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Original Article

Application of three dimensional-printed models in precise diagnosis and customized preoperative plan for knee injury

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Abstract: *Purpose:* The determination of joint replacement in young patients by imaging techniques alone is always a dilemma for all surgeons. In order to give a clear diagnosis of 19-year-old patients with traumatic knee arthritis, and to determine whether it is suitable for total knee replacement (TKR), the effect of three-dimensional (3D) printing knee joint model in preoperative diagnosis and preoperative design was explored. *Materials and methods:* After patient's computed tomography (CT) data were collected, the stereolithographic models of the knee were printed out for direct observation of the damage degree in bone. The selected parameters were compared by computer between the models and bones, and statistical analysis was completed. Based on the preoperative surgical simulation, the individual treatment plan was formulated. Through the above processes, the sizes of prostheses were determined finally, and then the TKR was completed. *Result:* All parameters did not show a significant difference between bones and models. All ICCs were 1.00. During the operation, it could be observed that the 3D models were highly consistent with bone lesion. The size and shape of prostheses were matched with patient's bones. The 6 months follow-up results of the patient were satisfactory. *Conclusion:* The application of 3D printing technology has provided a new way for the diagnosis and treatment of the similar cases when it is difficult to clarify diagnosis and treatment plans by virtue of imaging data.

Keywords: Three dimensional printing, anatomic model, traumatic arthritis, total knee replacement

Introduction

Traumatic knee arthritis is an acute arthritis with rapid destruction on articular surface due to the trauma of the knee joint such as joint fracture [1], and the main pathological change are the structural destruction of cartilage and subchondral bone. It is reported that traumatic arthritis following tibia plateau fracture is common [2-4], the incidence of osteoarthritis after a previous tibia plateau fracture ranges from 22% to 44% [5, 6]. For such patients, different therapies such as expectant treatment, arthrodesis, and prosthetic replacement surgery are usually chosen in accordance with the degree of joint damage as well as patients' age [3, 4]. For young patients with massive activity or patients who are heavy labors, doctors should be particularly cautious in the implementation of joint replacement surgery because of the limited life of prosthesis [7]. Furthermore, the types of tibia plateau fracture are multifarious, and the joint damage induced by tibia plateau fracture is difficult to diagnose, thus affecting the choice of treatment plans [8, 9].

A young patient with traumatic arthritis was described in this paper. X-ray and CT scans were insufficient to provide precise and intuitive information, while recently, the rapid development of 3D printing technology has provided an opportunity to solve such problems.

By using 3D printing technology, the bone model of the affected region can be printed out according to patients' imaging data before operation, and then it was presented to doctors and patients in an intuitive and precise manner.

