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Digital Technology-Assisted "Z" Osteotomy lower limb corrective procedures

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Background and study aims: **Digital technology is a transformative product of the information age. z-osteotomy is a surgical procedure that corrects limb angulation and lengthens shortening deformities within a 40 mm difference in limb length.The purpose of this study is to Introduce the surgical technique of digitally assisted "Z" osteotomy for correction of angular and length deformities of the lower limbs and investigating its clinical efficacy.**
Patients and methods: **A retrospective study was conducted on five patients with multiplanar angular deformities of the lower extremity combined with limb shortening(n=5). The objective of the study was to assess the effectiveness of computer-assisted preoperative design planning and 3D-printed surgical guide fabrication in guiding precise orthopedic procedures. The study compared various parameters, including femoral or tibial cross-sections, coronal and sagittal deformities, limb length, modified Barthel Index, and post-operative complications.**
Results: **Five patients were granted 17.20±6.83 months of follow-up after surgery, with adequate correction of lower limb deformity, significant improvement in postoperative self-care ability improved Barthel index 90±3.08 points (P<0.05). One patient experienced postoperative wound pain at 3 months, which subsequently diminished significantly by the 4-month follow-up assessment., four cases had no complications.**
Conclusions: **The new surgical method of digital technology-assisted "Z" osteotomy for correction of complex deformities of the lower limbs has remarkable clinical results, can accurately correct multi-planar angular deformities and realize limb lengthening at the same time, being safe and reliable.**

Keywords: Digital technology, lower limb length discrepancy, osteotomy, 3D printing.

INTRODUCTION

Knee joint deformity is a common orthopedic condition, including varus, valgus, and flexion deformities. Varus deformity is the most frequent, accounting for approximately 60% of cases[1]. Clinical presentations comprise pain, deformations, and disabilities, impacting quality of life. Current treatment options include osteotomy for extra-articular deformities and complex cases may require joint replacement or gradual correction with the Ilizarov technique[2-5]. Traditional imaging techniques are insufficient for cases involving multiple deformities. Osteotomy techniques may exacerbate limb shortening and delay healing[6,7]. The Ilizarov technique is primarily utilized to correct severe lower extremity shortening and deformities through a minimally invasive percutaneous approach. Furthermore, it has demonstrated effectiveness in treating conditions such as diabetic foot ulcers, bone nonunions, and bone defects. The Ilizarov technique was introduced in 1950 as a minimally invasive method for correcting severe lower limb deformities and discrepancies in length >40mm through percutaneous application of an external fixation frame. Additionally, it has demonstrated remarkable efficacy in treating diseases such as diabetic foot ulcers, nonunion fractures, and bone defects[8-10]. Therefore, in order to address length discrepancies of ≤40 millimeters and multi-plane deformities, we have introduced a digital technology-assisted personalized "Z" osteotomy technique that differs from traditional joint replacement and transverse or wedge osteotomies. This technique enables multi-plane correction and simultaneous achievement of limb length balance in a single surgical procedure. Detailed information is provided in the following sections.

MATERIALS AND METHODS

This retrospective study included a total of 5 patients who underwent Computer-Aided Design (CAD)-assisted "Z-shaped" osteotomy correction surgery for lower-limb deformities at Guangzhou First People's Hospital from March 2021 to April 2023. There were 3 male patients and 2 female patients. Among them, 3 patients had deformities of the femur, and 2 patients had deformities of the tibia. Detailed information is provided in Table I. The inclusion criteria for this study were as follows: (1) non-osteoarthritic patients with lower limb dysfunction and impaired daily activities resulting from malunion after knee joint injury; (2) patients with X-ray, CT, and other imaging examinations indicating the presence of rotational, varus/valgus, anterior/posterior inclination, and length discrepancy deformities in the knee joint, without significant degenerative changes; (3) A ≤40mm length discrepancy between both lower limbs should be addressed in order to prevent permanent nerve and vascular damage following one-stage osteotomy lengthening. The exclusion criteria were as follows: (1) knee joint deformity accompanied by severe infection, ulceration, or other conditions unsuitable for osteotomy correction and internal fixation device implantation; (2) a >40mm difference in length between both lower limbs; (3) significant peripheral vascular disease. This study has received approval from the Ethics Committee for Research at Guangzhou First People's Hospital (Approval Number: K-2018-137-01).

