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3D printing and its applications in orthopaedic trauma: A technological marvel

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ABSTRACT

Background: With rapid emergence of 3D printing technology, surgeons have recently started to apply this for nearly all areas of orthopaedic trauma surgery. Computed tomography or magnetic resonance images of trauma patients can be utilized for making graspable objects from 3D reconstructed images. Patient specific anatomical models can thereby be created. They enhance surgeon's knowledge of their patients' precise patho-anatomy, regarding both traumatized bones and soft tissue as well as normal areas, and therefore help in accurate preoperative planning. 3D printed patient specific instrumentation can help to achieve precise implant placement, and better surgical results. Most importantly, customized implants, casts, orthoses and prosthetics can be manufactured to match an individual's anatomy. Three dimensional (3D) printing, also called as 'additive manufacturing' and 'rapid prototyping' is considered as the "second industrial revolution", and this appears to be especially true for orthopaedic trauma surgery.
Methods: A literature search was performed for extracting all papers related to 3D Printing applications in orthopaedics and allied sciences on the Pubmed, and SCOPUS; using suitable key terms and Boolean operators ("3D Printing" OR "3 dimensional printing" OR "3D printed" OR "additive manufacturing" OR "rapid prototyping") AND ("Orthopaedics" OR "Orthopaedics") AND ("Trauma" OR "Injury")in June 2018. Search was also performed in Web of Science, Cochrane Central Register of Controlled Trials and Cochrane Database of Systematic Reviews. No limits were set on the time period or evidence level, as 3D printing in orthopaedics is relatively recent and mainly low level evidence is available. Titles and abstracts were screened and all duplicate and unrelated papers were excluded. Papers related to orthopaedic trauma were manually selected for this review.
Results: The search on Pubmed retrieved 144 Papers and similar search on SCOPUS retrieved 94 papers. Additional searches did not reveal more relevant papers. After excluding duplicates and unrelated papers, and on screening of titles and abstracts, 59 papers were considered for review. Papers related to spine fractures only were not included, as they have been covered in another paper in this journal issue.
Conclusion: All over the world, orthopaedic Surgeon's and allied professionals and scientists are enthusiastically using 3D printing technology for designing patient specific models, instrumentation, implants, orthosis and prosthesis, besides 3D bioprinting of bone and cartilage scaffolding, and the same has been applied for nearly all areas of orthopaedic trauma surgery, from head to foot.

1. Introduction

With rapid emergence of 3D printing (3DP) technology, surgeons have recently started to apply this in nearly all areas of orthopaedic trauma surgery. Computed tomography or magnetic resonance images of trauma patients can be utilized for making graspable objects from 3D reconstructed images. Patient specific anatomical models can thereby be created. They enhance surgeons' knowledge of their patients' precise patho-anatomy, regarding both traumatized bones and soft tissue as well as normal areas, and therefore help in accurate preoperative planning. 3D printed patient specific instrumentation can help to achieve precise implant placement, and better surgical results. Most importantly, customized implants can be manufactured to match an individual's

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anatomy. The role of 3D printing is not limited to the operation theatre as it can also help in the manufacture of better individualized orthoses and prosthetics.[1–5]

3D printing converts a computer-generated 3D image into a physical model. 3D model creation is based on 3D DICOM (digital imaging and communications in medicine) format data derived from CT or MRI. It needs to be converted into a file format which can be recognized by the 3D printer. The DICOM file is therefore uploaded into a program (e.g., Mimics from Materialize for Windows, Osirix (free-open source) for Mac) which enables 3D reconstruction of the image. It is then exported in a file format (stereolithography [STL]) making it readable by software (computer aided design- CAD) which is used to design 3D objects. Defects or errors in the STL file are corrected before exporting to the 3D printer. 3D printers "additively manufacture" or create objects layer by layer. Old manufacturing methods involved the subtraction of layers from raw material, but 3D printing works by "additive manufacturing", whereby the raw material is "added" layer by layer in a predetermined fashion, thereby achieving precise 3D framework. Industry-grade printers utilise lasers to accurately sinter granular substrates such as metal or plastic powders. On completion of each layer, the printer adds a new layer of unfused powder over the previous one and the cycle continues till the entire model is generated. These printers have high print speeds, can recycle unfused powder, and can use stronger materials with higher melting points such as titanium. Layers are joined and final shape is created. One can create unique patient-specific materials more cost-effectively than conventional implant manufacturing. 3D printing can make any complex shape and solid and porous sections can be combined for providing optimal strength and performance.[6–8]

