EOR | volume 5 | december 2020
DOI: 10.1302/2058-5241.5.200046
www.efortopenreviews.org

EFORT open reviews

Three-dimensional pre-operative planning of primary hip arthroplasty: a systematic literature review

Maria Moralidou
Anna Di Laura
Johann Henckel
Harry Hothi
Alister J. Hart

- Three-dimensional (3D) pre-operative planning in total hip arthroplasty (THA) is being recognized as a useful tool in planning elective surgery, and as crucial to define the optimal component size, position and orientation. The aim of this study was to systematically review the existing literature for the use of 3D pre-operative planning in primary THA.
- A systematic literature search was performed using keywords, through PubMed, Scopus and Google Scholar, to retrieve all publications documenting the use of 3D planning in primary THA. We focussed on (1) the accuracy of implant sizing, restoration of hip biomechanics and component orientation; (2) the benefits and barriers of this tool; and (3) current gaps in literature and clinical practice.
- Clinical studies have highlighted the accuracy of 3D pre-operative planning in predicting the optimal component size and orientation in primary THAs. Component size planning accuracy ranged between 34–100% and 41–100% for the stem and cup respectively. The absolute, average difference between planned and achieved values of leg length, offset, centre of rotation, stem version, cup version, inclination and abduction were 1 mm, 1 mm, 2 mm, 4°, 7°, 0.5° and 4° respectively.
- Benefits include 3D representation of the human anatomy for precise sizing and surgical execution. Barriers include increased radiation dose, learning curve and cost. Long-term evidence investigating this technology is limited.
- Emphasis should be placed on understanding the health economics of an optimized implant inventory as well as long-term clinical outcomes.

Keywords: 3D pre-operative planning; primary total hip arthroplasty (THA); surgical planning

Cite this article: *EFORT Open Rev* 2020;5:845-855.
DOI: 10.1302/2058-5241.5.200046

Introduction

Over 3.1 million primary total hip arthroplasties (THA) have been performed in Europe since the mid-20th century.[1] Estimations based on current trends in the UK indicate a significant increase in primary THA,[2] with the cost per procedure being up to £7,000.[3] Outside Europe, the United States report an expansion of 50% for primary THA in the young population,[4] while the Australian healthcare system expects a rise of 208% (2013 to 2030), and an overall cost over $AUD 5.32 billion.[5]

The main goal of primary THA is to relieve pain and eventually restore the normal hip function.[6] Implant selection and positioning are crucial in minimizing intra-operative difficulties and ensuring a good functional outcome.[7,8] The modern approach to THA involves a more targeted treatment relying on the use of advanced image modalities for both diagnosis and treatment. Three-dimensional (3D) planning is an important step for elective surgery. Its technical goals include optimal implant sizing and position as well the restoration of femoral offsets (FO), leg length (LLD) and centre of rotation (COR).[7–9] Achieving these can eventually lead to a more accurate surgical procedure[9] with reduced implant inventory[7] resulting in a more cost-effective surgery.[8] It also enables the use of other computer-assisted techniques such as robotic-assisted surgeries,[10] navigation techniques[11] as well as the use of patient-specific instrumentation (PSI) [12,13] and implants.[14]

The aim of this systematic review was to summarize the existing literature on the use of 3D pre-operative planning in primary THA, using off-the-shelf implants. We acknowledge that 3D planning has emerged with the use of customized implants. However, these components were excluded from this study and focus was placed on the 3D pre-operative planning using software which includes libraries of off-the-shelf implants.

In detail, we (1) reported on the accuracy in prediction of implant size, restoration of hip biomechanics and

Table 1. Inclusion criteria

Inclusion criteria
Original publication in English
Publication date between 2000 and 2020
Accessibility
Primary hip arthroplasty

component orientation; (2) highlighted benefits and barriers; (3) proposed new areas of research.

Methods

Search strategy and study design

This systematic review was prepared in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. PubMed, Scopus and Google Scholar were used, in the order mentioned, as search engines to access full scientific journals reporting the use of 3D planning in primary THA. The systematic search was performed from September 2019 to April 2020. Moreover, the references list of eligible articles were manually checked to identify any missing relevant records.

A series of consecutive search attempts was made, using the following terms, "3D or three-dimensional (quantitative) (preoperative) planning", "(pre-) surgical (preoperative) planning", "3D or three-dimensional templating", "three-dimensional preoperative planning software", "three-dimensional computerized planning" and "3D-CT preoperative planning", all of them in combination with "(Primary) Total Hip Arthroplasty (THA) or Total Hip Replacement (THR)".

Eligibility criteria: study selection

All clinical studies reporting the role of 3D pre-operative planning in primary THA were included. Additionally, articles addressing the technical aspects of 3D planning software were also considered. The search was limited to full scientific journals written in English and restricted to studies published since the year 2000. We excluded studies reporting revision THA, books, lecture notes and studies, which were not accessible. All titles and abstracts were screened by the lead author to select studies relevant to the research question. During the initial screening, studies exclusively related to navigation techniques, robots, 3D printing and patient-specific instrumentation (PSI) were excluded. Then, full articles were included or excluded based on the inclusion criteria given in Table 1.

Results

Search results

Electronic systematic research led to 144 studies; 51 in PubMed, 89 in Scopus and 4 in Google Scholar. After the removal of duplicates ($n = 3$), search resulted in the selection of 54 journal articles: 32 from PubMed, 18 from Scopus and four from Google Scholar. Of these, 11 were excluded according to the inclusion criteria. In detail, there were one book, two studies written in foreign languages, two revision studies, four not fully scientific journals, one bone tumour surgery and one study which was not accessible. Finally, 43 full scientific articles were reviewed. Fig. 1 depicts, in detail, the procedure of initial screening and study selection.

Current trend of 3D pre-operative planning

The first article proposing a framework of planning based on three planes of human anatomy was in 2002,[15] after which a gradual rise was noted until 2012. Subsequently, evidence around the use of 3D planning was considerably higher, reaching 100 citations around 2017 (Fig. 2).

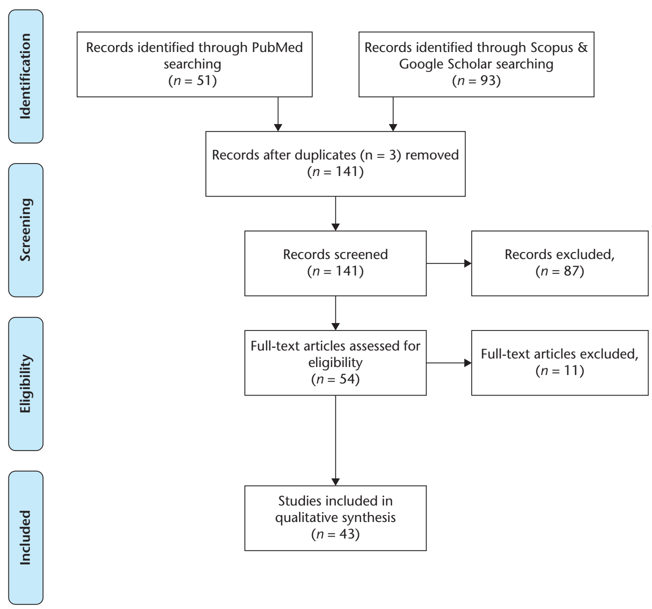

Fig. 1 PRISMA flow chart.