Preparation of Imaging Data

Bilateral anteroposterior and lateral knee radiographs, full-length standing anteroposterior X-ray images of the lower limbs, and bilateral lower limb continuous thin-slice CT scans with a slice thickness of 0.50-1mm were obtained.The data were saved in the Digital Imaging and Communications in Medicine (DICOM) format to facilitate data transmission and surgical planning.

Three-dimensional models construction

The CT data, obtained in DICOM format, was imported into MIMICS 21.0 software (Materialize, Leuven, Belgium) to create three-dimensional digital models of the patients' affected limbs, aiding in the identification of the region of deformity and providing an initial understanding of its nature. Subsequently, the resulting models were exported in STL format to enable further preoperative three-dimensional design.

Three-dimensional surgical planning

The STL format model obtained as output was imported into ImageWare 13.0 software (developed by UGS Corporation, Plano, TX, USA) for establishing reference lines, aligning the model, and measuring anatomical parameters. The femoral head was transformed into a sphere, while several reference lines were established, including the femoral head-neck axis, femoral anatomical axis, force line axis, medial and lateral femoral condyle lines, medial and lateral tibial plateau lines, tibial anatomical axis, and anterior-posterior joint surface lines of the tibial plateau. Spatial calibration and alignment of the lower limbs were performed, utilizing three-dimensional measurements to evaluate the lengths of both lower limbs (Fig. 1g), angles of femoral and tibial torsion (Fig. 1a, d), femoral and tibial angles (Fig. 1b, e), as well as the sagittal plane angle (Fig. 1c, f) along the X, Y, and Z axes, representing the transverse, coronal, and sagittal planes, respectively. The preoperative conditions are summarized in Table II.

Subsequently, mirror image alignment was conducted on both the healthy and affected sides. Initially, alignment was performed on the proximal ends, followed by the distal ends. The limb on the healthy side served as the reference. In three-dimensional space, precise localization of the "Z" osteotomy locations was

Table I. — Patient Details n=5.

Gender	Age	Deformity Region	Diagnosis	Follow-up Duration (months)
Male	37	Distal part of the left femur	Surgical nonunion	6
Female	9	Proximal right tibia	Fracture fixation malunion	17
Male	24	Distal part of the right femur	Internal fixation plate fracture malunion	24
Male	29	Distal part of the left femur	Fracture fixation malunion	18
Female	40	Distal part of the right femur	Untreated fracture malunion	21

