D-printed patient-specific guides may further facilitate individualized preoperative planning and precise intraoperative execution. This study aimed to evaluate the clinical efficacy and safety of 3D-printed patient-specific percutaneous guide-assisted TTT for diabetic foot.

Materials and Methods

This retrospective comparative study included 16 patients with diabetic foot who underwent TTT between January 2022 and March 2023. According to the surgical technique, patients were divided into a guide group ($n = 7$) and a control group ($n = 9$). The guide group underwent minimally invasive osteotomy and bone transport assisted by a 3D-printed individualized percutaneous guide, whereas the control group underwent conventional open TTT. Operative time, incision length, intraoperative blood loss, postoperative complications, ulcer healing index, ulcer healing time, and preoperative and postoperative Visual Analog Scale (VAS) and Barthel Index scores were analyzed.

Results

Compared with the control group, the guide group showed a shorter operative time (94.29 ± 13.05 vs 103.78 ± 8.71 min), less intraoperative blood loss (17.86 ± 6.39 vs 27.22 ± 5.97 mL), and a smaller incision length (6.43 ± 1.37 vs 7.67 ± 1.32 cm). Postoperative pain was reduced in both groups, but the postoperative VAS score was lower in the guide group (0.57 ± 0.79 vs 2.11 ± 1.05). Functional recovery was also better in the guide group, with the Barthel Index improving from 56.43 ± 9.88 to 85.71 ± 7.87 , compared with an improvement from 63.33 ± 6.12 to 75.00 ± 7.07 in the control group. The ulcer healing index was higher in the guide group (2.05 ± 2.01 vs 1.62 ± 1.34 cm²/week), and ulcer healing time was shorter. One patient in the guide group and three patients in the control group developed postoperative ulcer-related complications; all healed after dressing care and glycemic control. No patient underwent secondary amputation, and the limb salvage rate was 100%.

Conclusions

Compared with conventional TTT, 3D-printed patient-specific percutaneous guide-assisted TTT was associated with less surgical trauma, reduced blood loss, improved postoperative pain relief, better functional recovery, and faster ulcer healing in patients with diabetic foot. This technique may represent a useful minimally invasive and precise adjunct for limb salvage treatment, although larger prospective studies are needed to confirm these findings.

Level of Evidence:

Level III, retrospective comparative study.

Trial registration:

Not applicable.

INTRODUCTION

Diabetic foot ulcers (DFUs) are common complications of diabetes caused by neuropathy and circulation issues. Neglected ulcers can lead to severe complications, impacting patients' well-being. Approximately 6.3% of individuals with diabetes suffer from DFUs[1, 2], and 28% of amputations are related to DFUs[3]. Vascular surgery is the preferred treatment approach, but it's not suitable for all patients[4, 5]. Tibial transverse transport (TTT) has shown potential in DFU treatment, promoting bone formation and microcirculation network reconstruction[6]. However, the conventional TTT procedure has certain limitations. Therefore, we proposed an innovative treatment strategy that combines TTT technology with computer-aided design (CAD) simulation and a 3D-printed percutaneous guiding device, aiming to significantly improve surgical precision. This study aimed to investigate the clinical efficacy and safety of guide-assisted TTT in the treatment of DFUs and to compare its therapeutic outcomes with those of the conventional TTT procedure, thereby providing an innovative therapeutic approach for the comprehensive management of diabetic foot.

As this study mainly focuses on the application of individualized 3D-printed guides in TTT and the preoperative design process, the preoperative and intraoperative procedures of the conventional technique are not presented here. This study was conducted in full compliance with the ethical principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Second Affiliated Hospital of South China University of Technology (Guangzhou First People's Hospital) (Approval No. K-2018-137-01). All participants provided informed consent.

METHODS

1.1 Data Collection

In this retrospective study, the guide group consisted of 7 patients selected from cases treated at our institution with 3D-printed percutaneous guide-assisted transverse tibial bone transport for diabetic foot between December 2021 and March 2023. Patients were enrolled consecutively, including a total of 7 affected limbs and 14 ulcer sites. There were 5 male patients (5 affected limbs, 8 ulcer sites) and 2 female patients (2 affected limbs, 6 ulcer sites). According to the Wagner classification, 2 cases were grade II, 2 were grade III, and 3 were grade IV. Preoperatively, the VAS pain scores of the 7 patients ranged

from 6 to 8, with a mean of 7.28 ± 0.76 , while the Barthel scores ranged from 45 to 75, with a mean of 56.43 ± 9.88 (Table 1,At the end of the article).

