REVIEW ARTICLE

Application of 3D Printing in Hip and Knee Arthroplasty: A Narrative Review

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Abstract

Introduction Ideal surgical positioning and placement of implants during arthroplasty are crucial for long-term survival and optimal functional outcomes. Inadequate bone stock or defects, and anatomical variations can influence the outcomes. Three-dimensional printing (3DP) is an evolving technology that could provide patient-specific instrumentation and implants for arthroplasty, taking into account anatomical variations and defects. However, its application in this field is still not adequately studied and described. The present review was conceptualised to assess the practicality, the pros and cons and the current status of usage of 3DP in the field of hip and knee arthroplasties and joint reconstruction surgeries.

Methods A PubMed database search was conducted and a total number of 135 hits were obtained, out of which only 30 articles were relevant. These 30 studies were assessed to obtain the qualitative evidence of the applicability and the current status of 3D printing in arthroplasty.

Results Currently, 3DP is used for preoperative planning with 3D models, to assess bone defects and anatomy, to determine the appropriate cuts and to develop patient-specific instrumentation and implants (cages, liners, tibial base plates, femoral stem). Its models can be used for teaching and training young surgeons, as well as patient education regarding the surgical complexities. The outcomes of using customised instrumentations and implants have been promising and 3D printing can evolve into routine practice in the years to come.

Conclusion 3D printing in arthroplasty is an evolving field with promising results; however, current evidence is insufficient to determine significant advantages that can be termed cost effective and readily available.

Keywords 3 dimensional printing · 3D · Hip arthroplasty · Knee arthroplasty · Patient specific instrumentation · PSI

Introduction

Three-dimensional printing (3DP) is the process of utilising materials like plastic, ceramic or metals, to manufacture objects using a three-dimensional (3D) model data [1]. This has evolved from prior technologies where chunks of materials could be chiseled into 3D objects using various instruments [2–4]. With advancements in technology, easier availability and better understanding of its applications to improve surgical outcomes, 3DP application in multiple healthcare branches (including complex trauma and

orthopaedics) has witnessed a significant rise in the recent past. 3D models have the potential to act as visual and tactile aids, allowing surgeons to study complex cases and plan pre-operatively; pre-procedural planning could include implant sizing, quantity and type of graft needed, osteotomy site as well as rehearsing the procedure on the models to minimise intra-operative surprises and risks [4]. The technology comes in handy for teaching purposes of surgeons in training, and allows clear demonstration to the patient about the complexities of a planned surgery.

In orthopaedic surgery, combinations of plastic or metal are currently used in manufacturing 3D designs; an initial image of the required design is obtained in the form of 3D CT scan or MRI [5]. This is saved in a specific computer format and is subsequently converted to a STL (standard triangulate language) format, which is then sent to a 3D printing machine for obtaining the desired model [6]. These customised designs can be tweaked, allowing production

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of implants which are theoretically superior and practically could provide better incorporation with the bone [7].

3DP has now become widely accessible, and many orthopaedic disciplines are benefitting from this; scoliosis correction, complex intra-articular trauma cases, paediatric deformity correction and osteotomies, customised prosthesis and braces, as well as arthroplasty have all to gained from application of this technology [8, 9]. An ideal implant used in arthroplasty should be well fitted and have a prolonged life span. In hip arthroplasty, optimal anteversion and inclination of both the acetabular and femoral components in a “safe zone” are of paramount importance to improve implant longevity and minimise complications like loosening, dislocations and limb length discrepancies [10]. Similarly, in knee arthroplasties, appropriate femoral and tibial cuts correlate directly with soft tissue balancing, implant positioning and overall femorotibial alignments. Post-operative patient satisfaction and quality of life are very much dependent on these factors; in conventional surgeries, all of the above are a direct reflection of the expertise and skill levels of the operating surgeon, and with potential for human errors. Even minimal variations in these determinants could lead to sub-optimal outcomes for the patients; therefore, there is a need to technically improve all aspects of surgery. Any kind of technical modality that could improve planning and minimise intra-operative errors thus becomes relevant. This becomes doubly important in difficult cases like revisions, or in patients with poor bone stock and defects, where having a 3D model of the exact anatomy allows appropriate planning with the whole team for that specific surgical scenario [11]. With this in mind, the present narrative review was conceptualised to identify and understand the developments, and current status of 3DP in the field of hip and knee arthroplasties.