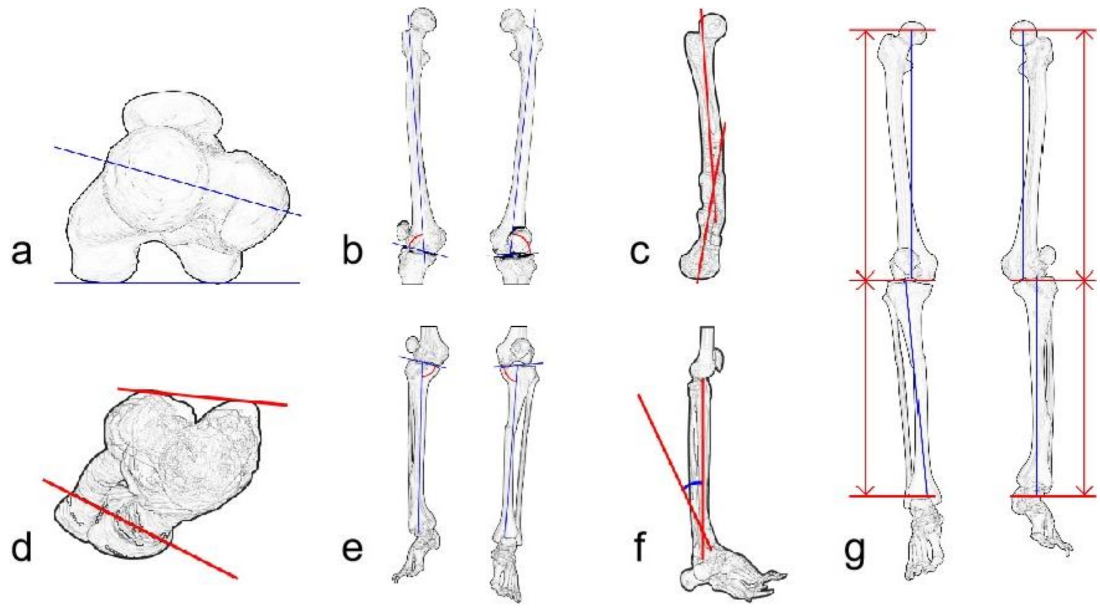

Fig. 1 — Three-dimensional measurements of lower limb angles. a is the femoral torsion angle, which is the angle between the posterior condylar line of the femur and the femoral neck line in the transverse plane; b is the femoral angle, which is the angle formed by the femoral axis line and the femoral condyle line in the coronal plane; c is the femoral coronal angle, also known as the femoral shaft angle, which is the angle between the femoral midline of the proximal and distal shaft in the sagittal plane; d is the tibial torsion angle, which is the angle between the posterior condylar line of the femur and the line connecting the center of the fitted ellipse of the tibia-fibula in the transverse plane; e is the tibial angle, which is the angle formed by the tibial axis line and the femoral condyle line in the coronal plane; f is the tibial coronal angle, which is the angle between the proximal and distal shaft midline of the tibia in the sagittal plane; g is the length of both lower limbs, which is the sum of the femoral length between the femoral head center and the femoral condyle line and the tibial length between the femoral condyle line and the lowest point of the distal tibial.

determined, while also considering the step height of the osteotomy surface based on the length of limb shortening. This ensured consistent limb lengths after the osteotomy procedure (Figure 2). It is crucial to avoid excessive lengthening, as it can cause damage to soft tissues such as nerves and blood vessels. Therefore, lengthening should not exceed 40mm. Subsequently, the osteotomy block was rotated and adjusted along the X, Y, and Z axes to achieve complete alignment with the healthy side model. These adjustments could be easily accomplished using three-dimensional software, enabling simultaneous correction of the deformity and limb lengthening from three different planes.

Next, data regarding the surface shape of the deformed lower limb bone was extracted. Taking into account the angles of rotation and movement of the osteotomy block, as well as the dimensions and characteristics of the steel plate screws, Computer-Aided Design (CAD) was employed to design the “Z” osteotomy guide, drilling positioning guide, and correction guide. Lastly, the data was imported into Unigraphics NX software (Siemens PLM Software, Plano, TX, USA) to create

Table II. — Preoperative.

Indicator	Values	Significance
Gender (male/female)	3/2	/
Transverse plane deformity (°)	15.45 ± 7.35	0.309
Coronal plane deformity (°)	13.99 ± 4.96	0.471
Sagittal plane deformity (°)	18.20 ± 11.38	0.743
Difference in lower limb lengths (mm)	24.95 ± 13.26	0.951
Modified Barthel Index	66.4 ± 4.50	0.175
Follow-up duration (months)	17.20 ± 6.83	/

Note: Significance (p) values indicate the level of significance for each measurement, with $p > 0.05$ suggesting conformity to a normal distribution.

