Injury, Int. J. Care Injured 50 (2019) 476–483

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Preliminary application of three-dimension printing technology in surgical management of bicondylar tibial plateau fractures

Wei Nie, Fei Gu, Zhaojun Wang, Rui Wu, Yang Yue, Anze Shao*

Department of Orthopaedic Surgery, Lianyungang Second People's Hospital, China

ARTICLE INFO

Keywords:
3D printing
Tibial plateau fracture
Guide template
Surgical simulation

ABSTRACT

Objective: Surgical management of bicondylar tibial plateau fractures, which is frequently associate with high wound complication rates and functional impairment, remains a challenge for orthopedic surgeons. Recently, the emergence of three-dimension(3D) printing provided orthopedic surgeons with a new technology which has revolutionary impacts on surgical planning, operative guidance and custom-made implants manufacture. The aim of this study is to explore the clinical feasibility and application value of 3D printing in the surgical management of bicondylar tibial plateau fractures.

Method: Data of this retrospective study was collected from 11 patients suffering bicondylar tibial plateau fracture from October 2015 to August 2016. All of them underwent surgical treatment with the assistance of 3D printing technology. Real-size solid models and screw guide templates were printed for preoperative planning, surgical simulation and intraoperative guidance. Patients' Demographics, surgery duration, intraoperative blood loss, the accuracy of preoperative planning were recorded and evaluated.

Result: The 3D printed models successfully provided the omni-directional exhibition of the fracture morphology. Model-based surgical simulation procedures and pre-selection of implants were generally consistent with the results of actual surgeries. There were no significant differences between the length of the osteosynthesis screws and that of actual surgeries (59.43 ± 11.13 mm vs 60.14 ± 12.05 mm). Beyond that, other parameters, such as surgical duration, intraoperative blood loss and HSS scores was satisfactory according to the surgical records and follow-up.

Conclusions: According to our experience, the assistance of 3D printing technology in the surgical management of bicondylar tibial plateau fractures provides a comprehensive understanding of fracture features, an accurate patient-specific preoperative planning and an intraoperative guidance for real surgeries, thus leading to the optimization of clinical outcomes.

Introduction

Bicondylar tibial plateau fractures are normally characterized by knee instability, pain, limited joint mobility, early post-traumatic osteoarthritis and are particularly difficult to treat successfully [1–3]. Surgery is considered to be a definitive treatment option as it can provide anatomical reduction, sufficient stabilization, early mobilization, and, subsequently, an optimal functional outcome [4]. Routine diagnostic imaging, including x-ray, magnetic resonance (MR), computed tomography (CT), play a major role in the surgical management of plateau fractures. However, the complex anatomical characteristic of the plateau fracture may still not be truly appreciated based on the above-mentioned radiographic examinations [5].

In recent decades, 3D printing technology (3DPT) has been introduced into orthopedics fields for the manufacturing of anatomical models, custom-made medical products and equipment [6]. A real-size 3D printed fracture model allows orthopedic surgeons obtain more detailed information on fracture morphology in all dimensions, and therefore is of great significance to diagnosis, fracture classification and surgical planning. Additionally, Additionally, intraoperative guiding templates is possible be designed and printed for the purpose of reducing the surgical duration and increasing the accuracy of internal fixation.

The purpose of this study is to investigate the clinical feasibility and to summarize the application experience of 3DPT utilized in the surgical management of bicondylar tibial plateau fractures. 3D printed models and guide templates for screw osteosynthesis were

* Corresponding author at: Department of Orthopaedic Surgery, Lianyungang Second People's Hospital, No. 41 Hailian East Road, Haizhou District, Lianyungang, Jiangsu, 222000, China.

E-mail address: shaoaz89889@163.com (A. Shao).

https://doi.org/10.1016/j.injury.2018.12.019
0020-1383/

applied in the preoperative preparation and actual surgeries for the advantage of providing accurate patient-special surgical planning and facilitating surgical procedures.

Materials and methods

Patients demographics

We retrospectively reviewed the medical records of patients (13 cases) with bicondylar fractures of tibial plateau (Schatzker types V–VI) treated operatively with the assist of 3DPT in our institution's trauma center from October 2015 to August 2016. Among of them, one patient was lost to follow-up, and one patient with concomitant ipsilateral femoral condylar fracture which would interfere the outcome measure was exclude. Thus there were 11 patients (7males and 4 females) enrolled in this study (Table 1). Patient data were kept anonymous to ensure confidentiality and privacy.

The mean age of the patients was 40.0 years (range from 22 to 58 years). There was no patient with bilateral fracture. The right limb was affected in 6 patients and the left limb in 5 patients. The mechanism of injury included traffic accidents (3 cases), fall and trip injuries (6 cases) and sport related injuries (2 cases). All the fractures were closed fractures without neurovascular injury or compartment syndromes. Four of them with concomitance fractures were treated conservatively. Hypertension and diabetes were identified in 2 patients and had been brought under control to meet the requirement of the surgery.

All patients received the anteroposterior (AP) and lateral plain radiographs and CT scan on admission (Fig. 1). MR was performed if necessary. Except detumescence and pain alleviation, preoperative management also extended to skeletal traction which brought the fractures into approximate axial alignment. All the selected patients underwent open reduction and internal fixation (ORIF) and were treated by the same surgical team.

