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Original Article

A versatile three-dimensional printing-technology-based digital design and experimental study for acetabular fracture surgery

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Abstract: The aim of this study was to investigate a versatile digital design platform for acetabular fracture reduction with internal fixation, and its specific implementation and evaluation. Fourteen adult cadaveric pelvises were selected, scanned using thin-section CT scans, and subjected to virtual fracture modeling to induce 28 fractures. The folding module was cut and printed three-dimensionally and the reconstructed steel plate was precisely prebent accordingly before implantation in the optimized position in the cadaver. The 3-dimensional (3D) images were reconstructed and 3D registration of pelvises was implemented pre- and postoperatively. The 3D coordinates of both preoperative design and postoperative screw channel entry points were collected and the difference of the eligible nail points at 2 different precision levels was statistically analyzed using the chi-square test. Results showed that Sixty-four pre-bent steel plates were implanted during surgery and achieved full card-bit unique position, with anchor point precision of ≥ 1.3 mm (χ^2=2.26; P>0.05) for 335 eligible screw entry points. In conclusion, the application of digital design and 3D printing allows the doctors to perform virtual reduction and pre-design the personalized steel plate. The pre-curved personalized steel plate could guide the reduction of acetabular fracture and achieve full card-bit unique position with high precision.

Keywords: Acetabular fractures, internal fixation, digitizing, 3-dimensional (3D) printing, simulation surgery

Introduction

Acetabular fractures, most frequently caused by high-impact injuries, are potentially life-threatening and result in high morbidity [1]. At present, open reduction and internal fixation (ORIF) is the gold standard treatment for displaced acetabular fractures [2-5]. However, acetabular fracture remains a major challenge in orthopedic trauma management [6, 7] because of the deep position of acetabulum, its complex anatomic relationships, and individual patient characteristics. Furthermore, to achieve the demanding goals pertaining to both reconstruction and function, anatomically accurate intraoperative reconstruction and plate implantation is required, which adds to the difficulty of open-reduction surgeries in this region [8-10]. Optimally, acetabular fracture surgery should achieve anatomic reduction and plate fixation according to the reduction plan for stable fixation.

Conventional surgeries, however, often do not achieve anatomic reduction of the articular surface and accurate internal fixation quickly given the limitations of access to surgical field and total reliance on the surgeon's experience. Intraoperative application of aluminum-plate bending not only increases the duration of surgery, but also may result in non-optimal steel-plate placement due to lower precision. Therefore, given the complex morphological structure of acetabular fractures, individualized surgical planning should be undertaken prior to ORIF. The 3-dimensional (3D) digital design can transform virtual CAD model into 3D prototype accurately and quickly. Because 3D digital design has a strong three-dimensional visualization, it has been widely used in different fields of medicine, such as complex bone tumor resection, pelvic fracture, hip dysplasia and fracture, spinal deformity and injury, cranioplasty, oral and mandible repair, limb deformity, bone defect and prosthesis manufacture [11-14].

Puchwein et al. used the Mimics platform (Mimics version14.0, Materialise, Belgium) to virtually insert percutaneous screws for acetab-

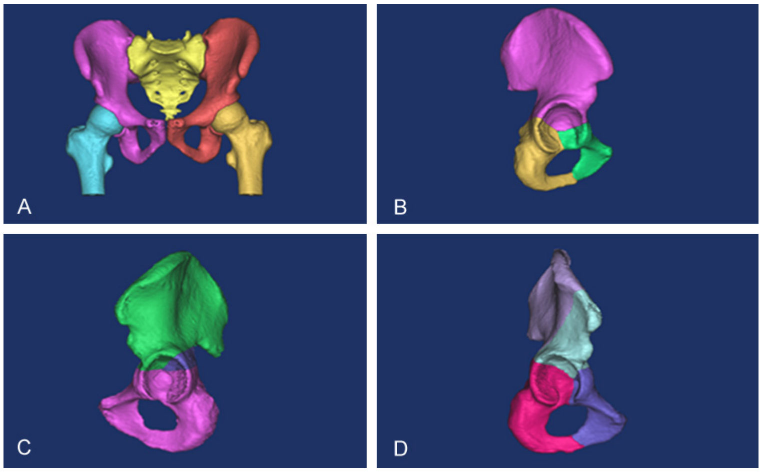


Figure 1. 3D model of virtual fracture. A. 3D reconstruction; B. T-type fracture; C. Transverse and posterior wall fracture; D. Both-column fracture.

ular fracture fixation to determine optimal screw-placement angle, diameter, and length [15]. Shen et al. applied computer graphics and augmented reality technology for virtual ORIF of acetabular fractures in surgical planning to simulate internal fixation and implantation to improve surgical outcome [16]. However, such a digital design merely provides a reference for the operation, and a specific real-time implementation plan integrating digital design techniques with actual ORIF in acetabular fracture surgery has not been reported yet.