Table 1
Case profile

Group	Index	Gender	Age (years)	Ulcer Location	Ulcer Count	Ulcer Area (cm ²)	Wagner Grade	VAS Score	Barthel Index Score
Guide group	1	Male	38	Right second toe	1	1.5	II	6	75
Guide group	2	Female	58	Right first, second, and third toes; right ankle	4	35	III	8	45
Guide group	3	Female	74	Left first toe; left plantar foot	2	9	IV	7	50
Guide group	4	Male	57	Left first, second, and fifth toes	3	2	II	8	60
Guide group	5	Male	55	All left toes amputated; extensive ulceration on the dorsum of the left foot	1	33	III	8	55
Guide group	6	Male	59	Left fourth toe	1	5.25	IV	7	50
Guide group	7	Male	56	Right first toe; right plantar foot	2	3	IV	7	60
Control group	1	Male	69	All right toes; dorsum of the right foot; right plantar foot	5	43	IV	8	65
Control group	2	Female	79	Right first toe	1	3	II	7	70
Control group	3	Female	70	All left toes; extensive ulceration on the left	5	37.35	IV	8	60

Group	Index	Gender	Age (years)	Ulcer Location	Ulcer Count	Ulcer Area (cm ²)	Wagner Grade	VAS Score	Barthel Index Score
				plantar foot					
Control group	4	Male	77	Left second and fifth toes	2	8	III	9	70
Control group	5	Male	53	Right first, second, and fifth toes	3	4	II	9	65
Control group	6	Male	53	Left first, third, and fourth toes	3	3	II	9	55
Control group	7	Male	73	Right second and third toes; right plantar foot	2	30	IV	8	55
Control group	8	Female	77	Left first toe	1	4.75	III	7	60
Control group	9	Male	40	Left second and fifth toes	2	3	IV	7	70

The control group consisted of 9 patients selected from cases treated at our institution with conventional transverse tibial bone transport between January 2020 and March 2023. A total of 9 affected limbs and 22 ulcer sites were included. There were 6 male patients (6 affected limbs, 15 ulcer sites) and 3 female patients (3 affected limbs, 7 ulcer sites). According to the Wagner classification, 3 cases were grade II, 2 were grade III, and 4 were grade IV. Preoperatively, the VAS pain scores of the 9 patients ranged from 7 to 9, with a mean of 7.89 ± 0.78 , while the Barthel scores ranged from 55 to 70, with a mean of 63.33 ± 6.12 (Table 1).

Inclusion criteria: Diabetic patients with Wagner grade II-IV diabetic foot non-responsive to conservative treatment, age < 80, stable mental state, treatment compliance, DSA patency rate > 50% in superficial femoral and popliteal arteries, and informed consent for foot bone translocation surgery. Exclusion criteria: 1. Mental disorders hindering treatment completion, severe diabetes complications diagnosed by endocrinologists (including uncontrollable systemic infections). 2. Wagner grade I diabetic foot, Wagner grade V or age > 80 where bone translocation is infeasible. 3. Poor preoperative glycemic control, cardiovascular disease (e.g., coronary heart disease), or impaired liver/kidney function preventing surgery

tolerance. 4. Lower limb arterial obstruction with < 50% patency rate in superficial femoral and popliteal arteries. 5. refusal of surgery .

1.2 Preoperative Treatment

Prior to surgery, the patients' oral antidiabetic drugs and/or insulin injections were adjusted, and their blood glucose levels were regularly monitored and controlled within the range of 4.4–10 mmol/L. For patients with mild infections, sensitive antibiotics were prescribed for 1–2 weeks, whereas moderate to severe infections required treatment for 2–3 weeks. Before the surgery, all patients underwent preoperative tibiofibular radiographs, CT scanning with contrast enhancement of both lower limbs (layer thicknesses of 0.50–1 mm), and some patients also underwent lower limb angiograms (DSA). The resulting data were stored in Digital Imaging and Communications in Medicine (DICOM) format and used for data transmission and surgical design, which allowed for individualized treatment planning based on the patients' specific needs. Additionally, a 3D printing technique was utilized to create a percutaneous tibial transverse bone transfer guide, also known as a transcutaneous tibial transverse osteotomy guide plate.