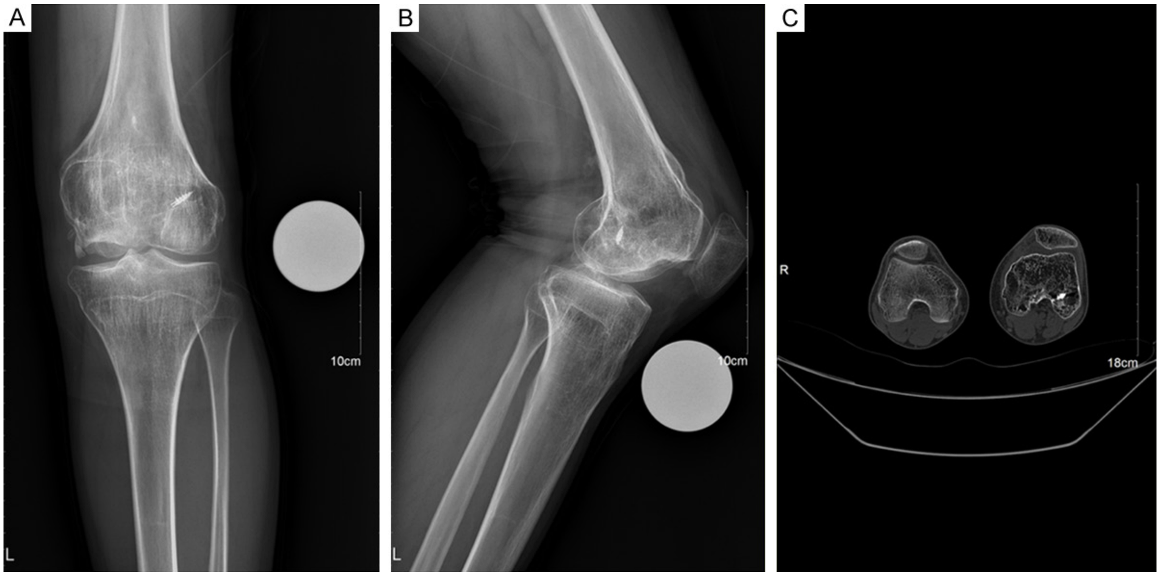

Figure 1. A 19-year-old man with traumatic arthritis of left knee. A. Posteroanterior X-ray of left knee; B. Lateral X-ray of left knee; C. CT of bilateral lower limbs.

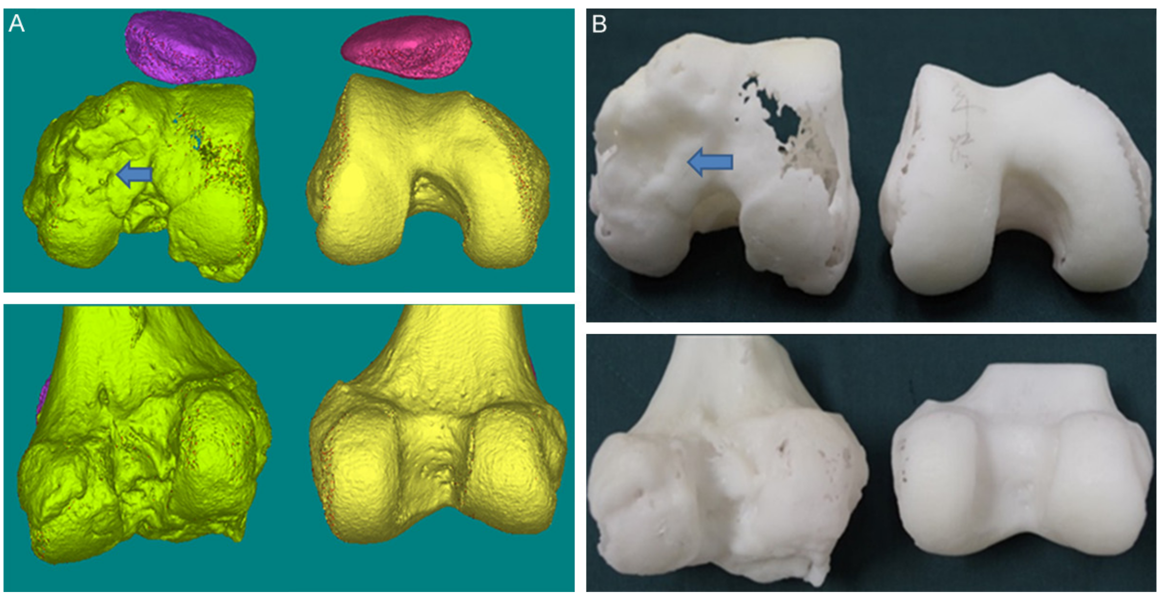

Figure 2. 3D reconstruction and 3D-printed models of patient's knee joint. A. 3D reconstruction; B. 3D-printed models.

Some research showed the preoperative applications of computer-assisted design (CAD) have been founded that can improve implant position accuracy compared with conventional surgery [2], and the 3D printing models are based on CAD. The preoperative application of 3D printing technology for aided diagnosis can shorten operation time and reduce surgical trauma [10, 11]. The patient that we included was a 19-year-old male; 4 years ago, open reduction and internal fixation surgery was performed due to tibia fracture, and postoperative traumatic arthritis occurred. Because of his age and complex lesion, there were some difficulties in diagnosing and determining whether joint replacement should be performed. Therefore, the 3D printing technology was chosen to print the knee-joint bone model of the affected region in order to diagnose and formulate a treatment plan in an intuitive and accurate way.