Ideally, acetabular fracture surgery should achieve anatomic reduction and precise implantation of steel plate and screw compliant preoperative surgical design for stable fixation. At present, surgical management of acetabular fracture involves difficulties in ensuring anatomic reduction of the articular surface and precise plate and screw placement relying on experience alone due to the limitations of surgical field access and operation time. For acetabular fractures, optimization of the preoperative surgical design is closely related to effective surgical outcomes, which could even be the key to a successful surgery [17]. This study integrated all crucial steps including design, implementation, and evaluation to achieve precise anatomic reduction of acetabular fractures during operation and to implant the prefabricated plates and screws for stable fixation.

The aim of this study was to investigate a versatile digital design platform for acetabular fracture reduction with internal fixation, and its specific implementation and evaluation.

Materials and methods

CT scanning

Cadaveric pelvises from 14 embalmed adults (12 men and 2 women) were imaged using CT scanning (130 kV, 21.6 mAs, and pitch 0.625 mm). CT images were saved in DICOM file format (512 × 512 pixels). All cadavers were provided by the Anatomy Laboratory of the School of Basic Medical Sciences, Putian College, Fujian province, China. This study was approved by the Ethics Committee of our Hospital.

Image editing

Dicom-formatted files were used in Mimics v14.0, with threshold value set at 120-Max Hu. Applying the region-growing method, images were three-dimensionally edited using the menu option "Edit Mask in 3D". In the three-dimensional (3D) editing box, the pelvis Mask was separated into individual components before 3D reconstruction (**Figure 1A**).

Virtual fracture modeling

All types of fracture models were generated in virtual 3D modeling using the menu option "Segmentation/Edit Mask In 3D" as briefly summarized here. In the 3D model, the Lasso tool was used to divide and obtain T-type, transverse and posterior wall, and two-column fracture models in the editing box along fracture lines specified in accordance with the Judet-Letournel classification system (**Figure 1B-D**).

Optimization of steel-plate position and nail implant simulation

The operative procedure mainly comprised 2 steps: (1) for simplified multiplanar 3D measurement, the "Measure Distance" menu option was selected; based on the reconstructed steel-plate gauge, the preset steel-plate position was marked every 12 mm, with their intervals as nail-hole positions, to be used to precisely implant the designed plate at the specified screw placement positions (**Figure 2A**); (2) from the "MedCAD\Create Cylinder" menu, an Φ2.0 mm cylinder was created for simulating pedicle screw implantation, ensuring the screw

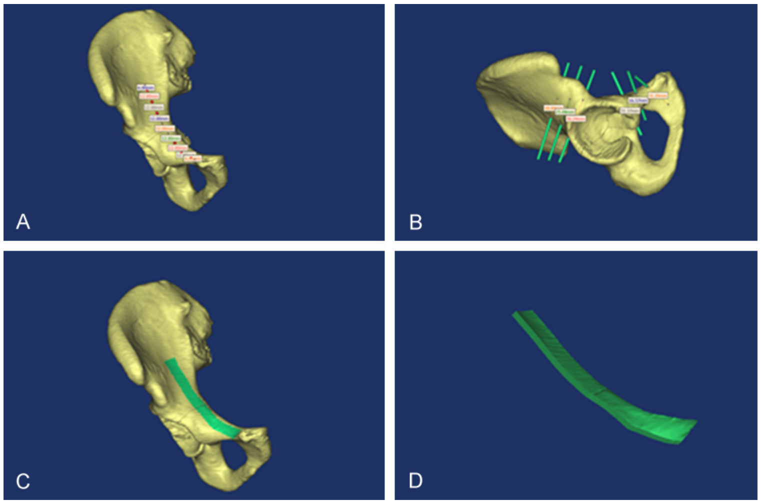


Figure 2. The operative procedure and bending module design and print for virtual internal fixation. A. Simplified multiplanar placement; B. Nail placement simulation; C. Optimized steel-plate placement; D. 3D-cut pre-bent module.

