CLINICAL ARTICLE

Feasibility of Computer-Aided Design in Limb Lengthening Surgery: Surgical Simulation and Guide Plates

Kai Cheng, MM[1,2], Yuanhao Peng, BM[1], Xiaonan Yan, BE[3], Xinghua Wen, ME[3], Huanwen Ding, MD,PhD[1,2]

[1]*School of Medicine, South China University of Technology,* [2]*Department of Orthopedic Surgery, Guangzhou First People's Hospital and* [3]*School of Biomedical Sciences and Engineering, South China University of Technology, Guangzhou, China*

Objective: To evaluate the feasibility and utility of computer-aided design (CAD) in surgical treatment of leg length discrepancy (LLD) using monorail external fixators.

Methods: In the present case series, we retrospectively analyzed seven patients diagnosed with LLD who were surgically treated using a monorail external fixator between June 2018 and August 2020. A personalized surgical emulation of each patient was designed using CAD based on preoperative CT scans to measure limb parameters. Through reverse engineering, a surgical guide plate was then designed to assist with correcting the limb deformity. Patient general information and clinical history, leg length, mechanical lateral distal femoral angle (mLDFA), anatomical anterior distal tibial angle (aADTA), and surgical parameters were recorded during the perioperative period. Three months after external fixator removal, distraction-consolidation time (DCT), healing index (HI), and lower extremity function score (LEFS) were calculated, and statistically analyzed by paired T-test.

Results: The mean limb lengthening achieved was 6.41 ± 2.54 (range, 3.30–10.54) cm with either varus or valgus correction. The mean operative duration was 151 ± 41.87 (84–217) minutes and mean blood loss was 53.58 ± 22.51(25–87) ml. The mean distraction-consolidation time was 3.67 ± 1.13 (range, 2.5–6.0) months and mean external fixator duration was 11 ± 2.45 (range, 8–14) months. The mean healing index (HI) was 18.11 ± 3.58 (range, 12.8–22.7) days/cm. Mean LEFS scores improved postoperatively from 32.17 ± 8.57 (range, 24–45) to 61.17 ± 6.68 (range, 50–67) with a significant difference ($T = -14.26$, $P < 0.001$).

Conclusions: Simultaneous length and angular correction can be achieved by incorporating CAD into the surgical treatment of patients with LLD, without compromising postoperative lower limb function. CAD demonstrates utility in the surgical treatment of LLD by improving the functionality of monorail external fixators.

Key words: 3D printing; bone lengthening; computer-aided design; external fixator; leg length discrepancy

Introduction

Leg length discrepancy (LLD) is one of the more common limb deformities. A 2005 review reported greater than 90% of the general population have at least a 1 mm discrepancy in leg length[1]. Numerous factors contribute to LLD, including congenital dysplasia and trauma injuries[2,3]. Mechanical imbalance of the lower limbs leads to pelvic tilt and compensatory scoliosis, followed by impaired mobility and hip pain. LLD may also cause imbalance in load distribution through the lumbar discs and facet joints contributing to degenerative changes in intervertebral joints[4–6]. LLD is frequently accompanied by abnormal bone angles, adding to the physical and mental burden placed on patients. Accordingly, the early diagnosis and treatment of

Address for correspondence Huanwen Ding, Department of Orthopedic Surgery, The Second Affiliated Hospital, School of Medicine, South China University of Technology, Panfu Road No.1, Guangzhou 510180, China. Email: dhuanwen@outlook.com
Received 15 December 2021; accepted 16 May 2022

LLD can substantially improve patient satisfaction and quality of life.

LLD is currently diagnosed based on measurement of the lower limbs from two-dimensional standing radiographs[7,8]. However, three-dimensional parameters provide improved reliability over two-dimensional images. A more comprehensive understanding of preoperative parameters informs treatment options. LLD can be treated conservatively or surgically depending on the complexity and severity of each case. An LLD of less than 2 cm can be corrected using insoles or extracorporeal orthoses, while an LLD greater than 2 cm is commonly considered an indication for surgical intervention[9]. A variety of lengthening methods have been utilized clinically including the Ilizarov apparatus, monorail external fixator, and intramedullary lengthening nails, each with their specific strength and weaknesses[10,11]. The Ilizarov apparatus, commonly known as the circular external fixator, is one of the earliest developed external fixators and represents a robust device used in the surgical correction of complex deformities[12]. However, the complex installation procedure exposes patients to increased surgical duration which exponentially increases the risk of postoperative complications. The Taylor spatial frame is a modified version of the Ilizarov apparatus, which uses computer software to calculate the required angular rotations, displacement, and the overall lengthening required. However, this device relies on patient compliance and is comparatively more expensive[13,14]. The monorail external fixator is frequently used in leg lengthening surgeries due to ease of usage and provision of adequate structural support. A commonly reported weakness of the monorail fixator is the strict requirement for proper alignment of Schanz screws during installation. The magnetic lengthening nail is a novel apparatus recently introduced for limb lengthening[15]. The major advantage of this apparatus is the lack of a need for extracorporeal devices; however, it is limited by the small range of lengthening (3–4 cm) it can provide. Previous studies have reported an increased risk of implant failure after 15 months following fixation, which warrants careful consideration in patients requiring prolonged fixation[16]. In addition, patients with LLD may present with an angular deformity, which further increases the technical difficulty of surgical correction, leading to increased risks of surgical complications. The different lengthening strategies presently in clinical use are unable to provide a satisfactory solution in every LLD patient, which further emphasizes the need for improved treatment methods.

The main treatment principle of LLD is lengthening of the shortened leg in order to achieve a physiological limb length similar to the healthy leg. Accurate measurement of the difference in limb length must first be performed, followed by the selection of a suitable limb lengthening method. An LLD limb accompanied by angular deformities increases the complexity of correction, in which traditional treatment methods may not suffice. Acquiring and processing the various parameters then changes a medical obstacle into a mathematical issue. CAD has been widely used in the field of orthopaedics and is garnering increasing attention. A previous review on the application of computer-assisted surgery and 3D printing reported improved treatment satisfaction and aesthetics in maxillofacial orthopaedic surgeries[17]. Xin *et al.* reported successful CAD-based preoperative surgical simulations and pedicle subtraction osteotomy guide plates in the treatment of thoracolumbar deformities, with results showing accurate intraoperative osteotomy[18]. Through reverse engineering software, preoperative patient data can be quantitatively analyzed to allow emulation of the surgical procedure and design of a personalized treatment plan for both surgeon and patient. Coupled with 3D printing, preoperative surgical simulation is then performed in the form of a surgical guide plate, which assists in replicating the surgical procedure. This minimizes dependence on the subjective judgment of individual surgeons, thereby reducing overall technical difficulty and surgical risks in addition to shortening surgical duration.

