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ORIGINAL STUDY

A systematic review of three dimensional (3-D) printing applications in hip and knee arthroplasty

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Three dimensional (3D) printing, a form of rapid prototyping (RP) which is based on computer aided design (CAD) has been around for decades. Its use in orthopaedic surgery is still under development. Specific indications of 3D printing include complex hip and knee procedures, deformities particularly in malignancy and infection, as well as complex trauma. The aim of this paper is to review the literature on the clinical application of 3D printing in orthopaedic surgery.

A literature search was carried out on MEDLINE using search terms 'three dimensional printing", "rapid prototyping", AND "hip surgery" and "knee surgery". The database search was conducted in December 2016. Sixteen papers (547 patients) were reviewed and these described the clinical application of RP in hip and knee surgery, particularly used in revision surgery and malignant conditions where bone structure had been severely deformed.

Eight studies reported reduced surgical time during hip and knee elective surgery. There was reduced intraoperative blood loss during hip arthroplasty in two studies and the post-operative alignment of the lower limb was reported as significantly more accurate in five studies compared to the conventional surgery.

Current literature suggests good outcomes to date based on the small number of clinical studies on 3D printing in orthopaedic hip and knee arthroplasty. Assessment of cost-benefit analysis as well as scoping exercises for wider clinical applications required to gauge the usefulness of this relatively new technique are lacking.

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Keywords : rapid prototyping ; three dimensional printing ; hip surgery ; knee surgery.

INTRODUCTION

Three dimensional (3D) printing is a form of rapid prototyping (RP), based on the creation of an accurate physical model, layer by layer, of a virtual model. It produces metal, plastic and rubber objects using an additive manufacturing process, with the use of computer aided design (CAD).

The manufacture of 3D models can be based on 3D Digital Imaging and Communications in Medicine (DICOM) format data from computed tomography (CT) and magnetic resonance imaging (MRI) scans.

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It has been around for decades, throughout which its applications have included the aeronautical industry, automobile as well as art and design.

Technological developments have reduced the cost of 3D printers, allowing their use to be expanded to new areas such as biotechnology, medicine and surgery *(15,20)*.

Recent years have seen the use of 3D printing technology evolve in Orthopaedic surgery. Specifically, 3D printing can be used to produce models and templates providing a visual and tactile aid for complex acetabular *(2,23)* or humerus fractures *(25)* ; as well as for in-vitro studies *(13)* ; training junior surgeons *(18)* ; prostheses manufacturing ; and for patient specific instrumentation *(17)*.

Custom-made 3D printed implants for lower limb arthroplasty have been developed that are particularly useful when the patient does not fit the standard range of implant size or the deformity/pathology requires custom made implants *(15)*.

Custom made implants may also be useful in revision scenarios where off the shelf implants can't be used.

In the knee surgery, simple and complex osteotomies can be planned using a pre-operative 3D printing model as well as the procedure can be executed using custom osteotomy guides *(21)*.

The aim of this study is to review the literature on the application of 3D printing specifically in orthopaedic hip and knee surgery.

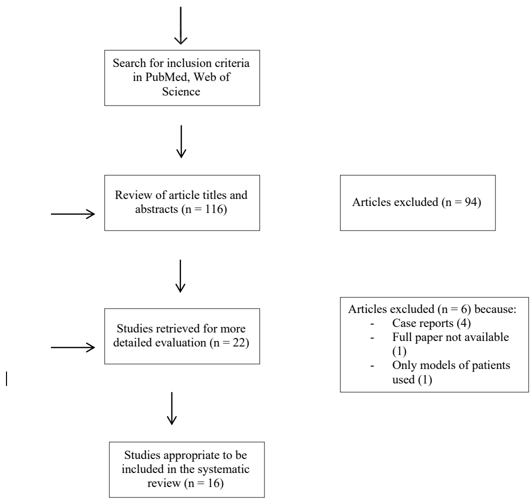

Figure 1. — Flow chart showing the study selection process and results.

MATERIALS AND METHODS

Search and study selection

A literature search was carried out on Web of Science and PubMed. The search terms used were : "three dimensional printing AND hip surgery", "three dimensional printing AND knee surgery", "rapid prototyping AND hip surgery", "rapid prototyping AND knee surgery". The database search was conducted in December 2016. We included studies published in English on the use of 3D printing in orthopaedic hip or knee surgery. Only case series with more than three cases were selected. Publications written in a language other than English, or with no full paper available, publications not relating to the hip or knee, review papers, publications on non-clinical studies, duplicate results, and publications discussing the application of 3D printing but where no study was conducted were all excluded. The search resulted in 116 articles. The titles and abstracts were reviewed and after the exclusion of 94 articles, 21 were reviewed and assessed in further detail. At the end of the study selection process, 16 relevant publications were included in this review (Figure 1).