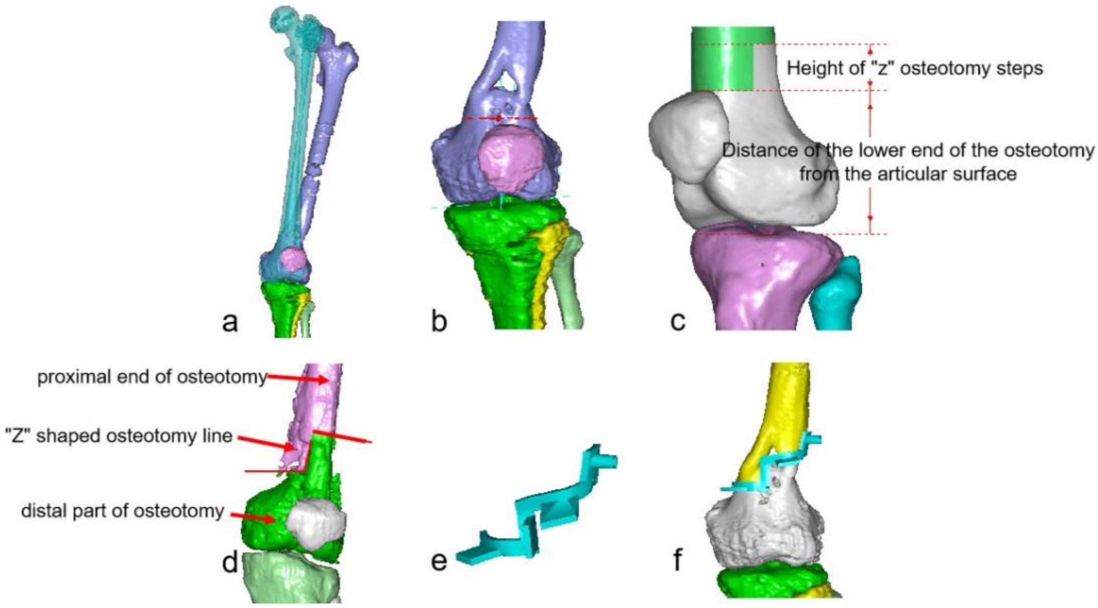

Fig. 2 — Digital technology-assisted "Z" osteotomy design. a involves aligning the distal ends on both the healthy and affected sides to determine the upper osteotomy surface in a Z-shaped manner. b involves aligning the proximal ends to determine the lower osteotomy surface. c involves determining the reserved osteotomy step height based on limb shortening. d involves determining the "Z" osteotomy line. e and f involve designing the outer shape of the osteotomy guide plate and simulating its compatibility.

the design for the surgical guides and Kirschner wire fixation holes. The model data was exported in STL format and then used with a 3D printer to produce a solid model using stereolithography technology and photosensitive resin as the material. Following sterilization with ethylene oxide, the guides were prepared for surgical use.

During the surgical procedure, the patient is positioned supine (Figure 3a) and administered either lumbar spinal anesthesia or general anesthesia. A tourniquet is applied to the affected limb. An incision is made to expose the area of knee joint deformity (Figure 3b). A drill guide is carefully inserted and secured with Kirschner wires for precise screw hole drilling, following the patient's personalized fixation plan (Figure 3e). A specialized "Z" osteotomy surgical guide is then placed and stabilized using Kirschner wires to perform the "Z" shaped osteotomy procedure (Figure 3f). To correct deformities of the knee joint, a corrective plate is positioned and secured with Kirschner wires. An internal fixation plate is installed and firmly secured using forceps and Kirschner wires. Bone defects resulting from the osteotomy are addressed by filling them with either autogenous iliac bone or allogenic bone grafting, supported by an allogenic bone plate (Figure 3h). Suitable screws are inserted and fixed within the nail track to provide stabilization. The surgical site is closed layer by layer, effectively completing the procedure (Figure 3i).

The obtained data underwent statistical analysis using SPSS 22.0 software. Descriptive statistics were reported as mean ± standard deviation (SD). Paired t-tests were used to compare normally distributed data within groups, while non-parametric tests like the Wilcoxon signed-rank test were used for data that did not follow a normal distribution. Statistical significance was determined using a significance level of $P < 0.05$, implying a meaningful difference when the P-value was less than 0.05.