Based on clinical trends in LLD patients and the need for personalized treatments, novel customized approaches are required to increase treatment efficacy and patient satisfaction. In the present study, we developed computer-aided surgical emulation and 3D-printed guide plates to allow simultaneous correction LLD and angular deformities using monorail external fixators. According, the present study aimed to: (i) measure and analyze patient limb parameters at a 3D level; (ii) evaluate the utility of preoperative computer-assisted surgical simulation of the surgical procedure; (iii) evaluate the feasibility of CAD-designed surgical guide plates in improving the surgical treatment of LLD patients using a monorail external fixator.

Methods

Patient Population

Clinical data of patients undergoing surgical treatment of LLD at our medical center between June 2018 and August 2020 was retrospectively collected and analyzed. The inclusion criteria for the present study was: (i) voluntary participation and signed informed consent; (ii) diagnosis of LLD with a length discrepancy greater than 2 cm requiring surgical correction. The exclusion criteria for this study were: (i) lost to follow-up; (ii) received other lengthening treatment prior to surgery. This study was approved by the local ethics institute (K-2018-137-04) and all patients provided signed informed consent before surgery.

Preoperative Limb Parameters

All patients underwent preoperative computed tomography (CT) of the lower limbs. During preoperative CT scanning, a metal object was placed at the approximate surgical site and marked to facilitate the design and proper placement of the surgical guide plate. Raw DICOM data were entered

into Mimics 21.0 (Materialize Software, Leuven, Belgium, USA) to reconstruct a 3D model of the lower extremities. The resulting STL files were then transferred to Imageware 13.0 (UGS Corporation, Plano, Texas, USA) to compare healthy and affected limbs (limb length and either mechanical lateral distal femoral angle, mLDFA, or anatomical anterior distal tibial angle, aADTA, were recorded; Figure 1). During preoperative planning, other lower limb angles including anatomical and mechanical femoral or tibial angles could also be modeled. However, for the purpose

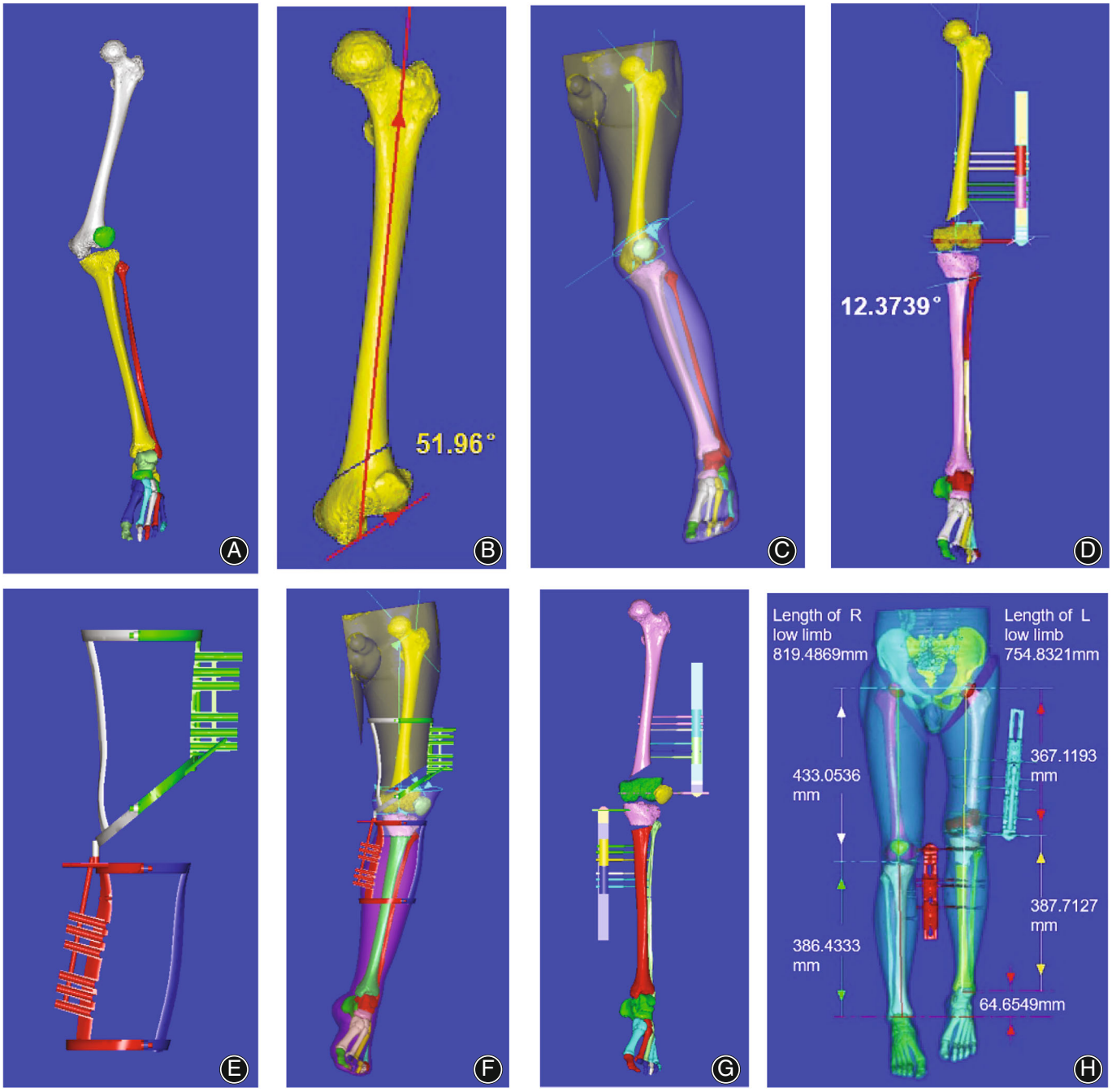

Fig. 1 Computer-aided design of the surgical plan. (A) Three-dimensional reconstruction of the lower limb. (B) Limb parameters of the lower limb, showing accurate measurements of the mLDFA. (C and D) Surgical emulation of tibial and femoral osteotomy. (E) Personalized design of the surgical guide plate used in each surgery. (F) Registration of the guide plate to the operated limb in the CAD surgical simulation. (G and H) Simulation of postoperative placement of the external fixator and simultaneous correction of length and angle

of the present study, only mLDFA and aADTA angles were included.

After the input of STL data into Imageware, the area of interest could be selectively displayed or hidden. A direct visual understanding of the deformity in multiple views could be obtained through rotation, adjustment of STL data, and the mirroring function. Using the point-based rendering function, we were able to accurately measure the length of the lower limb and angle parameters to compare the healthy and affected limb.