Quality assessment

A Coleman Methodology Score (3)(a quality scoring system widely used and validated in orthopaedic literature) was calculated for each study. The scoring system includes the criteria of study size, mean follow-up, number of different surgical procedures included in each reported outcome, type of study, diagnostic certainty, description of surgical procedure provided, description of post-operative rehabilitation, outcome criteria, procedure for assessing outcomes, and description of subject selection process to give a final score from 0 to 100. A perfect score of 100 represents that minimizes the influence of chance, bias, and confounding factors. Studies were not excluded on this basis. Two authors scored the methodological quality of the studies twice, with a 10-day interval between assessments. If disagreements were encountered, the two investigators debated controversial scores until a consensus was reached.

Data extraction

We extracted the data from each study included. Data were complied in an Excel document including the study design, number of patients, indication for 3D-printing technique, Coleman score, male :female ratio, technique and material used for 3D printing and conventional groups, functional outcomes, cost, advantages, and disadvantages.

RESULTS

16 studies reported on the outcomes of the use of 3D printing in reconstructive orthopaedic surgery. 11 studies reported on the outcomes of hip surgery and 5 reported on the outcomes of knee surgery. The studies were published between 2009 and 2016. The total number of patients in individual papers ranged from 10 to 80. The total number of patients included in this review is 547 (552 joints). Of these papers, 8 compared a 3D treatment and conventional group *(4,6,8,16,17,27,28,29)* and 8 reported 3D treatment results alone *(7,9-12,14,22,23)* (Table 1 and 2 respectively).

Coleman Score

The Coleman methodology score averaged 60.8 (range from 34 *(8)* to 75 *(6)*).

Indications for use of 3D printing technology

Several studies investigated if enabling the surgeon to visualize a custom-made model of the hip or knee helped to produce a more accurate result, in procedures such as patellar resurfacing *(8)*, THR *(11,14,22,23)*, and hip resurfacing *(10)* ; particularly in patients with complex anatomy for whom commercially available materials could not be used *(14)*. Custom templates were also studied for their role in intra operative guidance in periacetabular osteotomy *(16)* and arthroplasty *(4,9,28)*. Three studies investigated the advantage of using of 3D printing in producing desired alignment in TKA and osteotomy *(6,27,29)*.

Patient selection

The most common inclusion criteria for studies using 3D printing in patients undergoing reconstructive surgery was osteoarthritis of the knee *(6,17,27,29)* and hip *(4,7,10,23)*. Other inclusion criteria were Paprosky III *(11,12,14)* acetabular bone defects, development dysplasia of the hip *(12,28)*, varus deformity of the operative knee *(27)*, patellar resurfacing in total knee arthroplasty *(14)*, primary TKA for non-osteoarthritis indications *(6)*, osteonecrosis of the femoral head *(7)*, rheumatoid arthritis *(7)* high tibial osteotomy, and age younger than 60 years *(17)*. One study evaluating the use of RP models in planning complex THRs selected patients with a hypoplastic acetabulum, uncontained acetabular defect, or a fused hip *(22)*.

Exclusion criteria for routine use of 3D printing were outlined in 4 studies. They included severe comorbidities that could prolong time spent in hospital *(27)*, severe osteoporosis *(27)*, infections *(6)*, revision surgery *(6)*, severe knee instability *(6)*, and systemic inflammatory disease *(29)*.

Outcomes

Studies comparing 3D printing aided surgery vs. conventional surgery

Knee surgery : A reduction in operation time was reported by 4 studies. *Zhang et al.* reported an average TKA operative time of 46.8 minutes using printed femoral and tibial navigational templates (NT) compared to 57.5 minutes in the conventional group *(29)*. This is comparable to the average of 45 minutes using a NT method versus 60 minutes in the conventional control group reported by *Gan et al*. *(6)*. Another study reported that the use of a customized guide plate to facilitate osteotomy in TKA gave a mean operative time of 49 minutes compared to 62 minutes in traditional surgery *(27)*. Incorporating a 3D-printing positioning guide and wedge spacer into a high tibial osteotomy (HTO) gave a mean tourniquet time of 61 minutes compared to 92 minutes in controls *(17)*.

Table 1. — Summary of the results reported from papers comparing 3D treatment groups with conventional procedures