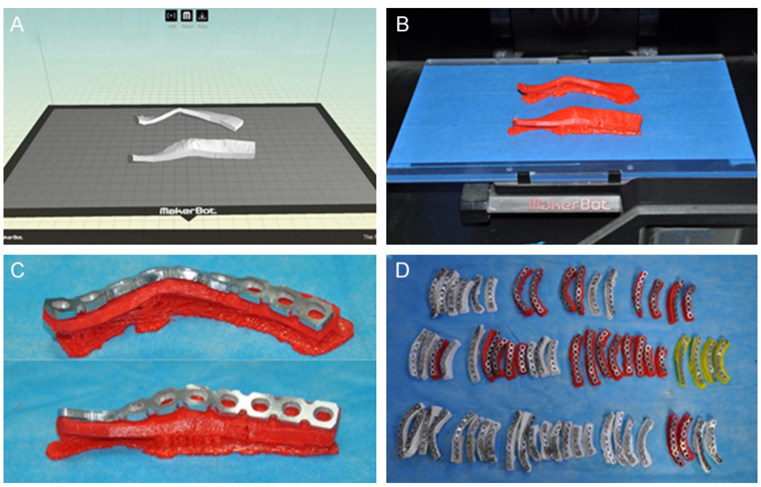


Figure 3. 3D printing and preoperative steel plate pre-bending. A. File printing; B. Module printing; C. Preoperative steel-plate pre-bending; D. All steel-plate pre-bending.

channel was vertical to the bone surface, and measuring screw channel length (**Figure 2B**).

Bending module design and print

We selected the "Simulation\Cut Orthogonal to Screen" from the menu options. The steel plates (nail-hole spacing 12 mm, width 12 cm; end nail holes to end of plate 6 mm) were three-dimensionally cut (as shown in **Figure 2C** and **2D**) into small module bending, defined as the bending module in this study. This reconstructed plate-bending module was extracted to Makerware as an STL file before standard printing (**Figure 3A** and **3B**).

Preoperative plate bending

According to the preoperative design, a suitable steel plate was chosen and, with the plate-bending module, bent precisely and molded simultaneously (**Figure 3C** and **3D**).

Internal fixation placement

Placement of reconstructed plate and screws was done along the ilioinguinal and Kocher-Langenbeck lines, respectively. Length of the screw placement and other specifications were preoperatively measured using Mimics. The surgical approach was undertaken layer by layer, and the bone surface was stripped. The steel plate was placed onto the bone surface to obtain a unique niche position, and a Φ2.0 mm Kirschner needle was used to perforate the bone surface vertically before fixation of the plate with Φ3.5-mm industrial grade screws (**Figure 4**).

3D registration and data acquisition

Thin-layer CT scan and 3D reconstruction were performed postoperatively. The "Simulation\Merge" menu option was used to combine the 3D-modeled pelvis, with all screws and output, with the preoperatively predesigned Mask as an STL format file. The postoperative 3D model of the pelvis was registered with the predesigned 3D pelvis model using the "Registration\Point & Global Registration" menu (**Figure 5C** and **5D**). Preoperative pelvis (**Figure 5E**) and postoperative (**Figure 5F**) internal fixation.

The "Apply Simulation\Split\All Parts" command was used to separate the postoperative model into the pelvis and the reconstructed plate with screws, and the "MedCAD\Cylinder" menu was used to build the screw path (Φ2.0 mm) along the central longitudinal axis of the