Surgical Simulation and Guide Plate Design

A personalized surgical plan was then designed according to the complexity of each patient, with an example shown in Figure 1. Our surgical guide plates were designed with the healthy limb used as reference. We first determined the site

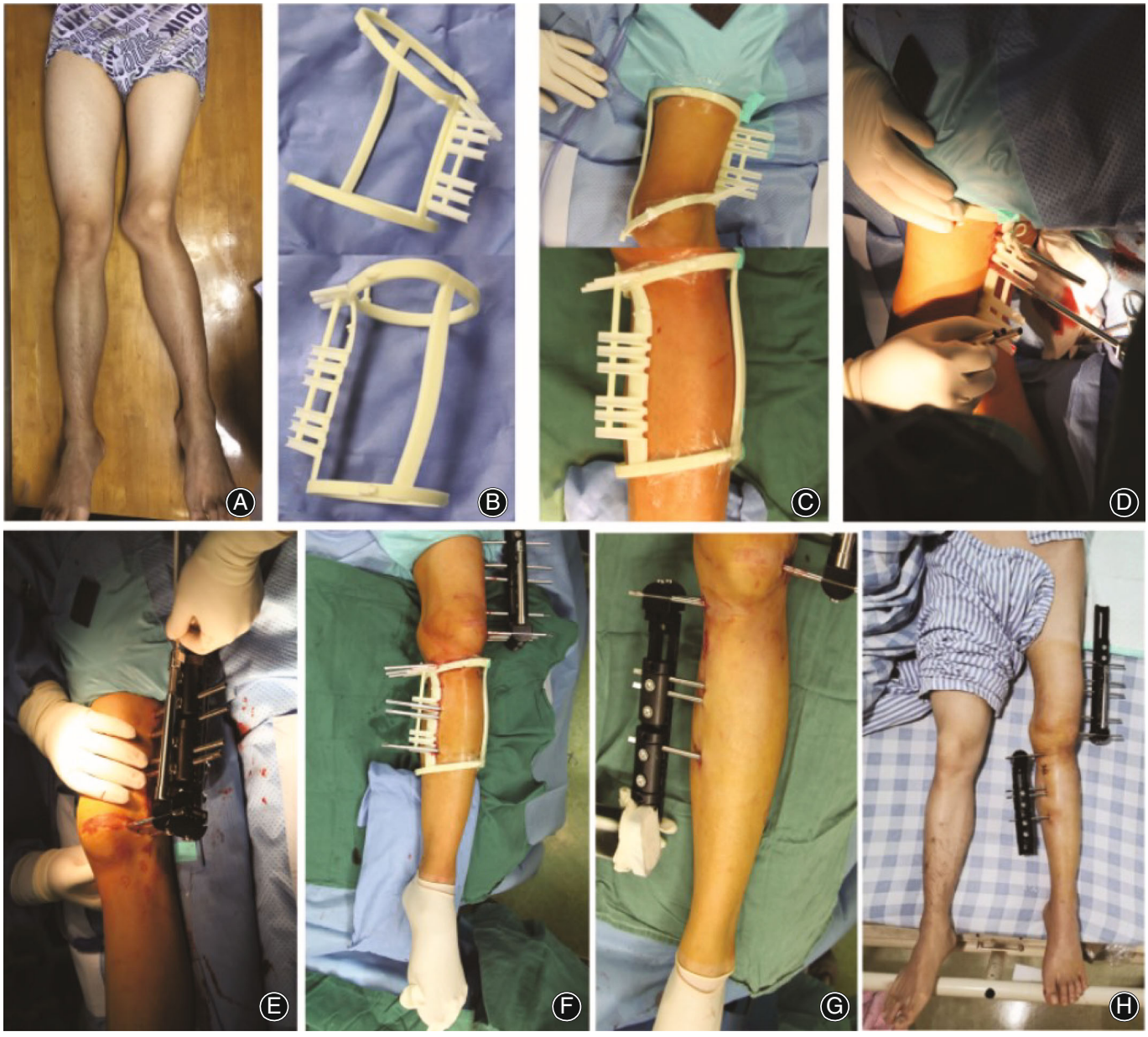

Fig. 2 Representation of a typical case of LLD in our study (A) Preoperative appearance of the affected limb, showing a prominent valgus deformity. (B) Completed 3D-printed resin-based surgical guide plate. (C) Placement of the surgical guide plate on the operated limb. (D and F) Semi-circular channels on the surgical guide plates acting as sleeves for Schanz Screws. (E and G) Intraoperative installation of a monorail external fixator. (H) Postoperative appearance of the LLD limb, showing valgus correction and installation of the external monorail

of deformity as either femoral or tibial, and the site of osteotomy was then selected according to the affected bone. Osteotomy was emulated within the software and abnormal limb parameters were corrected by rotation and movement to achieve satisfactory surgical positioning. Schanz screw placement and trajectory were determined on the premise that the mechanical axis of the affected limb was restored. After the position and trajectory of the Schanz screws had been determined, the corrected bone was restored to its deformed state. A surgical guide plate was then constructed based on reverse engineering, allowing surgical emulation of osteotomy site location and determination of vertical screw trajectory from the bone towards the skin. Convex protrusions and semi-tubular channels were added to the guide plate to function as landmarks for proper instrument positioning. Semi-tubular channels on the guide plate ranging from 15 to 20 mm in width acted as drill sleeves to ensure perpendicular insertion of Schanz screws without the need for additional equipment.

3D Printing of Patient-Specific Guide Plates

The guide plates used in the present study were resin-based and have been certified for use with medical devices as they provide adequate stability and rigidity. All guide plates used in this study were printed at the National Organization Function Reconstruction Technology Research and Engineering Center of South China University of Technology. Guide plates were printed using photocuring integrated molding technology and then sterilized before usage (Figure 2).

Surgical Method

Patients were placed in supine position after anesthesia and the surgical site was disinfected. The guide plate was then placed upon the exposed skin according to the preoperative simulation. An incision of 1 cm length was made below each screw placement channel and deep tissues were separated using forceps. A Kirschner wire was drilled into the proximal and distal tracks of the drilling channel to stabilize the guide plate and act as a marker for the position of screw insertion. Wires on the proximal and distal channels were kept in place in order to prevent movement of the guide plates. A Kirschner wire was then drilled into each channel to allow proper positioning of the Schanz screws. After removal of the Kirschner wire from the channels, the resulting aperture on the bone was used to facilitate screw insertion. An incision 1–2 cm in length was then made below the osteotomy site marked on the guide plate and the bony surface was then exposed. Osteotomy was completed using miniature drills and an osteotome.

In cases requiring tibial lengthening, fibular osteotomy was performed from the mid-upper section of the lower leg to prevent lateral malleolus instability. Drilling tracks were made in accordance with axial position after surgical correction rather than anatomical presentation during surgery, thereby allowing simultaneous lengthening and angular correction. Schanz screws were then drilled into each channel and the external fixator was fixed upon each screw following osteotomy. A typical surgical procedure is shown in Figure 2.

