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The Value of Computed Tomography Scan in Three-dimensional Planning and Intraoperative Navigation in Primary Total Hip Arthroplasty

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Total hip arthroplasty (THA) is a frequently performed procedure; the objective is restoration of native hip biomechanics and achieving functional range of motion (ROM) through precise positioning of the prosthetic components. Advanced three-dimensional (3D) imaging and computed tomography (CT)-based navigation are valuable tools in both the preoperative planning and intraoperative execution. The aim of this study is to provide a thorough overview on the applications of CT scans in both the preoperative and intraoperative settings of primary THA. Preoperative planning using CT-based 3D imaging enables greater accuracy in prediction of implant sizes, leading to enhancement of surgical workflow with optimization of implant inventory. Surgeons can perform a more thorough assessment of posterior and anterior acetabular wall coverage, acetabular osteophytes, anatomical landmarks, and thus achieve more functional implant positioning. Intraoperative CT-based navigation can facilitate precise execution of the preoperative plan, to attain optimal positioning of the prosthetic components to avoid impingement. Medial reaming can be minimized preserving native bone stock, which can enable restoration of femoral, acetabular, and combined offsets. In addition, it is associated with greater accuracy in leg length adjustment, a critical factor in patients' postoperative satisfaction. Despite the higher costs and radiation exposure, which currently limits its widespread adoption, it offers many benefits, and the increasing interest in robotic surgery has facilitated its integration into routine practice. Conducting additional research on ultra-low-dose CT scans and examining the potential for translation of 3D imaging into improved clinical outcomes will be necessary to warrant its expanded application.

Keywords: Total hip arthroplasty, Robotics, Patient reported outcomes, Planning techniques, Computed tomography

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INTRODUCTION

The objective in performance of total hip arthroplasty (THA), one of the most frequently performed surgical procedure, is restoration of a pain-free and stable hip joint with a functional range of motion (ROM). Restoration of native hip biomechanics requires accurate and precise positioning of the acetabular and femoral components, controlling implant version, center of rotation (COR), offset, and leg length (LL).

Preoperative computed tomography (CT) scans have been used conventionally in the study of bony anatomy in complex cases including both primary and revision surgery[1-3]. With the introduction of novel technologies, CT scans are now considered essential in planning robotic or navigated surgeries, as well as for development of patient-specific cutting guides or implants. With the increased interest in computer-assisted surgery, particu-

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larly robotics, the use of CT scans reported in statewide analyses increased fivefold between 2009 and 2013[1].

In addition, advances in understanding spino-pelvic dynamics have prompted a reevaluation of conventional dogma with regard to implant positioning, favoring the use of a personalized and functional approach to component orientation[4-6]. When using modern CT-based robotic software, surgeons can project a virtual ROM and assess the potential for impingement based on patient's phenotype, spino-pelvic mobility, and bony anatomy, enabling informed decision-making with regard to optimal component orientation.

Despite the considerable benefits of using a three-dimensional (3D) CT-based preoperative plan and intraoperative guidance, there are associated limitations. A primary concern impeding the widespread application of CT based planning is the higher radiation dose, typically ranging from 1.5 to 4 mSv, even with use of modern low-dose CT imaging[7,8]. In addition, the increased cost per patient and limited availability add to the challenges of implementation.

The purpose of this literature review is to provide an overview on the use of CT scan in elective primary THA, focusing on its use in preoperative planning and intraoperative execution, and highlighting the benefits of using this advanced imaging tool in the effort to optimize surgical outcomes.

PREOPERATIVE CT-BASED PLANNING

Accurate and reproducible preoperative planning tailored to the characteristics of individual patients is the first step in optimal performance of a surgical procedure and positioning of the implant[9]. Conventional bony landmarks can be identified and used in determining implant size and position for restoration of native biomechanics and optimization of LL. In addition, accuracy in preoperative planning is critical in the effort to optimize efficiency in the operating room through avoidance of an excessive inventory stock of implants and ensuring that the anticipated sizes are readily available.