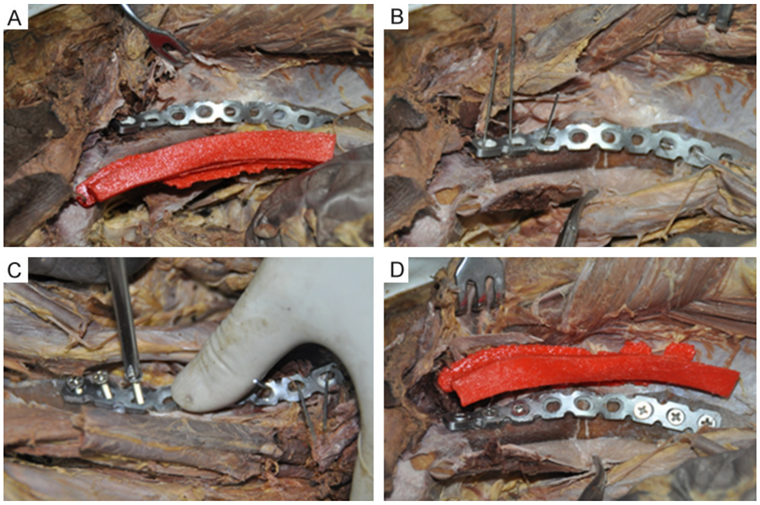


Figure 4. Placement method of internal fixation. A. Unique position of reconstructed steel plate during surgery; B. Kirschner needle slot; C. Removal of Kirschner needle and implant needle; D. Internal fixation screw placement.

screw and to observe whether the screw channel penetrated the joints (**Figure 6A** and **6B**). The screw channel was set to Φ0.02 mm and the "MedCAD\Point" command was used to construct pre- and postoperative anchor points at the junction between the screw channel and the pre-designed bone surface. The "Export txt" command was applied to extract the 3D coordinate value of each anchor point into MS Excel (**Figure 6C**). A schematic of the distribution of predesigned and surgical nail points with different precisions was shown in **Figure 7**.

Statistical analysis

The absolute value of differences between pre- and postoperative data was collected and screened starting from 0.4 mm with 0.1 mm intervals. The number of implanted screws that qualified under different accuracy requirements (number of occurrences) as well as the number of substandard screws (number of 0 occurrences) were statistically analyzed using SPSS13.0 (IBM, USA) using a chi-square test, with $P<0.05$ considered to be statistically significant.

Results

Sixty-four steel plates were pre-bent and implanted to achieve unique positions during surgery. The differences of the absolute XYZ coordinate values of anchor points before and after surgery were 0.35±0.29, 0.32±0.29, and 0.36±0.30 mm, respectively. Eligible entrance points under different precision requirements are shown in **Figure 8**. Results of the chi-square test suggested that when the anchor point precision was ≥ 1.3 mm, then χ^2 was 2.26 and *P*-value was 0.13, suggesting that the surgical procedure accurately reproduced the digitally designed surgical plan (**Table 1**).

Discussion

For the complete designing process, we relied entirely on Mimics, which was fast and easy-to-learn and provided high-precision simulation for good surgical outcome. This platform-based technique we developed has the following advantages: (1) it applies to all types of acetabular fractures; 3D editing was applied for virtual modeling of transverse and posterior wall, T-type, and both-column fractures and we subsequently performed both anterior and posterior reconstruction-plate placement, proving applicability of this method for all types of acetabular fracture; (2) it provides fast and high-accuracy simulation of virtual fracture reduction. Virtual fracture reduction is a critical step in planning surgery for acetabular fracture correction. The isolation of fracture fragments was completed in a pure 3D fracture interface, instead of a 2D interface, with the advantages of fast and high-accuracy simulation that provided clinical value; and (3) it facilitated determination of the exact location for the reconstruction steel plate. Furthermore, simplified multiplanar 3D measurement to design precise steel-plate position and to cut out the bending module accordingly not only reduced printing time and materials but also, most importantly, facilitated fast and accurate pre-curving of the reconstruction plate with the help of the pre-curving module.

The development of rapid prototyping/3D printing technology enabled a leap from digital designing to virtual simulation and application in reality [18-20]. Niikura et al. [21] used 3D printing technology to produce a complete and solid model of the pelvis. However, the preop-