Postoperative Rehabilitation and Management

Patients were administered intravenous antibiotics to prevent postoperative infection of the surgical site. Lower limb movement, sensation, and blood flow were monitored for postoperative neurovascular traction injury. Patients were encouraged to begin bedside rehabilitation (flexion of the knee and hip) starting from the second postoperative day. After postoperative radiology, the external fixator was lengthened at a rate lower than 1 mm/day; however, rates differed for each patient according to adjacent soft tissue and pain intensity. Patients were followed up for 6 months after surgery (1, 2, 3, and 6 months). A radiographic assessment was performed at each follow-up visit to evaluate the degree of extension and bone consolidation. The external fixator was removed only after satisfactory extension and bone bearing capacity was confirmed. Three months after removal of the external fixator, patients were followed-up to evaluate bone consolidation.

Patient Parameters

Patient operative evaluation was performed by measuring intraoperative blood loss and operative duration. Postoperative evaluation was performed by measuring the following parameters.

TABLE 1 Patient parameters

Case	Gender/age (y)	Diagnosis	Bone	Discrepancy (cm)	Angle (°)
1	M/21	Post-traumatic Epiphyseal Arrest	Femur (L)	6.64	51.96[a]
2	M/13	Congenital LLD	Tibia (R)	10.54	80.25[a]
3	F/10	Fibrous Dysplasia	Tibia (L)	8.43	102.57[a]
4	F/1	Tibial Pseudarthrosis	Tibia (R)	3.30	138.10[b]
5	F/11	Congenital LLD	Tibia (R)	4.10	79.03[a]
6	F/12	Post-traumatic Epiphyseal Arrest	Tibia (R)	4.88	132.70[a]
7	F/9	Fibrous Dysplasia	Tibia (L)	7.15	102.57[a]

[a] mLDFA, mechanical lateral distal femoral angle. [b] aADTA, anatomical anterior distal tibial angle.

Distraction-Consolidation Time (DCT)

Distraction-consolidation time (DCT) is defined as time from surgery to radiographic evidence of bone consolidation in three-fourths cortices, reflecting the formation of bone callus. Evaluation of DCT assists in determining suitable postoperative weight-bearing and removal of the external fixator.

Healing Index (HI)

Healing index (HI) is defined as the ratio of number of postoperative days until consolidation to the length of bone consolidation (days/cm). The index can be used to evaluate the rate of bone growth and tailor personalized postoperative functional exercise plans.

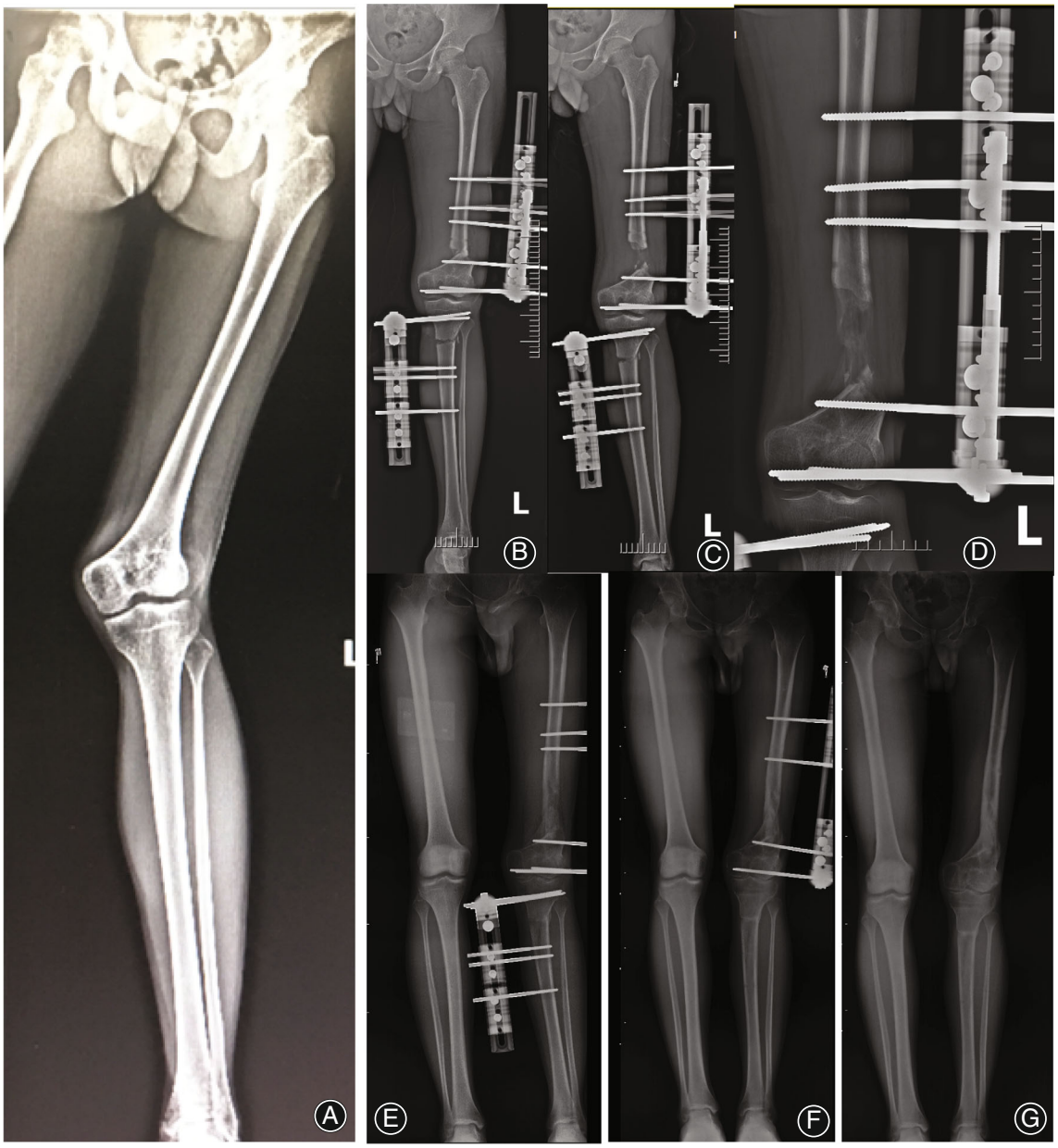

Fig. 3 Perioperative and follow-up radiographs of a typical LLD patient in our study. (A) Preoperative radiographs showing an apparent LLD. (B/C/D/E) Follow-up radiographs at day 1, 1 month, 2 months, 3 months, and 6 months after surgery demonstrating bone generation after lengthening. (F) Follow-up radiograph at 8 months after surgery demonstrating adequate lengthening allowing removal of the external fixator. (G) Patient follow-up at 3 months after removal of the external fixator