The cost of conventional two-dimensional (2D) planning using plain X-rays is lower and the procedure is less complex compared with CT scans (3D planning). However, there are limitations and challenges with use of conventional planning methods, such as the correct positioning of the calibration marker, which should be close to the hip joint plane. This can often result in magnification errors and inaccuracy in planning, particularly in patients with a high body mass index. Additionally, important landmarks and parameters including the anterior and posterior walls of the acetabulum, femoral version, and femoral intramedullary anatomy, are often not well defined in 2D images[7].

In contrast, use of CT-based preoperative planning has been reported to show >90% accuracy in prediction of component sizes with accuracy up to 100% when considering the femoral component, regardless of differences in software, patient selection, or observer expertise[7,10,11]. Consequently, use of 3D planning can facilitate a reduction in implant inventory sizes by up to 60%, resulting in savings of cost and time without compromising clinical outcomes[12]. In addition, prediction of stem size can reduce the risk of subsidence due to undersized stems, or intraoperative fracture due to oversized stems[7,13]. Further, a broach that was smaller than planned and showed a tighter fit than expected might indicate a technical problem, such as varus positioning, allowing the surgeon to make the necessary adjustments[7].

Introduction of the latest software available allows the projection of a virtual ROM based on the spino-pelvic parameters obtained from conventional standing and sitting lateral X-rays of the lumbar spine. This can be helpful to surgeons in recreating the postoperative ROM for predicting potential impingement and making the adjustments required to reduce the risk of hip instability[3,14]. In fact, 3D images can be helpful in recognition of potential periacetabular osteophytes that, if not removed during surgery, can cause impingement in flexion or extension, leading to an increased risk of posterior or anterior instability. Impingement has been reported to mainly occur in the antero-superior and posterior portions of the acetabulum when the width of the osteophyte is >6-7 mm[15]. Therefore, precise knowledge of the location and size of osteophytes can be helpful in improving the intraoperative workflow for achievement of postoperative stability.

In addition, 3D reconstruction of the acetabular anatomy in the coronal, sagittal, and axial plane enables greater accuracy of implant positioning in relation to both the anterior and posterior walls. This approach can facilitate a full ROM while minimizing the risk of anterior overhang, potentially triggering postoperative pain and impingement of the iliopsoas tendon[16,17].

Considering the importance of version of the acetabular component for achievement of optimal outcomes[18], accurate visualization of the posterior coverage can be helpful in the effort to ensure the correct position of the cup in the axial plane[19].

Regarding the femur, a 3D plan can be helpful in more accurate identification of the entry point in the axial plane thereby avoiding potential undersizing and malpositioning in varus or valgus. In addition, it can enable more precise identification of the neck cut, as identification of the lesser trochanter on a 2D X-ray may be challenging due to femoral rotation or anatomical variations. Consequently, more accurate calculation of preoperative measurements of the neck cut and distance from the lesser trochanter can be performed. Based on the reported evidence, estimation of femoral offset using plain X-rays can lead to erroneous results of up to 14 mm, which can be attributed primarily to malalignment or inappropriate radiological positioning[20].

The usefulness of a preoperative CT scan for assessment of bone health is another potential benefit, and excellent correlation with dual-energy X-ray absorptiometry scans has been reported[21,22]. The risk of periprosthetic hip fracture is higher for osteopenic and osteoporotic patients when cementless femoral fixation is used[23]. Bukowski et al.[21], utilized CT X-ray absorptiometry analysis using routine preoperative CT-scans obtained for robotic assisted THA for identification of osteoporotic patients, subsequently increasing the frequency of cemented femoral fixation in this category of patients. The implications of these findings are significant, considering the prevalence of underdiagnosis of osteoporosis prior to primary THA[24] and may potentially mitigate the long-term risks associated with osteoporotic-related fractures.