1.3 Surgical Template Design and 3D Printing

The collected CT data in DICOM format was then imported into the MIMICS 21.0 software (Materialize, Leuven, Belgium) for the creation of a comprehensive 3D digital model encompassing the patient's lower limb skin, bones, and blood vessels. This allowed for the analysis of the relationship between the blood vessels and bones, as well as the preliminary determination of the extent of necrosis and understanding of the lower limb blood circulation. Subsequently, the model was exported in STL format and imported into the Image Ware 13.0 software (UGS Corporation) was used to simulate a sphere with the center of the femoral head as the sphere center. Reference lines for various anatomical axes, like the femoral head-neck axis, femoral anatomical axis, lines tangent to the inner and outer condyles of the distal femur, lines tangent to the inner and outer posterior condyles of the femur, lines tangent to the medial and lateral platforms of the tibia, tibial anatomical axis, and lines of the anterior and posterior articular surfaces of the medial and lateral tibial platforms, were established. This facilitated the subsequent process of lower limb spatial calibration and alignment (refer to Fig. 1).

The upper middle tibia was selected as the appropriate location for osteotomy. The design of the trapezoidal osteotomy was individualized based on the diameter of the tibial medullary cavity and the tibia's length. By analyzing the point cloud, the width of the upper and lower edges of the osteotomy was determined to occupy approximately one-third of the tibial medullary cavity, with a height of 7–10 cm being deemed appropriate (refer to Fig. 2a). This design ensured the effectiveness of the osteotomy surgery and minimized the risk of postoperative tibial fractures. To further enhance stability, two parallel fixation pin channels were incorporated into the osteotomy based on the position of the external fixation frame. Additionally, one traction pin channel guide was included at the proximal and distal ends of the upper and lower osteotomy sections (refer to Fig. 2b). The bone cutting surface was determined from the point cloud data, wherein a circular canal was constructed by fitting a straight line to the bone cutting surface.

Subsequently, at 10° intervals, rotation on the sagittal plane was performed around the circular canal to design a total of 9 minimally invasive bone cutting canals, each with 4 pinholes (refer to Fig. 2d).

Finally, the surface skin model of the calf was reconstructed, and optimization of the template model was conducted to ensure conformity with the shape of the calf skin (refer to Fig. 2e). The data were imported into the Unigraphics NX software to design and incorporate surgical template pinholes. After exporting the model data in STL format, it was then imported into a 3D printer for the creation of a solid model using photo sensitive resin through stereolithography (refer to Fig. 2g). Following ethylene oxide sterilization, the model was prepared for use during surgery.

1.3 Intraoperative Situation

The patient is positioned supine and administered either epidural or endotracheal intubation anesthesia. Routine disinfection is conducted, sterile drapes are applied, and the foot ulcer site is thoroughly debrided and covered with sterile dressing. The 3D printed percutaneous guide plate, fixed according to the preoperative plan, is installed. Two Kirschner wires are inserted into the bone block surface under guide plate guidance, while one Kirschner wire is drilled into the upper and lower ends of the bone block osteotomy surface, totaling four Kirschner wires. The guide plate-guided drill bit enlarges the needle holes, and the Kirschner wires are replaced with Schanz pins and secured. Minimally invasive bone-cutting holes are drilled within the predetermined bone transportation range based on the guide plate's markings. The osteotomy is completed by connecting the drilled holes using a combination of the drill bit and osteotome. The external fixation frame is then installed, adjusted, and marked for the direction of bone transportation. After irrigation with saline solution, the incision is sutured, and the surgery concludes with the application of sterile dressings. Refer to Fig. 3 for the surgical steps.

1.4 Postoperative Management

Post-surgery, the affected limb should be elevated and medication adjusted to regulate blood glucose levels. It's important to daily change and sterilize the ulcerated surface, surgical incision, and external fixation bracket. After one week, lateral bone transport begins, with the tibial block being moved laterally at a rate of 1 millimeter per day for 4–8 movements over two weeks. A follow-up examination is conducted at three weeks. From the fourth week onward, the bone block is moved posteriorly at a rate of 1 mm per day for 4–8 times over another two weeks, followed by an additional examination. Once the bone block is repositioned, it is immobilized for 6–8 weeks until the initial healing of the bone window. After bone window healing, the external fixator is removed. The entire treatment course typically lasts 10–12 weeks.