Construction of 3D digital models

All the processes of model printing were accomplished in our department, and two of the authors(doctor Wei Nie and doctor Fei Gu)took the roles of engineer and operator. The original data acquired from CT scans (slice thickness 1 mm, reconstruction interval 1 mm) was saved as Digital Imaging and Communications in Medicine (DICOM) formatting and imported into Mimics Medical 16.0 (Materialise, Belgium) for 3D reconstruction and editing. By this software, a 3D digital plateau fracture model was reconstructed and each fragment was assigned with a different color (Fig. 2). Surgeons could get the information of the fragments including their sizes, positions and quantity. For most cases in this study, the simulation of fracture reduction was accomplished through the collaboration between surgical team and engineers by using 3-matic software, which allows surgeons to rotate and move the displaced fragments into the correct positions, as well as participate into the design of the guide template and give their advices. Mirror imaging technical, which could get a reduction model conveniently from the replica of the uninjured side, was also used in two cases with severe comminuted fracture. The guide template for osteosynthesis screws was designed based on the reduction digital model, which determined the position and direction of osteosynthesis screws in order to achieve an effective fixation of main fragments (Fig. 2). Whereafter, the data of the aforementioned digital models was stored as a “stl” file and was loaded into a 3D printer (dreamer, Flsaforge, Zhejiang, China) for rapid prototyping.

Surgical simulation on solid models

Vitro surgical simulation was conducted when the real-size model was presented in front of surgeons (Fig. 3). The 3D fracture model, which revealed the morphologic characteristics of the fracture from all dimensions, allowed surgeons to the deepen their insight into the fracture pattern, and to determine the surgical approach and to simulate fracture reduction under direct vision. The choices of the surgical approach and relevant surgical position were dictated principally by detailed fracture features displayed on the solid model. An ideal surgical approach could not only offer effective surgical exposure and internal fixation, but also minimalize the risk of soft tissue complications such as neurovascular injury and important structures damage. Analyses of fracture line location, type, fragments displacement and joint surface depression could provide surgeons the foreknowledge of more specifics of the surgical approach. The presence or absence of the depress fragment could give surgeons a hint to decide whether the submeniscal arthrotomy is needed or not, especially for the anterolateral approach. Sufficient width of the minimum distance of 7 cm between the incisions to avoid necrosis of the skin bridge should be considered before the incision design. When the approach was determined, special attention should be paid on the protection of the important normal structures, including the patellar ligament, the meniscus, the pes anserinus the saphenous nerve, great saphenous vein and so on. Visualization of the relative positions of the fracture fragments demonstrate on the solid model resulted in a major improvement of surgeons in understanding the fracture reduction. The reduction model was utilized as a template in the simulation to choose the appropriate fixators. The selected plate was molded to ensure the best fit between the implants and the bone surface. For the convenience of easy utilization in the actual surgery, the type and location of the plate, the intervals and

Table 1
Patients Demographics.

No.	gender	Age (year)	Side	Schatzker type	Mechanism of injury	Associated injury of knee	Concomitance injury	Chronic disease
1	M	42	L	V	fall			
2	M	36	R	VI	fall		fibula fracture	
3	F	31	L	V	traffic accident			
4	M	53	L	VI	fall		rib fractures	hypertension
5	F	35	R	V	sport injury			
6	F	44	L	V	fall			
7	M	35	R	VI	traffic accident	anterior horn tear of the lateral meniscus	distal radial fractures	
8	M	58	R	V	fall			hypertension; diabetes
9	F	45	L	V	fall	anterior horn tear of the lateral meniscus		
10	M	39	R	VI	traffic accident		fibula fracture	
11	M	22	R	V	sport injury			