RESULT

The postoperative data for the cases exhibited a normal distribution (Table III), and significant statistical differences were observed in the three-dimensional anatomical parameters of lower limb deformities before and after surgery (Table IV). All three dimensions of lower limb deformities were successfully corrected, and a significant improvement was observed in the postoperative discrepancy in leg lengths. The average follow-up period for the cases exceeded 6 months, with new bone formation and bony callus typically occurring within 3 months[9], and an overall average follow-up duration of 17.20±6.83 months. Notably, the modified Barthel Index displayed a significant increase, indicating a remarkable enhancement in patients' self-care ability following the surgery. Only one case experienced wound pain

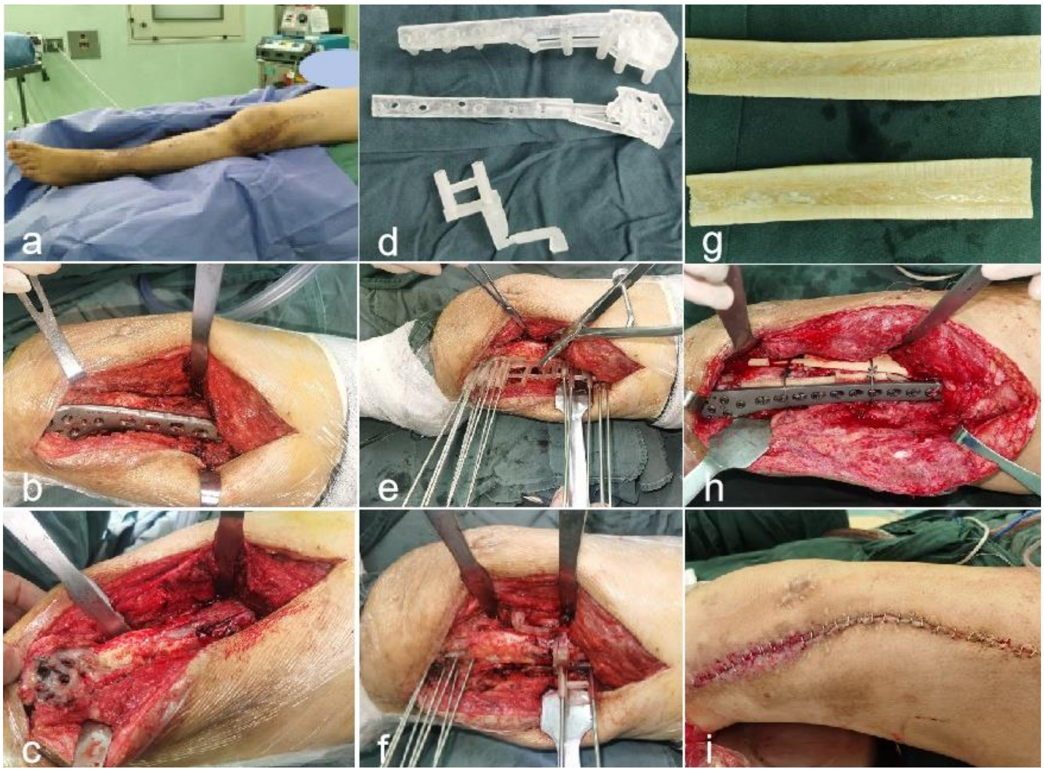

Fig. 3 — Clinical Application. a The patient was positioned in a supine position during surgery. b The original incision was opened to expose the steel plate. c The original steel plate was removed. d A 3D-printed surgical guide solid model was used. e A drilling guide template was used to pre-drill holes for the internal fixation steel plate. f A bone cutting guide plate was used to guide the bone cutting. g An allograft bone plate was used. h After fixing the distal screw of the steel plate, a corrective guide plate and Kirschner wire were used to fix the proximal end by rotating and moving the osteotomy segment to correct the deformity. Autogenous iliac bone and allograft bone plate were used to fill the bone defect. i The incision was sutured to complete the surgery.

during the three-month follow-up period after surgery, while the remaining four cases exhibited no significant complications.

Figure 4 presents a practical application of a clinical case. The patient presented a deformity in the distal end of the left femur (Fig. 4a). After three months, substantial new bone growth can be observed (Fig. 4b). By 18 months, the patient attained complete healing (Fig. 4c). Full-length standing X-rays taken at 7 months post-surgery revealed considerable recuperation of the lines of force in the lower extremities, as well as uniformity in the length of both limbs (Fig. 4d).