Although greater accuracy of 3D templating compared with both acetate and digital planning has been demonstrated (Table 1)[7,10,11,20,25-31], 2D templating is still considered the standard of care due to its accessibility and low cost[32]. Increased costs, ranging up to approximately £250-400 per patient, and higher exposure to radiation have been associated with adoption of 3D planning compared to conventional pelvic radiographs, with an increase of at least 30%[33-35]. In addition, incidental findings on imaging for preoperative planning reaching as high as 45% has been reported[36]. However, further investigation is only required for approximately 1% of these findings, which is noteworthy. While this aspect of preoperative imaging can be beneficial in identifying potentially critical issues, there is also a risk of incurring substantial additional costs, causing delays, or even necessitating cancellation of the intended surgical procedure[37]. Therefore, more evidence is needed to substantiate the translation of more accurate preoperative planning to superior longer-term clinical outcomes. However, with the advent of robotic surgery, efforts to incorporate 3D planning into daily practice are increasing and research endeavors are fo-

Table 1. Accuracy of Sizing Prediction of 2D and 3D Preoperative Planning

Study	Imaging	Exact implant size (%)		Implant size ±1 (%)	
		Cup	Stem	Cup	Stem
Kobayashi et al.[11] (2020)	CT	67	61	96	95
Wu et al.[27] (2019)	CT	71	-	100	-
Knafo et al.[26] (2019)	EOS	55	48	100	94
Schiffner et al.[28] (2019)	CT	57	59	86	94
Mainard et al.[25] (2017)	X-ray (digital)	45	46	80	84
	X-ray (analogic)	-	-	68	87
	EOS	-	-	84	93
Inoue et al.[29] (2015)	CT	92	65	100	98
Hassani et al.[7] (2014)	CT	94	100	100	100
Kniesel et al.[30] (2014)	X-ray	27	37	67	53
Schmidutz et al.[31] (2012)	X-ray	34	48	75	89
Sariali et al.[10] (2012)	X-ray (analogic)	43	43	-	-
	CT	96	100	-	-
Sariali et al.[20] (2009)	CT	86	94	100	100

2D: two-dimensional, 3D: three-dimensional, CT: computed tomography.

cused on evaluating the use of ultra-low-dose CT scans and demonstrating the clinical advantages in order to potentially facilitate the expansion of its application34).

INTRAOPERATIVE ADVANTAGES

3D planning must be combined with an accurate and reproducible method of execution in order to fully leverage its numerous benefits and for optimization of postoperative outcome. This ensures that all available information will be utilized effectively. In primary THA, adjusting LL, femoral offset, and acetabular offset to match the patient's native biomechanics is key to attainment of a highly performing joint and optimal outcomes9).

Increasing evidence has suggested an association of CT-based robotic surgery with superior preservation of acetabular bone stock, improved function of the abductor lever arm, and enhanced accuracy in restoring the patient's native COR and combined offset38). In addition, the utilization of CT-based robotic surgery has been associated with improved accuracy in positioning of acetabular components, potentially reducing the risk of revision due to instability39,40). Also, significant improvements have been reported based on comparison of CT-based navigation systems with conventional manual positioning, specifically in regard to the direct anterior approach. In particular, a substantial reduction in the mean absolute error of radiographic inclination, nearly two-fold smaller, has been reported (2.8°±2.5° vs. 4.4°±3.2°, P=0.01)41). Similar findings were reported for the mean absolute error of radiographic anteversion in comparison of the CT-guided approach with a fluoroscopy-guided technique (2.8°±1.9° vs. 4.8°±4.1°, P=0.02). In addition, use of the CT-guided approach resulted in the smallest deviation from the planned vertical COR compared with mechanical-guided (MG) and fluoroscopy-guided (FS) techniques (1.8±1.4 mm vs. MG=3.3±3.2 mm [P=0.007], FS=3.2±3.0 mm [P=0.017]).