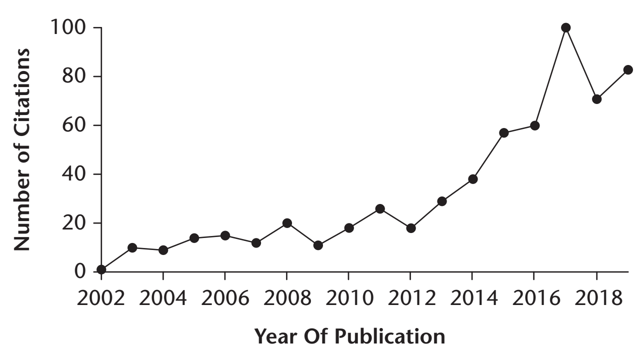

Fig. 2 Line graph showing the growing trend of the use of 3D planning.

3D pre-operative planning: the procedure

A typical process of 3D pre-operative planning is shown in Fig. 3. Pre-operative planning is executed through specialized programs (Table 2) that help surgeons positioning and orientating the implants in a 3D representation of the patient's anatomy (Fig. 4 and Fig. 5).[15] Medical imaging required, includes computed tomography (CT), magnetic resonance imaging (MRI) or low-dose bi-planar radiographs. Imaging data (Digital Imaging and Communications in Medicine-DICOM) of patients are subsequently imported into planning software, where segmentation and 3D reconstruction take place.[15] Surgeons then plan the surgery based on the anatomical variables of the patients.

Available implant databases, which vary amongst planning platforms, include 3D models of acetabular and femoral components. There are software solutions, which are either tied to one implant manufacturer[9] or incorporate a larger library of implants. The user can visualize the spatial relation between the implant and the host bone in three different windows, which represent the three different planes of the human body.[15,16] Combining three 2D view planes with a view representing the three-dimensional anatomy of the patient has been proven to be the most accurate way of depicting 3D pre-operative planning using software (Fig. 4 and Fig. 5).[17] Some software packages include an additional step of kinematic simulation for range of motion (ROM) of the planned hip (Fig. 6 and Fig. 7),[18,19] using motion databases[18] and collision detection algorithms,[16] to identify the possibility of impingement during daily activities.[18]

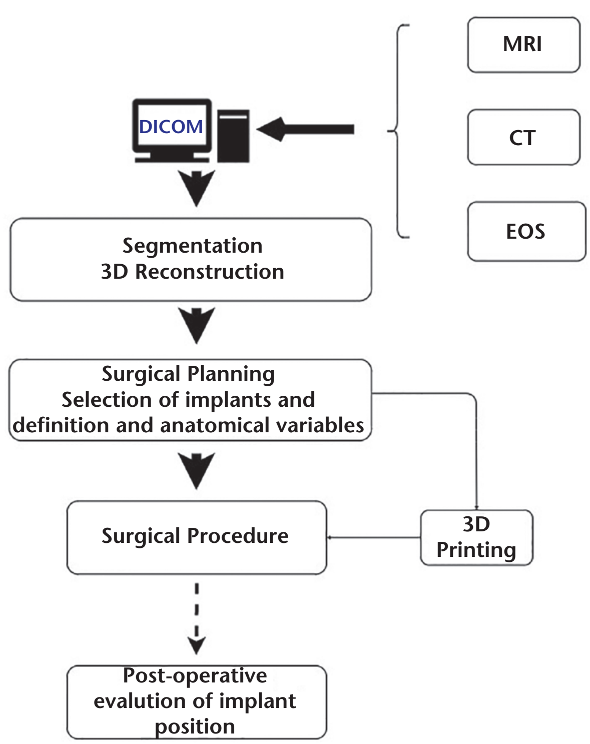

Fig. 3 Typical process of 3D pre-operative planning.

Note. MRI, magnetic resonance imaging; CT, computed tomography.

Table 2. **Software solutions encountered during systematic search**

Software	Manufacturer	Modality
HIP-PLAN	Symbios	CT
hipEOS	EOS Imaging	LDB Radiography
ZedHip	LEXI Co., Ltd	CT
HipOp-Plan	Rizzoli Orthopaedic Institute	CT
MyHip	Medacta International	CT
MAKO Planning	Stryker	CT
Arthroplan	Custom Orthopaedic Solutions	CT
Kyocera 3D-Template	Kyocera Medical	CT
modiCAS || Plan	modiCAS	CT
Hip 3D	mediCAD, HecTec GmbH	CT
Mimics	Materialise	CT

CT, computed tomography; LDB low-dose bi-planar.

As Fig. 3 indicates, 3D pre-operative planning may also work as an enabler to produce 3D printed models of patients' anatomy or PSI.[18,20] 3D printing is therefore a valuable step to further assist the surgery, though not always implemented.

Accuracy of 3D pre-operative planning in component size prediction

Optimal component sizing is of great importance to achieve a more precise surgery. The overall accuracy of 3D surgical planning in component size prediction has been proven satisfactory, with good inter-observer variability.[7–9,11,13,21–28] Prediction rates for femoral stem and acetabular cup sizes range between 34–100% and 41–100% respectively (Table 3). Considering this, 3D pre-operative planning may lead to a reduction in intra-operative guesswork and allow an optimal implant inventory.[7]

Most of the studies focussed around the role of planning in primary osteoarthritis (OA), while fewer included developmental dysplasia (DDH).[11,23,24] Generally, studies concerning primary OA reported superior results in comparison with DDH.[25] That was confirmed by Wako et al, who described a relation between hip deformity and reliability of 3D surgical planning.[25] This may be explained if considering that secondary OA is associated with serious deformities compared to primary OA, leading to misplaced acetabular components in 25.7% of Crowe Type III patients and 12% in Crowe Type I.[23]

Restoration of biomechanics

Besides the optimal component size, dimensional characteristics such as LLD, FO, COR and component orientation should be restored in THA to minimize complications such as pain, instability, wear and abnormal gait.[11]