Reference	Study Design	Patients Included	Sample Size		Indication for 3D printing technique	Statistics	Outcomes	Coleman Score
			3D treatment	Conventional				
Papers comparing 3D/RP techniques with conventional techniques - Hip Surgery								
Otsuki, B. et al., 2013. Developing a novel custom cutting guide for curved peri-acetabular osteotomy.	case control	18 Patients	7	11	RP of a model pelvis produced for Periacetabular Osteotomy, and subsequently 3D printed titanium cutting guide production	The number of complications (0/7) in the custom guide group vs. those in the conventional group (3/11) was not statistically significant p>0.1	Cutting lines were within 5mm of planned line at all points measured and there were no complications in template guided group compared to three in the conventional group	58
Du, H. et al., 2013. Use of patient-specific templates in hip resurfacing arthroplasty: experience from sixteen cases	case control	34	16	18	CT based model of the hip produced and used to manufacture a custom template to guide placement of the femoral component	The hip stem shaft angle was statistically significantly different 136.69 ± 7.70 for the template group and 121.22 ± 10.69 for the conventional group (t=−4.786, P=0.001)	Hip stem shaft angle was in the correct range, mean stem shaft angle was 136.69 (range 123-149) for the template group and 121.22 (103-145) for the conventional when aiming for a slight valgus of 140 to minimise notching and the risk of femoral neck fracture	64
Zhang, Y.Z. et al., 2011. Preliminary application of computer-assisted patient-specific acetabular navigational template for total hip arthroplasty in adult single development dysplasia of the hip.	case control	22	11	11	CT based virtual model used to create a RP template for guidewire placement to allow accurate acetabular positioning	The mean operative time for the NT group procedures was 119.6 min. The mean operative time for the conven- tional procedures was 125.3min (P < 0.05). The mean operative blood loss in the NT group was 409.8 mL, less than that of those undergoing conventional procedures, which was 480.6mL (P < 0.05). The deviation in cup abduction angle (1.6 0.4) was significantly less in the NT group than in the control group (5.8 ` 2.9 ) (P < 0.05). The deviation in cup anteversion angle (1.9 `1.1) was significantly less in the NT group than in the control group (3.9 ` 2.5) (P < 0.05)	Templates gave a more reliable orientation of the acetabulum closer to the ideal predetermined angle deviating by 1.6(+/-0.4) degrees in those with templates vs 5.8(+/-2.9) for those conventionally located - anteversion was 1.9(+/-1.1) degrees in templated vs 3.9(+/- 2.5) in conventional	64
Papers comparing 3D/RP techniques with conventional techniques - Knee Surgery								
Zhang, Y.Z. et al., 2016. Alignment of the lower extremity mechanical axis by computer-aided design and application in total knee arthroplasty. International journal of computer assisted radiology and surgery.	RCT	40 patients	20	20	CT scan data analysed and 3D models of the hip, knee, and ankle joint were reconstructed and adjusted to the weight-bearing status. The designed femoral and tibial navigation template was transformed into real templates through a SPSS 350B solid laser RP machine.	The average operative time for the NT group was 46.8 minutes (SD 9.1), which was significantly shorter than those for the conventional group time of 57.5 minutes (SD 12.3) (t = -2.9670, p = 0.0086). The average intraoperative bleeding was 463.8ml (SD 110.6) in the NT and 478.6ml (SD 105.4) in the conventional group; there was no statistically significant difference (t = -0.4110, p = 0.6862). Coronal femoral angle, coronal tibia angle, and posterior tibia slope were 89.4° (SD 1.5), 89.3° (SD 1.4), and 6.8° (SD 1.6) in the NT group and 87.3° (SD 3.8), 88.1° (SD 1.9), and 10.9 (SD 4.6) respectively; there were statistically significant differences between all three groups (t = 2.1398, p = 0.0472). The HHS for the NT group and conventional group 12 months post-operatively were 82.9 (SD 16.8) and 72.8 (SD 10.9) respectively; there was a significant difference (t = 2.1398, p = 0.0472).	The navigation template produced through mechanical axis of lower extremity may provide a relative accurate and simple method for TKA with a significant reduction in operative time.	69