Whilst initially, the products of 3DP were used for complex cases, it is now becoming routine, and is likely to have a significant impact on all of our practices in the coming years, as the have been seen to offer several additional advantages. They can help in the training of novice surgeons in complicated surgical areas like pelvi-acetabular trauma. The model can be sterilized and reviewed Intraoperatively if necessary.[6,9,10] Preoperative review of the 3D model allows the surgeon to anticipate intraoperative difficulties, select optimal surgical approach, plan implant placement, visualise screw trajectory etc. and access the need for special equipment. Finally, it can also help in evaluation of restoration of individual anatomy after surgery. In some cases, it can help in making a precise anatomical diagnosis, where it is not otherwise obvious, and in planning subsequent management. 3D printing of individualized artificial cartilage scaffolds and 3D bioprinting are some areas of growing interest. Three dimensional (3D) printing, also called as 'additive manufacturing' and 'rapid prototyping' is considered as the "second industrial revolution", and this appears to be especially true for orthopaedic trauma surgery.[1–10] To the best of our knowledge, there is no paper in the English literature which attempts to comprehensively review the applications of 3d printing in different areas of orthopaedic trauma. In this paper we have reviewed the literature on applications of 3D printing in orthopaedic trauma, focusing on limb trauma and pelvic injury in particular as other areas like spine have been covered in other papers in the issue.

2. Methods

A literature search was performed in order to extract all papers related to 3D Printing applications in orthopaedics and allied sciences on the Pubmed and SCOPUS databases; using suitable key words and Boolean operators ("3D Printing" OR "3 dimensional printing" OR "3D printed" OR "additive manufacturing" OR "rapid prototyping") AND ("Orthopaedics" OR "Orthopaedics"). AND ("Trauma" OR "Injury")in June 2018. Search was also attempted in Web of Science, Cochrane Central Register of Controlled Trials, and Cochrane Database of Systematic Reviews (Cochrane library). The search strategy has been depicted in Table 1. Titles and abstracts of these papers were reviewed and duplicate papers and papers not related to Orthopaedic trauma were manually excluded. We also looked at the reference lists of papers for getting more relevant literature. Selected papers were then considered for qualitative synthesis. Papers related to spine fractures only were not included, as they have been covered in another paper in this journal issue.

No limits were set on the time period or level of evidence, as 3D printing in orthopaedics is relatively recent and evidence available is mainly limited to low level studies.

3. Results

The search on Pubmed retrieved 144 Papers and similar search on SCOPUS retrieved 94 papers. Additional searches did not reveal more relevant papers. After excluding duplicates and unrelated papers, and on screening of titles and abstracts, 59 papers were considered for review(Fig. 1).

4. Discussion

3D printing has been increasingly used by several authors in the field of orthopaedic trauma for the last 2 decades. In 1997, Kacl et al. found that rapid prototyping might be useful for teaching and surgical planning. His paper did not reveal any difference between stereolithography and workstation-based 3-D reformations in the management of intra-articular calcaneal fractures.[11] Brown et al., in 2003, reported that 3-D printing helped in surgical planning and in reducing the exposure of radiation during 117 complex surgical cases.[12] Guarino et alien 2007, reported treatment of 10 patients with pediatric scoliosis and 3 complex pelvic fracture patients and concluded that 3-D printing improved the placement accuracy of pedicle and pelvic screws, and therefore decreased the risk of iatrogenic neurovascular trauma.[13] In the past decade the applications of 3D printing technology in orthopaedic trauma has seen a very rapid proliferation, and it now pervades nearly all anatomical areas.

5. Applications of 3D printing in specific anatomical areas of orthopaedic trauma

5.1. Upper limb

5.1.1. Acromion

Beliën et al used a 3D model for treatment of os acromiale and acromion fractures. Initially, a 3D acromial model was created and then a distal clavicular reconstruction plate was prebent to fit in the individual anatomical curvatures and shape of the acromion. They presented their experience on 5 cases, 3 had os acromiale and 2 had fractured acromion. Patients were evaluated using the Constant–Murley and DASH scores. The fracture or non-union had healed in all cases. If the surgery had been performed prior occurrence of additional damage (like an impingement syndrome), they saw that the patient's pain completely disappeared. The surgeon could prepare for the surgery in advance, which reduced the surgical time. The model could also be used to explain the patient and the operating team about the planned surgery.[14]

5.1.2. Clavicle

Jeong et al. devised minimally invasive plating for midshaft clavicular fractures utilizing intramedullary indirect reduction technique and prebent plates made with the help of 3D printed

Table 1
Search strategy.

Search Strategy	Key words combined with Boolean operators
1.	#1 “3D Printing” OR “3D printed” OR “3 dimensional printing” OR “additive manufacturing” OR “rapid prototyping”
2.	#2 “Orthopaedics” OR “Orthopaedics”
3.	#3 “Trauma” OR “Injury”
4.	#1 AND#2 AND#3

