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Review Article

Recent developments of 3D-printing technique assisted surgery in the management of complex fractures

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Abstract: Treating complex fractures or deformities has been a challenge, especially those involving articular surfaces, such as acetabulum, tibial plateau, distal radius and the ankle joints. Fractures of these parts require anatomical reductions to restore the articular surface of the joint for good and long-term function and for a better quality of life. Even an experienced surgeon who've performed many similar surgical procedures still needs a precisely designed preoperative plan when facing such cases. Conventional imaging like X-ray and computed tomography (CT) scan have their own limits in providing detailed information about the affected bones and unable to carry out measurements which are necessary for the pre-operative planning. However, with the help of 3D printing technique, surgeons can use a real-size physical model of the fractured bone to make diagnoses; to improve their understanding of the nature of complex fractures; and to simulate the surgical procedure on it directly. In this article, we review on the latest developments made in the management of complex fractures with 3D-printing technique.

Keywords: 3D printing, complex fracture, surgical treatment, preoperative planning

Introduction

When a fracture or a deformity involves joint surfaces, there's no doubt that it will be a great challenge for surgeons to classify them and plan the procedure because of their irregular anatomical structures, and limited anatomical information and other factors. Plain x-rays and CT scans, both are used to diagnose and identify the fracture configurations in orthopedics. The former presents a superimposed image of the bones, and the other gives a relatively clear picture of the joint surfaces, but still cannot tell the spatial relationships between the fracture-fragments [1]. Therefore, surgeons have to depend on their experiences and spatial imaginations to understand the fracture configurations. The main goals of the treatment are to restore the anatomical construction of the articular surface and achieve the alignments, so it is important to understand the osseous anatomy and planning the procedure preoperatively [2]. 3D (Three-dimensional) printing, also known as additive manufacturing or rapid prototyping (RP), is a relatively low-cost technology that can create solid objects from a computer-designed virtual reconstruction models [3]. Here are five different methods for "RP", FDM (Fused Deposition Modeling) which is widely used for its advantages like low-cost and relatively high accuracy. And the other four are those employing a stereo-lithography, selective laser sintering, laminated object manufacturing, and inkjet printing. So the brief process of 3D printing is using the specialized software to convert the DICOM (Digital Imaging and Communications in Medicine) data to a STL (Standard Triangulation Language) file format that can be utilized by the 3D printing machine [4]. With the help of the model, surgeons can observe the fracture details from any angle, select the proper plate and contour it preoperatively, plan the procedures by simulating surgeries directly on the models and design the personalized screw navigators in order to reduce the time and intraoperative blood loss and other potential risks.

The applications of 3D printing technique in orthopedics

Acetabulum, tibial plateau and ankle joints etc. have complex anatomical structures, and the fractures of these often involve the joint sur-