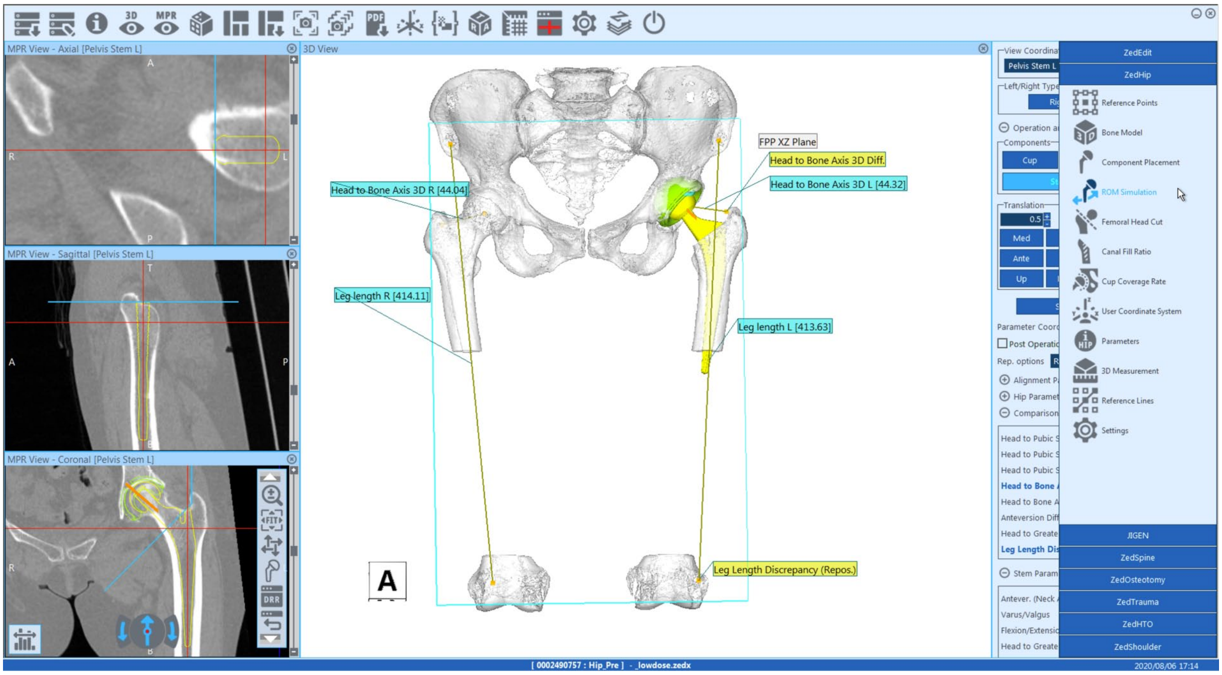

Fig. 4 Illustration of ZedHip (LEXI Co., Ltd) planning software combining orthogonal views of the human body together with the 3D representation of the bones and the implant.

Source. Image courtesy of Image courtesy of LEXI Co., Ltd, Tokyo, Japan.

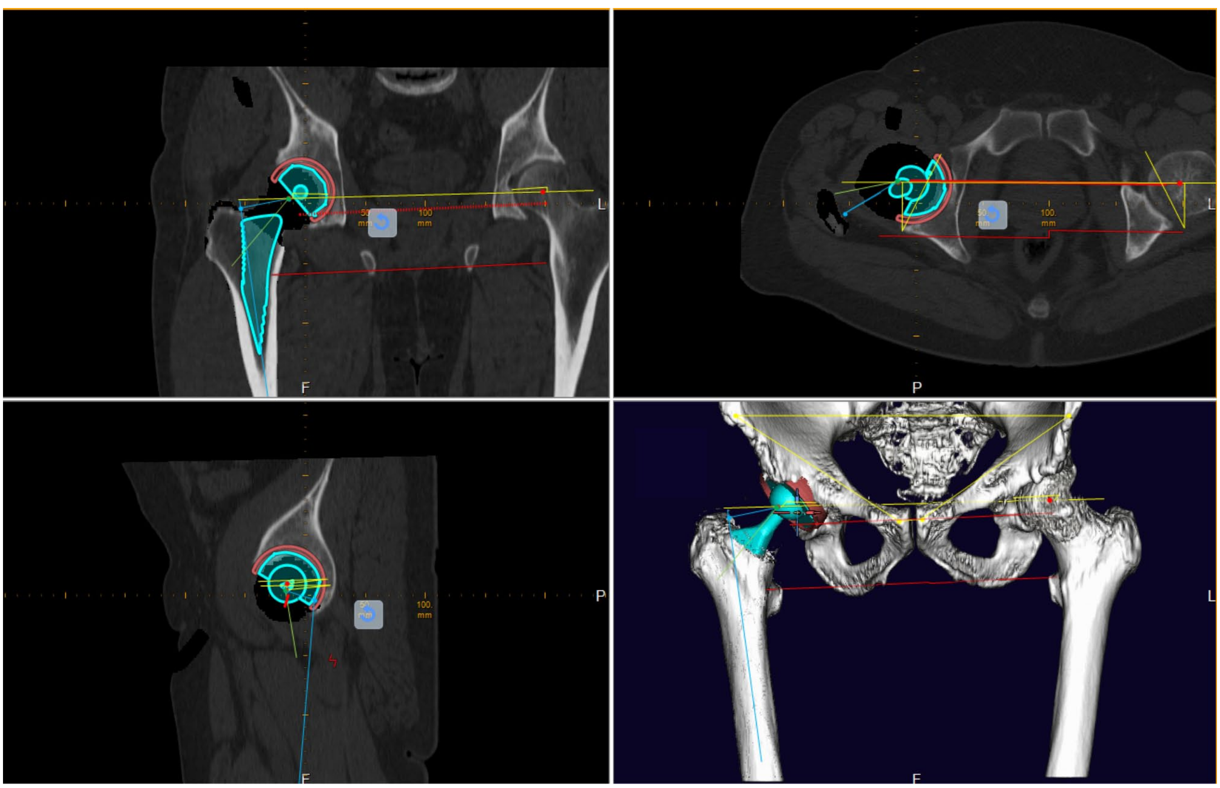

Fig. 5 Illustration of Hip 3D (mediCAD, HecTec GmbH) planning software combing orthogonal views of the human body together with the 3D representation of the bones and the implant.

Source. Image Courtesy of mediCAD, HecTec GmbH, Altdorf, Germany.

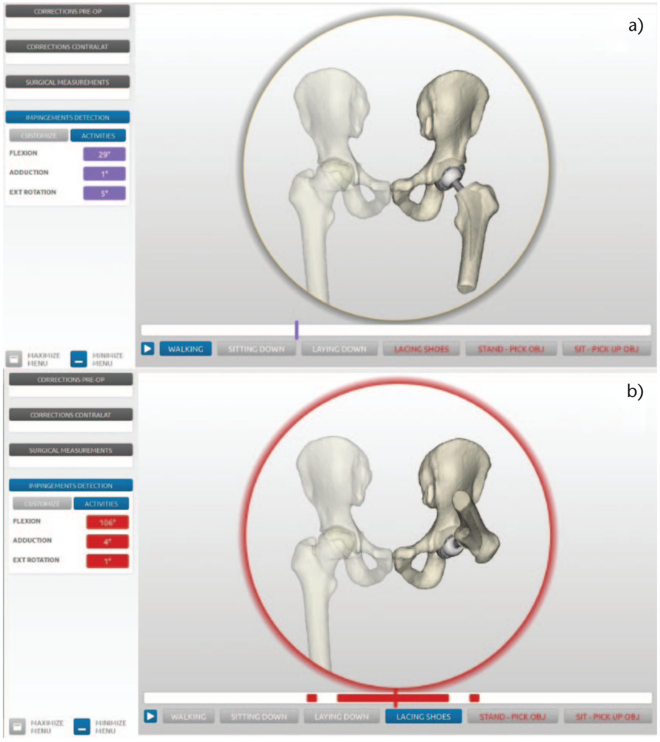

Fig. 6 Illustration of My Hip (Medacta International SA) planning software, which incorporates range-of-motion simulation during daily activities to detect the possibility of impingement. (a) Case example where no impingement was detected during simulation of walking; (b) however, more demanding activities such as shoe lacing are characterized by impingement.