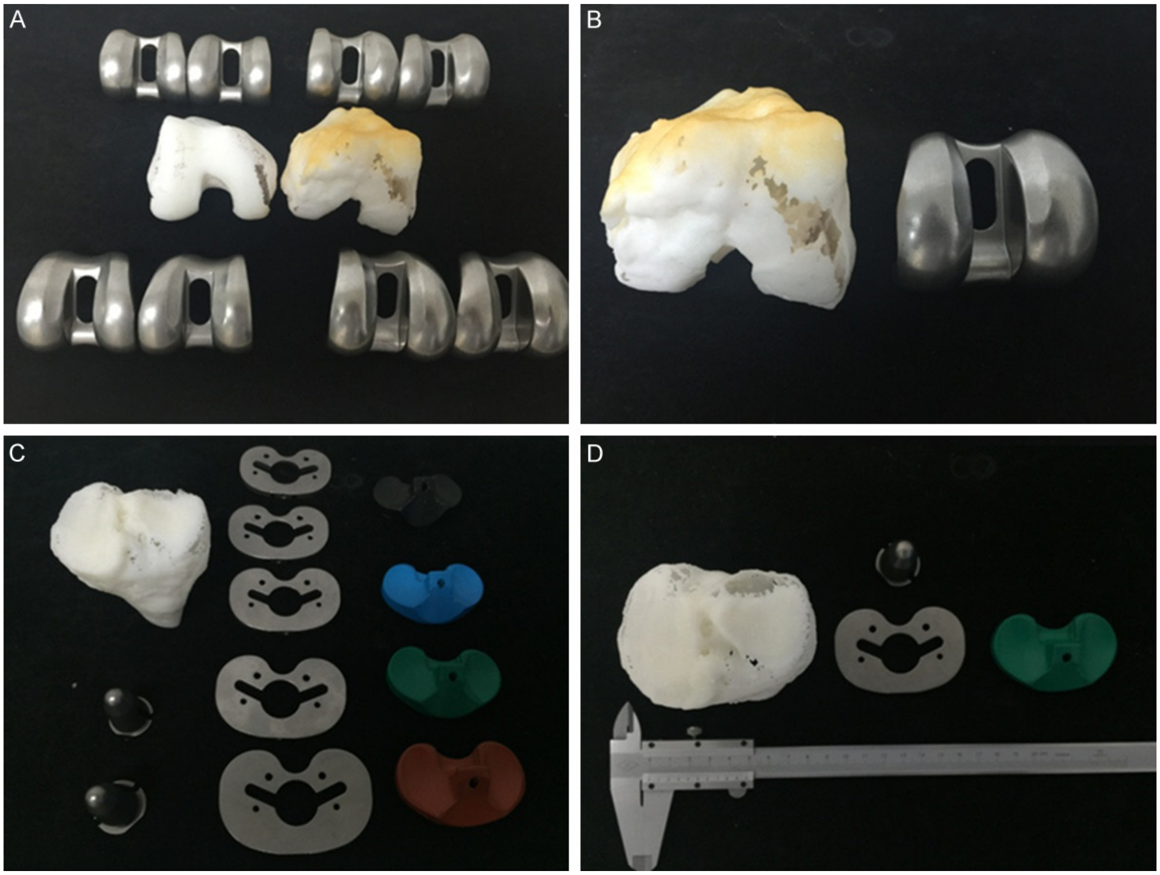

Figure 3. Selection of fitted prostheses. A and B. Selection of femoral prosthesis; C and D. Selection of tibia prosthesis.