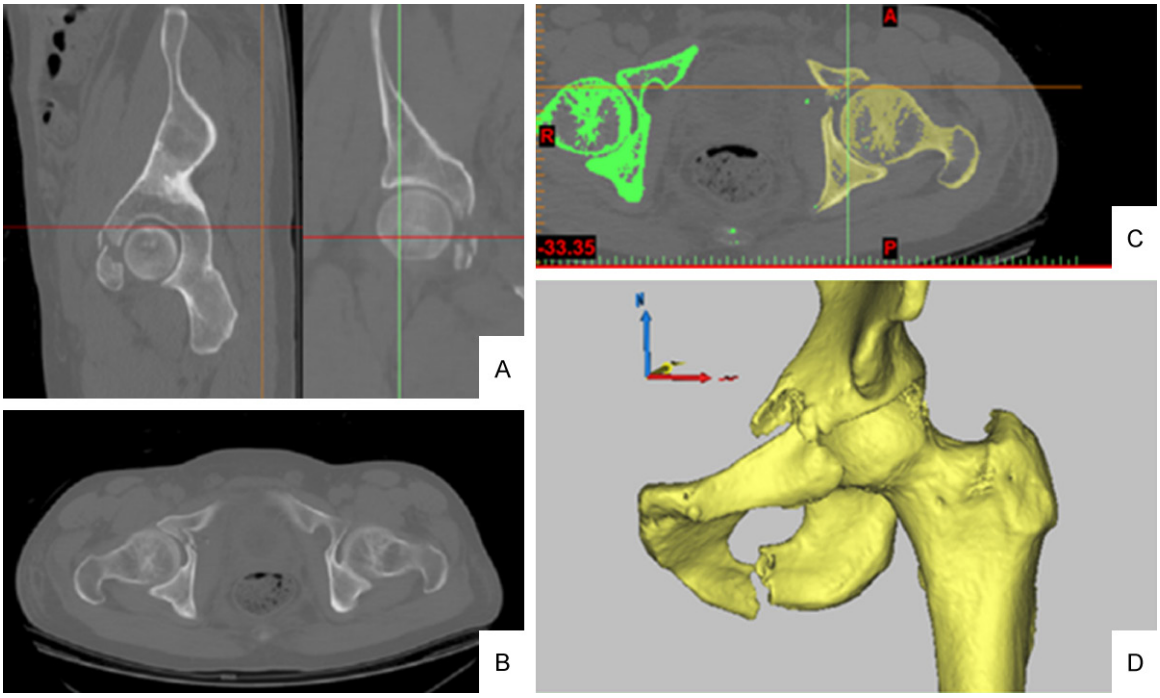

Figure 1. CT DICOM data (A, B) and computer-designed virtual models (C, D) of a 42 year-old male patient revealed a displaced fracture on the right acetabulum involving the inferior pubic ramus.

faces. So we must fully understand the osseous anatomy of the fracture before we make a decision. Surgery has been a common treatment option for those types of fractures. Thus there are some common surgical options, such as Open Reduction and Internal Fixation (ORIF), External Fixation (EF), Minimally Invasive Plate Osteosynthesis (MIPO) and so on. When we manage these types of fractures, it's important to restore the anatomical structures of the affected bone which involves articular surfaces. But conventional imaging such as X-ray and Computed tomography scans cannot show the osseous anatomy clearly, so surgeons usually depend on their experiences and spatial imaginations to make the diagnose and plan the procedure. Once the surgery is unsuccessful, it will lead to many complications, for instance, infection and osteoarthritis which will severely affect patients' life quality and long-term function.

Therefore, a precisely designed pre-operative planning and fully understanding of the fracture patterns are required in such cases. And a RP model of a fractured bone can be evaluated and used for preoperative planning, in order to select surgical approaches and decide the proper position of the osteosynthesis hardware and the optimal trajectories for screws.

Acetabular fractures

Anatomical reduction is required for good long-term function in the cases of acetabular fractures. Fully understanding of acetabular fractures is necessary for evaluation, classification and pre-operative planning, as well as to improve the reduction rates and patient outcomes. Bizzotto et al. concluded that the RP model gives better understating of the osseous anatomy of the fractured bone in comparison with the images of 2D and 3D reconstruction [5]. Francisco Chana-Rodríguez et al. in 2016 study suggesting that pre-planned procedure by using a printed physical model of the healthy site can achieve an acceptable outcome in both reducing the operating room time and achieving an anatomical reduction by presenting a case of an acetabular fracture with fractures of posterior wall [6]. They also reported that there were no intermediaries in the whole process of RP, and the cost was acceptable. Nie et al. in 2016 study of 98 patients with complex pelvis and acetabular fractures underwent surgery reported that, in comparison with the conventional group, the 3D group has advantages in blood loss, transfusion and operative time ($P<0.05$), and the anatomical reduction rates of the 3D and conventional group