Aims and Objectives

The aims of this review were to evaluate the current effectiveness of 3DP in total hip and knee arthroplasties on four main fronts; in pre-operative planning and decision-making, in teaching and patient education, in manufacturing patient-specific instrumentation (PSI) and cutting blocks, and custom-made components; additionally we tried to ascertain the future prospects of 3DP.

Methodology

Search Strategy

A PubMed search was conducted on 12th April, 2020 with keywords (“printing, three-dimensional”[MeSH Terms]

OR (“printing”[All Fields] AND “three-dimensional”[All Fields]) OR “three-dimensional printing”[All Fields] OR (“3d”[All Fields] AND “printing”[All Fields]) OR “3d printing”[All Fields] AND (“arthroplasty”[MeSH Terms] OR “arthroplasty”[All Fields]). This yielded only 120 hits.

A further search specifically for hip and knee arthroplasties with keywords (“printing, three-dimensional”[MeSH Terms] OR (“printing”[All Fields] AND “three-dimensional”[All Fields]) OR “three-dimensional printing”[All Fields] OR (“3d”[All Fields] AND “printing”[All Fields]) OR “3d printing”[All Fields]) AND (“hip”[MeSH Terms] OR “hip”[All Fields]) AND (“arthroplasty, replacement, knee”[MeSH Terms] OR (“arthroplasty”[All Fields] AND “replacement”[All Fields] AND “knee”[All Fields]) OR “knee replacement arthroplasty”[All Fields] OR (“knee”[All Fields] AND “arthroplasty”[All Fields]) OR “knee arthroplasty”[All Fields]) yielded additional 15 hits.

Selection of Studies (Inclusion and Exclusion Criteria)

Studies of any design in the English language discussing usage of 3DP in hip and knee arthroplasties were included. Animal studies, conference abstracts, posters, case reports, book chapters, and studies describing 3DP in non-arthroplasty patients were excluded as shown in Fig. 1.

Data Collection

All the hits were screened independently by two authors based on title and/or abstract, for inclusion. The full text of all the screened articles was read and the relevance was assessed. Discrepancies were resolved by discussions among the authors. A secondary search was also done from the bibliography list of all selected articles.

Results

Characteristics of the Studies

A total of 30 studies of interest were included in this review [12–41]. These studies deal with various aspects and implementation of 3DP in hip and knee arthroplasties.

15 out of 30 studies discuss 3DP in hip replacements, with 7 studies related to customised components [12–18], and 6 related to patient-specific instrumentation and positioning guides [19–24]. One study assessed the role of preoperative planning as well as usage of 3DP acetabular components [25]. One study focused on diagnostic accuracy of 3DP models in pelvic discontinuity [26]. Five studies were retrospective in design [12–14, 20, 26], while

Fig. 1 Flowchart depicting selection of articles

ten studies were prospective [15–19, 21–25]. 14 out of 15 studies related to 3DP and hip arthroplasties have been published between 2014 and 2020, demonstrating that 3DP is a very recent addition to the armamentarium of Hip arthroplasty surgeons (Table 1).

The minimum number of patients in included studies, who underwent THR with customised components, was 8 [16], while in a case series, the maximum number was 46 [14]. The lowest number of patients in studies assessing PSI and positioners was 18 [19], and the largest series included 100 cases [22].

15 studies discuss 3DP in knee arthroplasties (Table 2) [27–41]. 7 studies were prospective [27, 29, 30, 34, 36, 37, 41], while the remaining 8 studies were retrospective in design. The majority of studies addressed PSI and cutting blocks [26–36], while 3 studies reported customised TKR

components [38–40]. One study addressed both PSI as well as implants [41].