Methods and materials

Imaging data acquisition and processing

The X-ray of patient's left knee-joint and CT data (Philips iCT 256 with X-ray Tube Current 232 mA and KVP 120 kV, the pixel size is 0.52 mm, slice thickness is 0.9 mm and spacing between slices is 0.45 mm) of patient's bilateral knee-joint were collected when the patient came to the clinic for the first time (**Figure 1**). The CT data were exported in the format of DICOM, and then 3D reconstruction of images by software MIMICS 17.0 (Materialise's interactive medical image control system, Materialise, Belgium) was performed (**Figure 2A**) and then the tibia and femur were separated. Finally, the data were exported in the format of STL.

3D printed model

After obtaining the STL file, we imported the file into MAGICS 18.0 (Materialise's interactive medical image control system, Materialise, Belgium) to fix errors and add support structure, and then exported to 3D printing equipment (SLA-450, Shining, China) in format of magics, to start printing. After several hours, the model was obtained. Subsequently, the ultraviolet-curing and the support removing were performed. The models were photosensitive resin material (**Figure 2B**).

Surgical design

Given that the patient was young and the lesion was complex, the measurement and surgical planning were conducted by MIMICS 17.0 in order to fit the patient's condition. The matched prostheses were selected by comparison with some parameters of the 3D-printed models as **Figure 3** showed. The prostheses (Femoral, RP-F Cemented, sz4 Left; Tibia insert, Rotating platform RP-F, sz4 10 mm GVF; Tibia tray rotating platform, MBT Keel, sz3, Cemented) were selected finally which were manufactured by Johnson & Johnson DePuy International Ltd (**Figure 3**).

Table 1. The tibia and femurs parameters and comparison of data from bones and 3D-printed models

	Left-tibia	Left-femur	Right-femur
CT Image (mm)	65.96±14.65	66.98±20.78	60.73±24.44
Model (mm)	65.79±14.96	67.40±21.07	60.92±24.58
T	0.727	-2.063	-1.694
P	0.495	0.085	0.141
ICC	1.00	1.00	1.00

ICC: Intraclass Correlation Coefficient.

Table 2. Mean absolute (mm) and relative (%) differences for all model measurements in comparison with bones by MAGIS18.0

		Absolute (mm)	Relative (%)
Left-tibia	m-APD	0.14	0.17
	m-TD	0.01	0.02
	m-HD	0.75	0.96
	t-APD	-1.06	-2.42
	t-TD	0.21	0.26
	t-MAPD	-0.40	-0.66
	t-LAPD	-0.84	-1.58
Left-femur	m-APD	0.70	0.80
	m-TD	0.33	0.45
	m-HD	0.51	0.66
	c-MAPD	1.10	1.71
	c-LAPD	0.88	1.25
	c-AHD	-0.24	2.58
	c-TD	-0.32	-0.37
Right-femur	m-APD	0.34	0.40
	m-TD	0.24	0.35
	m-HD	0.68	1.12
	c-MAPD	0.22	0.39
	c-LAPD	-0.04	-0.06
	c-AHD	0.14	2.37
	c-TD	-0.26	-0.32
Total mean		0.45	0.90

Comparison of models and bones

The CT data of the 3D-printed models were obtained, and the parameters of the models and bones were selected as max anteroposterior diameter(m-APD), max transverse diameter (m-TD), max height (m-HD), transverse diameter of the condyle (c-TD), anteroposterior diameter of the medial condyle (c-MAPD), anteroposterior diameter of the lateral condyle (c-LAPD), height of the anterior condyle (c-AHD), anteroposterior diameter of the tibia (t-APD), transverse diameter of the tibia (t-TD), medial anteroposterior diameter of the tibia (t-MAPD) and lateral anteroposterior diameter of the tibia (t-LAPD), and measured by the MAGICS 18.0 in the format of STL.

Statistical analysis

Then the above parameters were analyzed by the SPSS 17.0 (Statistical Product and Service Solutions, IBM, America), the paired t-test was selected, with the level of significant set at $P \leq 0.05$. The intraclass correlation coefficient (ICC) was used to evaluate the similarity between the model and real bone (**Table 1**).