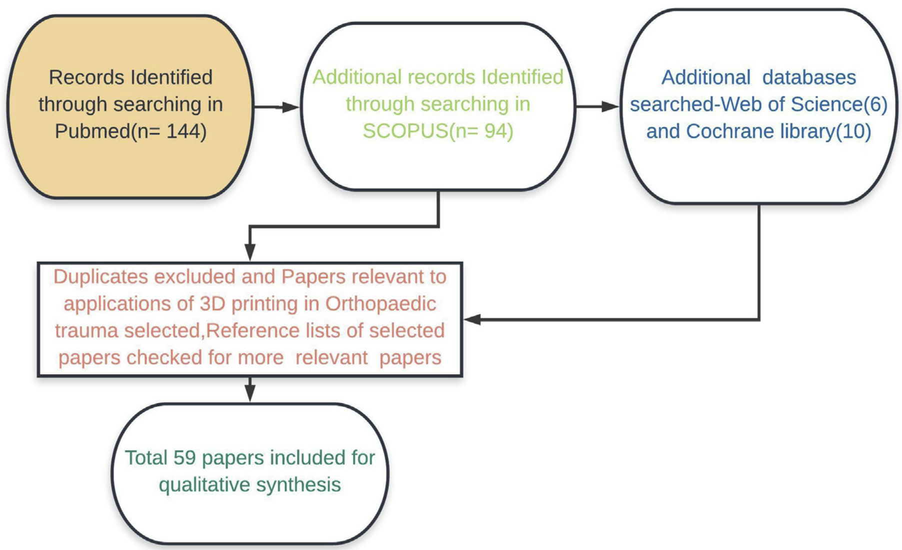

Fig. 1. Flowchart for searching selecting papers.

models. This allowed for fracture reduction, accurate plating and minimal soft tissue injury.[15] **Kim et al. also** used a 3D -printed clavicular model for presurgical planning and as tool during surgery for minimally invasive plating performed for displaced comminuted midshaft clavicular fractures. In this technique, CT scan of both clavicles was taken in cases with a unilateral comminuted displaced midshaft clavicular fracture. Both clavicles were then 3D printed to get real-size clavicular models. The uninjured clavicle was 3D printed into the opposite side model using mirror imaging technique to create a preinjury replica of the fractured side clavicle. The 3D-printed fractured clavicular model helped the surgeon to manipulate and observe exact anatomical replica of the fractured bone to rehearse fracture reduction prior to actual surgery. The 3D-printed uninjured clavicular model was used as a template for selecting the precontoured locking plate which best fitted the model. The plate was inserted through small incisions and fixed with locking screws without fracture site exposure. Seven comminuted clavicular fractures thus treated, united nicely. Authors conclude that this procedure was suitable for a unilateral comminuted displaced midshaft clavicular fracture, when achieving anatomic reduction by open reduction technique seemed difficult.[16]

5.1.3. Proximal humerus

You et al. treated 66 old patients aged 61–76 years with complicated proximal humeral fractures, who were randomly assigned to two groups (34 patients in the test group and 32 patients in the control group). In the test group, 3D printing was used to build the 3D fracture model, using data acquired from thin-slice CT scan and processed by Mimics software. It helped in confirmation of diagnosis, designing individual surgical plan, simulating operative procedures and performing the operation as planned. In the control group, only thin-slice CT scan was applied for preoperative planning. Surgery duration, blood loss, fluoroscopy usage and time to union were compared. Screw lengths planned before the surgery and actually measured during the surgery were also compared. The 3D model was able to provide 360° visual display and palpatory sense of the direction and severity of the fracture dislocation, which helped in precise preoperative diagnosis, surgical planning and design, implant measurement, preselection of appropriate anatomical locking plate and surgical outcome simulation. Lesser surgical duration, lower blood loss, and lesser number of fluoroscopies were seen compared with the control group ($P < 0.05$).[17]

5.1.4. Distal humerus

Kim et al. used 3D-printed osteosynthesis plates for treating intercondylar humeral fractures. Thirteen patients with intercondylar humeral fractures were randomized for open reduction and internal fixation with either conventional plates ($n = 7$) or 3D-printed plates ($n = 6$) between March and October 2014. They were compared for operating time and elbow function at minimum 6 month follow-up. All cases were followed-up for an average of 10.6 months (range: 6–13 months). The 3D-printing group had a significantly smaller average operating time (70.6–12.1 min) than the conventional plating group (92.3–17.4 min). At the last follow-up, no significant difference was found between groups in cases with good to excellent elbow function, although 3D-printing cases had a slightly higher rate of good or excellent outcomes (83.1%) compared to the conventional plating (71.4%). The technique thus proved to be safe and effective.[18]

Zheng et al. treated 12 male and 6 female cases with cubitus varus deformities from January 2006 to May 2008 using templates created by rapid prototyping. The average age was 15.7 years (range 13–19 years). 3D CT imaging data were used and 3D models of cubitus were created using MIMICS software. Osteotomy templates best fitting the angle and range of osteotomy were "reversely" manufactured from the 3D model, by rapid prototyping and were used for guiding the corrective surgery. Correction was confirmed by postoperative radiographs. Average postoperative carrying angle in 18 patients with cubitus varus deformity was 7.3° (range, 5°–11°), with an average correction of 21.9° (range, 12°–41°) at 12–24 months' follow-up.[19]