Pre-Operative Planning and Decision-Making

Primary hip arthroplasties, where the anatomy of the acetabulum or femoral head is distorted due to infection, dysplasia or trauma, and revision cases, present a serious challenge; the surgeon needs to address the anatomy as well as recreate the native biomechanics in terms of vertical and horizontal offsets, as well as equalise the leg lengths [41]. In complex scenarios with extensive bone loss, traditional planning using radiographs and conventional CT scans may not be enough, and 3DP models of the native anatomy can provide a better understanding to minimise intra-operative issues. All

Table 1 Literature review of publications on 3D printing in total hip arthroplasty

S. no.	Author	Study type	No. of patients	3DP use	Outcome parameters	Inferences
1	Hananouchi et al. (2010) [24]	Prospective	69 (38: conventional; 31 customized guide)	Tailor-made surgical guide for cup placement	Number of outliers from planned alignment	More reliable cup insertion compared to conventional methods (0 outliers)
2	Small et al. (2014) [19]	Prospective RCT	36 (18 each group)	PSI	Post-operative CT for accuracy of placement(anteversion)	PSI use had greater accuracy of ante version
3	Li et al. (2015) [12]	Retrospective	26 revisions	Customised cages	Revision THR-Harris hip score and radiographs	Custom cages using 3DP show stable fixation, improved HHS
4	Mao et al. (2015) [13]	Retrospective case series	23 revisions	Customised acetabular cups	Harris hip score and radiographs to assess loosening	Custom cups are viable options for revision THA with acetabular defects
5	Spencer-Gardner et al. (2016) [22]	Prospective case series	100	Patient-specific guide from 3D-printed model for acetabular cup positioning	Post-op CT for measuring acetabular inclination and anteversion	Using patient-specific guides gives more accurate placement than free-hand techniques (separate cohort of same authors)
6	Wang et al. (2017) [15]	Prospective cohort study	17/74	Acetabular prosthesis	Harris hip score, clinical data, radiographs	Time to weight bear and HHS were better in 3D print group
7	Citak et al. (2017) [17]	Prospective case series	9	Customised acetabular component	Implant-associated failure rate	Patient-specific acetabular component technique is encouraging for patients with massive acetabular defects
8	Kieser et al. (2018) [14]	Retrospective cohort	46	Tri-flanged acetabular implant	WOMAC, OHS, HHS and radiographic outcomes	Encouraging results with 3D printing, no patient needed revision surgery
9	Schneider et al. (2018) [21]	Prospective case series	30	Femoral neck osteotomy guide	Variation in level of osteotomy as per pre-planned level	Patient-specific osteotomy guides are more accurate in minimal invasive THA
10	Kavalerskiy et al. (2018) [25]	Prospective	17 revision case. (preoperative planning) Customised acetabular components used in 3 cases	3D models for preoperative planning 3DP tri-flanged acetabular component	Implant-related complications (infection, loosening, etc.) Comparison of number and type of augments in planning and in surgery	All 17 patients were alive and well at last follow-up. No complications Planned and used augments were same in all cases. Cup size same in 64.3% cases as planned. (difference < 2 mm in other cases) High accuracy if preoperative planning done using 3DP

Table 1 (continued)

S. no.	Author	Study type	No. of patients	3DP use	Outcome parameters	Inferences
11	Aprato et al. (2018) [16]	Prospective case series	8	Customised acetabular component	Complications	Pomade custom-made acetabular system showed encouraging results in complex acetabular defects
12	Angelini et al. (2019) [18]	Prospective case series	13	Custom-made prosthesis	MSTS score and Henderson et al. score	3D-printed prosthesis show promising results
13	Aprato et al. (2019) [26]	Retrospective	56 (9 cases of pelvic discontinuity)	Diagnostic accuracy	Pelvic discontinuity analyzed on plain CT and 3DP models	3DP models have higher specificity and intraobserver reliability to diagnose pelvic discontinuity preoperatively
14	Cao et al. (2019) [20]	Retrospective study	Group A-32 Group B-40	Cup positioner	Radiological parameters and clinical measurements	3D-printed positioner of cup helps restore COR position more precisely
15	Mishra et al. (2020) [23]	Prospective RCT	36 (3DP vs conventional)	3DP acetabular zig to guide cup placement	Anteversión (centre of range of safe zone); surgical duration blood loss	Better version with the usage of zig; no significant difference in duration and blood loss

CT computed tomography, THR total hip replacement, THA total hip arthroplasty, 3DP three-dimensional printing, HHS Harris Hip Score, AKS American Knee Score, HKA hip-knee angle, WOMAC Western Ontario and McMaster University Osteoarthritis Index, COR centre of rotation (of hip joint)

Table 2 Literature review of publications on 3D printing in total knee replacements