Source. Image Courtesy of Medacta International SA, Castel San Pietro, Switzerland.

The number of studies found on the subject was limited (n = 7) (Table 4). Assessing accuracy of 3D pre-operative planning in component position and orientation is more difficult compared to implant sizing, which seems straightforward. However, the limited number of articles on the subject demonstrated an absolute average difference between the planned and achieved values of leg length, offset and centre of rotation craniocaudally and mediolaterally of 1.192 mm, 1.136 mm, 2.052 mm and 1.998 mm respectively.

3D pre-operative planning may be considered a useful tool to restore hip biomechanics. It allows 3D representation of the human anatomy and anatomical variables such as FO, COR and LLD to be accurately estimated.[13,21,23,29] Using 2D radiographs, anatomical features, such as FO, may be wrongly estimated by up to 13.7 mm[21] due to patients' malposition.[29]

Femoral stem positioning

Stem positioning defines the patient biomechanics. If one considers that 98% of LLD depends on the femoral component, optimal positioning of the stem is of great importance.[9] Undersized stems can lead to stem subsidence (up to 3 mm accepted), while overestimation is often a cause of intra-operative fracture.[24]

Stem positioning is quantified through measuring the stem alignment (sagittal, coronal), which is the angle between the axis of the stem in the vertical and horizontal planes and the axis of the proximal femur, and constitutes an indication of the stem's fit-fill information inside the femoral canal.[30]

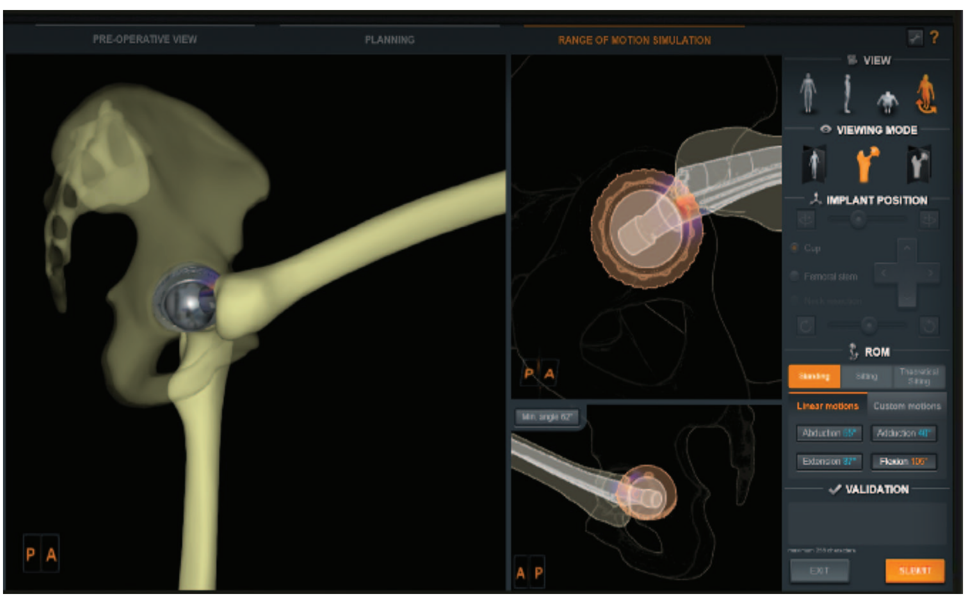

Fig. 7 Illustration of hipEOS (EOS, EOS Imaging) planning software, which incorporates range-of-motion simulation to detect the possibility of impingement.

Source. Image Courtesy of EOS imaging SA, Paris, France.

Table 3. Accuracy of 3D pre-operative planning in predicting component size

Reference	Indication for Surgery	*N* of patients	Surgical approach	Cemented/less	Match (%)		Software
					Stem	*Cup*	
Viceconti (2003)[27]	DDH	29	AL	C.less	65.50%	51.70%	HipOp
Sariali (2009)[21]	OA	223	P, AL	C.less	96%	86%	HIP-PLAN
Sariali (2012)[9]	OA	60	A	C.less	100%	96%	HIP-PLAN
Hassani (2014) [22]	NA	50	A	C.less	100%	94%	HIP-PLAN
Zeng (2014)[23]	DDH	20	PL	C.less	NA	70%	Mimics
Inoue (2015)[24]	DDH	65	PL	NA	65%	92%	Zed hip
Mainard (2017)[8]	OA	31	AL	C.less	34%	41%	hipEOS
Ogawa (2018)[11]	82% DDH	141	P,A	C.less	85.50%	94.40%	Stryker Navigation
Wako (2017)[25]	OA, AVN	60	NA	NA	43.00%	45.00%	ZedHip
Knafo (2019)[7]	OA	33	NA	C.less	48%	55%	hipEOS
Schiffner (2019)[26]	OA	116	AL	C.less	58.60%	56.90%	ZedHip
Savov (2020)[13]	Cadavers	8 hips	NA	NA	100%	100%	ModiCAS
Wu (2019)[28]	DDH	49 hips	NA	C.less	NA	71%	Mimics

P, posterior; PL, posterolateral; A, anterior; AL, anterolateral; NA, not available/not applicable; DDH, developmental dysplasia of the hip; OA, osteoarthritis; AVN, Avascular Necrosis.

Table 4. Accuracy of 3D pre-operative planning in restoring of LLD, FO and COR

Reference	Indication for surgery	*N* of Patients	Surgical approach	Cemented/less	LLD (mm)	FO (mm)	COR (mm)	
							Craniocaudally	*Mediolaterally*
Sariali (2009)[21]	OA	223	P, AL	C.less	0.30	0.80	0.73	1.20
Pasquier (2010)[29]	OA	61	PL	C.less	1.66	1.88	NA	NA
Sariali (2012)[9]	OA	60	A	C.less	1.80	1.30	1.70	–0.27
Hassani (2014) [22]	NA	50	A	C.less	0.30	1.40	0.40	0.40
Zeng (2014)[23]	DDH	20	PL	C.less	NA	NA	4.51	3.26
Knafo (2019)[7]	OA	33	NA	C.less	–1.90	0.30	NA	NA
Savov (2020)[13]	Cadavers	8	NA	NA	NA	L:4.53 A:3.61*	2.92	–4.86

CT, computed tomography; OA, osteoarthritis; DDH, developmental dysplasia of the hip; LLD, leg length discrepancy; FO, femoral offsets; COR, centre of rotation; P, posterior; PL, posterolateral; A, anterior; AL, anterolateral; NA, not available/not applicable.
*This measurement includes the lateral and anterior femoral offset and was excluded from the average FO mentioned in abstract.

Besides the sagittal and coronal alignment of the stem in the intra-medullary canal of the patient's femur, stem anteversion (AV) is another measurement necessary to ensure optimal end position of the stem. Recently, a procedure taking the combination of acetabular and stem AV angles has been proven accurate to evaluate post-operative stem position.[31] Two studies used 3D pre-operative planning to define stem anteversion and then compared the planned and achieved values, which was between 3.7° on average (absolute value) (Table 5).