Gan, Y. et al., 2015. Accuracy and efficacy of osteotomy in total knee arthroplasty with patient-specific navigational template	RCT	70 patients	35	35	RP techniques were used to create navigational templates. Operation was performed using a medial parapatellar arthrotomy with patellar eversion under pneumatic tourniquet control.	In the NT group, 97.1% of patients had a post-operative leg axis within the range of ±3°, compared to 77.1% in the conventional group (p < 0.001). In the NT group, the frontal femoral component angle was recorded in 97.1% of patients with a varus/valgus alignment within the range of ±3° compared to 71.4% in the conventional group. Mean deviation from the neutral axis in the NT group was 1.0° (SD 0.8; 3° valgus to 2° varus) and in the conventional group was 2.6° (SD 1.8: 6° valgus to 8° varus) (p < 0.001). Mean lateral femoral component angle was 4.5° (SD 3.2; 2°-9°) in the NT group and 9.3° (SD 4.3; 4°-12°) in the conventional group (p < 0.001). The NT group had a posterior slope of the tibial component of 5.3° (SD 2.1; 3°-8°), whilst the control group had 3.6° (SD 2.7;0°-7°) (p < 0.001). Average lateral tibial component angle was 84° (SD 2.9; 85° ventral to 90° dorsal) in the NT group compared to 87° (SD 2.5°: 86°-95°) in the conventional group. The mean preoperative and postoperative rotational femoral angle measured on the CT images were 4.5° (SD 0.8) and 2.3° (SD 1.2) in conventional patients and 4.8° (SD1.1) and 5.0° (SD 0.6) in the NT patients.	Overall, the NT method showed a high degree of accuracy and efficacy. In the NT group, 97.1% of the patients (34/35) had a post-operative leg axis within the range of ± 3° compared with 77.1% (27/35) in the conventional group. The mean value of the mechanical axis in the navigational template group was 181° and ranged from 3° valgus to 4° varus, whereas the mechanical axis in the conventional group was 177° and ranged from 7° valgus to 10° varus	75
Pérez-Mañanes R. et al. 2016 3D_Surgical_Printing_Cutting Guides for Open-Wedge High Tibial Osteotomy: Do It Yourself	Case control	28 patients	8	20	CT images were used to print a 3D positioning guide and wedge spacers to implement the osteotomy and obtain the planned correction.	Mean tourniquet time was 61 minutes (49-84) in the 3D printing group compared to 92 minutes (84-118) in the control group, which was statistically significant (p < 0.001). On average, 8 (6-14) intra-operative fluoroscopic images were required in the 3D group compared to 55 (41-73) in the control group (p < 0.001).	Digitally planned and executed osteotomies under 3D printed osteotomy positioning guides help the surgeon to minimize human error while reducing surgical time. Mean execution accuracy was 0.5° vs. 1.1° for the new and control techniques - however differences were not significant. There was also no significant difference in final valgus; in both techniques, a final valgus of 7° (± 2) was achieved.	46
Huang AB. 2016 Novel customized template designing for patellar resurfacing in total knee arthroplasty	Case control	40 patients	20	20	3D reconstruction model was generated from CT images and used to produce a customised cutting template	There was no statistically significant difference in patella residual thickness between the customised template and conventional groups (p = 0.52). When using the customised template, there was no statistically significant difference between planned and actual resection thickness; mean 0.23mm (range -0.19-0.64mm) (p = 0.27). No learning effect was achieved; there was no statistically significant difference in resection symmetry between the first 10 and remaining models (p > 0.05).	A significantly greater likelihood of obliquity of patella cutting in the conventional sawguide group was observed compared with the customized template group. A total of three cases with ML angle and four cases with SI angle >7° were observed in the conventional sawguide group; in contrast, there were no cases with the ML or SI angle >7° in the template group.	36

Zhang et al., 2016 Establishing a customized guide plate for osteotomy in total knee arthroplasty using Lower-extremity X-ray and knee Computed Tomography Images	RCT	42 patients	21	21	The digital design was created using Geomagic and 3D printed. Customised guide plate was then used in osteotomy for TKA	Mean operation time for the guide plate was 49 minutes (SD 10.5) and 62 minutes (SD 9.7) in the traditional group (p = 0.018). Coronal femoral angle, coronal tibial angle, posterior tibial slope, and the angle between the posterior condylar osteotomy surface and the surgical transepicondylar axis were 89.2° (SD 1.7), 89.0° (SD 1.1), 6.6 (SD 1.4), and 0.9° (SD 0.3) in the guide plate group, and 86.7° (SD 2.9), 87.6° (SD 2.1), 8.9° (SD 2.8), and 1.7° (SD 0.8) in the traditional group, respectively. The HSS knee scores 3 months after surgery were 83.7 (SD 18.4) after use of the guide plate and 71.5° (SD 15.2) after traditional surgery. Statistically significant differences were found between all comparisons.	A customised guide plate to create an accurate osteotomy results in lower operative times and better postoperative alignment compared to the traditional surgery.	70

Table 2. Summary of the findings from papers reporting on 3D printing results alone

Reference	**Study Design**	**Patients included**	Sample Size		**Indication for 3D-printing technique**	**Statistical Analysis**	**Outcomes**	**Coleman Scores**
			3D treatment	Conventional				
Case Series Reporting 3D techniques alone - Hip Surgery								
Li, H. et al., 2016. Custom Acetabular Cages Offer Stable Fixation and Improved Hip Scores for Revision THA With Severe Bone Defects	case series	26 patients	24 (26 initial one lost to follow up and one died)	n/a	Rapid Prototype model of pelvis produced from CT image data to allow customisation and in 2 cases additional 3D printed elements to be added to cages	Harris hip scores improved from a mean of 36 before surgery (SD, 8; range, 20–49) to 82 at latest followup (SD, 18; range, 60–96; p < 0.001). The mean vertical distance was 25 mm (SD, 5 mm; range, 19–40 mm) on the revised side and 24 mm (SD, 5 mm; range, 18–40 mm) on the contralateral side (p = 0.265); the difference between bilateral sides was 0.4 mm (SD, 3 mm; range, 4.5 to 5 mm). The mean horizontal distance was 106 mm (SD, 9 mm; range, 90–119 mm) on the revised side and 109 mm (SD, 9 mm; range, 94–123 mm) on the other side (p = 0.75), and the difference was 3 mm (SD, 7 mm; range, 19 to 8 mm). Radiographic analysis showed the mean inclination of the cage was 46° (SD, 6°; range, 38°–58°).	No rerevisions in follow up period and good cancellous allograft incorporation in 23 of 24, 4 complications recorded - 2 infections (one deep one superficial), 1 dislocation and 1 superior gluteal nerve injury - all resolved. No definite migration radiographically; one case with 2mm circumfrential line and one with 1mm incomplete, non-progressive line	67