Zheng et al. investigated a new navigation template for osteotomy in cubitus varus created by computer assisted design and 3D printing technique for feasibility and accuracy. Preoperative CT image data of 15 pediatric cases with cubitus varus between June 2015 and June 2016 were collected and individualized osteotomy navigation template matching the distal humerus was 3D printed. Osteotomy was performed with the assistance of this navigation template, followed by fixation with 2 Kirschner wires and immobilization in a long arm plaster in 20° of elbow flexion. No complication was observed, no revision surgery was necessary in any case and all had cosmetic appearance. Mean union time was 6.7 weeks (range, 6–8 weeks). Twelve patients had an excellent result and 2 had a good result according to Bellemore criteria. 3D printed guide thus appeared to be valuable for cubitus varus correction.[20]

Gemalmaz et al. treated an 18 years previously operated old male having 40° of cubitus varus deformity (with 20° flexion) following an 8 years old malunited right supracondylar humerus fracture, using a custom 3D printed resection guide during the surgery, and obtained a flawless osteotomy, accurate correction and nice functional outcome.[21]

Yang et al. treated 40 cases with elbow fractures, randomly divided into a 3D printing surgery group and a conventional surgery group with 20 cases in each. Surgery duration, blood loss, anatomical reductions achieved, complications and elbow function were compared between the two groups using unpaired t-tests. Advantages and the drawbacks of PLA and ABS materials were also compared A survey was used among orthopaedic surgeons for evaluating verisimilitude, real appearance, and effectiveness of the 3D printed model. Another survey was administered for evaluating doctor-patient communication. The 3D printing group showed smaller surgical time, smaller blood loss and greater elbow function score, compared to the conventional group. PLA is environment friendly, whereas ABS emits odour during printing. Curling of edges happened in the printing process in four of ten ABS models but in only single PLA model. PLA was thus found to be more appropriate material. Surgeons' scoring of the verisimilitude and effectiveness of the 3D model were higher. Patient satisfaction scoring for the 3D model was also higher.[22]

5.1.5. Distal radius

Muinck et al. systematically reviewed the literature on 3D planned corrective osteotomies for distal radial malunions. 3D-planning techniques addressed 3D-deformity that conventional planning techniques could not deal with. PubMed, EMBASE and the Cochrane library databases were searched for studies on 3D-planned osteotomies for cases with distal radial malunions. Fifteen studies including 68 patients were analysed. Palmar tilt, radial inclination and ulnar variance were significantly improved and restored to within 5 or 2 mm of their normal values in 96% of cases. Average grip strength, flexion–extension and pro-supination had also improved significantly. Complications were observed in 11 out of 68 cases (16%). Overall, 3D-planned corrective osteotomies appeared to be useful for the treatment of complex malunited distal radial fractures.[23]

5.1.6. Hand

Zang et al. Used 3D printing to plan thumb reconstructions with second toe transfer. From December 2013 to October 2015, thumbs of 5 cases with grade 3 thumb defects were reconstructed with a wrap-around flap and second toe transfer planned by 3D printing technique. CT scans of hands and feet were fed into Boholo surgical simulation software. Mirror image of the injured thumb was made using the uninjured thumb. Models of the great toe and the second toe were made for understanding the doner site dimensions and also for repairing the donor site defect by planning suitable iliac bone and superficial circumflex iliac artery flaps. Polylactic acid models of the donor toe and reconstructed thumb were 3D printed. Wrap-around flap of the first dorsal metatarsal artery and vein with bone and joint of the second toe was based on the 3D model of the donor site. Sensation was restored by anastomosing the dorsal nerve of the foot and the plantar digital nerve of the great toe. Exercises were started 2 weeks after the operation. All reconstructed thumbs had survived, but partial flap necrosis had happened in one case, which was managed on dressings. Reconstructed thumbs had overall good appearance and functionality.[24]

5.1.7. Miscellaneous

Taylor et al. utilized 3D printing technology as an adjunct in vascularized bone flap transfers to the upper limb. Using open source software and CT data, 3D models were printed in the surgeon's office and vascularized bone flaps were created during surgery based on it, examples included medial femoral trochlea (MFT) flap for avascular necrosis and nonunion of scaphoid, MFT flap for avascular necrosis and nonunion of lunate, medial femoral condyle (MFC) flap for wrist arthrodesis, and free fibular osteocutaneous flap for distal radial infected nonunion. 3D model based templates facilitated rapid and accurate contouring of vascularized bone flaps in situ, prior to ligation of the donor pedicle.[25]

3D printed implants for replacing eroded glenoids after total shoulder replacement surgery have shown excellent results.[26] 3D printed prosthesis modeled on the contralateral wrist for replacement of whole scaphoid or lunate, following avascular necrosis has suitable geometry, mechanical properties, and cytocompatibility properties for *in vivo* usage.[27] Berg et al. have experimentally explored the use of 3D models of fractured and intact scaphoids and prebent plates created using the model, and advocated for its usage after economic justification.[28]