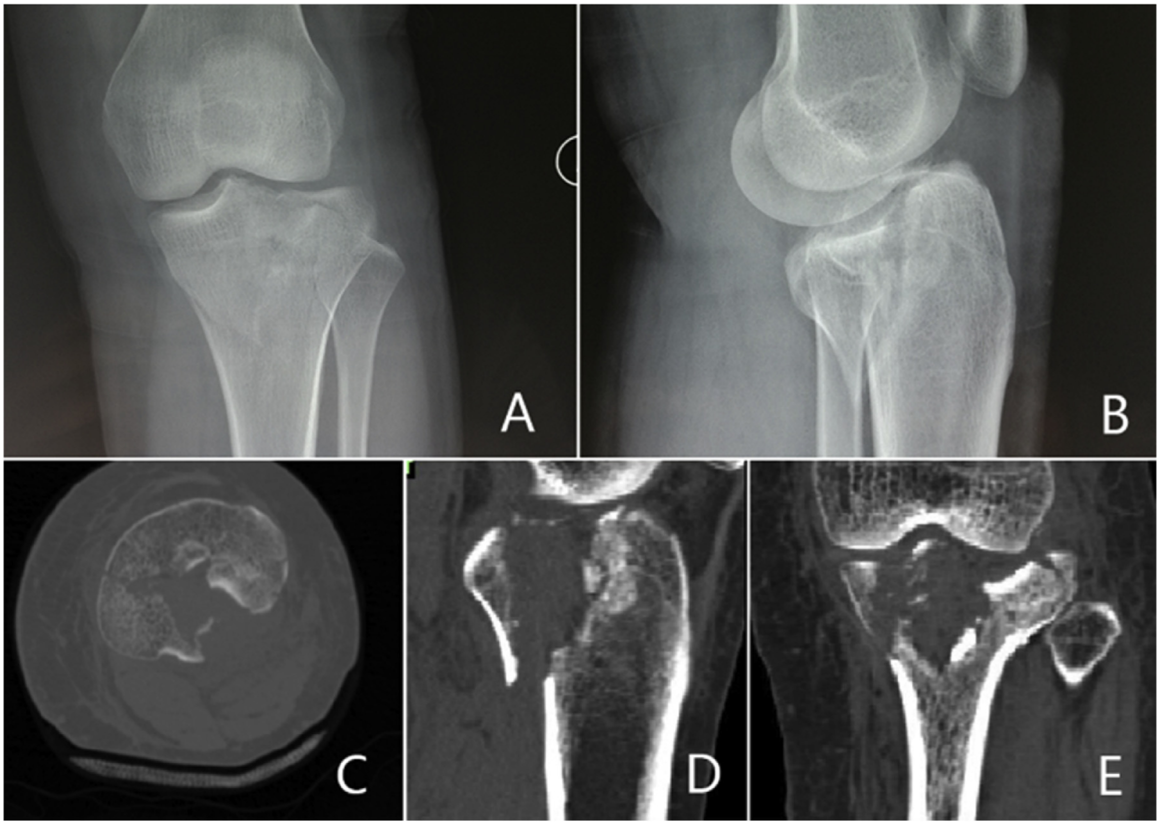

Fig. 1. Preoperative anteroposterior (A) and lateral (B) plain radiographs of a 31-year old woman who presented with a tibial plateau fracture in the left side. CT scans, including the transverse plane (C) and multiplanar reconstruction in the coronal (D) and sagittal (E) plane, was taken after two days of limb traction.

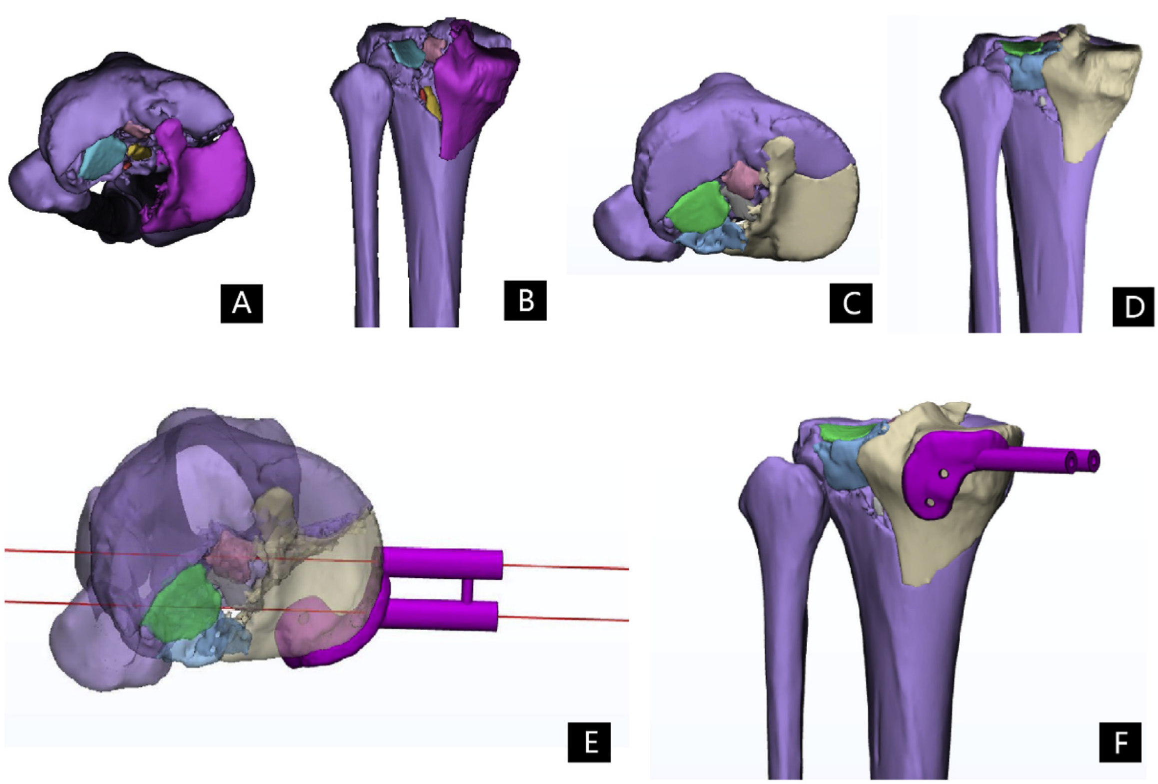

Fig. 2. Once a 3D reconstruction image of the plateau fracture was constructed (A, B). Digital fracture reduction model was subsequently accomplished (C, D). The guide template for screw osteosynthesis was designed base on the digital reduction model (E, F).