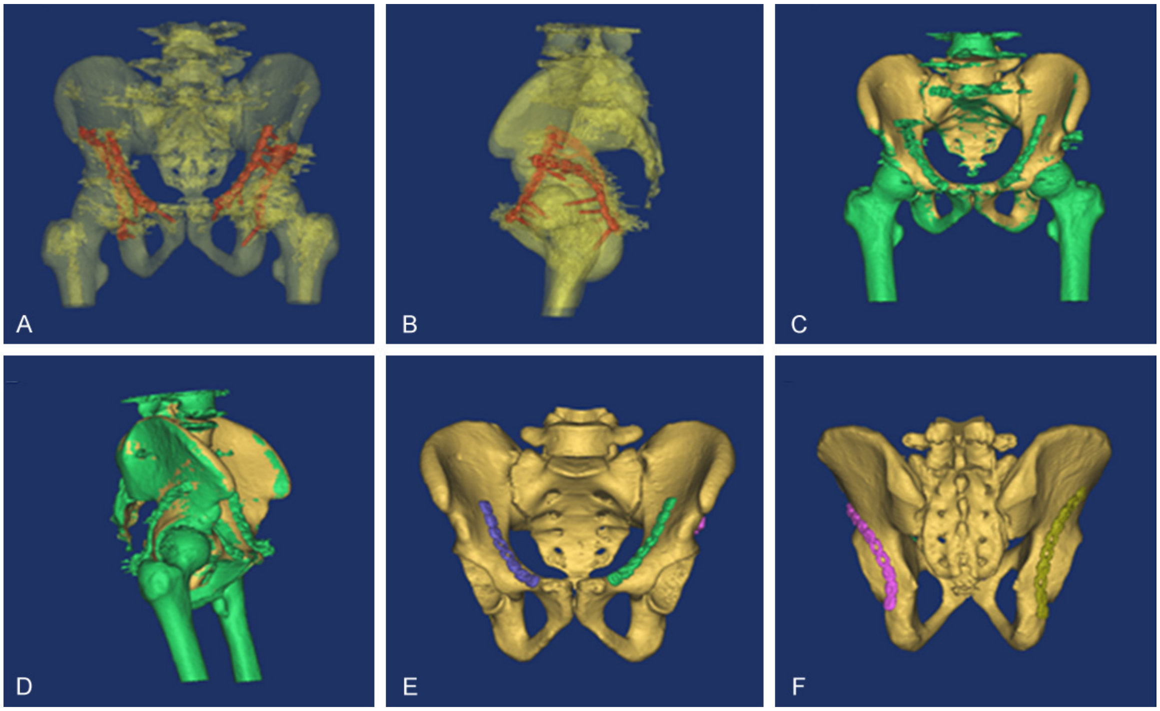
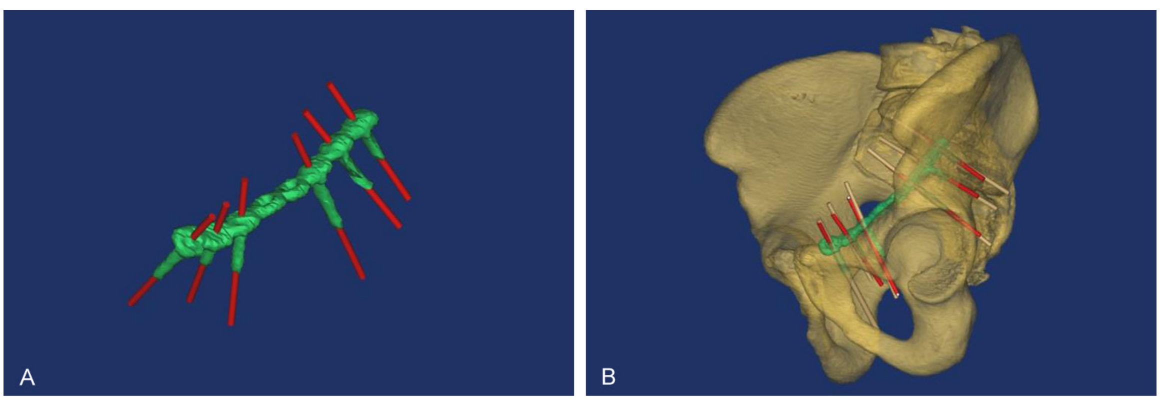


Figure 5. 3D registration method. A and B. Postoperative pelvis and internal fixation; C and D. Pre- and postoperative 3D registration in module; E and F. Preoperative pelvis and postoperative internal fixation.