5.2. Lower limb

5.2.1. Acetabulum

Hurson et al. reported 12 acetabular fracture cases classified and planned using 3D printing before surgery and proved that these models appreciably assisted surgeons in understanding the individual fracture anatomy, more so for new surgeons.[29] **Maini et al** in their case control study with 10 cases in whom 3 d printing was used for planning and precontoured plate manufacturing and 11 controls in whom conventional planning and operation was performed, found that patient-specific pre-contoured plates for acetabular fractures made using 3D model was a better implant than intra-operatively contoured plate. Also, real-time 3D pelvis model was found to be an accurate technique for pre-operative planning in acetabular fractures.[30] **Bagaria et al.** found that 3D printing could help surgeons understand complex fractures and achieve near anatomical reduction.[31]

Kim et al. retrospectively analysed their experience in 14 cases with acetabular fractures and 10 cases with clavicular fractures treated utilizing 3D printed bone models.3D printed acetabular models helped in understanding complex pathoanatomy of acetabular fracture and in planning the appropriate positioning of reduction clamps, screws entry sites and trajectories. Prebending reconstruction plates reduced surgical time. Optimal position of guide wire planned during the simulation was used as a reference during the real surgery for percutaneous posterior column screw fixation and helped resident training, besides precise positioning. Optimal positioning of anatomical plates were similarly planned using 3D printed clavicular models, and gave nice results.[32] Role of 3D printing in acetabular fractures has been extensively studied by other authors.

5.2.2. Pelvis

Cai et al. used 3D printing technique for minimally invasive cannulated screw fixation of unstable pelvic fractures in 137 cases operated between 2014 and 2016. Participants had been assigned to 3D printing group (n = 65) and control group (n = 72), and were assessed retrospectively for operative time, intraoperative fluoroscopy needs, postoperative reduction, fracture healing time, and function on follow-up. No significant difference was there in these two groups with regard age, gender, fracture type, time from injury to operation, injury cause, and combined injury. Duration of surgery and mean number of fluoroscopies were significantly more in the control group. Reduction was scored excellent in 21/65 patients (32.3%) and good in 30/65 patients (46.2%) in the 3D printing group, whereas 22/72 patients (30.6%) scored excellent and 36/72 patients (50%) good in the control group on Matta radiological scoring systems. There were 27/65 (41.5%) excellent and 26/65 (40%) good patients in the 3D printing group as compared to 30/72 (41.7%) excellent and 28/72 (38.9%) good patients in the control group using Majeed functional scoring criteria. Overall, no significant difference in function outcomes was there between the two groups.[33]

Wu et al. assessed 3D printing technology for operative treatment of old pelvic fractures. Initially, 16 dried cadaveric pelvic human bones were used for confirming the anatomical precision of the 3D models created by utilizing radiographic data. Then, 9 patients from January 2009 to April 2013 were used for evaluation of the surgery based on the 3D printed models. The pelvic injuries were all type C, and the average time from injury to reconstruction was 11 weeks (range: 8–17 weeks). Model creation from CT DICOM data needed 7 h (range: 6–9 h). There was good correlation between the preoperative planning and postoperative follow-up radiographs in all 9 patients. No wound problem, or nonunion occurred. The result was excellent in 2 cases, good in 5, and poor in 2 patients based on the Majeed score.[34]

Zeng et al. evaluated the efficacy 3D printing assisted internal fixation for unstable pelvic fracture using minimally invasive pararectus approach in 38 cases between August 2012 and February 2014. The best entry points, plate positioning and screw trajectories were rehearsed in simulated surgery on 3D printed pelvic model. Radiographs confirmed accurate implant placement. Outcomes were 97.37% excellent and good on Matta scoring and 94.4% excellent and good on Majeed assessment. The average surgical time was 110 min, intraoperative blood loss 320 ml, and incision length 6.5 cm. The technique was thus feasible, safe and effective with advantages of minimal trauma, little bleeding, rapid healing and accurate reduction.[35] Interestingly, 3D printed intraoperative guides have also been used in pelvic and hip surgery for curved peri-acetabular osteotomies[36]

5.2.3. Distal femur

Lin et al. studied 21 cases with distal femoral fractures treated using 3D printing with Mimics software. Positioning of plates and screws were rehearsed by the navigation module. 3D coordinate values of screws entry points were obtained. 21 plates and 180 screws were placed with the assistance of navigation module. CT with 3D reconstruction was performed in 21 cases postoperatively. Plate position was consistent with prediction Mimics software. with no significant differences in spatial location of screw entry sites.[37]

Arnal-Burró et al. used 3D printed cutting guides for opening-wedge distal femoral osteotomies in 12 consecutive cases and compared them with 20 controls in whom traditional technique was used. Axial correction accuracy, surgical time, fluoroscopic time and costs were optimum in the 3D guides group.[38]