S. no.	Author	Study type	No. of cases	3DP use	Outcome parameters	Inferences
1	Nunley et al. (2012) [32]	Retrospective case control	57 in each group	PSCB	Operative time (total in-room time and tourniquet time), component alignment on plain X-rays	PSCB show slight improvement in operative time management, but none in alignment. (may not be cost effective)
2	Lustig et al. (2013) [29]	Prospective case series	45	Patient-specific cutting blocks (PSCB) for TKA	Pre-operative and intra-operative measurements with respect to femoral (coronal, sagittal and rotation) and tibial (coronal and slope) alignment	Unsatisfactory in the coronal plane and even less accuracy in the sagittal and rotational planes with use of PSCB's
3	Victor et al. (2014) [30]	Randomised control trial	128 (64 each)	Patient-specific guides (PSG)	Post-op radiographs and CT to evaluate overall coronal alignment, femoral coronal and axial alignment, tibial coronal and sagittal alignment	Similar outliers in overall coronal and femoral component alignment, but more outliers in tibial coronal and sagittal alignment. PSGs do not improve accuracy in TKA
4	Stronach et al. (2014) [31]	Retrospective case-control	58 knees and 62 knees	PSI	Radiographic evaluation of mechanical axis and alignment of femoral and tibial components	No improvement in overall alignment in both the groups and rather worsening of tibial slope with PSI's
5	Barret et al. (2014) [37]	Prospective multicenter non-randomized study	66	PSI	Absolute mechanical axis, component alignment, intraoperative time, adverse events	Alignment results were comparable, intraoperative time was lower with use of PSI (compared with different cohorts of conventional and computer-assisted surgeries)
6	Denis Nam et al. (2015) [33]	Retrospective cohort	190 (2 groups of 95)	Custom cutting guides (CCG) made from 3D images	HKA, OKS, SF-12, UCLA	No advantage in validated knee outcome scores
7	Qiu et al. (2017) [34]	Randomised control trial	26 (PSI:10 Conventional:16)	PSI	Proximal osteotomy amount, distal osteotomy amount, valgus angle, tibial posterior slope	PSI group showed significantly better results ($p < 0.05$)
8	Gemalmaz et al. (2018) [36]	Prospective cohort	20 each in 2 groups	PSI	MFTA, FCA, TCA	Better mechanical alignment with PSI
9	Ogura et al. (2018) [39]	Retrospective	55 (59 knees)	Customised implants	VAS, WOMAC, SF-36, survival rates	High survival rate: 92% at 2 years. 3DP allowed precise fit and significant improvement with patients' satisfaction
10	Arbab et al. (2018) [39]	Retrospective	107: conventional; 125: patient-specific TKR	Customised implants	Deviation from target mechanical axis	More outliers in conventional surgeries (26% vs 16%)

Table 2 (continued)

S. no.	Author	Study type	No. of cases	3DP use	Outcome parameters	Inferences
11	Levengood et al. (2018) [41]	Prospective	63	PSI and customised implants	Intra-op navigation assessed mechanical alignment	Significant improvement in deformity post-operatively ($p < 0.0001$). Restored neutral axis accurately
12	Tian et al. (2018) [28]	Retrospective	31	PSI (femoral intramedullary rod)	KSS, surgical time, drainage volume, coronal alignment	No difference in KSS, alignment or surgical duration Lesser drainage in 3DP (no significant advantage)
13	Shen et al. (2019) [35]	Retrospective	20 (10 in each group)	PSI (osteotomy guide)	MFTA, KSS, blood volume, operative time	MFTA, blood loss and operative time reduced; KSS increased (with 3D-printing-guided osteotomy)
14	Sultan et al. (2019) [38]	Retrospective series	496 (568 knees)	Cementless tibial base plate	KSS, implant survival, surgical and medical complications	The 3DP tibial plates showed clinical success and excellent survivorship
15	Sun et al. (2020) [27]	Prospective RCT	80 (40 each group)	PSI (femoral guide)	HSS, AKS, HKA, PCA, PFA	No difference in outcome with PSI