Mao, Y. et al., 2015. The use of customized cages in revision total hip arthroplasty for Paprosky type III acetabular bone defects	case series	22 patients (23 hips)	22 (23 hips)	n/a	Custom acetabular cages revision surgery with Paprosky type III bone defects (3 IIIA and 20 IIIB) Rapid prototyping of CT model allows the cage to be altered to give optimum fit	The mean Harris hip score improved from 39.6 (range, 12–60) pre-operatively to 80.9 (range, 53–93) at the final follow-up ($P < 0.01$).	Reported a lower failure rate that comparable cages and a lower risk of dislocation. Reported one intraoperative bleed and two dislocations. 22 of 23 radiographically stable with 3 showing some lucency	67
Xu, J. et al., 2015. Application of Rapid Prototyping Pelvic Model for Patients with DDH to Facilitate Arthroplasty Planning: A Pilot Study.	case series	10 patients (14 hips)	10 (14 hips)	n/a	Pre-operative models used for planning the placement of the acetabular cup and reinforcing ring	The difference of excellence rate (a difference of ≤ two sizes) in the prediction of prosthesis between 3-D preoperative planning and 2-D template measuring method was of statistical significance($\chi2 = 8.023$, $P < 0.05$).	Excellent size concordance between model and that used intraoperatively compared with standard 2D - (71.4% exact match in 3D vs 7.1% in 2D modelling). All 10 appeared stable at follow up	60
Li, H. et al., 2013. Revision of complex acetabular defects using cages with the aid of rapid prototyping	case series	25	25	n/a	Rapid prototyping used to produce pelvic models and assess the suitablility of acetabular cages (Lima Lto or custom made)	The average Harris score was 36.1 (range, 20 to 58) preoperatively, and reached an average of 82.6 (range, 60–96) by the last follow-up (Pb0.05).	Economical in this small trial), one dislocation in post operative period and 24 of 25 were radiographically stable at follow up and none failed in follow up period	67
Kunz, M. et al., 2011. Registration stability of physical templates in hip surgery.	case series	80	80	n/a	CT based virtual imaging used to produce a template to guide the location of femoral head replacement	Anterolateral approaches with an alignment error of greater than 3 degrees had a mean anterior displacement of 4.03mm (SD 3.4) compared with 1.68mm (SD 3.0)in those with alignment error less than 3 degrees ($P=0.004$)	Good alignment was achieved - comparable or better than similar reports of computer assisted procedures, Templated patients had valgus deviation 0.05 (SD 3.3) degrees, anteversion 2.8 (SD 5.5) degrees, placed 0.47 (SD 1.86)mm superiorly and 2.6(SD 3.6)mm anteriorly	62
Case Series Reporting 3D techniques alone - Knee Surgery								
Kunz, M. et al., 2010. Computer-assisted hip resurfacing using individualized drill templates	Case series	45 patients	45	n/a	Individualised templates produced from CT imaging to provide an accurate and reliable computer-assisted system for femoral component placement during hip resurfacing.	43 patients completed WOMAC pain, stiffness, and function scores pre-operatively, 3 months, and 6 months post-operatively. There was a significant change in pre- and post-operative assessments of pain ($p = 0.015$) and function ($p = 0.0004$). In regards to deviated between planned and navigated central pin alignment, there was an average varus deviation of 1.1° (SD 3.1°). In retroversion, average deviation was 4.3° (SD 3.9°). The average deviation between the planned and final entrance point 0.1mm superior (SD 2.1mm) and 3.5mm anterior (SD 3.3mm). There was a statistical difference between the variances for varus and valgus alignment between the first 20 and last 25 patients ($p = 0.14$).	Mean deviation between planned and actual central pin alignment of 1.14° in varus and 4.49° in retroversion, individualized templates were as accurate as conventional computer-assisted hip resurfacing.	60