Similarly, **Shi et al.** performed medial closing-wedge distal femoral osteotomy (MCWDFO) assisted by 3D-printed cutting guides and locking guides to treat valgus knee malalignment combined with lateral compartment disease in 12 cases and by conventional technique in 21 cases. 3D-printed cutting and locking guides can increased the precision of the MCWDFO in patients with lateral compartment disease and valgus deformity, made surgery shorter and reduced fluoroscopic time.[39] Interestingly, **Chen et al.** also concluded that 3D printed cutting blocks could greatly improve the accuracy of distal femoral osteotomy for correction of valgus knees with osteoarthritis.[40]

5.2.4. ACL reconstruction

Rankin et al. designed a patient-specific, arthroscopic ACL femoral tunnel guide for anatomical positioning of ACL graft in the femoral tunnel based on MRI scan of the patient's uninjured contralateral knee, for identifying the femoral footprint relative to the borders of the femoral articular cartilage, in their proof of concept study. Transparent acrylic based photopolymer, PA220 plastic and 316 L stainless steel patient-specific ACL femoral tunnel guides were created by 3D printing technique. There was no significant difference in size and positioning of the center of the ACL femoral footprint guide to MRI site.[41]

5.2.5. Proximal tibia

Huang H et al. applied 3D Printing technique managing tibial plateau fractures and accessed for fixation outcomes in term of the deviations of screw placement between preoperative and postoperative screw trajectories were measured and compared, including the screw lengths, entry point locations and screw directions. They achieved optimally accurate fixation outcomes. There was no significant difference in the deviations of screw length, entry point and projection angle between the ideal and real screw trajectories.[42,43]

Giannetti et al compared the outcomes after minimally invasive reduction and internal fixation with and without using 3D printing for patients with displaced tibial plateau fractures in 40 consecutive adult cases, 16 cases had preoperative and intraoperative 3D-model, while 24 cases had only CT images. Significant reduction in surgical time, blood loss and radiation exposure was observed in 3D printing group. There were no complications, and functional outcomes were equivalent.[44]

Vaishya et al treated a 36-year-old male with Schatzker type 2 right proximal tibial fracture following road traffic accident, using 3D-printed model for delineating fracture pattern and identifying exact placement of the plate and the trajectories of the screws. Using 3D-printed model, it was found that the fracture required an extra screw from above the proximal end of the plate to fix the fragments adequately. LISS system was used, along with an extra 7 mm cancellous screw proximally to achieve anatomic reduction with minimal soft-tissue dissection and blood loss. Surgeon could demonstrate the plan preoperatively to the patient, and all this incurred minimal extra cost. Thus, this technology can be quite useful in the Indian set up.[6]

Yang et al. studied of 3D printing assisted osteotomy for the treatment of malunited lateral plateau fractures in 7 patients from September 2012 to September 2014. CT image data were utilized for 3D reconstruction. The original fracture types were 3 type I, 1 type II and 3 type III as per Schatzker classification. Mean lateral tibial plateau collapse was 9.4 mm (range from 4 mm to 12 mm). 3D printing technology was helpful in accurately planning and performing the osteotomy, reduced the risk of postoperative deformity, decreased intraoperative blood loss, shortened the surgical time.[45]

5.2.6. Tibial Pilon and malleolar fractures

Chung et al. used 3D printing to understand complex fracture patterns, preoperative templating, selection of anatomical plates and planning screw trajectories for reduction and fixation of complex distal tibial fractures and achieved nice results.[46]

5.2.7. Talus

Wu et al. investigated 3D printing techniques for achieving optimal posterior screw placement and safe zones geometry for screw fixation of talar neck using CT data of 15 normal feet. Mimics software was used for 3D reconstruction and 4 mm screws were simulated from lateral tubercle of posterior process to talar head. Screw trajectories and lengths at 9 locations which did not breach the cortex were evaluated. Farthest and nearest points of the safe zone to the subtalar joint, anteversion angle-parallel to the sagittal plane, and horizontal angle-perpendicular to the sagittal plane, were also measured. The safe zone was found between the 30% location and the 60% location; the width of each safe zone was $13.6^\circ \pm 1.4^\circ$; the maximum height of each safe zone was $7.8^\circ \pm 1.2^\circ$.The safe zone of posterior screw fixation were defined, assuming fractures to be reduced. It may help to enhance stability, shorten the surgical time and decrease surgical complications.[47]

5.2.8. Calcaneum

Chung et al. used 3D printing to create models of calcaneal fractures and intact ipsilateral calcaneum by mirror imaging from the opposite side. They also made preshaped calcaneal plates and utilized these for percutaneous fixation of calcaneal fractures[48]

Wu M et al. evaluated the effectiveness 3D printing assisted percutaneous minimally invasive reduction and cannulated screw fixation for intraarticular calcaneal fractures in 19 feet treated from March 2015 to May 2016.12 cases were type II, 7 cases were type III, by Saunders, whereas 13 cases were tongue type and 6 cases were joint-depression type by Essex-Lopresti classification,. A thin slice CT scan of bilateral calcanei was taken and mirror image of contralateral side (to achieve pre-fracture anatomy) and fractured side calcaneal models were printed. Bohler and Gissane angles measured on X-ray films showed significant improvement immediately after operation and did not change significantly on last follow-up. The AOFAS score was 76–100 (mean 88.2), and the results were excellent in 10 feet, good in 7, and fair in 2.[49]