DISCUSSION

This study presents a novel approach that utilizes digital technologies, including Computer-Aided Design (CAD) and 3D printing, for the three-dimensional assessment and measurement of deformities. The healthy side is used as the reference standard in this approach. This approach was applied to develop individualized surgical plans for Z-plasty osteotomy. During the surgery, surgical guides were utilized to achieve precise and comprehensive correction of angular and length deformities in the limb, leading to

Table III. — Postoperative.

Indicator	Value (mean ±SD)	Significance
Transverse Plane Deformity (°)	11.11±4.75	0.514
Coronal Plane Deformity (°)	5.77±4.93	0.823
Sagittal Plane Deformity (°)	6.22±4.30	0.291
Limb Length Discrepancy (mm)	4.26±3.04	0.623
Modified Barthel Index	90±3.08	0.429
Note: Significance (P) > 0.05 indicates a normal distribution.		

Table IV. — Comparison of Data Preoperative and Postoperative.

Indicator	Transverse Plane Deformity (°)	Coronal Plane Deformity (°)	Sagittal Plane Deformity (°)	Limb Length Discrepancy (mm)	Modified Barthel Index
Preoperative	15.45±7.35	13.99±4.96	18.20±11.38	24.95±13.26	66.4±4.50
Postoperative	11.11±4.75	5.77±4.93	6.22±4.30	4.26±3.04	90±3.08
T	-5.753	-3.932	-3.192	-2.839	-19.47
P	0.000	0.003	0.011	0.019	0.00

Note: The table displays measurements before and after surgery, with the corresponding T-values indicating the statistical significance of the differences in the data sets. A significance level of P < 0.05 indicates the presence of statistical differences.

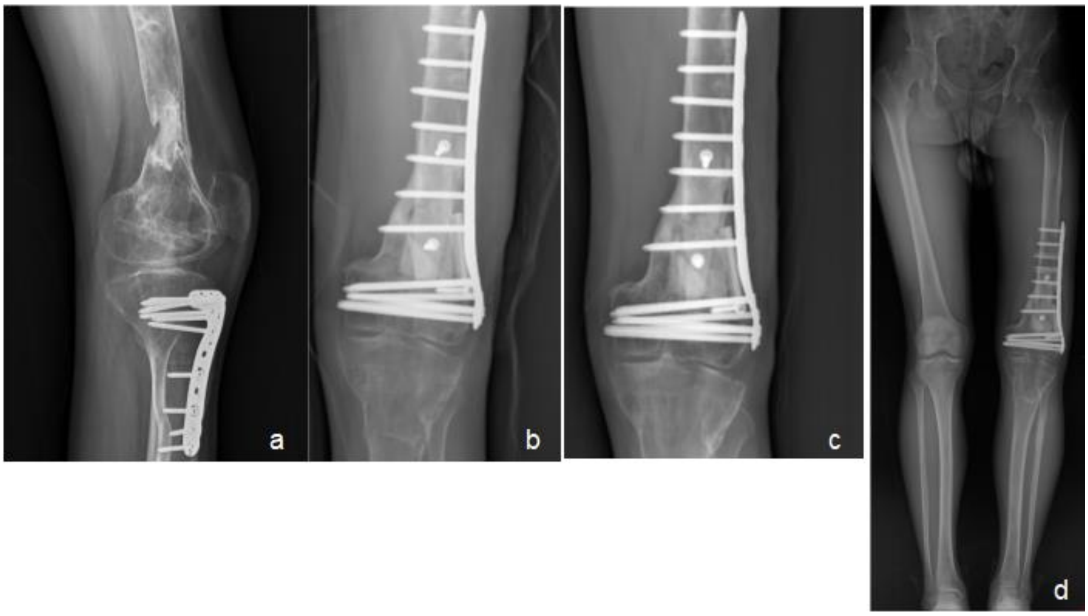

Fig. 4 — Application of the Technique. a Preoperative X-ray, b 2 days postoperative, c 3 months postoperative, d 7 months postoperative, e) 18 months postoperative.

accurate correction. During surgery, surgical guides are used to achieve accurate and comprehensive correction of angular and length deformities in the limbs. Postoperatively, CT scans are conducted 1-2 days after the procedure to generate 3D models and measurements for comparison with preoperative data, allowing for assessment of surgical outcomes. The correction of deformities yielded excellent results. The patients were followed up for an average of 17.20±6.83 months after the surgery. The modified Barthel Index showed a significant increase from 66.4±4.50 points before the surgery to 90±3.08 points after the surgery, indicating a notable improvement in the patients' self-care abilities. Out of the five patients, only one reported experiencing wound pain three months post-surgery. Overall, there was an 80% absence of postoperative complications.