1.5 Statistical Analysis

The statistical analysis for this study was performed using SPSS 22.0 software. Descriptive statistics were used to present continuous data in the form of mean $\pm$ standard deviation (Mean $\pm$ SD). Paired t-tests were employed for within-group comparisons in cases where the data followed a normal

distribution. For non-normally distributed data, the Mann-Whitney U test was used. A p-value less than 0.05 was considered statistically significant.

RESULTS

Both groups of patients underwent surgery successfully. In the guide group, intraoperative blood loss in the 7 patients ranged from 10 to 30 mL, with a mean of 17.86 ± 6.39 mL. In the control group, intraoperative blood loss in the 9 patients ranged from 20 to 37 mL, with a mean of 27.22 ± 5.97 mL. The operative time was 94.29 ± 13.05 min in the guide group and 103.78 ± 8.71 min in the control group. Compared with the control group, the guide group had a significantly shorter operative time and significantly less intraoperative blood loss ($P < 0.05$). The incision length in the guide group ranged from 5 to 9 cm, with a mean of 6.43 ± 1.37 cm, whereas that in the control group ranged from 6 to 10 cm, with a mean of 7.67 ± 1.32 cm. The guide group therefore showed a smaller surgical trauma range ($P < 0.05$) (Tables 2 and 3).

All patients were followed up for 10.57 ± 6.40 months. Postoperative pain was markedly relieved in both groups compared with the preoperative level, and the differences in VAS pain scores were statistically significant. In the guide group, the VAS score decreased to 0–2 points, with a mean of 0.57 ± 0.79 , whereas in the control group it decreased to 1–4 points, with a mean of 2.11 ± 1.05 . The postoperative follow-up pain score was significantly lower in the guide group. In addition, patients' ability to perform activities of daily living improved significantly after surgery. The Barthel Index showed a statistically significant difference: in the guide group, it increased from 56.43 ± 9.88 preoperatively to 85.71 ± 7.87 postoperatively; in the control group, it increased from 63.33 ± 6.12 to 75 ± 7.07 . Improvement in self-care ability was more pronounced in the guide group ($P < 0.05$) (Tables 4 and 5).

Among the patients in the two groups, one patient in the guide group developed a postoperative ulcer at the incision site. After strict aseptic management, adjustment of medication for glycemic control, and enhanced dressing changes, the ulcer healed completely within 5 weeks. The remaining 6 patients had no complications such as infection, ulcer recurrence, loosening or breakage of the external fixator, or tibial fracture. None of the postoperative patients underwent secondary amputation, yielding a limb salvage rate of 100%. In the control group, three patients developed postoperative ulcers. These were managed in the same way as in the guide group and healed completely after 7, 11, and 19 weeks, respectively. No complications occurred in the remaining control group patients.

The percutaneous surgical guide manufactured using computer-aided design combined with 3D-printing technology enabled completion of transverse tibial bone transport within a surgical trauma of < 9 cm and blood loss of < 30 mL. Postoperative ulcers healed within 5.14 ± 1.95 weeks, pain in the affected limb was significantly reduced, and patients' self-care ability was improved. In terms of long-term outcomes, patients achieved a 100% limb salvage rate and good recovery of lower-extremity blood perfusion after surgery. Presented below are two representative cases in which 3D-printed surgical guides were utilized. The cases illustrate the pathological changes spanning from the preoperative period through

postoperative recovery. Both patients recovered favorably, and the surgical outcomes were considered satisfactory. (Figure 4 and Fig. 5)

Table 2
Surgical outcomes of the 3D-printed guide group (n = 7)

Measurement	Mean $\pm$ SD	Significance (P)
Intraoperative Blood Loss	17.86 $\pm$ 6.39	0.448
Surgical Time	94.29 $\pm$ 13.05	0.282
Incision Length	6.43 $\pm$ 1.37	0.140
*A significance level of P > 0.05 indicates a normal distribution.		