The absolute difference (mm) and relative difference (%) were conducted by the following formulas (**Table 2**):

Absolute difference (mm) = model value-bone value

Relative difference (%) = 100 (model value-bone value)÷bone value

Surgical techniques

The patient was maintained at supine position, and placed under anesthesia, the left knee-joint midline incision was taken from the juncture of tendon and belly above the patella to the medial tibia tubercle 1 cm, with a total length of 14 cm. Skin, subcutaneous tissue, joint capsule and medial patellar ligament were cut and exposed layer by layer, and severe abrasions of tibia, femur and patellar articular surface were revealed, especially, the articular surface was highly consistent with the 3D-printed model (**Figure 4**). Then the knee-joint was flexed; the medial joint capsule was released, and hyperplastic tissues were resected.

Distal femoral osteotomy and proximal tibia osteotomy were performed successively with protecting the related ligaments. An osteotomy module was installed in the thighbone, and epicondyles, postartis, and bevel osteotomy were performed to install the tested prosthesis model; the model could be buckled firmly, which showed good matching. Then, based on preoperative planning, the appropriate titanium prosthesis was taken, and guided by template, the proximal tibia was slotted. After routine disinfection by iodine immersion, the femoral and tibia prostheses were inserted successively

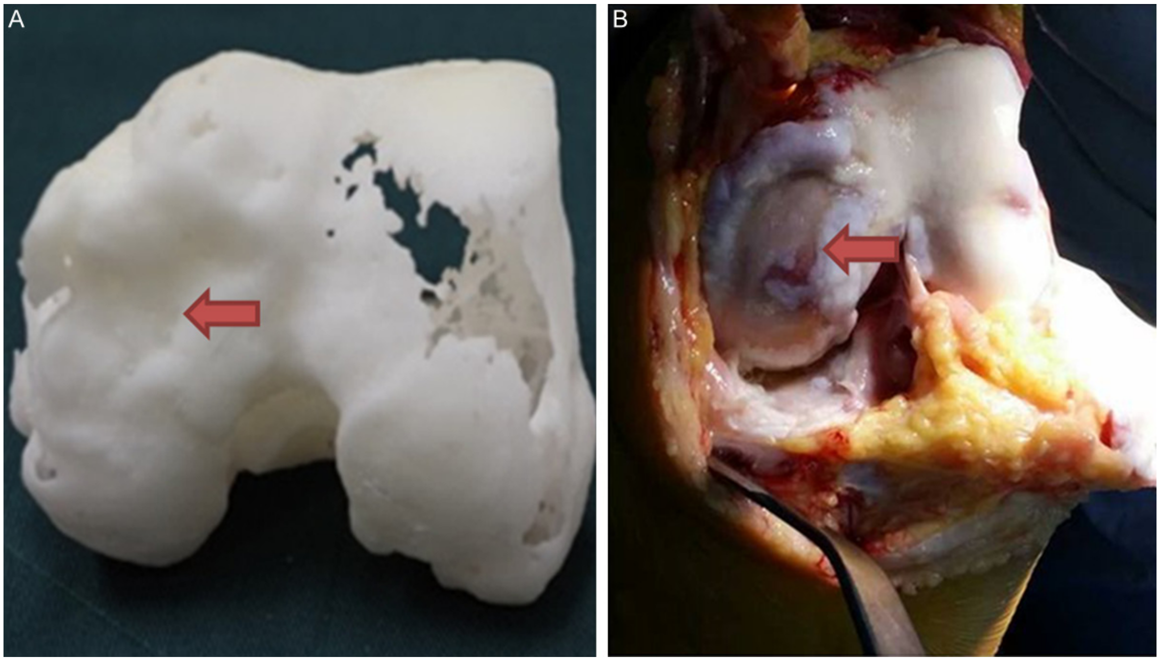

Figure 4. 3D-printed model of patient's knee and intraoperative observation. A. 3D-printed model of damaged joint; B. Damage observed in operation.