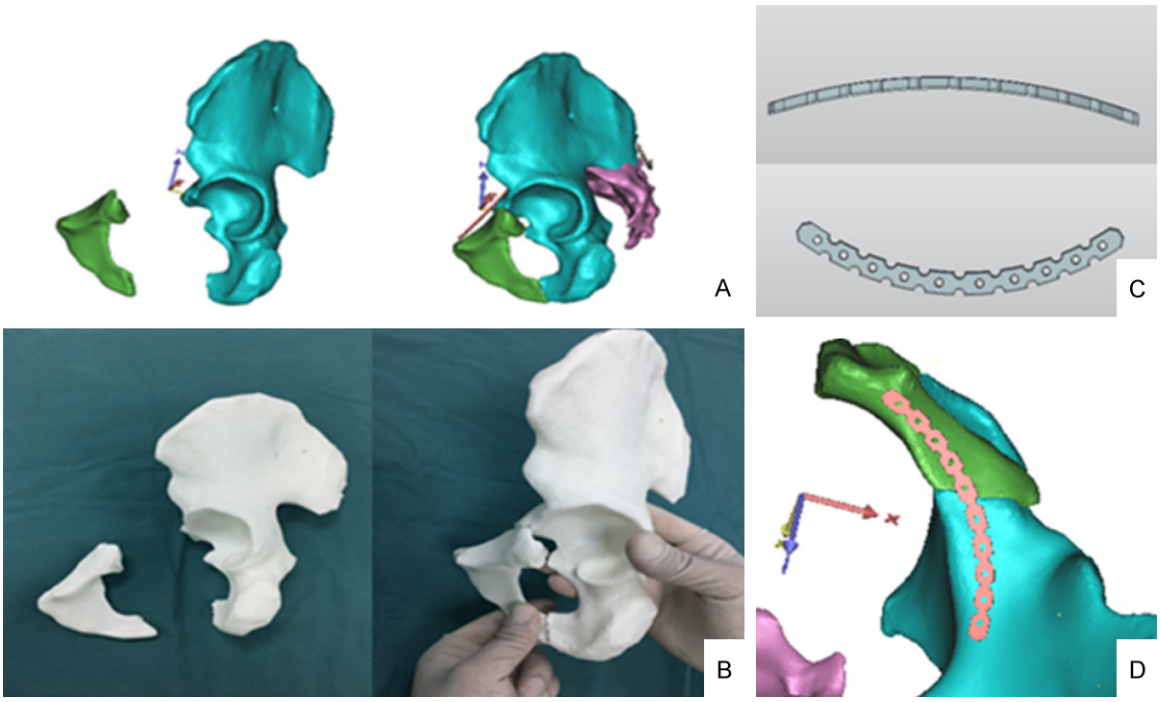

Figure 2. Computer-designed virtual models (A), Rapid prototyping models (B), and pre-plan the procedure (C, D).

were 90.0% (0-1 mm) and 51.4% (0-1 mm) [7]. Zhou et al. suggested that three-dimensional reconstruction technique is easy to use, and can meet the requirement of contouring plates intraoperatively [8]. This technique can significantly improve the outcomes of surgeries through providing a better understanding of the anatomy and better preoperative planning [5, 9, 10].

In our study, despite the fact that it took a relatively longer time to get the RP model, 10 to 25 minutes were saved in the operating room, the time which in the past be spent on selecting and contouring instruments during the surgery. And the intraoperative bleeding was reduced as well. Here, we present a case of 42-year-old male patient was transferred to our department from another hospital with a history of a car crash injury for 4 days, and the diagnosis of a fracture of sacrum and left acetabulum. On examination, the left leg showed apparent shortening. The CT scan of the pelvis was taken after stabilization and revealed a displaced fracture on the right acetabulum involving the inferior pubic ramus (**Figure 1A-C**). Using DICOM files of the patient's CT data a three-dimensional virtual reconstruction model of the fractured acetabulum was created by MIMICS (Materialise's Interactive Medical Image Control System) software version v.17.0 (**Figure 1D**). After a virtual plate was designed by UG (Unigraphics NX, version 8.0 (**Figure 2C**), we simulated the surgical procedure preoperatively including reducing the fracture, selecting the proper position for the plate and the fixation by 3-Matic software (**Figure 2A**, **2B**, **2D**). We preselected the proper plate one by one over the printed model as well as the ideal position before the actual operation (**Figure 3A**, **3B**). The postoperative X-ray showed that the position of the implant was favorable (**Figure 3C**). The operation was successful and the results were satisfactory. No serious complications occurred in our case.

Tibial plateau fractures

Fractures of the tibial plateau account for 1-2 percent of all the fractures, and 8 percent of which occurs in the elderly. Tibial plateau fractures often involve articular surface which brings challenges to the treatment. The goal of operative treatment is to restore congruity of the articular surface and axial alignment of lower extremity, and enable early mobilization for the patient to improve functional outcomes and to reduce the risk of complications, such

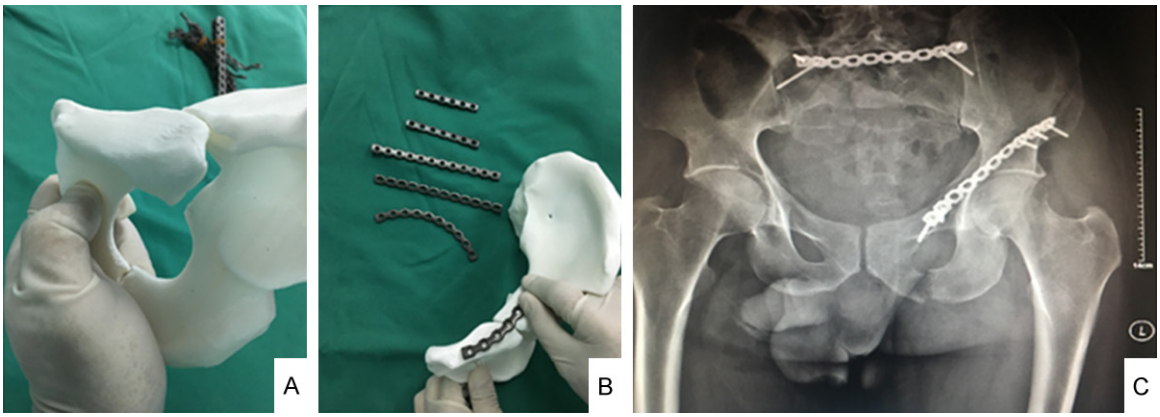

Figure 3. Simulating the surgical procedure on the model (A, B) and the post-operative radiograph was taken (C).

as post-traumatic arthritis etc. [11]. Peng et al. in 2016 prospective study of 3D printing-assisted treatment malunited tibial plateau fracture concluded that using 3D printed physical model gives more detailed information about osseous anatomy, fracture locations, displacement, collapsed depth etc. [12]. Unlike the conventional plane X-rays and CT scans, this new technique enables a more effective pre-operative planning in order to shorten the surgical time, and decrease intraoperative radiation, reduce the risk of complications [13, 14].