5.2.9. Ankle ligament reconstruction

Sha et al. studied anatomical reconstruction of lateral ankle ligaments by making fibular channels with patient-specific navigational template in 15 cases with chronic ankle instability treated between August 2010 and February 2014. Using the 3D template, fibular channels were made easily and lateral ligaments were precisely reconstructed safely and individually.[50]

5.3. Miscellaneous topics

5.3.1. Atypical femoral fracture: bowed femur

Park et al. used preoperative templating and 3D printed model to study technical difficulties encountered in using commercially available intramedullary nailing systems for treating atypical femoral with severe bowing. The 3D printing-modeled femur had an average anterior bow radius of curvature of 772 mm and a lateral bowing angle of 15.48°. Position of nail in the medullary canal, perforation of femoral cortex by distal tip, and site of perforation in relation to the knee joint were studied. In the sagittal plane, the unreamed femoral nail, cannulated femoral nail and Sirus nails were properly contained in the medullary canal, the same was true for the "opposite side" expert Asian femoral nail and Zimmer Natural Nail. Only Sirus nail was contained in the coronal plane. Distal tips of all other nails perforated the anterior cortex, at distances ranging from 2.8 to 11.7 cm above the distal femoral condylar end. On simulated fracture reduction none of the nails, including proximal femoral nail gave acceptable fracture reduction. Fitting of these nails can be improved by using a nailing system with a small radius of curvature and by applying patient specific techniques.[51]

5.3.2. Validity of 'Mirroring'

Most surgeons consider bilateral bones to be symmetrical and use mirror imaging 3D technology without actually judging their symmetry. **Zhang W et al.** measured long axis and short axis at the three selected transverse sections of bilateral tibia and femora; at 5, 10 and 15 cms from each end to judge the symmetry on CT images. They printed full-size mirror image of opposite long bone which is considered similar to the affected side and used it as a reference for reduction of fractures.78 cases with lower limb fractures were included and 24 groups of data were generated. Significant differences were found between the short axes of the left and right femoral condyles 5 cm above intercondylar keel, and short axis of distal tibia 15 cm above the talar dome. No significant difference was detected between the left and right sides in any of the other 22 groups. The "Comparison of long axis and short axis of three equidistant transverse sections" allows one to judge the symmetry of the bilateral long bones, and prevents blind preoperative planning with contralateral mirror model directly.[52]

Bagaria et al., in a multicetric study involving 5 surgeons, created 3D printed biomodels for 50 surgical cases including periarticular fractures (24), pelvic fractures (11), complex primary (7), and revision replacement surgeries (8) using CT scan data and used these for understanding pathoanatomy and conducting simulated surgery. Models were sterilized for intraoperative referencing. Models provided information in addition to conventional imaging that enhanced surgeon's understanding of complicated pathoanatomy. Preoperative planning, surgical rehearsal, surgical simulation, intraoperative referencing, navigation, preoperative implant selection, and inventory management were all its advantages besides reduced operating time and better surgical accuracy. All researchers agreed that they would recommend this to other surgeons, besides using it personally.[53]

5.3.3. External fixation

Qiao et al. used 3D printing and computer-assisted reduction techniques to develop a customized external fixator which can assist fracture reduction. CT data was used for reconstituting and reducing the 3D image of the fracture, and based on this Q-Fixator was created by 3D printing techniques. Experiments on three fracture models demonstrated nice reduction results. It allowed easy manipulation, accurate reduction, was minimally invasive and easy. Stress adjustment and fracture healing optimization may be other future applications.[54]

Table 2
Table summarizing applications of 3D Printing in different areas of orthopaedic trauma.

S No.	Anatomical Region	Applications of 3D Printing
Upper Limb		
1	Acromion	3D model used for plate pre-contouring[14]
2	Clavicle	3D model used for planning and plate pre-contouring[15,16]
3	Proximal Humerus	3D model used for planning[17]
4	Distal Humerus and elbow	3D-printed plates,[18] templates and guides[19–21], 3D model[22]
5	Distal radius	3D planned osteotomies[23]
6	Hand	3D model for planning thumb reconstruction,[24] vascularized bone flaps,[25] scaphoid plate- experimental[28]
Lower Limb		
7	Acetabulum	Several applications [see Table 2]
8	Pelvis	3D model used for planning[33–35]
9	Distal Femur	3D model used for planning[37]
10	ACL Reconstruction	Patient-specific, arthroscopic ACL femoral tunnel guide (MRI based)[41]
11	Proximal Tibia	3D model used for planning[6,42–44]
12	Tibial Pilon and Malleoli	3D model used for planning[46]
13	Talus	3D model used for planning safe zones for screws[47]
14	Calcaneum	3D model used for planning[48,49]
15	Ankle	Patient specific navigational template for ankle ligament reconstruction[50]
16	Bowed femora: atypical fractures	3D model used for planning nailing[51]