PCA porous coated anatomic, *PFA* patello-femoral arthroplasty, *MSTS* Musculoskeletal Tumor Society Scoring, *PSI* patient-specific instrumentation, *COR* centre of rotation, *MFTA* mechanical femoro-tibial angle, *VAS* visual analogue scale, *SF-36* Short Form Survey-36, *FCA* femoral component angle, *TCA* tibial component angle, *PSCB* patient-specific cutting block, *PSG* patient-specific guides, *KSS* Knee Society Score, *HSS* Hospital for Special Surgery Score, *AKS* American Knee Society Score, *HKA* hip-knee angle, *OKS* Oxford Knee Score, *UCLA score* University of California at Los Angeles

the studies included in this review utilised CT or MRI to create a 3D model, which was subsequently printed to get the three-dimensional design of the patients' anatomy. In the published literature, these models were primarily used for assessing acetabular deficiencies and determining the number and nature of augments, grafts and cages [25]. Kavalerskiy et al. assessed the impact of planning of revision hip replacements in 17 patients, utilising 3D-printed models of the patients' hip joint [25]. They even planned the number and types of augments as well as size of the cups on their models. They showed 100% match of what was planned and what was achieved in terms of augments, while 64.3% of cup sizes matched the preoperatively planned sizes. In the remaining eight cases also, the difference was not more than 2 mm between the plan and the execution. The authors concluded that 3DP models of the patient's anatomy could make the planning and decisions precisely accurate.

Aprato et al. compared 3D CT with conventional CT to diagnose pelvic discontinuity in 56 patients undergoing revision THRs [26]. They concluded that 3D models demonstrated a higher specificity for identifying acetabulum defects, with perfect intra-observer reliability, and suggested that 3DP could help make more reliable diagnosis and subsequent decisions for management, compared to conventional radiographic means.

Another issue with conventional imaging and planning during revision are the artefacts in CT scans, caused by implants in situ. In such scenarios, especially for periprosthetic fractures, Marongiu et al. have shown that a 3DP model aids in preoperative templating and sizing [42]. It includes measures of shape, location and extent of distorted anatomy including bone loss. The centre of rotation compared with the normal side can be determined from the model. Overall, there is some evidence that THR related planning and decision-making can be aided by 3DP, but the literature is currently scarce in this aspect.

In TKR, the angle and extent of tibial and femoral cuts are commonly determined using preoperative radiographs and intraoperative use of conventional instruments. These methods have a reported accuracy in postoperative alignments of up to 75%, when compared to the normal side [35]. Although there is insufficient evidence in the literature that addresses the accuracy of 3D models in planning and decision-making, the models produced with computer-assisted design software could help in determining the required levels of osteotomy to reconstruct the mechanical axes [43]. However, further studies are needed to compare the planned and actual intraoperative cuts and sizing to assess the role of 3DP in TKR planning.

Therefore, on evaluating the published literature in both hip and knee arthroplasties, the role of 3DP in preoperative planning and surgical decision-making remains inconclusive.

Although there are a few studies addressing these specific points, further evidence needs to be available to recognise the efficacy of 3DP in this aspect of arthroplasty.

Customised Implants

Li et al. described the usage of individualized custom cages in 26 patients undergoing revision THA with severe bony defects [12]. After a mean follow-up of 67 months, they showed that such cages manufactured by 3DP provide stable fixation and improve the functional scores.

Mao et al. described a similar method using customised cages to reconstruct acetabuli with massive defects [13]. The cage used a hook, crest, flange or braids for added stability in 23 hips, and the authors concluded that these customised cages are a promising option for revision THA, with acetabulum defects.

Kieser et al. retrospectively evaluated 46 cases with mean age of 68 years, where customised 3DP acetabular implants had been used, at a mean follow-up of 38 months. 10 of these patients could not be included in final analysis due to mortality and attrition. In the 36 cases they could evaluate, they found the mid-term results of these innovative implants to be promising, with improved hip functional and radiological scores, and no incidence of aseptic loosening [14].

A case series by Wang et al. compared 57 cases of conventional THA to 17 cases of 3D-printed acetabular prostheses for hips with severe deformities caused by either tuberculosis or developmental dysplasia, with a minimum follow-up of 2 years. Their results showed that the time to weight bearing ($p < 0.001$) as well as Harris Hip Score ($p = 0.013$) were better for the 3DP group. However, complications like loosening ($p = 0.009$) and infections ($p = 0.022$) were relatively higher in the 3DP group. Femoral anteversion was significantly different from the non-affected side in the conventional group, inferring it to be closer to the native value in the 3DP cases [15].