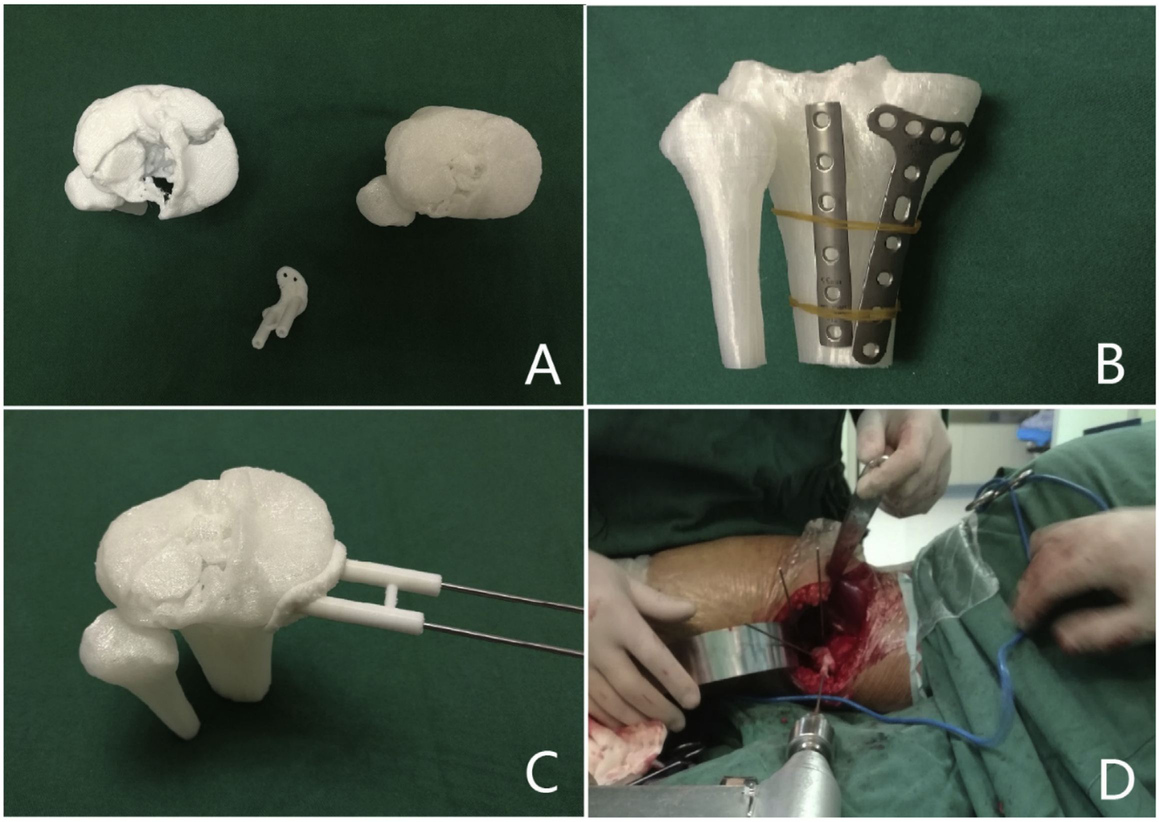

Fig. 3. The real-size rapid prototyping models could demonstrate the fracture morphology in all dimensions (A). The reduction model was used as a template to select the best fitted plate, and the pre-selected plates were attached on the reduction model to check the suitability and to decide which holes could be used (B). The guide template was attached on the model for per-operative test and to gain the length of screws (C). Intraoperative photograph showed the application of the guide template (D).

the length of the screws were evaluated and recorded during the simulation. The guide template was also tested to ensure that it could suitably fit the bony surface and provide accurate navigation for screws to stabilize the fracture (Fig. 3).

Surgical technique and procedures

Prophylactic intervention of antibiotics was administered intravenously in all cases. All the patients were treated by the same surgical team. After satisfactory anesthesia, the operation was performed on radiolucent table with the assist of the fluoroscopic guidance. The 3D printed models were sterilized and were used as reference during the operation. Combined approach including anterolateral, medial and/or posteromedial approaches were mainstay choices for most cases, and were performed according to preoperative planning. Fractures involved posterior condylar of the plateau were always dealt first through an inverted L-shaped posteromedial approach. The lateral and medial fragments were reduced and fixed through the corresponding approach in the later stage of the operation. Submeniscal arthrotomy technique was used to reduce the articular surface. The depressed fragment was elevated to restore the articular surface, and the consequential defect was filled with allogeneic bone grafts (5 cases). The reduced fracture fragments and articular surface were provisionally fixated with bone tenaculums and K-wires. Internal fixation was accomplished with preselected implants determined by the pre-operative simulation. Screw osteosynthesis was performed with the navigation of guide templates in 4 cases (Fig. 3). The associated menisci injuries were identified and repaired with suture anastomosis or be partial excised. No tendon transplantation was performed. The dissected structures, including the pes anserinus, the semimembranosus tendon and the edge of menisci were reattached with nonabsorbable sutures. The quality of reduction and fixation was examined using a c-arm fluoroscopy (Siemens, Germany) during the operation. After the placement of a suction drain, standard wound closure and pressure dressing were performed.