5.3.4. 3D Printed bone clips

Yeon et al explored the usage of 3D printed PLA/HA/Silk composite bone clips in experimental rat models. These clips are relatively noninvasive (drilling of bone is not necessary), have patient-specific design, are mechanically stable, and are highly biocompatible. They suggested 3D printed bone clip as possible internal fixation device.[55]

5.3.5. Wound care

Three-dimensional bioprinting refers to a layer-based technology regenerative medicine, in which cells or cell-based materials are dispensed in fine spatial arrangements to mimic original tissues. Bioprinting techniques employed in skin tissue engineering range from laser-induced forward transfer to extrusion-based techniques. Vascularization of new tissues and biological linkage are major challenges. Progress in this multidisciplinary field needs close interactions between material scientists, tissue engineers, and clinicians.[56]

5.4. Scaffolding for bone and cartilage

Turnbull et al. has reviewed in very detail the role of 3D printing in tissue engineering for the generation of appropriate scaffoldings for bone and cartilage, which has possible transformative and paradigm shifting applications in the field of orthopaedic trauma.3D printing can create new alternatives to bone grafts. But, materials like polymers, ceramics and hydrogels used alone are unable to fully demonstrate properties of bone. Bioactive composite 3D scaffolds (polymers, hydrogels, metals, ceramics and bio-glasses) can overcome this limitation.[57] A detailed or comprehensive discussion of Scaffold fabrication methodology, biocompatibility, bioactivity, and mechanical performance and potential clinical translations is beyond the scope of our review.

Li et al. attempted to create a multilayer composite scaffold of cartilage, bone, and calcified layers simulate physiological full-thickness bone-cartilage structure. The bone and calcified layers were made using 3D printing. The cartilage layer was made by an improved temperature-gradient thermally induced crystallization technology. The layers were confirmed by micro CT, scanning electron microscopy and biomechanical testing showed superior mechanical properties, compared to scaffolds without calcified layer. These scaffolds might be used for bone and cartilage full-thickness injury repair methods[58]

5.5. Bracing

Saharan et al. reported a, 3D printed, lightweight exoskeleton (iGrab) based on Twisted and Coiled Polymer (TCP) muscles, which are lightweight, provide high power to mass ratio and enough stroke. Silver coated nylon threads were used to make TCP muscles, which can easily be actuated electrothermally. Hand orthosis created using various actuation technologies were reviewed by authors and they presented their design of tendon-driven exoskeletal prosthesis with muscles confined to the forearm area.[59] Paterson et al. reported usage of customized wrist splints manufactured by 3D printing.[60]

5.6. Prosthesis

Patient-specific sockets may be manufactured by 3D printing techniques for precisely customized rehabilitation solution after lower limb amputation surgery. They are anatomical and provide higher strength and durability.[61–63]

Combination of rapid prototyping and robotic technologies has allowed the advent of functional prosthetic hands.[64] 3D printing permits creation of customized, lightweight, well-fitting and affordable prosthesis, especially for the growing children. Xu et al. treated an 8-year-old boy, who had a traumatic right wrist amputation as result of a mincing machine accident. A 3D-printed prosthetic hand was made, and the child was well rehabilitated. Such relatively low cost solutions may be useful even in developing countries. Authors recommended more clinical studies to validate the superiority of similar 3D-printed prostheses.[65]

5.7. Reliability

Some respected physicians have distrusted the reliability of 3 d printing for clinical usage. **Zou et al.** evaluated the reliability and precision of stereolithography appearance of 3D printed model. CT data for bone/prosthesis and model were collected and 3D reconstructed. Intraclass correlation coefficient (ICC) was used for evaluating the degree of similarity between the model and real bone/prosthesis with regard to selected anatomical parameters. No significant difference was found in the anatomical parameters except maximum height of long bone. ICCs were all greater than 0.990. Overall, use of 3D printed model for diagnosis and treatment purpose in complex orthopaedic disease was reliable and precise.[66]

6. Conclusion

We see that all over the world, orthopaedic surgeons, allied professionals and scientists are enthusiastically using 3D printing technology for designing patient specific models, instrumentation, implants, orthosis and prosthesis, besides 3D bioprinting of bone and cartilage scaffolding, and the same has been applied for nearly all areas of orthopaedic trauma surgery, from head to foot.(Table 2). Publications related to 3D printing applications in medical sciences, and in orthopaedics in particular are rapidly growing, along with its expanding applications, and several papers related to the same were recently published in this journal also.[67–70] We are sure that future will show us further and rapid expansion of indications and technology of 3D printing, along with basic and applied research in the field for planning, patient specific implants, patient specific guides, jigs and other instrumentation and tissue scaffolds for both bone and cartilage, along with their fast adoption by most orthopaedic trauma surgeons.

Conflicts of interest

The manuscript has been approved by all authors, and they do not have any conflict of interest to be disclosed.

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