The ideal fitting of the stem is achieved when the bone–implant contact area in the proximal femur is maximized.[26] Statistical atlases of bone–implant interface, based on already made surgical plans, can be incorporated in 3D pre-operative planning to automatically define the distance between the stem and the femoral bone.[30] Elsewhere, incorporated spectrum maps assist the surgeon to evaluate those and avoid them, while customized stems following the natural intra-medullary cavities can be designed and 3D printed to ensure good fixation.[32] In this regard, 3D surgical planning is a useful tool to assess the contact area of the stem and intra-medullary cavity of the femur.[33,34]

3D planning has enabled the understanding that stem positioning is strongly related with the internal morphology of the femur. Understanding this will help define important femoral variables, which in turn may allow the optimization of stem design and its implantation inside the femur.[35]

Acetabular cup position

The correlation of cups' size and the risk of dislocation is strongly supported by evidence.[36] Improper positioning of the cup also leads to edge-loading and implant wear.[37] When positioning the cup, the goals should be to restore the COR and the anteversion angle of the native acetabulum, prevent cup excess towards the anterior wall and achieve an abduction angle of 40º.[38]

Three-dimensional surgical planning has been proven to increase the accuracy of cup implantation. Osmani et al compared the prediction of cup sizes, proving the superiority over 2D digital templating.[39] Other studies

Table 5. Studies addressing planned and achieved stem anteversion

Reference	Indication for Surgery	N of Patients	Surgical approach	Anteversion (degrees)
Inoue (2015)[24]	DDH	57	NA	4
Imai (2016)[31]	DDH	65	Hardinge	–3.4

Anteversion angles expressed as differences between planned and achieved values. P, posterior; PL, posterolateral; A, anterior; AL, anterolateral; NA, not available/not applicable; DDH, developmental dysplasia of the hip.

Table 6. Studies addressing planned vs. achieved acetabular angles in primary THA

Reference	Disease	Patients	Surgical approach	Anteversion (degrees)	Abduction (degrees)	Inclination (degrees)
Saliari (2009)[21]	OA	223	P, AL	6.30	2	0.8
Small (2014)[12]	OA	36	PL	–0.20	–2	NA
Hassani (2014)[22]	NA	50	A	6.90	NA	–0.4
Zeng (2014)[23]	DDH	20	PL	NA	9.71	NA
Sariali (2016)[38]	OA, ON	28	A	–2.70	–2	NA
Savov (2020)[13]	Cadavers	8	NA	15.06	NA	–0.10
Wu (2019)[28]	DDH	45	NA	9.79	NA	–0.03

Note. Anteversion, abduction and inclination angles expressed as differences between planned and achieved values.
P, posterior; PL, posterolateral; A, anterior; AL, anterolateral; NA, not available/not applicable; OA, osteoarthritis; DDH, developmental dysplasia of the hip; ON, Osteonecrosis.

addressed the use of 3D planning in restoring acetabular angles (version, inclination, abduction), by comparing the planned values with the post-operative acetabular angles. The absolute average differences (planned vs. achieved) of cup version, inclination and abduction were 6.825°, 0.3325° and 3.92° respectively (Table 6).

It should be mentioned though, that 3D planning has shown lower accuracy in positioning the cup, compared to CT-based navigation techniques.[40,41] For this reason, Elbuluk et al proposed a new way of intra-operatively evaluating the position of the cup using 3D templating without the presence of navigation techniques.[42] However, 3D pre-operative planning does not increase the surgical time to that extent.[22] It is, therefore, a compromise between accuracy and time effectiveness.

Long-term clinical outcome

Although the accuracy of 3D surgical planning has been proven, we found only two studies with long-term clinical outcome (five and ten years follow-up). These studies reported high survival rates; however, it is not clear whether the incorporation of the three-dimensional planning resulted in improved clinical results compared to standard practice.[43,44]

Benefits

Technical benefits

Conventional radiographs are associated with magnification issues; 3D-CT pre-operative planning overcomes this,[32] even when it is compared with 2D digital radiographs.[45] Better representation of human anatomy allows optimal component size prediction, which in turn may reduce intra-operative guesswork with the potential to decrease surgical time and complications.[7] Besides the more realistic representation of native anatomy, 3D surgical CT-based planning provides information on the quality of the bone, through the evaluation of the contact state of the implant and host bone and the differentiation of the cortical and cancellous bone.[33,34]

Surgeons

Since computer-assisted orthopaedic surgical software has enabled the visualization of pelvic anatomy, surgeons can accurately assess all the detailed anatomical characteristics and prepare for any possible intra-operative complications. Additionally, component size can be easily defined by either the software or the surgeon to match the native anatomy. This has been proven to scale down the intra-operative questioning regarding the size of hip components which in turn may reduce the components repository.[22]

Patients

The technical benefits mentioned above apply for patients too, since a more accurate surgical procedure leads to a more accurate restoration of biomechanics.[21] Besides the clinical relevance of 3D surgical planning, the simplified visualization of anatomy that this technology incorporates, enables patients to understand their surgery and multidisciplinary professions to communicate well, such as engineers and surgeons, things that are not always straightforward.

Barriers

Cost

Orthopaedic pre-operative planning software usually entails a certain annual cost to hospitals.[32] Huppertz et al reported a direct cost of 3D pre-operative planning per patient of 53–116 euros.[46] Although this cost is not insignificant, it has been proven that the automatic selection of hip implants can reduce the total cost for THA by up to 25.7%.[32] In addition, optimal implants' inventory based on correct size prediction may waive the cost associated with THAs without compromising the clinical aspect.

Technical difficulties

The complexity associated with learning new technological programs constitutes a significant barrier that 3D pre-operative planning encounters. As such, both medical personnel and engineers may need to put effort into learning. Knowing how to use a 3D specialized planning software is not translated to successful pre-operative planning though. A necessary step in pre-operative planning is the anatomical landmark extraction. However, pelvic and femoral reference points (RPs) are not visible in complicated cases, such as large acetabular defects.[35] Besides that, matching of pre-operative and post-operative RPs is also a burdensome task and may induce an error. Computer-matching techniques of pre-operative and post-operative RPs are regarded a valuable method, yet have not been adopted.[47]

Radiation dose

CT-based orthopaedic planning software is associated with the concern of increased radiation exposure. Recent evidence supports the finding that improved scanners and hardware, as well as dedicated CT protocols, may further reduce CT radiation exposure to a level comparable to that of conventional radiographs,[29,32,46,48–50] without compromising image quality.[32]

However, current innovative software hipEOS (EOS, EOS Imaging, Paris, France) offers the possibility of pelvic 3D reconstruction using a radiation dose of 800–1000 (mSv) lower than with CT-based software. This is why EOS may be considered an ideal solution for younger patients suffering from hip diseases.[51–56] However, EOS does not offer an accurate quantification of bone density, even though it is a radiographic imaging modality that allows visual assessment of bone quality.[57]

Discussion

There is growing evidence around 3D planning mostly after the 20th century. In the past, analogue templating was mostly used as a way to plan elective surgeries such as primary THA. The introduction of computers in every field assisted the transition of analogue to digital templating,[58] where innovations in informatics may have made feasible the transformation of patient data to 3D models. This can possibly explain the rise of clinical studies around 3D planning during that period, which were even more apparent after 2012 (Fig. 2).