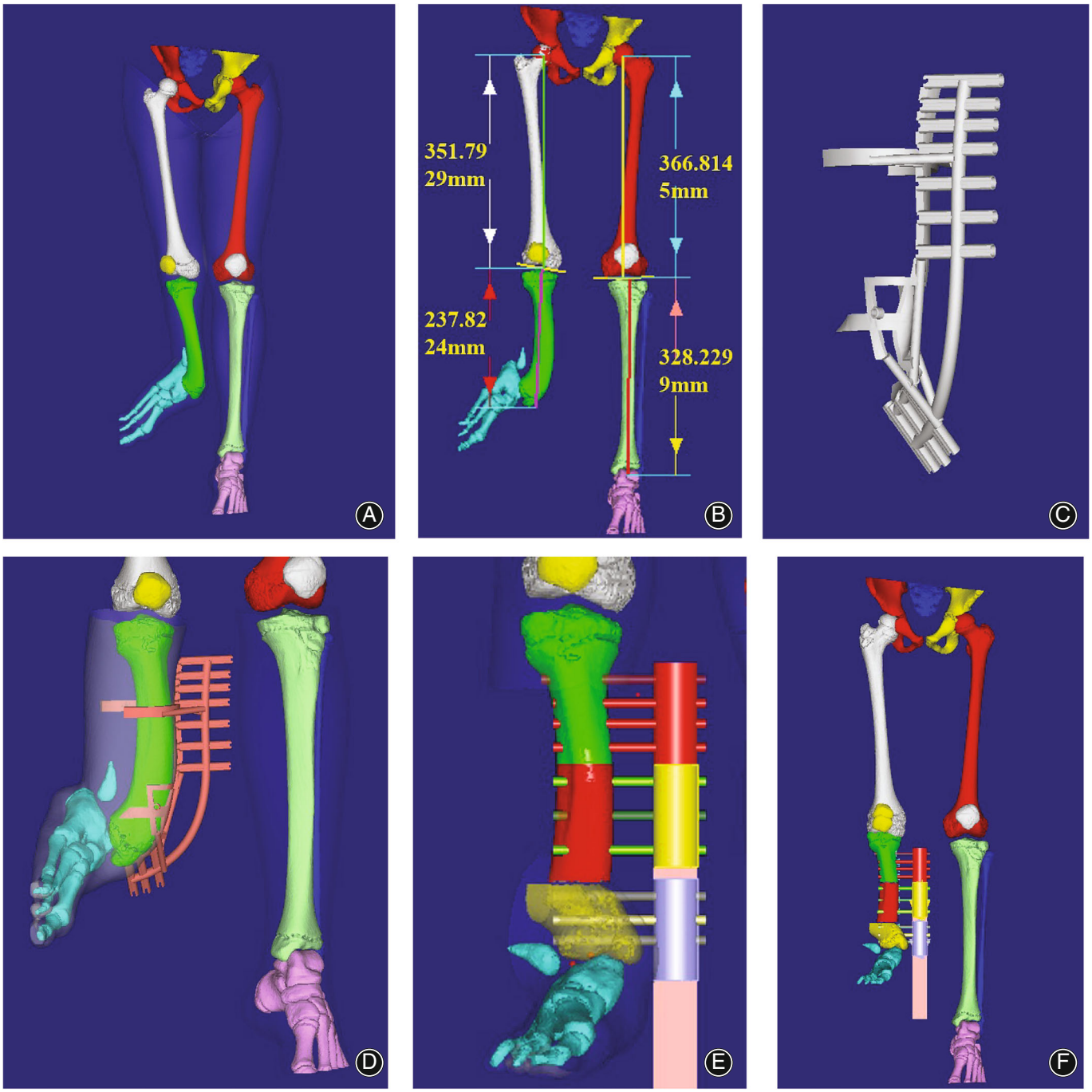

Fig. 4 Computer-aided design of the surgical plan. (A) Three-dimensional reconstruction of the lower limb. (B) Limb parameters of the lower limb. (C) Personalized design of the surgical guide plate used in each surgery. (D) Registration of the guide plate to the operated limb in the CAD surgical simulation. (E and F) Simulation of the postoperative placement of the external fixator and the simultaneous correction of the length and angle

Lower Extremity Function Score (LEFS)

Lower extremity function scores are derived from a questionnaire containing 20 questions regarding the ability to perform everyday tasks. Scores were measured before surgery and after removal of external fixators.

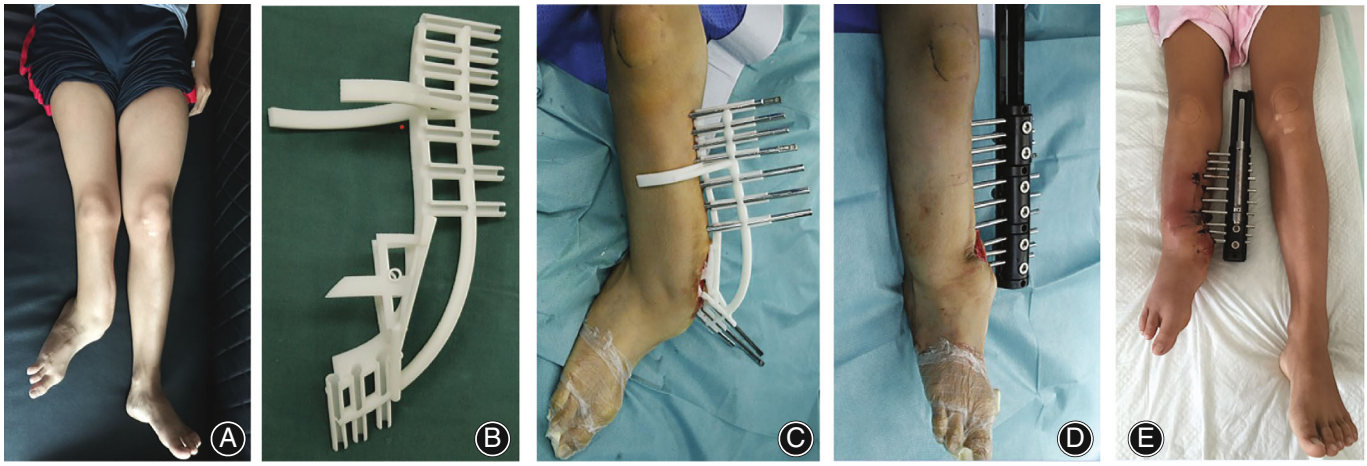

Fig. 5 Representation of another typical case of LLD. (A) Preoperative appearance of the affected limb, showing a prominent valgus deformity. (B) The 3D printed resin-based surgical guide plate. (C) Placement of the surgical guide plate on the operated limb and inset Schanz Screws. (D) Intraoperative installation of a monorail external fixator. (E) Postoperative appearance of the LLD limb, showing valgus correction and installation of the external monorail

Statistical Analyses

Data collected were recorded as mean ± standard deviation and analyzed in SPSS version 22 (IBM Corp., Armonk, NY, USA). The paired T-test was used to compare lower extremity function scores. *P*-values less than 0.05 were regarded as statistically significant.