Won, SH et al., 2013. Improving pre-operative planning for complex total hip replacement with a rapid prototype model enabling surgical stimulation	Case series	21 patients	21	n/a	Pre-operative models based on CT imaging to aid planning for challenging hips with severe acetabular deformities	17/21 acetabular components (80.9%) were within 2mm of predicted size. Mean total blood loss was 3245.9ml (SD 4027; 1050-20,460) and the mean transfusion requirement was 8.3 units (SD 8.3; 2-39). The mean abduction and anteversion angles of the acetabular components were 37.3° (SD 7.5; 20.1°-50°) and 28.5° (SD 17.4; -6.8°-57.4°) respectively. Mean leg length discrepancy was reduced to 1.5cm (SD 1.3; 0-5).	Allowed a simulated procedure pre-operatively - used to determine feasibility of THR, and to decide on implant size (80.9% within 2mm of predicted), type, and position in complex THRs.	66
Hananouchi, T. et al., 2009. Tailor-made surgical guide based on rapid prototyping technique for cup insertion in total hip arthroplasty	Case series	24 patients	24	n/a	Surgical guide based on CT imagin produced via rapid prototyping and used to guide cup insertion in THA	Mean post-operative orientations of the cup were 38.6° (SD 2.7; 34.0°-43.1°) of abduction and 17.4° (SD 5.6; 6.3°-27.2°) degrees of anteversion. Mean cup accuracy (deviation between pre- and post-operative cup orientation) was 2.8° (SD 2.1; 0.4°-7.7°) for abduction and 3.7° (SD 2.7; 0.1°-9.3°) for anteversion. Time from set up to removal of the surgical guide was an average of 3.5 minutes (SD 1.4; 2-6). Mean operative time was 106 minutes (SD 23.7; 79-169). Mean intraoperative blood loss was 655ml (SD 330; 190-1768).	The surgical guide was useful in the clinical setting. Results are more favourable than conventional THAs and comparable to navigated THAs. Cup accuracy using the surgical guide was acceptable within, 10 degrees of preoperative planned angle	44

Gan et al. reported a significant difference in mean intraoperative blood loss between the NT and conventional groups of 200ml and 290ml, respectively *(6)* ; although this difference was not noted by other authors *(29)*.

The templates designed from the virtual surfaces were reported as perfect match to the anatomy intra-operatively *(6,29)*. Using 3D models of patellae and custom cutting templates during resurfacing allowed accurately executing planned resection *(8)*.

Two studies, reporting post-operative alignment compared the coronal femoral angle, coronal tibial angle, and posterior tibial slope between 3D printing and conventional controls groups. For the NT group, angles were 89.4°, 89.3°, and 6.8° and this was a significant improvement from the conventional group (87.3°, 88.1°, and 10.9°, respectively) *(29)*. Use of a 3D printed custom made guide plate to plan and simulate TKA gave angles of 89.2°, 89°, and 66°, compared to 86.7°, 87.6°, and 8.9° in controls *(27)*.

Similar observations were reported by *Gan et al* *(6)*. They reported that intra-operative use of the NTs during TKA to guide osteotomy resulted in a post-operative mechanical leg axis within the range of ±3° in 97.1% of patients, compared to 77.1% with use of the conventional methods *(6)*.

The use of a custom positioning guide based on patients' individual anatomy have also been reported to improve executional accuracy to 0.5° from conventionally observed 1.1° ; however, these values were not significantly different *(17)*.

Two studies measured outcomes using Hospital for Special Surgery (HSS) scores after TKA. At 12 months follow up using a 3D reconstruction model, HSS scores were 82.9 (±16.8) and 72.8 (±10.9) for the 3D and conventional groups respectively *(29)*. In another study, at 3 months follow up after using a guide plate, scores were 83.7 (±18.4) in the guide plate group and 71.5 (±15.2) in the traditional surgery group *(27)*. Both results were statistically significant.

Hip Surgery

Zhang et al. used a 3D-printed template to allow guide pin placement for acetabular cup orientation in a series of patients with developmental dysplasia of the hip. They reported a reduction in mean blood loss during THA with an average of 409.8 ml lost in the template guided procedure compared with 480.6 ml in the conventional operation *(28)*. In the same study a reduction in operation duration from 125 minutes to 119 minutes was observed. Other studies also recorded a reduction in the duration of hip resurfacing procedures, however, this was of unspecified length *(18,11)*.

Several studies reported the effects of template guided resurfacing or replacement compared with traditional approaches on relative positioning of the acetabulum and femoral head. *Du et al.* reported that with hip resurfacing arthroplasty 3D printed templates achieved better reproduction of the hip stem/shaft angle *(4)*. *Zhang et al.* also reported the alignment of prosthetic acetabular cups that had been placed with template guidance vs. those traditionally implanted. The target abduction angle was achieved more accurately in 3D printed template (mean discrepancy of 1.6° (±0.4°) vs 5.8° (±2.9°)) compared to the conventionally operated group. A similar case was made for better achievement of anteversion angle has also been made (discrepancy of 1.9° (±1.1°) NT vs. 3.9° (±2.5°)) *(28)*.

Otsuki et al. investigated the use of custom made cutting guides for peri-acetabular osteotomy (PAO), and reported that in the 7 patients treated with the custom made titanium guide there were no major complications while the control group of 11 had 3 major complications associated with the procedure, however, this was not statistically significant *(16)*. They also demonstrated that the cutting line achieved was no more than 5mm away from the ideal line established during pre-operative planning at all points measured along its length.

Studies reporting 3D planned surgery data without comparison groups

The average time of various studies have been reported using 3D templates and vary between 91 minutes for hip resurfacing using individualized templates to facilitate the alignment of central pin placement *(10)*, 253.4 minutes for THR using a printed model of the pelvis in patients with complex hip deformities *(22)*, and 106 minutes for THR using surgical guides for accurate cup insertion *(7)*. In the absence of comparison groups clear inferences cannot be drawn. This is also the case with intra-operative blood loss reported by two studies ; one showing mean intraoperative blood loss was 3245.8ml during THR in patients with complex hip deformities *(22)*, and another study reporting 655ml blood loss using a 3D printed surgical guide in THR *(7)*.