The increasing trend of evidence regarding 3D planning may be affected by the introduction of European Medical Device Regulations, which intend to impose stricter rules on orthopaedic implants and software, to strengthen surgical safety. The European Union will closely coordinate the market of orthopaedic implants, by introducing a medical device identifier, registered in the European Database of Medical Devices (EUDAMED). These changes are expected to reinforce the rules on clinical evidence of both implants and software. In light of this, it is unknown how the use of 3D planning will change in the future.[59]

The emergence of clinical studies around 3D planning is closely related to the development of specialized orthopaedic planning software. Research has mainly included two planning software packages, HIP-PLAN and Zed Hip, followed by hipEOS. The most cited pre-operative planning software package, HIP-PLAN, which is characterized by high precision in measuring angles (2°) and distances (1 mm),[60] has been used to plan THAs with stems featuring modular neck designs. However, these components have been proven to perform poorly in a number of material and design combinations.[61,62]

Studies so far have proven the superiority of 3D surgical planning in predicting the size of implants over conventional templating. In detail, 2D planning is characterized by inferior results in predicting component sizing: 32–45.7% for the stem and 25–44.8% for the cup.[8,9,23,26,27]

Studies addressing the restoration of biomechanics are limited. Evaluating accuracy and reproducibility of 3D planning in implant position is challenging; not only because it requires post-operative CT image acquisition and analysis, therefore increasing radiation dose but also due to the lack of standardization of scanning protocols. Research should be carried out into whether 3D orthopaedic planning can optimize post-operative hip biomechanics, since many planning software packages offer the possibility of kinematic simulation.[18,19]

All studies investigated the role of 3D pre-operative planning in cementless THA. This is understandable, since 3D planning is necessary to enable fixation between the stem and the femur avoiding risk of fracture, while cemented fixation works well with the variable thickness of the cement mantles.[63] Similarly, only two studies (5 and 10 years follow-up) addressed the long-term survival rate of 3D planned THA.[43,44] However, it was not clear whether the presence of 3D computerized planning contributed to a better survival rate and a long-term clinical outcome.[64] It is only assumed that an increased prediction rate of implant sizing may positively affect the clinical outcome, based on the correlation between implant size and hip biomechanics. Studies, so far, have yet to show the contribution of 3D planning to a better post-operative clinical outcome.[64] This may be more apparent in complex cases.[65]

This can possibly explain the number of surgeries performed using 3D pre-operative planning. According to the National Joint Registry (NJR) of England, Wales, Northern Ireland and the Isle of Man, only 565 primary THAs of the total 97792 surgeries which were performed between 2010 and 2017 incorporated the use of computer-assisted (CA) surgery. That is equivalent to 1% of the total surgeries performed in the UK in that time-frame.[66]

Proving the accuracy of this newly introduced technology is important. This accuracy though, was not found to be excellent and scientists should investigate the reasons why. Table 7 includes all the factors that are potentially

Table 7. Overview of the factors influencing cup and stem implantation[11]

Factors	Cup	Stem
Gender	✓	✓
Age	✓	
Body mass index (BMI)	✓	✓
Surgical approach	✓	✓
Body weight (BW)	✓	✓
DDH existence	✓	
Differences in cup position/orientation	✓	
Differences in stem alignment		✓
Cortical index		✓
Canal flare index		✓

Note. DDH, developmental dysplasia of the hip.

associated with choosing the wrong size of implant intra-operatively.[11] Many studies are therefore necessary to identify the correlation between these factors, the host anatomical environment and the bone–implant interface dynamics with the final position of the implant.

There are undeniable advantages for the use of 3D surgical planning over conventional techniques. High accuracy eventually leads to a more precise surgical procedure, from which both surgeons and patients benefit. More precise surgery is translated to reduced surgical time and implant inventory.[7] Based on this, 3D planning may lead to a more cost-effective THA. However, the cost of available software should be also taken into account. Assessing the cost-effectiveness of 3D computerized planning in primary and revision hip surgeries should be addressed in future research.

Concerning the limitations of this systematic search, we focused only on the usage of image-based 3D pre-operative planning for primary THA, using standard off-the-shelf implants. 3D planning of customized implants was excluded from this study. Navigation, robotic-assisted surgeries and patient-specific guides were excluded from the keywords of this systematic research. Additionally, imageless pre-operative planning and three-dimensional quantitative analysis of anatomical characteristics were not addressed.

Conclusion

3D planning is a relatively recent technique in the field of orthopaedics. High predictability of 3D planning in component sizing has been widely proven. It enables a more precise surgical procedure with reduced intra-operative guesswork. The latter may result in a more contained implant inventory with the potential to reduce the cost for companies and hospitals without compromising clinical outcomes. However, limited studies have addressed the predictability rate of 3D planning in components position. Post-operative evaluation is of great importance in order to answer this question, though difficult to widely adopt.

3D pre-operative planning may be considered a useful tool to restore hip biomechanics. It allows better representation of the human anatomy compared to conventional templating, where patient malorientation usually leads to incorrect planning. Short and medium-term clinical studies have documented good clinical results. It is uncertain, though, due to lack of long-term studies, whether long-term good clinical outcomes will compensate for barriers to the widespread adoption of this technology, such as the increased radiation dose and the learning curve. This may be more evident in complex cases. Understanding the reasons for discrepancies between plan and execution is also of great importance. Long-term clinical data are needed and may result in improved approaches to primary THA, with benefits for all the parts involved in the chain.

AUTHOR INFORMATION

Institute of Orthopaedics and Musculoskeletal Science, University College London and the Royal National Orthopaedic Hospital, Stanmore, UK.

Correspondence should be sent to: Maria Moralidou, Institute of Orthopaedics and Musculoskeletal Science (University College London), Royal National Orthopaedic Hospital, Brockley Hill, Stanmore, Middlesex, HA7 4LP, UK.
Email: maria.moralidou.19@ucl.ac.uk

ACKNOWLEDGEMENTS

This research study was funded by The Maurice Hatter Foundation, the RNOH Charity, the Rosetrees Trust and the Stoneygate Trust and supported by researchers at the National Institute for Health Research University College London Hospitals Biomedical Research Centre.

ICMJE CONFLICT OF INTEREST STATEMENT

AJH reports receipt of a grant to UCL from Medacta.
The other authors declare no conflict of interest relevant to this work.

FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

REFERENCES

1. **Lübbeke A, Silman AJ, Barea C, Prieto-Alhambra D, Carr AJ.** Mapping existing hip and knee replacement registries in Europe. *Health Policy* 2018;122:548–557.

2. **Culliford D, Maskell J, Judge A, Cooper C, Prieto-Alhambra D, Arden NK; COASt Study Group.** Future projections of total hip and knee arthroplasty in the UK: results from the UK Clinical Practice Research Datalink. *Osteoarthritis Cartilage* 2015;23:594–600.

3. Jenkins PJ, Clement ND, Hamilton DF, Gaston P, Patton JT, Howie CR. Predicting the cost-effectiveness of total hip and knee replacement: a health economic analysis. *Bone Joint J* 2013;95-B:115–121.