Table 3
Surgical outcomes of the control group (n = 9)

Measurement	Mean $\pm$ SD	Significance (P)
Intraoperative Blood Loss	27.22 $\pm$ 5.97	0.614
Surgical Time	103.78 $\pm$ 8.71	0.605
Incision Length	7.67 $\pm$ 1.32 cm	0.545
*A significance level of P > 0.05 indicates a normal distribution.		

Table 4
Comparison of preoperative and postoperative outcomes in the 3D-printed guide group (n = 7)

Preoperative	Ulcer Healing Index (cm ² /week)	VAS Pain Score	Barthel Score
	0	7.28 $\pm$ 0.76	56.43 $\pm$ 9.88
Postoperative	2.05 $\pm$ 2.01	0.57 $\pm$ 0.79	85.71 $\pm$ 7.87
T	-2.695	21.617	-11.520
P	0.036	0.000	0.000

Table 5
Comparison of preoperative and postoperative outcomes in the control group (n = 9)

Preoperative	Ulcer Healing Index (cm ² /week)	VAS Pain Score	Barthel Score
	0	7.89 $\pm$ 0.78	63.33 $\pm$ 6.12
Postoperative	1.6156 $\pm$ 1.3373	2.11 $\pm$ 1.05	75 $\pm$ 7.07
T	-3.624	26	-9.89
P	0.000	0.000	0.000

DISCUSSION

TTT employs the principle of tensile stress on tissues to facilitate tissue regeneration and healing of diabetic foot ulcers. This technique activates signaling pathways, including SDF-1[7], which enhances the release of tissue growth factors like vascular endothelial growth factor (VEGF), basic fibroblast growth factor (bFGF), and platelet-derived growth factor (PDGF)[6]. Currently, the conventional procedure for bone removal involves a curved incision of 12–15 cm along the anterior medial tibia[8]. Subsequently, a rectangular window is created in the middle or upper third of the tibia, measuring approximately 10–12 cm in length and 1.8–2.0 cm in width. This extensive incision and debridement significantly worsen microcirculatory deficits. Researchers have devised minimally invasive approaches[9, 10] that modify the bone transfer window[11], aiming to mitigate surgical trauma and attain improved outcomes. Notwithstanding, substantial improvements are still necessary to enhance the precision and safety of bone transfer procedures and reduce the risk of complications such as fractures and ulcer recurrence[12].

In this study, CAD-based preoperative planning and a 3D-printed surgical guide were used to assist in the precise placement of traction pins and minimally invasive trapezoidal osteotomy, thereby minimizing the risk of postoperative fracture to the greatest extent possible. This approach achieved a total incision length for bone transport of 6.43 ± 1.37 cm and intraoperative blood loss of 17.86 ± 6.39 mL, thus substantially reducing surgical trauma. The operative time was relatively long in both groups, being 94.29 ± 13.05 min in the guide group and 103.78 ± 8.71 min in the control group. This was mainly because a high proportion of the included patients had Wagner grade III or IV diabetic foot ulcers with large areas of ulceration and necrosis, and approximately 60 min were spent on preoperative disinfection of the ulcer area and thorough debridement. In actual practice, however, the 3D-printed guide could effectively facilitate rapid, minimally invasive, and precise osteotomy as well as quick placement of traction pins. Moreover, no intraoperative C-arm fluoroscopy was required in the guide group. Compared with the control group, this not only shortened the operative time but also reduced the number of intraoperative fluoroscopic exposures, thereby lessening radiation-related effects on the patients. In addition, the postoperative ulcer healing rate in the guide group was 2.05 ± 2.01 cm²/week, and the postoperative VAS pain score and Barthel Index score were both significantly improved ($P < 0.05$). The guide group showed better outcomes than the control group in terms of intraoperative blood loss, incision size, operative time, and postoperative scores, which strongly demonstrates that this technique can achieve minimally invasive and precise TTT while also promoting postoperative ulcer healing and reconstruction of blood microcirculation in the affected limb.

Digital technology[13] is increasingly used in the medical field to revolutionize the treatment of diabetic foot. It enhances preoperative planning, personalization, and customization, with the integration of virtual reality (VR) and augmented reality (AR) providing real-time guidance and data analysis[14, 15]. These advanced technologies significantly improve surgical outcomes, reduce complications, and increase patient satisfaction. Zhang[16] et al. utilized computer-assisted simulation and 3D printing to create surgical guides for tibial transverse transport, leading to improved efficiency, safety, and ulcer healing.