Results

General Results

A total of seven patients diagnosed with LLD who underwent surgical correction at our hospital between June 2018 and August 2020 were included in the present study. The mean patient age was 11 ± 5.91 (range, 1–21) years. The study population comprised two male and five female patients. Except for two patients with congenital LLD, five patients had acquired disease (two cases of post-traumatic epiphyseal arrest, two cases of fibrous dysplasia, and one case of tibial pseudarthrosis). Three patients had LLD with knee varus, two with knee valgus, and two with tibial procurvatum. The basic parameters of each patient are shown in Table 1. A typical case in our study is represented in Figure 3 (a separate typical case is shown in Figures 4–6).

Intraoperative Results

All surgical procedures were performed according to preoperative surgical simulation and surgical design. Closed osteotomy and Schanz screw placement were performed with the aid of a surgical guide plate without the need for intraoperative fluoroscopy. The mean number of Schanz screws used in the study was 9.57 ± 2.29 (range, 6–13). The mean operative duration was 151 ± 41.87 (range, 84–217) minutes and the mean intraoperative blood loss was 53.58 ± 22.51 (range, 25–87) ml.

Functional Evaluation

All patients underwent standard postoperative care, functional rehabilitation, and regular wound dressing changes. Blood chemistry was monitored at regular intervals to evaluate postoperative conditions and patients were discharged upon having normal levels of inflammatory indices. Radiographs were taken at each follow-up appointment. Patient parameters were as follows: the mean length of extension in all the operated limbs was 6.41 ± 2.54 (range, 3.30–10.54) cm. Mean DCT was 3.67 ± 1.13 (range, 2.5–6.0) months and the mean retention time of the external fixator was 11 ± 2.45 (8–14) months. The mean final HI was 18.11 ± 3.58 (12.8–22.7) days/cm. Lower extremity function score criteria were used for preoperative and postoperative evaluation. One patient in our study was too young for lower limb function scoring. The mean LEFS score increased from 32.17 ± 8.57 (range, 24–45) to 61.17 ± 6.68 (range, 50–67) after surgery ($T = -14.26$, $P < 0.001$), the data was shown in Table 2.

Complications

During the follow-up period, two patients presented at 1 week and 1 month after discharge, respectively, with erythema and edema at the needle outlet. Both patients were readmitted to the hospital and treated symptomatically with regular dressing change and intravenous antibiotics. Infection was diagnosed upon confirmation of increased inflammatory indicators; C-reactive protein and procalcitonin. Bacterial culture was conducted on exudates and suitable

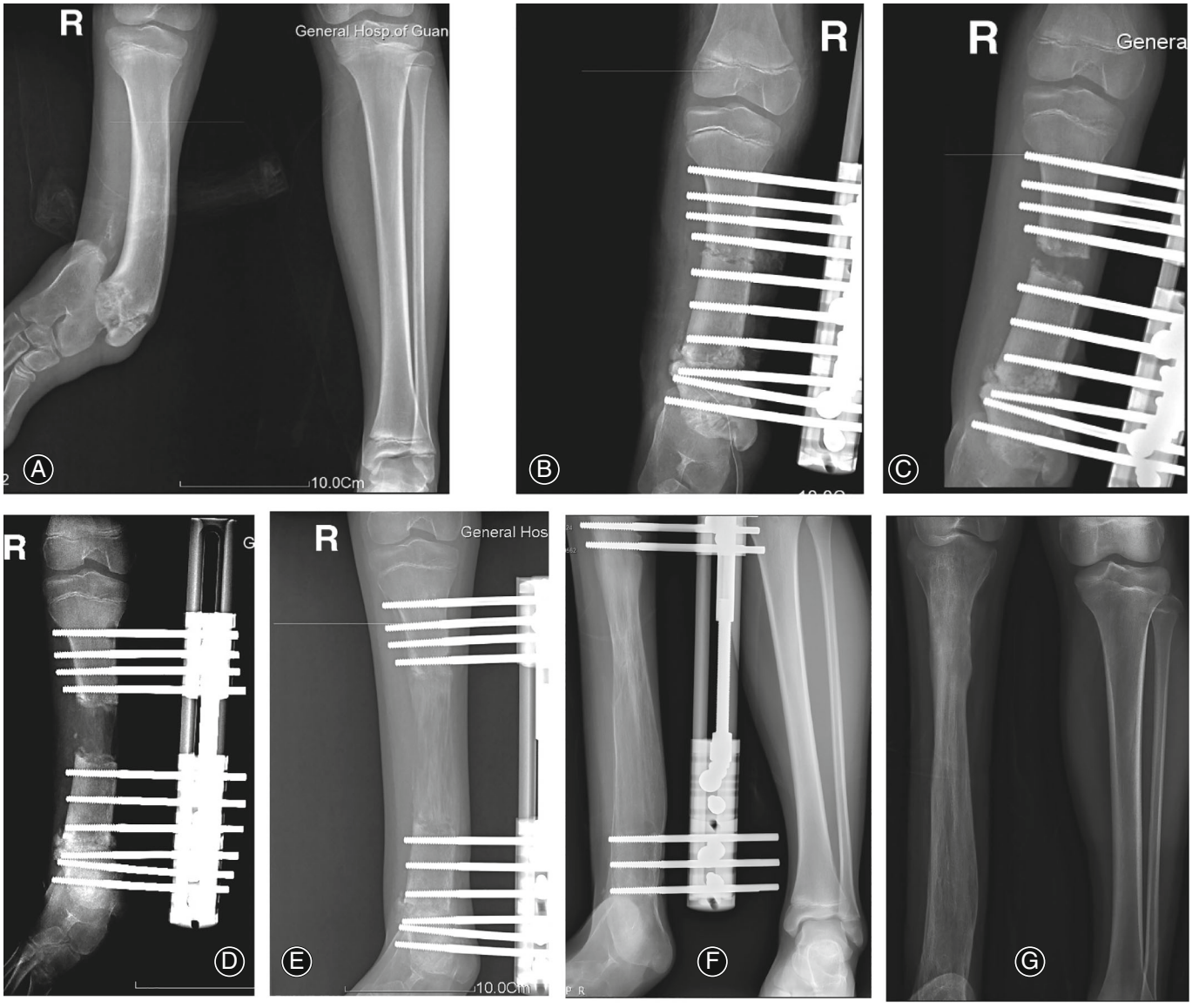

Fig. 6 Perioperative and follow-up radiographs of a typical LLD patient in our study. (A) Preoperative radiographs showing an apparent LLD. (B/C/D/E) Follow-up radiographs at day one, 1 month, 2 months, 3 months, and 6 months after surgery, showing bone generation after lengthening. (F) Follow-up radiograph at 8 months after surgery showing adequate lengthening and ready for removal of the external fixator. (G) Patient follow-up at 3 months after removal of the external fixator

TABLE 2 Postoperative outcomes. LEFS could not be evaluated in one patient in our study (Case 4) due to young age

Case	Lengthening(cm)	Angle (°)	Nails Used	External Fixation Period(m)	DCT(m)	Follow- Up(m)	HI (d/cm)	LEFS (pre/post)
1	6.35	86[a]	13	14	3.5	17	16.3	38/66
2	9.86	83[a]	9	8	6	13	17.1	24/50
3	7.93	94[a]	9	9	3.6	12	12.8	35/67
4	2.94	87[b]	6	11	2.5	14	22.8	—/—
5	3.82	90[a]	9	9	3.1	13	22.7	45/66
6	4.59	85[b]	12	14	3	17	18.5	24/57
7	6.84	88[a]	9	12	4	15	16.8	27/61

[a] mLDFA, mechanical lateral distal femoral angle. [b] aADTA, anatomical anterior distal tibial angle.

antibiotics were selected for each patient. Patients were discharged after resolution of inflammatory indices and symptoms.