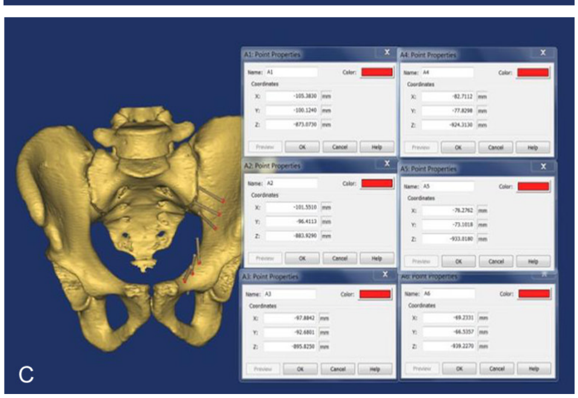


Figure 6. Data collection. A. Reconstruction of screw channel; B. Pre- and postoperative screw channel; C. 3D coordinate values on data collection.

erative pre-curving steel plate consumes considerable time and materials for printing, and the position of the bending steel plate is also uncertain. Hu et al. [22] used 3D Studio Max

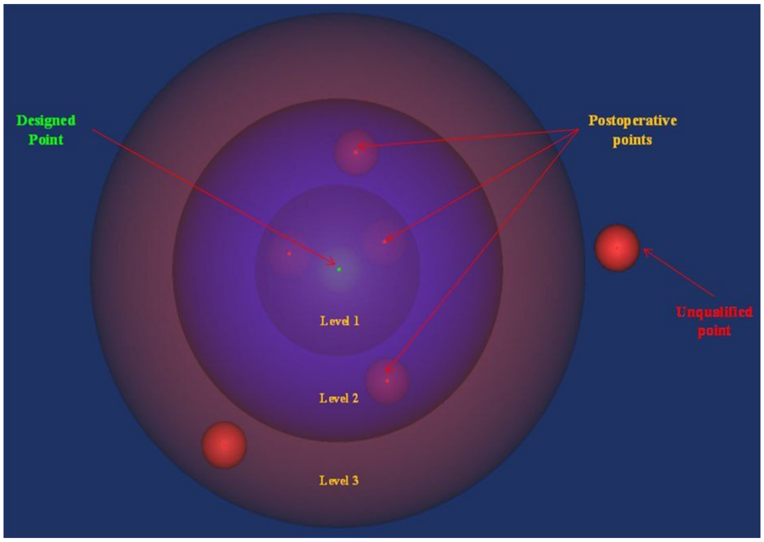


Figure 7. A schematic of the distribution of predesigned and surgical nail points.

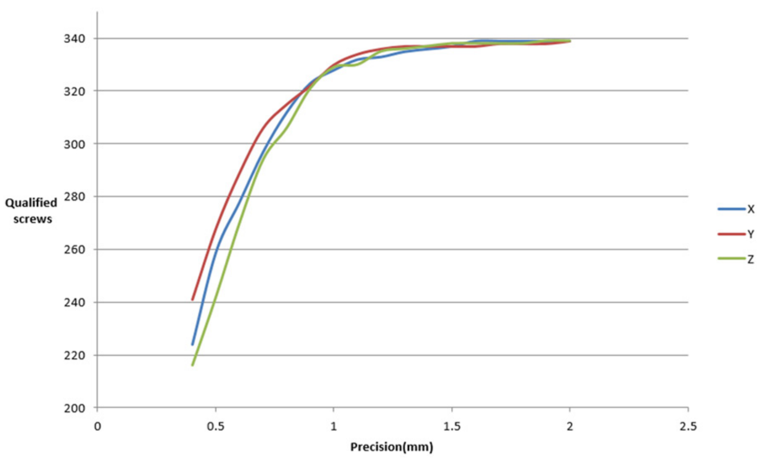


Figure 8. Number of nail points with differently qualified precision.

software to draw a virtual reconstruction plate and pre-curve the steel plate virtually and then guided plate pre-curving during surgery accordingly. However, in this study we found it difficult to repeat this method by drawing and bending the steel plate using software to accurately guide the actual steel plate curving. This study used digital methods to precisely design placement position and print out an entity module of this area in 3D. This novel technique has the advantages of high-precision plate curving, conservation of material, shortening of printing time, and avoidance of repeated bending that could lower the biomechanical properties of plate. The pre-curved steel plate can be used as an "indicator" to guide fracture block reset during surgery. After reduction, a good bone plate applicator can be used as evidence of achieving anatomic reduction. In real surgeries, it is difficult to obtain anatomic reduction because of the narrow surgical field and complications of fractures, and the lack of an "indicator" for guiding fracture reset. Our experience in this clinical application study has shown: (1) reduction of the fracture with steel plate as closely as possible for complete reduction, with the help of tightening screws to achieve stability; and (2) advantages of precise internal fixation, less invasiveness, less operative time and blood loss, and faster postoperative recovery.