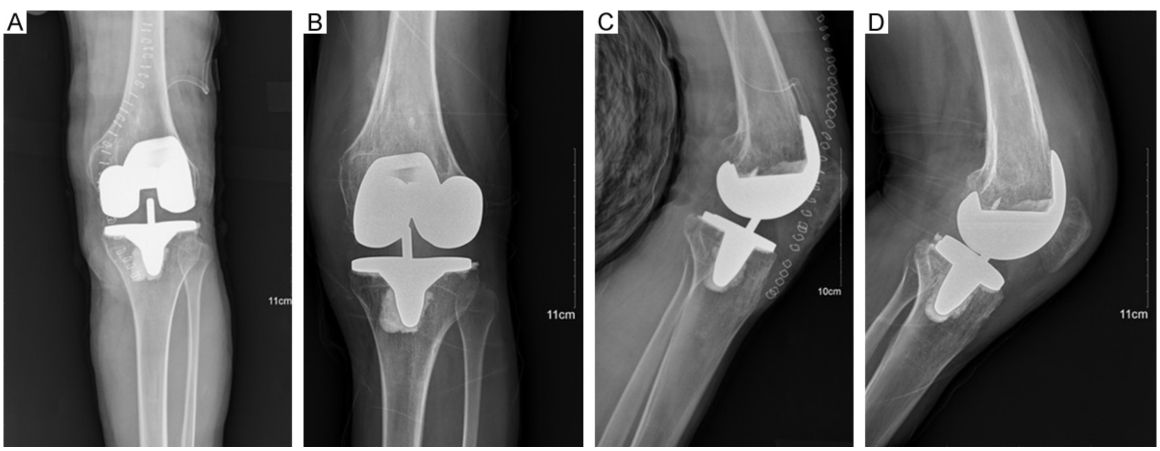

Figure 5. X-ray appearance of patient during operation and 6 months follow-up after operation. A and C. Posteroanterior and lateral X-ray of left knee during operation; B and D. Posteroanterior and lateral X-ray of left knee 6 months after operation.

and were fixed with bone cement, with the pad installed. After the curing of bone cement, knee-joint flexion and extension were good; the patellar running track was regular and inside and outside tensions were moderate. Finally, the wound was washed, sutured, and bandaged by compression with catheter drainage.

Results

It was observed intraoperatively that the surface of medial femoral condyle and lateral condyle were highly consistent with the preoperative 3D printed model (**Figure 4**). An intraoperative X-ray showed that the prosthetic position and size were precise (**Figure 5A**, **5C**). Because of the sufficient preoperative design by the application of 3D printing technology, the surgical time and the amount of bleeding were 61 min and 450 ml respectively, which played a positive role in the rehabilitation of the patients after operation. A six months follow-up after operation showed that the patient's knee-joint function was satisfactory (**Figure 5B**, **5D**). The preoperative KSS clinical score and functional score were 68 points and 80 points, respectively. The scores of six months follow-up after operation were up to 90 points and 95 points, respectively.

The CT data of models and bones were reconstructed and the above parameters were measured, the mean absolute difference and relative difference were 0.45 mm and 0.9%, respectively (**Table 2**); the ICCs were all 1.00, and the P>0.05 (**Table 1**). It showed that there was no significant difference between two groups of parameters.

Discussions

This paper reported a case of a 19-year-old patient with traumatic arthritis. When the X-ray and CT of patient were showed to us for the first time, there was a great difficulty in the course of diagnosis and the determination of the treatment plan, because of the young age and relatively complex condition; X-ray image was not enough to provide definite diagnosis for patient, and CT information cannot show the every visual angle of the knee, so we were hesitant on whether to perform joint replacement or not. On the other hand, using imaging data alone to make the diagnosis and determine the surgical treatment is difficult, because the patient and his family members cannot gain an intuitive understanding of the disease condition. Based on the above reasons, the 3D-printed models were considered to be used for simulation the damaged bones of the patient before operation, so as to judge the patient's condition in a precise and intuitive way, and the 3D-printed models can provide a reliable basis for the communication between doctors, patients and their family members.