Two separate studies by Aprato et al. and Citak et al. used customised components for acetabular defects in 8 and 9 patients, respectively, and assessed the associated implant-related complications [16, 17]. Aprato et al. had two cases of dislocations while Citak et al. had only one case of implant failure. The overall cup orientation and position were satisfactory in both the studies. Citak et al. reported significant improvement of Harris hip scores (HHS) from 22.1 at admission to 58.7 at final follow-up [17].

Angelini et al. analyzed 13 patients including 10 tumour prosthesis and 3 revision hip replacements, where 3DP-customised prosthesis had been used, and concluded that the technology is promising with good survival and functional outcome at a mean follow-up of 13.7 months [18].

All these studies prove the overall effectiveness of these customised acetabular components in difficult THRs with minimal complications. 3DP implants potentially allow earlier mobilisation and better functional outcome when compared to conventional implants [15].

Additional promise of 3DP has been in developing fully porous femoral stems that would lead to reduction in stress shielding after THA, and prolong the implant life. Arabnejad et al. introduced such a stem with “tunable” mechanical properties [44]. It was a short stem taper-wedge design, the microstructure of which can be fine-tuned to match the individual bone properties of the patient. It involved a multi-level computerised program to tune the stiffness of the implant in relation to the bone. The results were mapped into a lattice mould which was then used to make the implant using a procedure called “selective laser melting”. This intricate procedure optimises the 3D-printed implant for minimal resorption. They showed that such a stem potentially reduces the bone loss secondary to stress shielding by 75% and could be an important addition to the armamentarium of hip arthroplasty surgeons in the future.

Three recent studies of 2018 and 2019 specifically tested the efficacy of customised knee arthroplasty implants using 3DP. Sultan et al. demonstrated 99% survivorship of a cement-less 3DP highly porous titanium-coated tibial baseplate after an average of 3 years follow-up, in 496 patients [38]. The clinical scores of pain relief and functional scores were also excellent. Ogura et al. used a customised implant for bicompartamental knee replacements (medial or lateral with patellofemoral) in 59 knees and reported 92% survival rates after 5 years with good patient satisfaction [39]. It was a resurfacing implant which enabled better bone stock preservation, and could be a novel option in younger patients. Arbab et al. compared 107 conventional TKRs with 125 patient-specific TKRs and assessed the deviation of mechanical axes postoperatively with the target set preoperatively [40]. They confirmed more outliers in conventional surgeries and showed efficacy of customised implants in achieving better alignments. Additionally, Levengood et al. used both customised implants and PSI in 63 patients and used intra-operative navigation to assess mechanical alignment. They had significant improvements in deformity correction as well as exhibited accurate femorotibial axis [41].

From the available literature, we can infer that customised 3DP implants have shown considerable promise and efficacy in TKR, and it seems that the scope of these implants will expand as more and more surgeons become familiar with the technique, and there is better availability of 3DP.

Patient-Specific Instrumentations (PSI), Guides and Cutting Blocks

Six studies assessed the benefits of patient-specific instrumentation in hip arthroplasty [19–24]. Small et al. did an RCT comparing THA with PSI and conventional surgeries. Both groups had 18 patients and the results showed that the anteversion with PSA was significantly closer to the safe zone [19]. Cao et al. described the use of a custom-made positioner for accurate positioning of the acetabular shell in 32 patients and compared the outcomes with conventional techniques in 40 patients. They concluded that the 3DP allowed better accuracy of component positioning (0.19 mm closer to anatomical Centre of rotation) [20]. Schneider et al. used a patient-specific femoral osteotomy guide for the neck cut in 30 uncemented hip replacements and found that 29 cases had accurate cuts within 3 mm of the planned level at the femoral neck [21]. In our literature search, the largest series describing patient-specific guide for acetabular cup positioning was by Spencer-Gardner et al. who published their experience of 100 cases [22]. They concluded that such instrumentation allowed more accurate placement of the acetabular component in terms of achieving preoperative patient-specific target inclination and anteversion, with minimal deviation, than free-hand methods used in a previously reported different control group of 188 THRs. The most recent study published in 2020 by Mishra et al. further confirms that using a 3D-printed guide jig to place the acetabular cup provides better anteversion than conventional methods [23]. Additionally, the difference in duration of surgery and blood loss in both the methods were insignificant implying that no additional time was wasted. Overall for PSI in THR, the current literature mostly describes the use of 3DP zigs which are attached to the acetabular instrumentation to guide the component into better position, focusing on anteversion and inclination.