The key to accurately reproduce a surgical design in operative procedure is to achieve intraoperative "unique positioning" of the steel plate between the plate and the bone surface, which is the only position that fits accurately. This was confirmed by show ing that, with pressure, the steel plate could not be moved and rotated on the bone surface. Our results show that such "unique positions" were achieved for 64 accurate pre-bent steel plates in surgery. Key factors to achieve this "unique position" can be summarized as follows: (1) structural characteristics of bone for steel-plate placement position. Arcuate line, sacral share bow, bow, and other sacral bones have characteristics of bone structure, such as being curved and rotational, which makes these locations a good fit for the reconstructed plate because of their unique niche positions; (2) the pre-bent reconstruction plates are designed precisely according to curved modules. Accurate bending is key to achieve steel-plate unique niche position, and a good applicator surface of the bone plate can enhance biomechanical performance on internal fixation.

Table 1. The precision test for steel plate implantation according to surgical design

Nail point precision (mm)	*x*-axis		*y*-axis		*z*-axis		χ^2	*P*
	Pass	Fail	Pass	Fail	Pass	Fail		
1.2	333	6	337	2	336	3	4.20	<0.05
1.3	335	4	337	2	336	3	2.26	>0.05
1.4	336	3	337	2	337	2	1.34	>0.05

The purpose of digital design is to accurately produce a preoperative optimized surgical design. However, it is impossible to implement such a preoperative design with absolute accuracy. Researchers have compared preoperative planning and postoperative evaluation of fixation accuracy [16] and found inaccuracies when only postoperative CT scans and 3D reconstruction images were compared with the preoperative results to evaluate the accuracy of the design reduction and fixation implementation during surgery. This study used the absolute difference from 3D coordinate values of the anchor point, both pre- and postoperatively, as an evaluation index for precision. 3D registration and data collection were easily performed using Mimics. The results of chi-square test suggested that, when anchor point accuracy was ≥ 1.3 mm (chi-square test, χ^2= 2.26), the *P*-value was greater than 0.05 when postoperative steel-plate position was considered against the designed position, suggesting that the surgery accurately reproduced the preoperative design.

The limitation of this study is that virtual modeling is adopted for anatomic specimen, the segmentation of fracture block cannot be completely consistent with the actual fracture, and there is still a gap between the operation simulation and the actual operation, such as the actual operation often cannot fully achieve the degree of simulated reduction. At present, in the field of Orthopaedics, 3D digital design is still limited to printing the bone model, and the steel plate used for internal fixation is also pre bent on the printed bone model, so it is still unable to make the internal fixation device fully attached. If the fracture is reduced in the computer and the internal fixation device is printed together with the bone to be attached, it will make the internal fixation device infinitely close to the anatomical form of the bone to which it is attached. This will be a new proposition, which needs to be solved by the majority of clinical workers and researchers. The author believes 3D digital design will promote the further development of digital orthopaedics in the future, and has a good application prospect.

Conclusion

In conclusion, the application of digital design and 3D printing allows the doctors to perform virtual reduction and pre-design the personalized steel plate. The pre-curved personalized steel plate could guide the reduction of acetabular fracture and achieve full card-bit unique position with high precision. This technique possesses potential universal application value for fracture reduction and personalized plate implantation. Due to the limitation of funding for this study, we used precision machining reconstruction plate and screws. In the near future, a biomechanical study should be conducted to validate the findings of this pilot study before investigation in clinical studies.

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Disclosure of conflict of interest

None.

Abbreviations

ORIF, Open reduction and internal fixation.

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References

[1] Romeo NM and Firoozabadi R. Classifications in brief: the pipkin classification of femoral

head fractures. Clin Orthop Relat Res 2018; 476: 1114-1119.

[2] Cao H, Li YG, An Q, Gou B, Qian W, Guo XP and Zhang Y. Short-term outcomes of open reduction and internal fixation for sanders type III calcaneal fractures with and without bone grafts. J Foot Ankle Surg 2018; 57: 7-14.

[3] Ahmed AF, Salameh M, AlKhatib N, Elmhiregh A and Ahmed GO. Open reduction and internal fixation versus nonsurgical treatment in displaced midshaft clavicle fractures: a meta-analysis. J Orthop Trauma 2018; 32: e276-e283.