Postoperative management and follow-up

AP and lateral plain radiographs (Fig. 4) were taken at 1 day after the operation. Postoperative drainage was kept for 48 h, and intravenous antibiotic was administrated within 3 days. Patients were advised to do quadriceps exercises and active motion of the knee without weight-bearing as much as possible in the first 6 weeks, and then partial weight-bearing as tolerable was recommended for additional 6 weeks. At 12 weeks or more, full weight-bearing and strengthening were commenced depending the radiographic finding of bony union, which was defined as 3 out of 4 cortices showed continuity on X-rays. Reexamination of X-rays photographs were taken at follow-up for radiographic evaluation of fracture healing, joint degeneration and malalignment (Fig. 4).

Outcome measures

The primary assessment parameter was the comparison on the differences between the preoperative planning and real surgeries, including surgical approaches, types and sizes of implants. Other parameters include surgical duration, intraoperative blood loss and perioperative complications. Clinical evaluation was performed according to the Hospital for Special Surgery Knee (HSS) score at 1 year following the surgery [7]. When assessing the

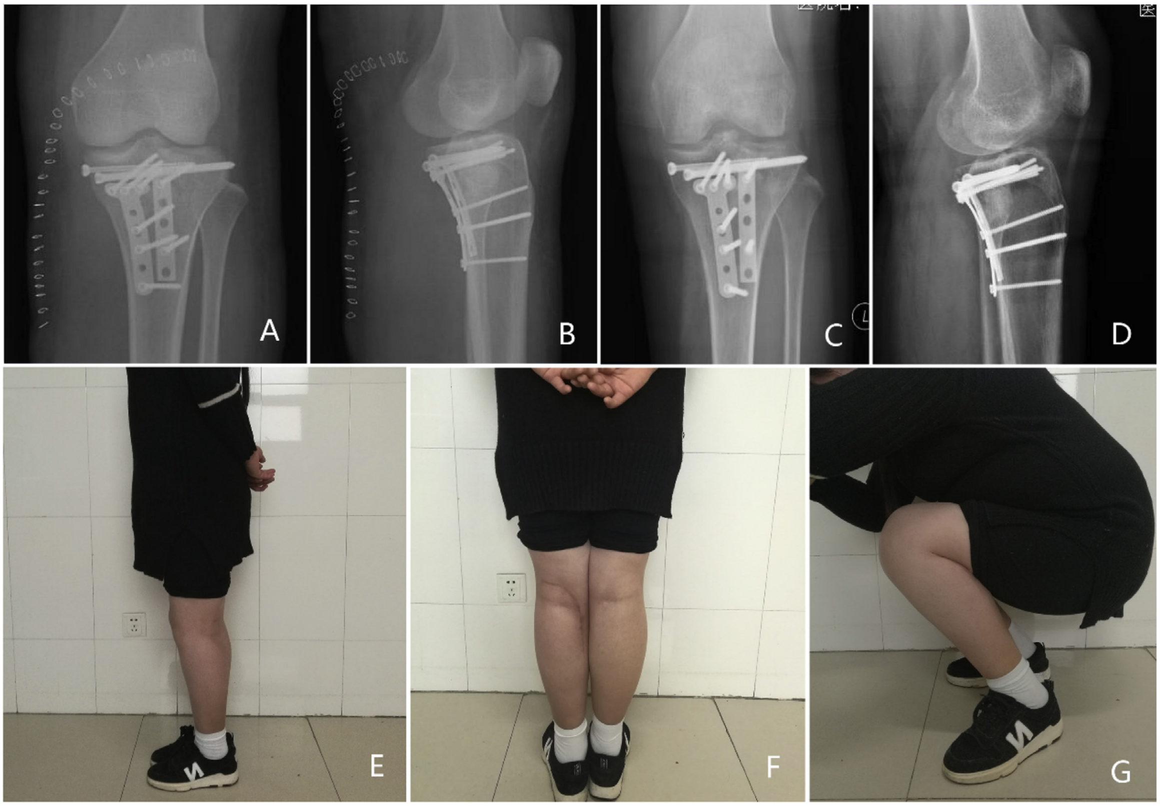

Fig. 4. Postoperative anterioposterior (A) and lateral (B) position films of X-ray were taken two days after surgery. The follow-up radiographic image showed bony union was achieved at 12 weeks postoperatively (C and D). The functional outcome was encouraging at the one-year follow-up (E–G).

radiographs, clinicians should pay special attention to bony union, articular degeneration, internal fixation failure, malreductions and malalignment. Malreduction was defined as the collapse of the articular surface more than 2 mm. Malalignment was considered to be a deviation of varus or valgus angulation more than 5° from the average tibial plateau angle (TPA) of Chinese adults, which is 5° inclining towards to the medial side [8].

Statistical analysis

Data analysis was performed using SPSS statistical software (version 20.0; SPSS, Chicago, IL, USA). Surgical duration, blood loss and HSS scores were analyzed by descriptive Statistics. Independent *t*-test was used to compare the difference between the length of osteosynthesis screws measured in simulations and that of actual surgeries. A P value of <0.005 was considered to be statistically significant.