However, implementation of this technique requires preoperative CT scanning of both lower limbs, which may increase the patient's medical expenses to some extent. Nevertheless, it can ensure that the procedure is more precise, efficient, and minimally invasive. At the same time, the design and printing process of the guide is time-consuming, and the materials used for its fabrication still require further improvement. In addition, to fully realize the benefits of this technique, the operator must possess solid expertise in 3D printing and related software applications, which places higher technical demands on the surgical team.

This study was a single-center retrospective study with a relatively limited sample size (7 cases in the guide group and 9 cases in the control group), and the related conclusions still need to be further validated in studies with larger sample sizes. Owing to the limited number of cases, no further multivariate adjustment analysis was performed in this study, and other factors may still have influenced the results. Despite the limited sample size, both groups adopted consistent inclusion criteria, perioperative management, and follow-up assessment procedures, which helped reduce selection bias and information bias to some extent. In the future, prospective study designs with larger sample sizes and more standardized follow-up and outcome evaluation should be conducted to improve the robustness of the findings.

Conclusions

The 16 case studies in this research reveal that 3D printing personalized tibial transposition percutaneous guide plates assist in treating diabetic foot ulcers, which is an innovative medical technology that plays a significant role in improving patients' quality of life and promoting the rehabilitation process. The personalized minimally invasive treatment through this technology can minimize surgical risks, reduce surgical trauma, and facilitate wound healing. Although there are certain issues to consider, for those who can benefit from it, it provides a unique and precise treatment approach, offering a more advantageous option for the treatment of diabetic foot ulcers.

Abbreviations

DFU

diabetic foot ulcer; DFUs—diabetic foot ulcers; TTT—tibial transverse transport; CAD—computer-aided design; VAS—Visual Analog Scale; DSA—digital subtraction angiography; CT—computed tomography; DICOM—Digital Imaging and Communications in Medicine; STL—stereolithography file format; SPSS—Statistical Package for the Social Sciences; SDF-1—stromal cell-derived factor-1; VEGF—vascular endothelial growth factor; bFGF—basic fibroblast growth factor; PDGF—platelet-derived growth factor; VR—virtual reality; AR—augmented reality

Declarations

Consent for publication:

Written informed consent was obtained from the patient for publication of this article, including the identifiable details such as age, sex, and other identifiers presented in Table 1.

Funding:

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Code availability: Not Applicable.

Ethics approval and consent to participate: Informed consent was obtained from all individual participants included in the study, This retrospective study involving human participants adhered to the ethical standards set by the Institutional and National Research Councils, as well as the 1964 Helsinki Protocol and its subsequent amendments or any other comparable ethical standards. This study was conducted in full compliance with the ethical principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Second Affiliated Hospital of South China University of Technology (Guangzhou First People's Hospital) (Approval No. K-2018-137-01). All participants provided informed consent.

Author Contribution

All authors contributed to the conceptualization and design of the study. Huanwen Ding, Qingtao Li, Han Yan, Yadi Zhang, Jiayi Wu, Bo Shang, and Guifeng Luo were responsible for program implementation, data collection, and analysis. Zekai Ma and Wenyi Yang designed and optimized the surgical protocol. Yadi Zhang and Jiayi Wu initially drafted the manuscript, which was subsequently reviewed and revised by all authors to produce the final draft. All authors acknowledge their responsibility for all aspects of the manuscript and the study.

Acknowledgments:

Not applicable

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

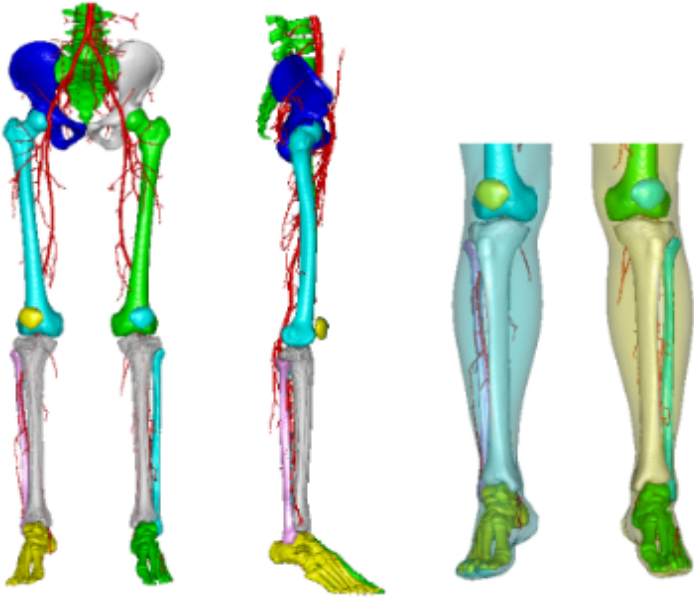


Figure 1

Three-dimensional anatomical model of bones and blood vessels of both lower limbs

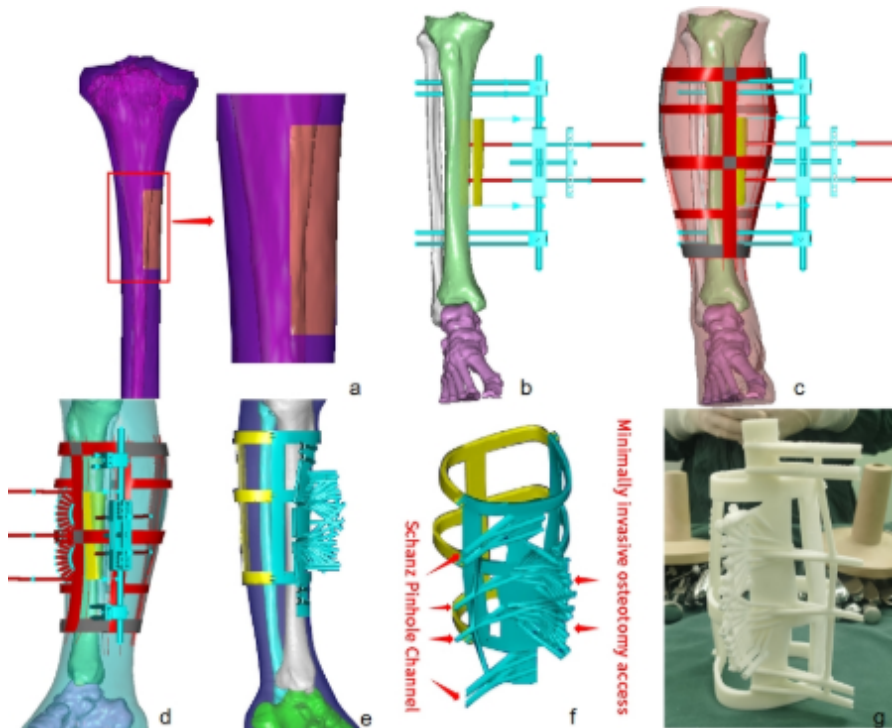


Figure 2

Workflow for Surgical Template Design: **a)** Designing the size of the osteotomy, with the width of the upper and lower edges occupying approximately one-third of the tibial medullary cavity and a height design of 7-10cm. **b)** Matching the design of the external fixation frame. **c)** Visualization of the lateral skin

of the tibia, point cloud design of the percutaneous template shape, and creation of entry holes for traction pins. **d)** Designing minimally invasive bone cutting canals based on the position and size of the osteotomy. **e)** Displaying and ensuring a perfect match of the skin model, optimizing the external appearance of the template to ensure complete adherence. **f)** virtual model of the percutaneous guide plate. **g)** solid model of the surgical guide plate created using 3D printing technology.