1. Bone Stock Preservation

In manual THA, the true acetabular floor often represents a reference landmark for use in determining the final position of the acetabular component both preoperatively and intraoperatively9). Acetabular preparation typically consists of reaming down to the true floor, medializing the COR of the hip, and reducing the acetabular offset. A limited decrease in acetabular offset (5 mm) can be balanced by an increase in the femoral offset (5 mm), resulting in no changes in the global offset. However, use of a high-offset stem may be required in the case of excessive medialization of the acetabular component in order to restore the native lever arm of the abductor mechanism and to avoid a reduction of the body weight lever arm42). When using CT-based planning the surgeon is able to template the final position of the acetabular component in the subchondral bone, avoiding excessive reaming and acetabular medialization. A decrease of ROM free from impingment can occur in case of reduced acetabular offset, and fully compensating it with and increased femoral offset may not always be possible43). Thus, use of CT-based and haptic navigation during surgery can enhance the capacity for accurate reproduction of the preoperative plan, and guide the reaming and final positioning of the cup towards a more anatomical position of the horizontal and vertical COR. There are several advantages associated with use of this approach, including prevention of under- or oversizing, excessive reaming of the native bone stock, and medialization of the acetabular COR, reducing the risk of low-quality fixation and oval reaming44).

2. Acetabular Component Positioning and Combined Version

Dislocation, which is the among the most common indications for revision THA, accounts for approximately one-third of acetabular component revisions45). The accepted "safe zone" for positioning of the acetabular component was originally described by Lewinnek et al.46) as an anteversion of 5° to 25° and an inclination of 30° to 50°. Later, this range was modified to 30° to 45° of inclination by Callanan et al.47), primarily due to concerns regarding metal-on-metal (MoM) bearing implants. To date, the previously mentioned "safe zones" are often still used to guide orientation of acetabular components, despite emerging evidence suggesting that dislocations continue to occur within the perceived safe zones48,49). In addition, there are challenges to accurately determining the 3D position of the pelvis intraoperatively due to factors such as pelvic tilt, obesity, and hip flexion contractures, which can significantly impact the pelvic position and consequently the final placement of the acetabular component. Conventional THA is reliant on preoperative 2D templating and intraoperative anatomical landmarks to guide component orientation, often having an impact on the final positioning. Conversely, intraoperative CT-based navigation enables acquisition of precise real-time information regarding the pelvic position, thus improving accuracy in the effort to achieve the desired component placement[46,47] (Table 2)[38,39,50-55]. In a study reported by Domb et al.[50], the cup was placed within the desired position range with accuracy of 90%-100% in all cases assessed (50 THA), demonstrating the importance of intraoperative technology assistance.

The importance of achieving a combined anteversion within the desired range of 40°±15°[56] has recently been emphasized, considering both the sagittal position of the cup and the femoral component[57,58]. However, femoral anatomy shows a high level of intrinsic variability, as demonstrated by a wide range of reported differences in femoral rotation[59] and version ranging from –20° (retroversion) to 40°[57]. In this regard, Domb et al.[51] reported that robotic assistance was effective in controlling the axial positioning of the femoral component and was helpful in achievement of the correct femoral version.

3. Leg Length Discrepancy and Femoral Positioning

Leg length discrepancy (LLD), which is a relatively common problem associated with inferior outcomes, disability, and revision surgery, is known as the most common cause of litigation against orthopedic surgeons[60]. Shortening <10 mm or lengthening <6 mm is regarded as an acceptable threshold for patient awareness[61]. LLD can result in hip pain, impaired function of hip abductors and/or flexors, and it can potentially predispose to hip instability and abductor insufficiency[60,61]. It can be classified as intra- or extra-articular and adequate assessment of the extra-articular component is often not possible with use of conventional 2D imaging. In addition, assessment of LLD on an anteroposterior pelvis X-ray has been reported to result in underestimation of the actual measurements by approximately 3-6 mm[62].

Greater effectiveness and accuracy have been demonstrated using low-dose CT-scans (mean±standard deviation, 0.6±0.037 mSv; range, 0.53-0.64 mSv) compared with 2D techniques for assessing LLD[34]. This is particularly important in cases where identifying the anatomical landmarks can be difficult due to internal/external rotation of the femur, obesity, or fixed flexion deformity of the hip or knee. In such cases, LLD can be overestimated, increasing the risk of overlengthening[63].