With the development and maturity of 3D printing technology, the application of 3D printing in the medical field has become widespread increasingly, especially in fields such as preoperative design of fracture, tissue reconstruction and so on [11-23]. 3D printing technology has been applied in maxillofacial surgery, hip-joint disease, soft tissue reconstruction, 3D printing guide plate in posterior lumbar pedicle screw fixation, and some preoperative design of complex diseases such as finger reconstruction, fracture and pelvic fracture are also reported [11-17, 20-23]. To our knowledge, there are rare studies on 3D-printed model for preoperative precise aided diagnosis, as well as the determination of the treatment plan and preoperative design. In this study, 3D-printed model showed that there were serious abrasions on the medial femoral condyle, lateral femoral condyle and patellar articular surface, clearly. Therefore, combined with clinical examination, the TKR was imperative. Then, according to the models, the different sizes of prostheses were used in preoperative design, by measuring the relevant parameters, prosthesis size was determined. The prostheses that we finally selected were the artificial knee joint system TC-PLUS TM System produced by Johnson & Johnson. Because of sufficient understanding of the damaged bone in the patient through the 3D printing models, the patient's surgical time and intraoperative blood loss were reduced to 61 min and 450 ml compared with 67.6±11.1 min and 647.6±146.6 ml studied by Li X et al [18] 84 min by Lozano LM et al [19] and 980 ml (range, 111-2032 ml) by Amit Singla et al [24], of conventional TKR surgery; although one case is not significant statistically, it also showed a trend that the 3D-printed models is helpful for reducing the surgical time and blood loss. The reduction of surgical time further reduced the risk of postoperative infection, which played a positive role in the rehabilitation of the patient after operation.

The present study using 3D printing technology for preoperative aided diagnosis and preoperative design can help surgeons make accuracy preoperative diagnosis, and choose suitable prosthesis for patients. Well matched prosthesis could reduce the surgical time, simplify the surgical procedure, and accelerate patients' recovery after operation. For similar cases as complex fractures, deformities and bone tumors, diagnosis and treatment plan were often difficult to define. 3D printing model could also help surgeons achieve intuitive diagnosis and preoperative design, and especially for junior surgeon, the technology could help them to improve the surgical technology faster. For resident doctors, the opportunity to operate directly on a patient was very rare, but with the application of 3D printing model, some complex operations could be performed on the model before the real operation which was very beneficial for the growth of resident doctors.

Currently, CT scans could perform 3D reconstruction, but the essence of 3D reconstruction was presenting the image on a two dimensional computer screen, cannot visually observe the spatial structure of the bone, whereas the 3D printed model could reproduce bone damage and lesion in proportion of 1:1 in an intuitive way, making diagnosis precise. At the same time, we could choose the suitable type of prosthesis according to the size and shape of the model, in order to achieve the optimum effect.

For emerging technology, a cautious attitude should be maintained for clinicians. In terms of the application of 3D printing technology for diagnosis and preoperative design, sufficient attention should be payed to the structural error that may exist between real bones and models. Therefore, before the operation, the precision comparison analysis of bones and models were performed by MAGICS 18.0 and SPSS 17.0 software. The ICCs were all 1.00, $P>0.05$, showed that model data were highly consistent with bone data, and the mean absolute difference and relative difference were 0.45 mm and 0.9% respectively, which are lower than the 0.90 mm, 1.79%, 1.44 mm, 3.14%, 1.23 mm, 2.14% of SLS models, 3DP™ models and PolyJet™ models respectively [25], so the models can be considered to be accurate and reliable. In this study, although the model was consistent with the patient's damaged bone, only one case limited the persuasiveness of the results, and the more cases need to be accumulated and studied. The systematic and rigid research of the accuracy error between real bone and model was still needed in order to make 3D printing technology widely used in clinical field on a large-scale in the future. In addition, the model could only reflect the pathological changes of the bone, however, the cartilage, soft tissue and other structures cannot be presented, which was the factors to limit the application of the technology. But with the development of 3D printing technology, this problem would be solved.

Conclusion

The application of 3D printing technology has provided a new way for the diagnosis and treatment of the similar cases when it is difficult to clarify diagnosis and treatment plans by virtue of imaging data.

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Informed consent was obtained from all individual participants included in the study.

Disclosure of conflict of interest

None.

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