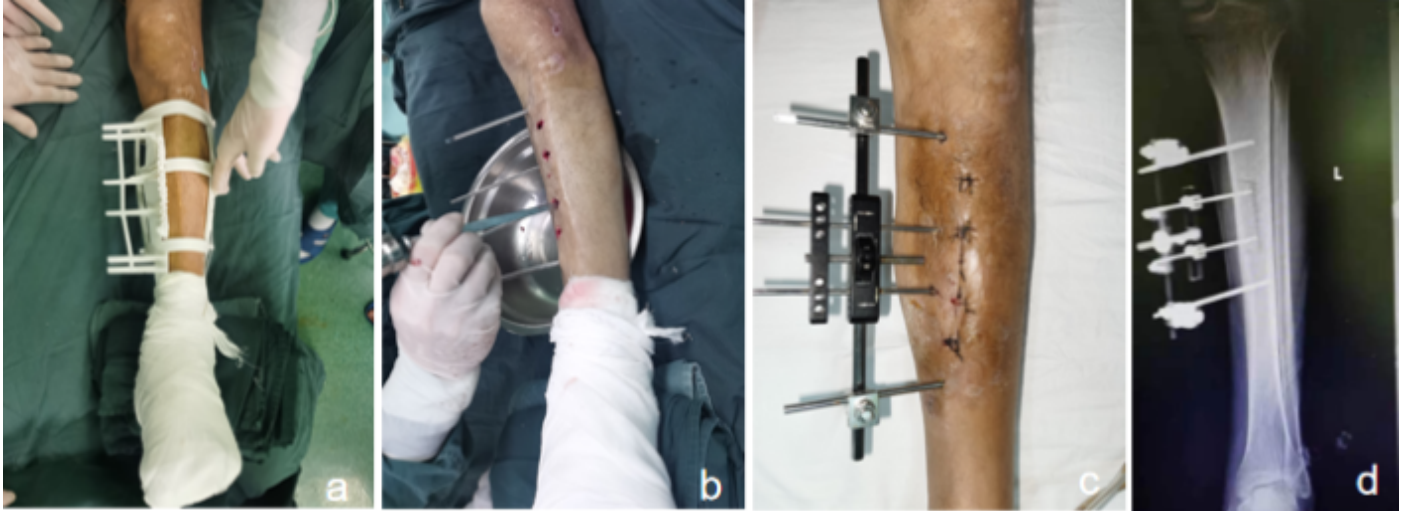


Figure 3

Process of surgery assisted by a 3D printed guide plate: **a)** Installation and fixation of the percutaneous guide plate created through 3D printing. **b)** Simultaneous drilling of the traction pin pathway for the external fixation frame and insertion of the Schanz traction pin, guided by the percutaneous guide plate, during minimally invasive bone-cutting procedures. **c)** Placement and adjustment of the external fixation frame, followed by suturing of the incision site. **d)** Postoperative X-ray confirms accurate positioning of the traction pins and the absence of any loosening or detachment of the internal fixation frame.



Figure 4

Typical Case 1: A 56-year-old male with a 10-year history of diabetes presented with dry gangrene in the right foot as a result of diabetic foot. After undergoing 3D-printed percutaneous guided plate-assisted transverse transport of the tibia, wound healing was observed at 4 weeks after the surgery. **a)** Prior to the surgery, the patient exhibited necrosis and pain in the right first toe. **b)** Two weeks post-surgery, the wound showed the presence of fresh granulation tissue. **c)** At 4 weeks post-surgery, the wound had fully healed, resulting in a significant reduction in pain. **d)** One week after the surgery, the wound exhibited favorable healing without any ulceration or necrosis. **e)** At 12 weeks postoperatively, the external fixation bracket had been removed and the wound had healed completely. **f) and g)** The radiographic image taken 1 day postoperative depicts the accurate placement of the traction pin without any indications of displacement or loosening. Additionally, the trapezoidal osteotomy window is highlighted within the red box.



Figure 5

☒**Typical Case 2**☒: A 56-year-old male presented with Wagner IV diabetic foot ulcer on the left foot, which had necessitated the complete amputation of the toes. **a)** The preoperative appearance of the foot was assessed. **b)** At 4 weeks after the surgery, the wound exhibited the growth of fresh granulation tissue. **c)** By the 7th week post-surgery, significant healing of the ulcer was observed. **d)** By the 9th week post-surgery, complete healing of the ulcer had occurred, indicated by scab formation. **e)** At 2 weeks post-surgery, negative pressure wound therapy was applied to the ulcer site using a supporting frame. **f)** A week following the surgery, X-ray imaging revealed a distinct area of bone resection and initiation of bone transport, with well-positioned traction pins and even spacing. **g)** By the 4th week post-surgery, notable elevation of the transported bone segment was noted. **h)** By the 6th week post-surgery, gradual realignment of the bone segment was observed.