4. Kurtz SM, Lau E, Ong K, Zhao K, Kelly M, Bozic KJ. Future young patient demand for primary and revision joint replacement: national projections from 2010 to 2030. *Clin Orthop Relat Res* 2009;467:2606–2612.

5. Ackerman IN, Bohensky MA, Zomer E, et al. The projected burden of primary total knee and hip replacement for osteoarthritis in Australia to the year 2030. *BMC Musculoskelet Disord* 2019;20:90.

6. Classen T, Zaps D, Landgraeber S, Li X, Jäger M. Assessment and management of chronic pain in patients with stable total hip arthroplasty. *Int Orthop* 2013;37:1–7.

7. Knafo Y, Houfani F, Zaharia B, Egrise F, Clerc-Urmès I, Mainard D. Value of 3D preoperative planning for primary total hip arthroplasty based on biplanar weightbearing radiographs. *Biomed Res Int* 2019;2019:1932191.

8. Mainard D, Barbier O, Knafo Y, Belleville R, Mainard-Simard L, Gross J-B. Accuracy and reproducibility of preoperative three-dimensional planning for total hip arthroplasty using biplanar low-dose radiographs: a pilot study. *Orthop Traumatol Surg Res* 2017;103:531–536.

9. Sariali E, Mauprivez R, Khiami F, Pascal-Mousselard H, Catonné Y. Accuracy of the preoperative planning for cementless total hip arthroplasty: a randomised comparison between three-dimensional computerised planning and conventional templating. *Orthop Traumatol Surg Res* 2012;98:151–158.

10. Maddah MR. 3D visualization and interactive image manipulation for surgical planning in robot-assisted surgery. https://tel.archives-ouvertes.fr/tel-02007359/document/ (date last accessed 20 October 2020).

11. Ogawa T, Takao M, Sakai T, Sugano N. Factors related to disagreement in implant size between preoperative CT-based planning and the actual implants used intraoperatively for total hip arthroplasty. *Int J Comput Assist Radiol Surg* 2018;13:551–562.

12. Small T, Krebs V, Molloy R, Bryan J, Klika AK, Barsoum WK. Comparison of acetabular shell position using patient specific instruments vs. standard surgical instruments: a randomized clinical trial. *J Arthroplasty* 2014;29:1030–1037.

13. Savov P, Budde S, Tsamassiotis S, Windhagen H, Klintschar M, Ettinger M. Three-dimensional templating in hip arthroplasty: the basis for template-directed instrumentation? *Arch Orthop Trauma Surg* 2020;140:827–833.

14. Abdelaal O, Darwish S, El-Hofy H, Saito Y. Patient-specific design process and evaluation of a hip prosthesis femoral stem. *Int J Artif Organs* 2019;42:271–290.

15. Lattanzi R, Viceconti M, Zannoni C, Quadrani P, Toni A. Hip-Op: an innovative software to plan total hip replacement surgery. *Med Inform Internet Med* 2002;27:71–83.

16. Lattanzi R, Viceconti M, Petrone M, Quadrani P, Zannoni C. Applications of 3D medical imaging in orthopaedic surgery: introducing the hip-op system. In: Proceedings of the First International Symposium on 3D Data Processing Visualization and Transmission. Padova, Italy: IEEE Comput. Soc, 2002:808–811. http://ieeexplore.ieee.org/document/1024165/ (date last accessed 15 April 2020).

17. Viceconti M, Lattanzi R, Zannoni C, Cappello A. Effect of display modality on spatial accuracy of orthopaedic surgery pre-operative planning applications. *Med Inform Internet Med* 2002;27:21–32.

18. Schmid J, Chênes C, Chagué S, et al. MyHip: supporting planning and surgical guidance for a better total hip arthroplasty: a pilot study. *Int J Comput Assist Radiol Surg* 2015;10:1547–1556.

19. Iwai S, Kabata T, Maeda T, et al. Three-dimensional kinetic simulation before and after rotational acetabular osteotomy. *J Orthop Sci* 2014;19:443–450.

20. Henckel J, Holme TJ, Radford W, Skinner JA, Hart AJ. 3D-printed patient-specific guides for hip arthroplasty. *J Am Acad Orthop Surg* 2018;26:e342–e348.

21. Sariali E, Mouttet A, Pasquier G, Durante E, Catone Y. Accuracy of reconstruction of the hip using computerised three-dimensional pre-operative planning and a cementless modular neck. *J Bone Joint Surg Br* 2009;91:333–340.

22. Hassani H, Cherix S, Ek ET, Rüdiger HA. Comparisons of preoperative three-dimensional planning and surgical reconstruction in primary cementless total hip arthroplasty. *J Arthroplasty* 2014;29:1273–1277.

23. Zeng Y, Lai OJ, Shen B, et al. Three-dimensional computerized preoperative planning of total hip arthroplasty with high-riding dislocation developmental dysplasia of the hip. *Orthop Surg* 2014;6:95–102.

24. Inoue D, Kabata T, Maeda T, et al. Value of computed tomography-based three-dimensional surgical preoperative planning software in total hip arthroplasty with developmental dysplasia of the hip. *J Orthop Sci* 2015;20:340–346.

25. Wako Y, Nakamura J, Miura M, Kawarai Y, Sugano M, Nawata K. Interobserver and intraobserver reliability of three-dimensional preoperative planning software in total hip arthroplasty. *J Arthroplasty* 2018;33:601–607.

26. Schiffner E, Latz D, Jungbluth P, et al. Is computerised 3D templating more accurate than 2D templating to predict size of components in primary total hip arthroplasty? *Hip Int* 2019;29:270–275.

27. Viceconti M, Lattanzi R, Antonietti B, et al. CT-based surgical planning software improves the accuracy of total hip replacement preoperative planning. *Med Eng Phys* 2003;25:371–377.

28. Wu P, Liu Q, Fu M, et al. Value of computed tomography-based three-dimensional pre-operative planning in cup placement in total hip arthroplasty with dysplastic acetabulum. *J Invest Surg* 2019;32:607–613.

29. Pasquier G, Ducharne G, Ali ES, Giraud F, Mouttet A, Durante E. Total hip arthroplasty offset measurement: is CT scan the most accurate option? *Orthop Traumatol Surg Res* 2010;96:367–375.

30. Otomaru I, Nakamoto M, Kagiyama Y, et al. Automated preoperative planning of femoral stem in total hip arthroplasty from 3D CT data: atlas-based approach and comparative study. *Med Image Anal* 2012;16:415–426.

31. Imai H, Miyawaki J, Kamada T, Takeba J, Mashima N, Miura H. Preoperative planning and postoperative evaluation of total hip arthroplasty that takes combined anteversion. *Eur J Orthop Surg Traumatol* 2016;26:493–500.

32. Huppertz A, Radmer S, Wagner M, Roessler T, Hamm B, Sparmann M. Computed tomography for preoperative planning in total hip arthroplasty: what radiologists need to know. *Skeletal Radiol* 2014;43:1041–1051.