Discussion

CAD increases the accuracy of the analysis of LLD parameters

The presence of LLD disrupts limb biomechanics, leading to pelvic tilt and compensatory scoliosis commonly manifesting as an improper pressure distribution on lumbar vertebrae and articular processes[4,6]. This leads to progressive immobility, pain, and progressive degeneration of the lower limbs and joints. Symptomatic LLD greater than 2 cm is commonly accepted as an indication for surgical correction[13]. This further emphasizes the importance of accurately obtaining limb parameters to determine surgical indications in individual patients. In the present study, we measured limb parameters (length, curvature, and angular measurements) from 3D reconstructions obtained from limb CT scanning. This allowed us to obtain multiple measurements from several angles, an advantage over 2D imaging which may be unable to sufficiently display lesions or defects due to a planar view[19].

Preoperative CAD-based Simulation Improves the Surgery Procedure

Previous studies have reported the advantages of preoperative surgical simulation, particularly for complex orthopaedic surgeries[20,21]. We utilized reverse engineering using patient preoperative parameters, the healthy limb, patient age, epiphyseal growth plates, and parental height as references. Personalized treatment and surgical plans were then designed for individual patients by selecting a suitable degree of lengthening, site for osteotomy, trajectory of screw insertion, and number of screws required. Multiple comparisons of different surgical plans were performed allowing for selection of the most suitable strategy. This method allows for comprehensive testing and prediction of operative outcomes. Surgical treatment was performed according to the predetermined surgical strategy, effectively reducing dependence on personal subjectivity. Farsetti *et al.* and Tjernström *et al.* reported intraoperative blood loss ranging from 150 to 600 ml using traditional treatment procedures[22,23]. In the present study, the mean intraoperative blood loss volume was significantly lower at 53.58 ± 22.51 (range, 25–87) ml. This may be due to the small incision used in our surgeries minimizing soft tissue trauma, indicating a further benefit of CAD-based surgical emulation. In addition, we did not encounter intraoperative changes from the surgical plan in our case series, further demonstrating the utility of CAD as a surgical guide.

CAD Guide Plate Assisted-Monorail External Fixation Provides a Suitable Surgical Method for the Treatment of LLD

The monorail external fixator allows axial extension and is relatively easier to install compared to the other apparatus currently used clinically. Decreased technical difficulty shortens operative duration and the improved mobility increases patient satisfaction. However, this approach has a major flaw of not being able to correct angular deformities of the limb[24]. In the present study, we used a computerized simulation of the surgical method and personalized guide plates during the installation of the monorail external fixator. We were able to accurately insert the fixator screws into their desired positions after angular correction even prior to surgery without the need for multiple intraoperative radiographs.

Surgical guide plates have been widely used in trauma and spine surgeries and have been reported to improve the overall surgical process[25,26]. However, in our study, the usage of guide plates greatly attenuated the precision Schanz screw positioning. Traditionally, determination of screw trajectory is performed using multiple intraoperative fluoroscopies to avoid fixation failure or injury to surrounding vasculature and nerves[27,28]. Computerized design based on preoperative parameters allows for more personalized guide plate design and surgical planning through preoperative emulation. Increasing the precision of screw positioning during fixation greatly reduces the risk of articular rupture and fixation failure. Computer-assisted planning of the osteotomy also shortens overall operative duration, further reducing intraoperative bleeding, and effectively omits the risk of radiation exposure during surgery.

Using CAD-based preoperative surgical emulation and 3D-printed surgical guide plates to guide surgical procedures, we found follow-up parameters (DCT, HI, LEFS) were comparable to other studies of leg lengthening surgical procedures. Zak *et al.*[29] utilized magnetic-actuated intramedullary nails to treat LLD limbs in their case series of 19 patients and reported an average DCT and HI of 8.4 months and 72.8 days/cm respectively. In a similar study, Cosic *et al.*[15] reported an average DCT and HI of 8.9 months and HI of 83 days/cm using PRECICE nails in the treatment of 21 patients with LLD. However, the average age of the participants in these studies was 43 and 36.4 years, respectively, which may explain the relatively high numerical value for the reported DCT and HI values due to adults having poorer bone healing functions than adolescents. In a study by Szymczuk *et al.*[30] comparing treatment results following the use of monorail external fixators with a mean patient age of 9.4 years and intramedullary nails with a mean patient age of 15.4 years, the average HI was 29.3 days/cm and 34.77 days/cm, respectively, showing no statistical significance. The mean DCT and HI in our study was similar to the results reported in the studies mentioned above, showing promising LLD treatment results. CAD-based surgical emulation and 3D-printed guide plates demonstrates utility in aiding the

surgical treatment of LLD using external monorail fixators. Accurate osteotomy and screw placement allows for simultaneous correction of length and angular deformity, thereby improving postoperative quality of life.

Limitations

The primary limitation of the present study was the small retrospective case series due to the long duration of external fixation leading to loss of patients from follow-up. Proper positioning of the surgical guide plate on the skin of the operated limb may also represent a technical limitation. Skin and muscles have a degree of elasticity, leading to difficulties in the proper placement of the surgical guide plate according to preoperative designs and causing a shift in the predetermined position of the screw trajectories and osteotomy. The surgical guide plates used in the present study maintained a fixed position of the proximal and distal Schanz screws relative to the osteotomy line. A small degree of displacement of the osteotomy does not affect the treatment result (both mLDFA and aADTA). In cases where angular correction of the LLD limb deviates 5° from the preoperative plan, computer-assisted design can be implemented to manufacture a personalized external fixator using the original screws.

Conclusion

In the present study, the use of computer-aided design of guide plates and personalized surgical planning through emulation allowed surgical correction based on 3D modeling. Incorporation of CAD into the diagnostic procedure provides a more comprehensive understanding of each LLD limb. Combining surgical simulation and surgical guide plates allows more personalized LLD surgery. Future studies of different types of external fixators in larger study population, combining augmented reality or infra-red marking, are required to further strengthen the benefits and overcome the limitations of our reported method.

Declaration

Ethics Approval and Consent to Participate

This study was approved by the Ethics Institute of Guangzhou First People's Hospital (K-2018-137-04). All of the patients signed informed consent before surgery.