Distal radius fractures

A distal radius fracture is a common bone fracture of a forearm, which is usually caused by high-energy trauma and often impacted fractures of the articular surface of the distal radius with displacement of the fragments. The required type of treatment depends on many factors, such as palmar tilt, radial shortening, displacement and stability of the fracture fragments. Failure of non-operative treatment is common and is the largest risk of an adverse outcome. Surgery is a common treatment option, especially for comminuted intra-articular distal radius fracture. Nicola Bizzotto, Ivan Tami et al. reported that this new technique improves the surgical outcomes of the articular fractures with articular gaps or steps of ≥ 2 mm, or/and with a multi-fragmentary pattern in their 2016 study of 40 patients with distal radius fracture (AO classification, 23-A/B/C) underwent ORIF [3]. Unlike the conventional images, physical models can also provide better understanding and improve patients' compliance. Philipp et al. in 2015 study of corrective osteotomy presented a patient diagnosed with malunited distal radius fracture, and reported that the total time spent in operative room was 60 minutes in comparison with conventional surgery (an average of approximately 90 minutes). And postoperatively, the osteotomy was healed, and the patient recovered to full wrist range of motion and without any pain detected in a one-year follow-up observation [15]. The 3D printed patient-specific osteotomy templates and guides can be safe to use for drilling and cutting, and also can save time by simplifying the surgical procedures.

Foot and ankle fractures

Ren-li Zeng et al. in 2015 study of 32 comminuted fractures of ankle joints treated with internal fixation using 3D printing technique, reported that 3D technique assisted surgery can reduce the surgical time and intraoperative blood loss. And VAS score is relatively lower than the conventional group and faster fracture unions [16]. A case report study of 2016 by James R. Jastifer et al. presented a 46-year-old male patient with malunion of the fibula after treated non-operatively. They virtually plan the corrective osteotomy and simulate it on the printed model, the surgery was performed as planned. As a result, in a 7-month follow-up visit, the patient achieved union at the osteotomy site. And the patient's visual analog scale score had improved to a score of 2 of 10. His American Orthopedic Foot and Ankle Society ankle-hindfoot scale score was 89 of 100 compared with the preoperative score 8 of 10 and 47 of 100 respectively [17]. Chung et al. in their 2014 study of displaced intraarticular calcane-

al fracture treated by Minimally Invasive Fixation using RP, they printed the normal side with mirror technique which is likely to be similar to the affected calcaneus before the injury to help decide the proper position of the plate [18].

Medical education

Li et al. 2015 study of testing 120 medical students in understanding of complex spinal fractures, reported that 3D group was the first finished all the answers with higher scores in comparison with other CT groups (plain CT scan group and CT scan 3D reconstruction group) [19]. Its application in medical education helps to save abundant valuable medical resources by printing the reproduction of bones, and allows more students to study and identify the fracture patterns, and practice varies surgical procedures on the model.

Recommendations-conclusion

3D printing is a relatively low cost technology that reproduces a real-size physical model of fractured bone. Surgeons use this model in classifying and diagnosing complex fractures, and even in pre-selecting the appropriate plates and screws, and in simulating the surgical procedures to reduce surgical time and blood loss, and communicating with patients about their conditions and the process of the surgery in order to raise the efficiency of patient-doctor conversation. This technique can also provide an opportunity for medical students to learn and practice surgical procedures themselves. However, this technique has some limitations, for example, printed models fail to include soft tissues around the fracture such as muscles, nerve and vessels, thus it cannot completely represent the actual fracture condition. And also, there are many factors that can affect the accuracy of the models, for instance, slice thickness of the CT scan image, technical capabilities of the printer, and the digital processing made on the 3D data such as surface rendering and smoothing filters. It takes several hours in the process from obtaining the data and designing the three-dimensional reconstruction of the fracture to printing the physical model. Despite the fact that it takes relatively longer time preoperatively, it saves the operative room time and blood loss, and reduces radiation exposure, and provides stable fixation and early mobilization, especially, in cases that managing complex dislocated fracture with irregular osseous anatomy and involves articular surfaces. In some places, like Xinjiang, with this new technology, surgeons can provide pre-operative plans and display surgical procedures for hospitals those in remote areas.

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Disclosure of conflict of interest

None.

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