33. Inoue D, Kabata T, Maeda T, et al. The correlation between clinical radiological outcome and contact state of implant and femur using three-dimensional templating software in cementless total hip arthroplasty. *Eur J Orthop Surg Traumatol* 2016;26:591–598.

34. Inoue D, Kabata T, Maeda T, et al. Usefullness of three-dimensional templating software to quantify the contact state between implant and femur in total hip arthroplasty. *Eur J Orthop Surg Traumatol* 2015;25:1293–1300.

35. de Almeida DF, Ruben RB, Folgado J, et al. Automated femoral landmark extraction for optimal prosthesis placement in total hip arthroplasty. *Int J Numer Method Biomed Eng* 2017;33:e2844.

36. Peter R, Lübbeke A, Stern R, Hoffmeyer P. Cup size and risk of dislocation after primary total hip arthroplasty. *J Arthroplasty* 2011;26:1305–1309.

37. Seagrave KG, Troelsen A, Malchau H, Husted H, Gromov K. Acetabular cup position and risk of dislocation in primary total hip arthroplasty. *Acta Orthop* 2017;88:10–17.

38. Sariali E, Boukhelifa N, Catonne Y, Pascal Moussellard H. Comparison of three-dimensional planning-assisted and conventional acetabular cup positioning in total hip arthroplasty: a randomized controlled trial. *J Bone Joint Surg Am* 2016;98:108–116.

39. Osmani FA, Thakkar S, Ramme A, Elbuluk A, Wojack P, Vigdorchik JM. Variance in predicted cup size by 2-dimensional vs 3-dimensional computerized tomography-based templating in primary total hip arthroplasty. *Arthroplast Today* 2017;3:289–293.

40. Iwana D, Nakamura N, Miki H, Kitada M, Hananouchi T, Sugano N. Accuracy of angle and position of the cup using computed tomography-based navigation systems in total hip arthroplasty. *Comput Aided Surg* 2013;18:187–194.

41. Sugano N, Takao M, Sakai T, Nishii T, Miki H. Does CT-based navigation improve the long-term survival in ceramic-on-ceramic THA? *Clin Orthop Relat Res* 2012;470:3054–3059.

42. Elbuluk AM, Wojack P, Eftekhary N, Vigdorchik JM. Three-dimensional templating for acetabular component alignment during total hip arthroplasty. *Orthopedics* 2017;40:e708–e713.

43. Sariali E, Catonne Y, Pascal-Moussellard H. Three-dimensional planning-guided total hip arthroplasty through a minimally invasive direct anterior approach: clinical outcomes at five years' follow-up. *Int Orthop* 2017;41:699–705.

44. Tostain O, Debuyzer E, Benad K, et al. Ten-year outcomes of cementless anatomical femoral implants after 3D computed tomography planning: follow-up note. *Orthop Traumatol Surg Res* 2019;105:937–942.

45. Bayraktar V, Weber M, von Kunow F, et al. Accuracy of measuring acetabular cup position after total hip arthroplasty: comparison between a radiographic planning software and three-dimensional computed tomography. *Int Orthop* 2017;41:731–738.

46. Huppertz A, Radmer S, Asbach P, et al. Computed tomography for preoperative planning in minimal-invasive total hip arthroplasty: radiation exposure and cost analysis. *Eur J Radiol* 2011;78:406–413.

47. Kyo T, Nakahara I, Kuroda Y, Miki H. Effects of coordinate-system construction methods on postoperative computed tomography evaluation of implant orientation after total hip arthroplasty. *Comput Aided Surg* 2015;20:52–60.

48. Lattanzi R, Baruffaldi F, Zannoni C, Viceconti M. Specialised CT scan protocols for 3-D pre-operative planning of total hip replacement. *Med Eng Phys* 2004;26:237–245.

49. Huppertz A, Lembcke A, Sariali H, et al. Low dose computed tomography for 3D planning of total hip arthroplasty: evaluation of radiation exposure and image quality. *J Comput Assist Tomogr* 2015;39:649–656.

50. Geijer M, Rundgren G, Weber L, Flivik G. Effective dose in low-dose CT compared with radiography for templating of total hip arthroplasty. *Acta Radiol* 2017;58:1276–1282.

51. Escott BG, Ravi B, Weathermon AC, et al. EOS low-dose radiography: a reliable and accurate upright assessment of lower-limb lengths. *J Bone Joint Surg Am* 2013;95:e1831–e1837.

52. Szuper K, Schlégl ÁT, Leidecker E, Vermes C, Somoskeöy S, Than P. Three-dimensional quantitative analysis of the proximal femur and the pelvis in children and adolescents using an upright biplanar slot-scanning X-ray system. *Pediatr Radiol* 2015;45:411–421.

53. Than P, Szuper K, Somoskeöy S, Warta V, Illés T. Geometrical values of the normal and arthritic hip and knee detected with the EOS imaging system. *Int Orthop* 2012;36:1291–1297.

54. Guenoun B, Zadegan F, Aim F, Hannouche D, Nizard R. Reliability of a new method for lower-extremity measurements based on stereoradiographic three-dimensional reconstruction. *Orthop Traumatol Surg Res* 2012;98:506–513.

55. Folinais D, Thelen P, Delin C, Radier C, Catonne Y, Lazennec JY. Measuring femoral and rotational alignment: EOS system versus computed tomography. *Orthop Traumatol Surg Res* 2013;99:509–516.

56. Clavé A, Maurer DG, Nagra NS, Fazilleau F, Lefèvre C, Stindel E. Reproducibility of length measurements of the lower limb by using EOS™. *Musculoskelet Surg* 2018;102:165–171.

57. Chun KJ. Bone densitometry. *Semin Nucl Med* 2011;41:220–228.

58. Steinberg EL, Segev E, Drexler M, Ben-Tov T, Nimrod S. Preoperative planning of orthopedic procedures using digitalized software systems. *Isr Med Assoc J* 2016;18:354–358.

59. Melvin T, Torre M. New medical device regulations: the regulator's view. *EFORT Open Rev* 2019;4:351–356.

60. Sariali E, Mouttet A, Pasquier G, Durante E. Three-dimensional hip anatomy in osteoarthritis: analysis of the femoral offset. *J Arthroplasty* 2009;24:990–997.

61. Krishnan H, Krishnan SP, Blunn G, Skinner JA, Hart AJ. Modular neck femoral stems. *Bone Joint J* 2013;95-B:1011–1021.

62. Di Laura A, Hothi HS, Henckel J, Kwon Y-M, Skinner JA, Hart AJ. Retrieval findings of recalled dual-taper hips. *J Bone Joint Surg Am* 2018;100:1661–1672.

63. Carter LW, Stovall DO, Young TR. Determination of accuracy of preoperative templating of noncemented femoral prostheses. *J Arthroplasty* 1995;10:507–513.

64. Colombi A, Schena D, Castelli CC. Total hip arthroplasty planning. *EFORT Open Rev* 2019;4:626–632.

65. Kuroda Y, Akiyama H, Nankaku M, So K, Goto K, Matsuda S. A report on three consecutive cases using computer tomography 3D preoperative planning for conversion of arthrodesed hips to total hip replacements. *HSS J* 2015;11:76–83.

66. Young E, Mccormack V, Swanson M. National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. 16th Annual Report 2019.