Result

Operational procedures were performed according to preplanning. The fracture morphology observed intraoperatively was entirely consistent with the printed model. Surgical approaches, types of plate, the number of screws used in actual surgeries agreed well with the preoperative planning in all cases except one (No.3). In this case, we reduced the number of screws due to the difficulty of surgical manipulation and the complexity of topographic anatomy, and no fixation failure was observed on postoperative radiographies. There were no significant differences between the length of the osteosynthesis screws measured in simulations and that of actual surgeries (59.43 ± 11.13 mm vs 60.14 ± 12.05 mm, with $t = 0.115$, $p = 0.910$). All the above results suggested satisfying accuracy of the preoperative planning (Table 2).

The mean total surgical duration was 116.82 min (range 90–150 min). The mean intraoperative blood loss was 290.91 ml (range 200–500 ml). There were no case who received blood transfusion. No patient had perioperative complications such as infection, deep venous thrombosis (DVT) or neurovascular injury within 4 weeks of follow-up.

The average period of follow-up was 18.73 months (range 16–24 months), and the average radiographic bony union time was 13.18 weeks (range 12–16 weeks). There was no fail of fixation, postoperative articular malreduction or malalignment occurred during the follow-up. Five cases underwent an additional operation to remove the internal fixation templates. HHS score measured 1 year postoperatively range from 55 to 87 with a mean value of 71.36. Nine out of eleven patients were satisfied with their clinical and functional outcomes. Two patients (No.2, No.7) complained of some discomfort in winter caused by hardware irritation, which was alleviated after a second operation for removal. Radiographic signs of joint degeneration of the lateral compartment with accompanying valgus (7°) were found in one patient (No.2). Except for slight walking pain, no significant stiffness or dysfunction had been observed on him.

Discussion

Bicondylar tibial plateau fractures are serious intra-articular fractures associated with joint surface depression, condylar displacement and soft tissue injuries, and therefore might result in various complications such as infection, non-union, malunion, post-traumatic osteoarthritis, persistent pain and disability [2,9]. As a weight bearing joint, anatomic reduction and restoration of articular congruity with stable fixation is indispensable for rebuilding normal knee joint biomechanics and achieving optimal functional rehabilitation [10]. For the aforementioned goals, full

Table 2
Information of surgical planning, actual operation and outcome parameters.

No.	surgical approach		selection of implants		length of osteosynthesis screws (mm)		surgical duration (min)	intraoperative blood loss (ml)	follow-up period (months)	HSS scores
	preoperative planning	actual operation	preoperative planning	actual operation	preoperative measurement	actual length				
1	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 5 holes tibial proximal locking compression plate with 9 screws medial: a 4 holes nonlocking T-plate with 5 screws	consistent with pre-planning			90	200	24	87
2	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 5 holes L-plates with 6 screws medial: a 7 holes tibial proximal medial locking compression plate with 11 screws	consistent with pre-planning			135	350	16	55
3	postero-medial approach	consistent with pre-planning	postero-lateral: a 5 holes 1/3 tubular plates with 3 screws postero-medial: a 5 holes nonlocking T shape plate with 6 screws	postero-lateral: a 5 holes 1/3 tubular plates with 2 screws postero-medial: consistent with per-planning	60;75	60;75	115	250	24	69
4	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 7 holes tibial proximal locking compression plate with 9 screws medial: a 4 holes nonlocking T-plate with 7 screws	consistent with pre-planning			125	300	18	68
5	Dual approaches (antero-lateral + postero-medial)	consistent with pre-planning	lateral: a 5 holes anatomical nonlocking plate with 7 screws postero-medial: a 4 holes nonlocking T-plate with 6 screws	consistent with pre-planning	65; 70	65;75	105	250	21	70
6	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 5 holes tibial proximal locking compression plate with 7 screws medial: a 4 holes nonlocking T-plate with 6 screws	consistent with pre-planning	46;50	46;50	110	250	18	84
7	Dual approaches (antero-lateral + postero-medial)	consistent with pre-planning	lateral: a 7 holes tibial proximal locking compression plate with 9 screws postero-medial: a 5 holes nonlocking T-plate with 5 screws	consistent with pre-planning			120	350	21	68
8	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 5 holes nonlocking anatomical plate with 6 screws medial: a 4 holes nonlocking T-plate with 5 screws	consistent with pre-planning			105	200	15	68
9	Dual approaches (antero-lateral + postero-medial)	consistent with pre-planning	lateral: a 7 holes tibial proximal locking compression plate with 8 screws postero-medial: a 5 holes T-plate with 5 screws	consistent with pre-planning			100	200	16	86
10	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 9 holes tibial proximal lateral locking compression plate with 10 screws medial: a 5 holes nonlocking T plate with 6 screws	consistent with pre-planning	50	50	150	500	18	66
11	Dual approaches (antero-lateral + medial)	consistent with pre-planning	lateral: a 5 holes tibial proximal locking compression plate with 9 screws medial: a 4 holes nonlocking T plate with 6 screws	consistent with pre-planning			130	350	15	64

understanding of the fracture morphology and sufficient preparation before surgery are essential prerequisites. Currently, 2D-CT and 3D reconstruction imaging are the most common used radiological tools for preoperative assessment of fracture morphology, which will influence clinical and surgical decision making, and sequent outcome [11,12]. However, a study published by Mellema et.al demonstrated that the CT-based evaluation of tibial plateau fracture characteristics showed moderate reliability and accuracy on average, with the diagnostic accuracy of fracture characteristics ranging from 70% to 89%. Furthermore, the added value of 3D CT after 2D CT is limited and does not significantly improve diagnostic accuracy or interobserver reliability [5]·