Consent for Publication

All the authors in this study agreed to be involved and have agreed upon the submission and publication of this manuscript.

Availability of Data and Materials

All the data and materials in this study are available upon request.

Competing Interests

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

Funding

This study was supported by the Science and Technology program of Guangdong Province (2021A1515012564) and the Science and Technology program of Guangzhou city (202007020002).

Authors' Contributions

Huanwen Ding and Kai Cheng were responsible for the design of the study and supervision during the entire duration of the study. Kai Cheng was responsible for data analysis and the preparation of the manuscript. All the authors participated in the study, and contributed to the writing and revisions of the manuscript.

Acknowledgements

We would like to acknowledge the National Organization Function Reconstruction Technology Research and Engineering Center of South China University of Technology for its technical support.

REFERENCES

1. Knutson GA. Anatomic and functional leg-length inequality: a review and recommendation for clinical decision-making. Part I, anatomic leg-length inequality: prevalence, magnitude, effects and clinical significance. Chiropr Osteopat. 2005;13(11):12.
2. Morrison SG, Georgiadis AG, Dahl MT. What's new in limb lengthening and deformity correction. J Bone Joint Surg Am. 2020;102(16):1391–6.
3. Mano H, Fujiwara S, Haga N. Body knowledge in children with congenital lower limb deficiency. Pediatr Int. 2019;61(2):158–65.
4. Sheha ED, Steinhaus ME, Kim HJ, Cunningham ME, Fragomen AT, Rozbruch SR. Leg-length discrepancy, functional scoliosis, and low Back pain. JBJS Rev. 2018;6(8):e6.
5. Nichols PJ. Short-leg syndrome. Br Med J. 1960;1(5189):1863–5.
6. Song KM, Halliday SE, Little DG. The effect of limb-length discrepancy on gait. J Bone Joint Surg Am. 1997;79(11):1690–8.
7. Heath MR, Aitchison AH, Schlichte LM, Goodbody C, Cordasco FA, Fabricant PD, et al. Use caution when assessing preoperative leg-length discrepancy in pediatric patients with anterior cruciate ligament injuries. Am J Sports Med. 2020;48(12):2948–53.
8. Bedoya MA, Chauvin NA, Jaramillo D, Davidson R, Horn BD, Ho-Fung V. Common patterns of congenital lower extremity shortening: diagnosis, classification, and follow-up. Radiographics. 2015;35(4):1191–207.
9. Gordon JE, Davis LE. Leg length discrepancy: the natural history (and what do we really know). J Pediatr Orthop. 2019;39(Suppl 1):S10–3.
10. Calder PR, Faimali M, Goodier WD. The role of external fixation in paediatric limb lengthening and deformity correction. Injury. 2019;50(Suppl 1): S18–23.
11. Ilizarov GA. The tension-stress effect on the genesis and growth of tissues. Part I. the influence of stability of fixation and soft-tissue preservation. Clin Orthop Relat Res. 1989;238(249–281):263–85.
12. Gubin AV, Borzunov DY, Marchenkova LO, Malkova TA, Smirnova IL. Contribution of G.a. Ilizarov to bone reconstruction: historical achievements and state of the art. Strategies Trauma Limb Reconstr. 2016; 11(3):145–52.
13. Horn J, Steen H, Huhnstock S, Hvid I, Gunderson RB. Limb lengthening and deformity correction of congenital and acquired deformities in children using the Taylor spatial frame. Acta Orthop. 2017;88(3):334–40.

14. Keshet D, Eidelman M. Clinical utility of the Taylor spatial frame for limb deformities. Orthop Res Rev. 2017;9:51–61.
15. Cosic F, Edwards E. PRECICE intramedullary nail in the treatment of adult leg length discrepancy. Injury. 2020;51(4):1091–6.
16. Hidden KA, Dahl MT, Ly TV. Management of a Broken PRECICE femoral nail at an Ununited distraction osteogenesis site: a case report. JBJS Case Connector. 2020;10(1):e0267.
17. Lin HH, Lonic D, Lo LJ. 3D printing in orthognathic surgery - a literature review. J Formos Med Assoc. 2018;117(7):547–58.
18. Xin X, Wang F, Liu X. A 3D-printed personalized, combined, modular pedicle subtraction osteotomy guide plate system: an experimental study [published online ahead of print, 2021 Sep 24]. Spine. 2021. https://doi.org/10.1097/BRS.0000000000004229.
19. Vogt B, Gosheger G, Wirth T, Horn J, Rödl R. Leg length discrepancy-treatment indications and strategies. Dtsch Arztebl Int. 2020;117(24):405–11.
20. Thornberry RL, Hogan AJ. The combined use of simulation and navigation to demonstrate hip kinematics. J Bone Joint Surg Am. 2009;91(Suppl 1):144–52.
21. Fletcher JWA, Windolf M, Richards RG, Gueorguiev B, Buschbaum J, Varga P. Importance of locking plate positioning in proximal humeral fractures as predicted by computer simulations. J Orthop Res. 2019;37(4):957–64.
22. Farsetti P, De Maio F, Potenza V, et al. Lower limb lengthening over an intramedullary nail: a long-term follow-up study of 28 cases. J Orthop Traumatol. 2019;20(1):30.
23. Tjernström B, Olerud S, Rehnberg L. Limb lengthening by callus distraction. Complications in 53 cases operated 1980-1991. Acta Orthop Scand. 1994;65(4):447–55.
24. Ruan H, Zhu Y, Liu S, Kang Q. Humeral lengthening and proximal deformity correction with monorail external fixator in young adults. Int Orthop. 2018;42(5):1107–11.
25. FFA IJ, AML M, BBJ M, et al. Feasibility of imaging-based 3-dimensional models to design patient-specific osteosynthesis plates and drilling guides. JAMA Netw Open. 2021;4(2):e2037519.
26. Zeng C, Xing W, Wu Z, Huang H, Huang W. A combination of three-dimensional printing and computer-assisted virtual surgical procedure for preoperative planning of acetabular fracture reduction. Injury. 2016;47(10):2223–7.
27. Bible JE, Mir HR. External fixation: principles and applications. J Am Acad Orthop Surg. 2015;23(11):683–90.
28. Ziran BH, Smith WR, Anglen JO, Tornetta P 3rd. External fixation: how to make it work. J Bone Joint Surg Am. 2007;89(7):1620–32.
29. Zak L, Arnhold R, Tiefenboeck TM, Wozasek GE. The influence of advanced age in bone healing after intramedullary limb lengthening. Orthop Traumatol Surg Res. 2021;107(8):103055.
30. Szymczuk VL, Hammouda AI, Gesheff MG, Standard SC, Herzenberg JE. Lengthening with Monolateral external fixation versus magnetically motorized intramedullary nail in congenital femoral deficiency. J Pediatr Orthop. 2019;39(9):458–65.