[4] Lai TC and Fleming JJ. Minimally invasive plate osteosynthesis for distal tibia fractures. Clin Podiatr Med Surg 2018; 35: 223-232.

[5] Ostrander JD, O'Connell M and Dolch HJ. Open reduction internal fixation of a medial epicondyle avulsion fracture with incarcerated fragment. J Orthop Trauma 2019; 33 Suppl 1: S9-S10.

[6] Caviglia H, Mejail A, Landro ME and Vatani N. Percutaneous fixation of acetabular fractures. EFORT Open Rev 2018; 3: 326-334.

[7] Wang C, Liu H, Lin X, Chen J, Li T, Mai Q and Fan S. A single lateral rectus abdominis approach for the surgical treatment of complicated acetabular fractures: a clinical evaluation study of 59 patients. Med Sci Monit 2018; 24: 7285-7294.

[8] Matias M, Zenha H and Costa H. Three-dimensional printing: custom-made implants for craniomaxillofacial reconstructive surgery. Craniomaxillofac Trauma Reconstr 2017; 10: 89-98.

[9] Alfouzan AF. Review of surgical resection and reconstruction in head and neck cancer: traditional versus current concepts. Saudi Med J 2018; 39: 971-980.

[10] Splavski B, Lovric I, Muzevic D, Soldo I, Pinotic K and Splavski B. Reducing pain and improving quality of life for patients suffering the acetabular fracture. Coll Antropol 2013; 37: 183-187.

[11] Chen KN, Wang G, Cao LG and Zhang MC. Differences of percutaneous retrograde screw fixation of anterior column acetabular fractures between male and female: a study of 164 virtual three-dimensional models. Injury 2009; 40: 1067-1072.

[12] Hanasono MM and Skoracki RJ. Computer-assisted design and rapid prototype modeling in microvascular mandible reconstruction. Laryngoscope 2013; 123: 597-604.

[13] Zhang YZ, Chen B, Lu S, Yang Y, Zhao JM, Liu R, Li YB and Pei GX. Preliminary application of computer-assisted patient-specific acetabular navigational template for total hip arthroplasty in adult single development dysplasia of the hip. Int J Med Robot 2011; 7: 469-474.

[14] Otsuki B, Takemoto M, Kawanabe K, Awa Y, Akiyama H, Fujibayashi S, Nakamura T and Matsuda S. Developing a novel custom cutting guide for curved peri-acetabular osteotomy. Int Orthop 2013; 37: 1033-1038.

[15] Puchwein P, Enninghorst N, Sisak K, Ortner T, Schildhauer TA, Balogh ZJ and Pichler W. Percutaneous fixation of acetabular fractures: computer-assisted determination of safe zones, angles and lengths for screw insertion. Arch Orthop Trauma Surg 2012; 132: 805-811.

[16] Shen F, Chen B, Guo Q, Qi Y and Shen Y. Augmented reality patient-specific reconstruction plate design for pelvic and acetabular fracture surgery. Int J Comput Assist Radiol Surg 2013; 8: 169-179.

[17] Schatzker J, Tile M and Axelrod TS. The rationale of operative fracture care. Springer 2005.

[18] Vaishya R, Patralekh MK, Vaish A, Agarwal AK and Vijay V. Publication trends and knowledge mapping in 3D printing in orthopaedics. J Clin Orthop Trauma 2018; 9: 194-201.

[19] Morgan C, Khatri C, Hanna SA, Ashrafian H and Sarraf KM. Use of three-dimensional printing in preoperative planning in orthopaedic trauma surgery: a systematic review and meta-analysis. World J Orthop 2020; 11: 57-67.

[20] Bagaria V, Bhansali R and Pawar P. 3D printing-creating a blueprint for the future of orthopedics: current concept review and the road ahead. J Clin Orthop Trauma 2018; 9: 207-212.

[21] Niikura T, Sugimoto M, Lee SY, Sakai Y, Nishida K, Kuroda R and Kurosaka M. Tactile surgical navigation system for complex acetabular fracture surgery. Orthopedics 2014; 37: 237-242.

[22] Hu Y, Li H, Qiao G, Liu H, Ji A and Ye F. Computer-assisted virtual surgical procedure for acetabular fractures based on real CT data. Injury 2011; 42: 1121-1124.