On the other hand PSI have been used more extensively in TKRs. Currently, the required osteotomies and steps are performed on the 3D image in the software and then a 3D model facilitating accurate osteotomies is manufactured. This theoretically reduces the intra-operative time, blood loss, the number of instruments needed in inventory as well as reduced number of surgical steps. 12 of the 15 articles describing 3DP in knee arthroplasty described the usage of PSI, and assessed whether or not these are actually superior to conventional surgeries in terms of providing better mechanical alignments and functional outcomes. The evaluation of the published data gives debatable results; some studies find PSI fruitful and superior [34–37], while some do not [27–33]. Sun et al. evaluated PSI in 40 patients and compared outcomes with 40 cases of conventional TKR [27]. It was a randomized study and clinical as well as functional outcomes were compared. They noted no

difference in hip–knee–ankle alignment angles between the groups, and short-term range of motion, knee scores and drainage were comparable. Similarly, Tian et al. did not find any difference in their 31 patients operated with 3DP PSI and conventional cases, in terms of Knee Society Score, alignment and surgical duration [28]. Prior to these, two prospective studies by Lusting et al. and Victor et al. also concluded that patient-specific guides and cutting blocks do not provide adequate accuracy in postoperative mechanical alignments in TKR [29, 30]. In three other retrospective studies as well, the authors could not find significant improvement in post-operative alignments and validated outcome scores, in TKRs with patients' specific instrumentation and cutting blocks [31–33]. All these studies were comparative studies and none of them found superiority of PSI over conventional techniques. The only positive finding was that PSI helped reduce the overall duration of the surgery [32].

On the other hand, Qiu et al. did a RCT with 26 patients and showed improved outcomes in 10 patients with PSI as compared to 16 conventional cases, due to more precise cuts and better postoperative alignments [34]. Shen et al. applied 3D-printed osteotomy guide plates in the treatment of 10 valgus knees with TKR, and compared the Knee Society Score (KSS) and postoperative mean femoro-tibial angles (MFTA) with 10 conventional TKRs [35]. The overall surgical duration, intra-operative blood loss and post-operative MFTA were significantly less in the 3DP group. Additionally, the KSS was more in that group and the authors concluded that 3DP-assisted osteotomy is more effective than conventional TKR.

A study by Gemalmaz et al. compared 2 groups of 20 patients each, where PSI was used in one group and conventional instrumentation in the other, and eventual outliers ($> 3^\circ$ variation in mechanical axis) were assessed post-operatively [36]. Their study reported significantly fewer outliers in the PSI group as compared to the conventional group (1 versus 7). Barret et al. in their prospective multi-centre study used PSI in 66 TKRs and compared them with another cohort of conventional TKR ($n=81$); they found that alignment was as good as conventional cases, with intra-operative time being lesser when PSI was used. Additionally, they also found that the alignments achieved were comparable to another cohort of computer-assisted surgeries [37].

In terms of cost-effectiveness, the comparison of the cost of the 3D printing setup and procedure with operating room time and associated cost needs to be done.

Martelli et al. in their systematic review concluded that although 3DP guides save the operating time, but the additional costs they incur is an important limitation for routine and widespread usage [45].

On the contrary, Ballard et al. in a review of 3D printing in Orthopaedic and maxillofacial surgeries, specifically analysed cost-effectiveness of surgical guides; they demonstrated a mean of 23 min less time in the operating room saving approximately 1488 US dollars/case [46]. In terms of evening out the fixed costs of 3DP in terms of setup and procedure, they recommended an estimated usage of 63 guides per year and concluded that potential cost-savings of these guide are substantial.

Vitali et al. also suggested that in complex cases, 3DP fare better than conventional methods, but they cautioned against its expenses in routine cases [47]. Overall, further validation of these analyses is needed owing to heterogeneity of data in these reviews.