In hip resurfacing, several studies have looked at accuracy of achieving desired orientation of implants. The average deviation of planned and actual central pin placement was 1.14° in varus and 4.49° in retroversion ; the mean error of 1.1° (SD 3.1°) is analogous to other studies using conventional methods *(24)*. Subsequent studies in 80 patients by Kunz et al. have shown that the difference in central pin placement from planned orientation when measured with optoelectronic CT and compared with the predefined target had a valgus deviation of 0.05° (SD 3.3°), and an anteversion deviation of 2.8° (SD 5.5°), and was placed 0.47mm (SD 1.86) superiorly and 2.6mm (SD 3.6) anteriorly to the target point *(9)*. *Hananouchi et al.* reported post-operative orientations of the inserted cup of 38.6° of abduction and 17.4° degrees of anteversion, within the defined 'safe-zone' associated with a lower risk of post-operative complications such as dislocation *(7)*. Inserted cups during THR were all within 10° of the preoperative planned alignments *(7)*. When the size of the acetabular components in THR was determined based on an RP model of the pelvis ; the component was successfully implanted in all patients, and 80.9% were within 2mm of predicted size *(22)*. The size of the femoral head necessary was also determined using a RP model of the pelvis ; while 71.4% were an exact match, the prediction from 2D imaging was accurate in only 7.1% of cases *(23)*.

Several of these studies reported outcomes. The implanted acetabular components and femoral stems were noted to ingrowth with no detectable articular wear *(22)*. The mean Harris Hip Score (HHS) was 79.9 at final follow-up (mean 35.5 months) *(22)*.

Several studies report on the beneficial effects of using custom acetabular cages on stability of the joint and the Harris Hip Score in those with complex acetabular defects *(11,12,14)*. With this technique *Li et al.* in 2013 showed favorable improvement in HHS from 36.1 (20-58) to 82.6 (60-96) and a lower failure rate than comparable procedures. When assessed radiographically, 24 of 25 hips were stable, with 1 case showing some radiolucency classified as possible loosening *(12)*. *Mao et al.* using a similar protocol reported an increase from 39.6 (range 12-60) to 80.9 (53-93), and a lower rate of nerve palsies than with comparable surgical interventions ; they also reported that 22 of 23 were stable when assessed radiographically *(14)*. *Li et al.* reporting from a different patient cohort in 2016 showed results of using more extensively customized acetabular cages, some incorporating 3D printed components. They reported an increase in HHS from 36 (SD 8, range 20-49) to 82 (SD 18, range 60-96) post-operatively with good restoration of the hip centre and good bone allograft incorporation in 23 of 24 patients, of the 24 hips : 22 were radiographically stable, 1 had a 2mm circumferential radiolucent line, and 1 had a 1mm incomplete non-progressive radiolucent line *(11)*.

Cost and availability

Cost

7 papers reported the cost of the 3D printing process *(6,11,12,17,22,23,28)*. Two studies using patient-specific navigational templates produced using a RP technique during TKA and THA reported a cost of $60 per template *(6,28)*. Patient-specific models of the proximal tibia were printed for less than €5 each, after paying €490 for the printer *(17)*. The total cost of producing a life-sized RP model of the pelvis in planning for THR was $500 *(22)*. The cost of a 3D printed custom acetabular cage was reported at $5500 *(11)*.

Additional manufacturing & surgical time

The production time for navigational templates using RP for TKA was reported as being 2 days *(6)*. The production of patient-specific 3D models of the proximal tibia, an osteotomy positioning guide, and polyhedral wedges before HTO included 60 minutes pre-operatively used by the operators and 225 minutes for printing, giving an additional time of 285 minutes on average *(17)*. However, the authors reported a reduction in pre-operative planning time by the operators with each subsequent case, from 75 minutes to 32 for the final operation *(17)*. *Kunz et al.* reported an additional 5-10 minutes added to each surgery with the use of an optoelectronic CT-based navigation system to measure the final alignment of the central pin during hip resurfacing ; however, this step would not be necessary in routine clinical use *(10)*. Pre-operative planning and production of a 3D surgical guide to aid with cup insertion in THA took 60-120 minutes ; intraoperative use added an additional 3.5 minutes to each surgery *(7)*.

Materials used for manufacturing 3D templates

Navigational templates of the femur and tibia used during TKA were produced in acrylate resin *(6)*. A surgical guide to aid with cup insertion in THA was3 produced with photosensitive medical-grade resin *(7)*. Thermoplastic 1.75mm diameter acrylonitrile butadiene styrene was used in one study for printing three components : an osteotomy positioning guide, polyhedral wedges, and a model of the patient's proximal tibia *(17)*, and for the production of patient-specific drill templates in hip resurfacing in another *(10)*. 3D osteotomy guide plates were printed with polylactic acid *(27)*. Models of patellae were produced in gypsum, with their associated customized cutting templates produced in nylon via selective laser sintering *(8)*.