Recently, the emergence and increasing popularity of 3D printing have introduced a new assistant technology into orthopedic surgeries, which could bring advantages to various aspects such as injury assessment, preoperative planning, surgical simulation and custom-made implants [13–15]. Compared with traditional radiologic images, a tangible real-size model could demonstrate further delineation of fracture patterns which would enhance surgeons' cognition on fracture features. Related information about location of fracture line, displacement of fragments and collapse of articular surface could be clearly displayed on the solid model. Surgical planning and simulation, such as mimic of fragments reduction, screw measurement, implant prebending and positing, could be conducted with the aid of the solid model [6]. All the benefits provide surgeons with more possibilities of increasing surgical accuracy, decreasing surgical duration and potential iatrogenic complications [16]. Additionally, a 3D printed model is an effective tool to facilitate doctor-patient communication and to improve patients' compliance [13], which has been verified in our study.

The time of model production reported by Kim et al. was 2 to 3 days from data acquisition to obtaining the solid model [14]. Benefiting from the rapid advance in digital medicine and rapid prototyping technology, the processes of printing were streamlined. In our study, the time consumption for a tibial plateau model was approximately 8–12 h after the acquisition of CT scan date to obtaining the solid model, with the cost price of 200–300 CNY (30–50 US Dollars). Even so, it is still not applicable to emergency cases.

Using CAD and computer-aided manufacture (CAM) techniques, Xu et al. manufactured custom-made plates to treat acetabular fractures and achieved excellent outcomes [17]. However, the high cost of plate manufacturing is a limitation to its application as a routine clinical practice. You et al. demonstrated the implementation of implant pre-selection for proximal humeral fractures in virtual surgical simulations [13]. They integrated digital implant models with reconstructed humeral fracture models to choose appropriate plate and screws, but plate prebending still had to be accomplished on solid models. In our study, both the pre-selection and prebending of implants were simulated on solid models. The distribution of screws, the type and size of the plate were determined in the simulation. When the selected plate was a locking plate, the length of pre-selected screws was recorded for rapid utilization in real operation. Due to adequate preparation and operative rehearsal, it could be concluded that the surgical duration and exposure to radiation would be reduced, even though the control group was absent.

However, in certain circumstances, plate prebending, as well as screw measurements, was hard to be accomplished in surgical simulations. When the fracture involves the medial or posterior column of tibial plateau, there is no standard implants for this situation, and a variety of implants are on the optional list [18,19]. The choice of implants for 4 cases with posterior plateau fragments in the current study was a simple T-plate or a 1/3 tube plate used as an antiglide plate, which should be contoured according to the bone surface when it is being applied in actual surgeries and thus creating sufficient forces to stabilize and buttress the fragment and, thereby, making it impossible to obtain appropriate steel plate shaping [20]. As a consequence, the accurate length of screws was not be determined due to the lack of plate prebending and the uncertainty of screw directions. Despite that, we still obtained the information about plate types and distribution of screws. Regardless of the cost, using a custom-designed plate or a locking plate instead of the nonlocking plate might be a possible solution for these problems.

The utilization of 3D printed guide templates for screw osteosynthesis was to ensure that bone screws could be facilely placed in optimal position and direction, which has previously mainly relied on surgeon's operative skills and repetitious intraoperative fluoroscopies. In actual surgeries, the assistance of the navigation template could broaden the possibility of improving surgical precision and reducing both the surgical duration and the difficulty of operation. And the maintenance of fracture reduction seems to be satisfactory in terms of postoperative radiographic results. However, it should be noticed that the 3D printed guide template was designed according to the clean cortical surface, and the measurement of screw length was based on the anatomical reduced model, which may not always possible in actual operations, and therefore, leading to the appearance of the difference between the screw length measured in simulations and in actual surgeries. The attached soft tissue will be a minus factor to the best match between the guide template and bone. With some forethought to avoid the difficulty of dissection and the iatrogenic injury, the pre-defined region for the placement of the template should be chosen carefully to evade the area with critical organizational structures or with complicated anatomic shape (e.g., tibial tubercle, proximal tibiofibular joint, etc.).

Our study is not meant to be a demonstration of the advanced utilization of 3DPT and CAD system. Many sophisticated techniques, such as more elaborate virtual surgical simulations and patient-specific designed implants, were not applied in our study due to the technical and economic impediments. However, our experience indicated that the pre-selection of implants and rehearsing of operation with the aid of 3D printed models might advance to the improvement on preoperative assessment and planning, surgical simulation and intraoperative guidance. Other limitations of this study include its descriptive nature, small series of patients, and the lacking of long term follow-up. Although the mean values of surgical duration, blood loss, postoperative outcomes are satisfying, given to the absent of a control group, it seems to not rigorous to draw the conclusion that 3DPT led to superior clinical parameters compared with traditional operations. Furthermore, severe relative factors might influence aforementioned parameters, such as patient's age, fracture types and the experience and skills of surgeons, which might be the primary determinant to the surgical planning, execution and outcome [21].