Although this novel surgical technique achieved favorable orthopedic outcomes and prognosis, with promising clinical applications, certain challenges need to be addressed to realize even better clinical efficacy.

Digital Technology

Digital technology, originating from the field of computer science, is a product of the modern era[11]. Its extensive utilization has advanced CAD-assisted methodologies for managing complex clinical cases. In the field of orthopedics, digital technology enables comprehensive and precise diagnosis and resolution of lower limb deformities. It facilitates 3D simulation of surgical procedures, reducing complexity and unnecessary risks, thereby enhancing surgical outcomes and safety. By integrating CAD with 3D printing, surgical navigation templates significantly improve accuracy[12]. Digital technology, compared to conventional methods, reduces surgical time, minimizes fluoroscopy, and enhances outcomes through 3D reconstruction and virtual simulation[13]. Its implementation relies on electronic devices and software, leading to potential equipment issues that can contribute to surgical rescheduling and increased patient distress. Additionally, pre- and post-operative

CT scans increase patient radiation exposure. The use of surgical navigation templates, made of photosensitive resin, carries the risk of debris and potential allergic reactions in patients. Moreover, electronically stored patient data faces the possibility of leakage and loss. The application of digital technology in surgery holds significant potential, necessitating specialized expertise. Our study demonstrates the effectiveness of this technology in achieving precise correction and excellent outcomes for complex malformations. Despite the existing limitations, continuous technological advancements are expected to further enhance clinical outcomes in the future.

Correction of Limb Length Discrepancy

Major leg length discrepancy is a prevalent orthopedic deformity that profoundly affects patients' quality of life. Current treatment options, such as the Ilizarov technique and bone transplantation, aim to restore both the function and appearance of the limb. The Ilizarov technique involves a gradual lengthening of limbs through the application of an external fixation device and can effectively address complex conditions[14-16]. Bone grafting after osteotomy offers partial correction[17], but it presents clinical challenges including postoperative bone nonunion, rejection, and limited availability of viable graft sources. Current research focuses on exploring artificial bone graft materials[18-19].

"Z" Osteotomy

The "Z-shaped" osteotomy technique is utilized to correct foot deformities, specifically calcaneal varus deformity[20,21]. This technique involves sequential soft tissue dissection and a "Z"-shaped cut in the calcaneus and toe bones, allowing for direct visualization of the correction. Surgeons have also employed this technique to address lower limb shortening deformities, resulting in partial limb lengthening[22]. However, accurately determining the site and extent of lengthening during surgery poses a challenge visually and tactually, leading to complications such as recurrent fractures and vascular nerve injuries. Another study conducted an osteotomy in the midshaft of the femur using the "Z" technique during total hip replacement, successfully achieving over 2 cm of postoperative lengthening in the lower limbs[23]. While these studies demonstrate the effectiveness of the "Z" osteotomy, improper site selection can increase the risk of nerve and vascular damage and negatively impact limb function[24]. To address these challenges, our computer-assisted three-dimensional design utilizes digital technology in the precise surgical design. With accurate measurements and personalized surgical guide plates, this approach ensures precise osteotomy cutting, reducing surgical time and the learning curve, while maximizing overall success.

Authors contribution: All authors contributed to the conceptualization and design of the study. Huanwen Ding, Han Yan, Haotian Zhu, Kai Cheng, and Yuanhao Peng were responsible for program implementation, data collection, and analysis. Kang Liu and Yuning Wang designed and optimized the surgical protocol. Haotian Zhu 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.

Conflict of interest: The authors declare that they have no conflict of interest.

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Informed consent: 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. The study was also approved by the First People's Hospital of Guangzhou (K-2018-137-01).

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