Advantages and disadvantages

Reported advantages of 3D printing

One of the most widely-reported advantages was the benefit of pre-operative planning allowing for a more accurate surgery, and simplification of the intra-operative procedure associated with a reduced surgical time *(6-8,10,17,22,27)*. The reduction in TKA operative time is reported to be equivalent to a saving of €507 per surgery *(17)*. In patients with atypical anatomy, the 3D model was used to predict the viability of operating and in establishing a surgical strategy *(22)*. Operations can also be simulated pre-operatively *(6)*. Customized surgical guides could be used in any hospital, with no additional staff needed *(7)*. The use of tailor-made positioning guides in osteotomy simplifies the procedure, making it amenable for the surgery to be performed by less experienced surgeons *(17)*.

Several studies reported a lower incidence of complications, fewer dislocations, and fewer superior gluteal nerve palsies with a lower failure rate in the follow up period than that expected of conventional techniques *(11,14,23)*.

Reported disadvantages of 3D printing

Reported disadvantages include an increased pre-operative planning time, as well as associated complexity *(7,17)*. The necessity for a pre-operative CT scan carries an additional exposure to radiation *(7,8,27)*, although this may be justified by the imaging benefits *(7)*. The accuracy of the 3D model could be altered by several parameters such as the slice thickness, layer spacing, and pitch of the CT scan *(27)*.

DISCUSSION

This article reviews the current application of 3D printing technology applied to hip and knee surgery showing that the applications varied from the industrial application to produce customized prosthesis or planning models for complex anatomy to the everyday use for pre-operative planning and for the education purpose.

To our knowledge, this is the first paper reviewing specifically the applications of 3D printing technology in hip and knee elective surgery.

The most important finding of the present study is that the using of 3D printing in knee and hip surgery has showed promising outcomes compared to the conventional operations.

Most of the selected papers *(6-9,17,22,29,27)* suggest that the 3D printing is cost-effective due to the simplification of the intra-operative procedure associated with a reduced surgical time that translates to a reduction of theater costs.

The other main advantage of 3D printing technology, *(6,13,14,23,29)*, is that an accurate pre-calculated pre-operative plan and customized cutting block or custom implants, may result in lower incidence of peri and post-operative complications. Although in knee arthroplasty surgery some studies have reported approximately 20% dissatisfied rates due to a constant pain or suboptimal functional outcomes *(27)* patient-specific implants and cutting guided manufactured based on 3D printing models haven't shown yet evidence of better functional outcomes or regarding the pain.

In hip replacement as well as resurfacing surgery component alignment is a key element for long-term good outcomes. Du et al. *(4)* reported that the use of 3D printing model of the hip improved the accuracy of the prosthesis position ensuring desired stem placement.

In hip revision surgery, in particular in acetabulum revision, loss of effective host bone contact and support for placement of a cage is a significant cause for mechanical failure *(19)*, Li et al. *(11)* showed improved outcomes scores with an average follow-up of 4.4 years using customized cages based on a pre-operative 3D pelvic model obtaining a better secure host-bone support system for the cage and a rigid fixation of the cage to the acetabulum as well.

The 3D printing opens up new possibilities for tailoring surgical procedures allowing a better understanding of the anatomy, and the possibility to simulate the surgical operation on a virtual model using the size and the design of the hardware that would be used during the real surgery *(5)*.

Although the benefit of 3D printed models in education and patient counseling has been studied mainly for the treatment of complex fractures *(24)*, this role can be expanded to hip and knee elective surgery.

There are some limitations to the present review article. The lack of homogeneity in each study design, inclusion and exclusion criteria, small series of patients with a relatively short follow-up, and dissimilar outcomes measures have limited our ability to perform a proper meta-analysis of the extracted data.

The study was limited to English articles and relevant papers published in other languages may have been missed.

Other practical disadvantages the surgeon should consider are the added time and resources taken to prepare the models from the pre-operative CT or MRI scans. Where CT scans are used there is the added disadvantage of radiation, although the effect of this is unclear.

In future, well planned randomized control trials and prospective cohort studies reporting long-term outcomes will enable better understanding of the real advantages that the surgical techniques based on 3D printing could bring.

CONCLUSION

3D printing is a valuable aide in elective orthopaedic hip and knee surgery. It has multiple uses, including the production of personalised prostheses, and the production of models and templates for planning and execution of complex procedures, surgical training and clinical/ non-clinical studies. Orthopaedic surgeons should familiarize themselves with its potential roles, advantages and disadvantages. Further research with long-term follow-up is required, specifically looking at cost- benefit analysis, resource availability and importantly, durability and biomechanics of prostheses designed and manufactured using RP in comparison to the traditional techniques.

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