From the published literature, we can summarise that although PSI decrease the surgical time, its superiority in terms of the post-operative alignments is debatable. Results from different studies have been variable with some showing worse rotations and alignments, while some showing comparable to improved results with 3DP. Further large scale randomised studies are needed to determine the effectiveness of PSI and cutting blocks in TKR.

Teaching and Patient Education

In the present review, none of the included articles on arthroplasties specifically mention the role of 3DP in teaching and patient education. However, in a previous review, Javaid et al. highlighted the application of 3D printing in orthopaedics, and stressed upon the fact that this technology can be used comprehensively to understand the native anatomy with visual and tactile stimuli; for learning and teaching of students, trainees, surgeons as well as patients [5]. The possibilities of practicing surgeries on the printed prototypes, as well as educating a patient regarding detailed aspects of his proposed surgery, could further strengthen the doctor patient relationships. Accurate and high-quality printing of three-dimensional human pathologic specimen is very much achievable and learning anatomy and application of clinical aspects to benefit undergraduate and postgraduate education and practice is feasible [48].

In the field of trauma, Hurson et al. showed that 3DP aids in understanding the acetabular fractures and classifying them, with lesser inter-observer variability among lesser experienced trainees, in comparison to consultants [49]. This indicates that such models provide better understanding of the anatomy by the lesser experienced and this aspect could also be crucial in arthroplasty cases with distorted native anatomy.

Although only two published studies have looked at this point, there definitely seems to be a case for utilising 3DP in education and training of students and trainees.

Future Prospects

An interesting application of 3DP in arthroplasty could be in periprosthetic joint infections. Usage of an antibiotic eluting polymethylmethacrylate (PMMA) spacer or liner is a routine in the management of these infections. PMMA has its own set of disadvantages: brittleness, unsustainable elution of antibiotics and limitation of only using heat-stable antibiotics. Kim et al. hypothesized the usage of a liner made of polylactic acid (PLA) made by 3DP that can overcome disadvantages of PMMA [50]. They did mechanical testing of the two and found PLA to be stronger and ductile. They also demonstrated controlled elution of antibiotics using PLA with usage of reservoirs and micro channels. Controlling the porosity of the liner can aid in sustained release of antibiotics, which becomes significantly important in arthroplasty related infections. Similarly, Allen et al. in their research demonstrated the potential of 3DP in creating reservoirs for implants that could elute antibiotics and have better structure than a conventional PMMA spacer [51]. Although the proposed designs are still not an invention, the idea put forth by the authors can go on a long way in overcoming and transforming periprosthetic joint infections and their management.

Concepts of 4D and 5D printing have also been put forward. 4DP differs from 3DP in terms of the fourth dimension of time; this implies that while 3DP gives a final 3D structure, 4DP-created structure can change forms over time. 5DP on the other hand includes two theoretical mathematical spatial dimensions and allows the print part to move while being printed which helps produce curved layers instead of flat ones as printed by 3DP [52]. This could be a prospective tool in producing artificial bones with curved surfaces mimicking human bones and usage of those models in surgeries [53]. This could help in revision surgeries as well as tumour excisions.

Conclusion

The changing nature of modern medicine, as well as the dependence on newer technologies, make it obligatory for surgeons to aim for perfection, especially in the field of arthroplasty. A point of note is the increasing complexity of cases that now present for arthroplasties, as a host of cases are presenting for revisions, with bone defects and anatomical variations demanding more ingenuity and advanced skills. Creativity of surgical thought has to be combined with advances in technology to optimize surgical outcomes. Our review of the literature has shown significant potential for 3DP, especially in preoperative planning, customised acetabular implants and to some extent in designing zigs. However, these new technologies

need to be tested with statistical long-term proof, before they can be applied routinely to larger populations. The role of 3DP in surgeon/patient education has great potential despite limited publications; on the other hand, the utility of patient-specific implants remains unsubstantiated by the available literature. The future for this technology, nevertheless, seems bright, despite the need of better designed studies and larger sample sizes to identify significant improvement in outcomes that 3D printing promises.

Compliance with Ethical Standards

Conflict of interest All the authors declare no source of funding and no conflict of interest.

Ethical Standard Statement This article does not contain any studies with human or animal subjects performed by the any of the authors.

Informed Consent For this type of study, informed consent is not required.

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