Conclusions

In the current study, the clinical applications of 3D printed anatomical models and guide templates were associated with encouraging feasibility to the surgical management of bicondylar tibial plateau fractures, including deep understanding of the fracture pattern, an accurate surgical planning, an opportunity to surgical simulation, an improvement on surgical precision, thus decreasing surgical duration, intraoperative haemorrhage and operation difficulty.

Conflict of interest statement

The authors declare that they do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in the manuscript entitled "Preliminary application of three-dimension printing technology in surgical management of bicondylar tibial plateau fractures".

Acknowledgement

We would like to extend our sincere gratitude to Huikang Zhang, who has provided us with valuable guidance in relevant technology consulting on 3D printing.

References

[1] Canadian Orthopaedic Trauma Society. Open reduction and internal fixation compared with circular fixator application for bicondylar tibial plateau fractures. Results of a multicenter, prospective, randomized clinical trial. J Bone Joint Surg Am 2006;88(12):2613–23.
[2] Young MJ, Barrack RL. Complications of internal fixation of tibial plateau fractures. Orthop Rev 1994;23:149–54.
[3] Watson JT. High-energy fractures of the tibial plateau. Orthop Clin North Am 1994;25(4):723–52.
[4] Yu Z, Zheng L, Zhang Y, Li J, Ma B. Functional and radiological evaluations of high-energy tibial plateau fractures treated with doublebuttress plate fixation. Eur J Med Res 2009;14(5):200–5.
[5] Mellema JJ, Doornberg JN, Molenaars RJ, Ring D, Kloen P. Tibial plateau fracture characteristics: reliability and diagnostic accuracy. J Orthop Trauma 2016;30 (5):e144–51.
[6] Eltorai AE, Nguyen E, Daniels AH. Three-dimensional printing in orthopedic surgery. Orthopedics 2015;38(11):684–7.
[7] Insall JN, Ranawat CS, Aglietti P, Shine J. A comparison of four models of total knee-replacement prostheses. J Bone Joint Surg Am 1976;58(6):754–65.
[8] Tang WM, Zhu YH, Chiu KY. Axial alignment of the lower extremity in Chinese adults. J Bone Joint Surg Am 2000;82-A(11):1603–8.
[9] Wang SQ, Gao YS, Wang JQ, Zhang CQ, Mei J, Rao ZT. Surgical approach for high-energy posterior tibial plateau fractures. Indian J Orthop 2011;45(2):125–31.

[10] Tscherne H, Lobenhoffer P. Tibial plateau fractures. Management and expected results. Clin Orthop Relat Res 1993;292:87–100.
[11] Raschkw MJ, Kittl C, Domnick C. Partial proximal tibia fracture. EFFORT Open Rev 2017;2(5):241–9.
[12] Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online 2016;15(1):115.
[13] You W, Liu LJ, Chen HX, Xiong JY, Wang DM, Huang JH, et al. Application of 3D printing technology on the treatment of complex proximal humeral fractures (Neer3-part and 4-part) in old people. Orthop Traumatol Surg Res 2016;102(7):897–903.
[14] Kim HN, Liu XN, Noh KC. Use of a real-size 3D-printed model as a preoperative and intraoperative tool for minimally invasive plating of comminuted midshaft clavicle fractures. J Orthop Surg Res 2015;10(1):91.
[15] Melican MC, Zimmerman MC, Dhillon MS, Ponnambalam AR, Curodeau A, Parsons JR. Three-dimensional printing and porous metallic surfaces: a new orthopedic application. J Biomed Mater Res 2001;55(2):194–202.
[16] Diment LE, Thompson MS, Bergmann JHM. Clinical efficacy and effectiveness of 3D printing: a systematic review. BMJ Open 2017;7(12):e016891.
[17] Xu M, Zhang LH, Zhang YZ, Zhang LC, He CQ, Wang Y, et al. Custom-made locked plating for acetabular fracture: a pilot study in 24 consecutive cases. Orthopedics 2014;37(7):e660–70.
[18] Bhattacharyya T, McCarty [65_TD$DIFF]3rd LP, Harris MB, Morrison SM, Wixted JJ, Vrahas MS, et al. The posterior shearing tibial plateau fracture: treatment and results via a posterior approach. J Orthop Trauma 2005;19:305–10.
[19] Luo Cong-Feng, Sun Hui, Zhang Bo, Zeng Bing-Fang. Three-column fixation for complex tibial plateau fractures. J Orthop Trauma 2010;24(11):683–92.
[20] Weil YA, Gardner MJ, Boraiah S, Helfet DL, Lorich DG. Posteromedial supine approach for reduction and fixation of medial and bicondylar tibial plateau fractures. J Orhtop Trauma 2008;22(5):357–62.
[21] 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.