The significant impact of intraoperative positioning of the femoral component on patient biomechanics, which is responsible for 98% of LLD, is well-established[10]. Use of robotic-arm assistance, compared with

Table 2. Accuracy of Implant Positioning within the Defined Safe Zones

Study	Technique	Safe zone accuracy	
		Lewinnek (%)	Callanan (%)
Clement et al.[52] (2021)	Conventional	67	66
	Robotic	95	93
Kayani et al.[38] (2019)	Conventional	80	76
	Robotic	96	92
Illgen et al.[39] (2017)	Conventional	45	-
	Robotic	77	-
Kamara et al.[53] (2017)	Conventional	55	45
	Fluoroscopic	70	64
	Robotic	90	82
Domb et al.[51] (2015)	Conventional	69	59
	Fluoroscopic	73	60
	Navigation	91	53
	Robotic	98	94
Domb et al.[50] (2014)	Robotic	100	92
	Conventional	80	62
Hohmann et al.[54] (2011)	Navigation	77	-
	Conventional	20	-
Parratte et al.[55] (2007)	Navigation	80	-
	Conventional	43	-

conventional manual techniques, was reported to result in significantly reduced LLD (difference of 3.6 mm, $P<0.001$)[52]. Therefore, precise positioning of the stem in all three planes is crucial in the effort to optimize hip biomechanics and achieve favorable clinical outcomes and patient satisfaction. In addition, accuracy in 3D implants positioning is of critical importance to achieve the desired LL, ROM, and intra-medullary canal fit.

4. Offset and Center of Rotation

Femoral, acetabular, and global offset are key metrics that influence the biomechanics of the hip. The femoral offset represents the distance from the center of the femoral head to the line bisecting the long axis of the femur. Acetabular offset, also known as the body weight lever arm, represents the distance from the center of the acetabulum to the center of the pelvis[64]. Finally, the global offset represents the summed distance of the femoral and acetabular offsets. These three parameters are directly related to the hip COR and their effect on function of the abductor mechanism, hip longevity, ROM, and polyethylene wear has been demonstrated[65,66]. An association of reduction of the femoral offset >5 mm with inferior outcomes and alteration of gait has been reported[67,68]. The majority of studies caution against intraoperative reduction of femoral offset. In addition, available data strongly indicate an association of reducing the global offset by more than 5 mm with poorer clinical outcomes, reduced abductor strength, increased use of walking aids, impaired gait, and increased risk of dislocation, thus it is not recommended[69-71]. Therefore, despite the enhanced accuracy associated with 3D planning, intraoperative decision-making and reproducibility remain critical factors in the effort to achieve optimal restoration of hip biomechanics.

Kobayashi et al.[11] reported that, despite the utilization of advanced CT-based preoperative planning, conventionally implanted components matched the planned orientation with an error of ±5 mm in only 40% of cases. Likewise, other researchers have observed mean differences of approximately 1.3±3 mm for femoral offset and up to 3.5±1.5 mm for acetabular COR between 3D-templated values and postoperative measurements[10]. In contrast, improved accuracy in restoring the native horizontal and vertical COR ($P<0.001$) and preserving the patient's native combined offset ($P<0.001$) has been demonstrated with use of intraoperative 3D CT-based navigation in robotic surgery compared to conventional THA[38,72].

Kanawade et al.[72] reported successful restoration of the horizontal and vertical COR in over 80% of robotic guided THA procedures, with a mean superior shift of 0.9±4.2 mm and a medial shift of 2.7±2.9 mm. Similar findings were reported by Peng et al.[73], who observed approximately twice the variation in combined vertical offset in conventional manual THA compared with robotic THA. Limiting superior displacement of the hip COR to 3 mm or less and medialization to 5 mm or less has been reported to provide protection from an increase in offset more than 5 mm, thereby optimizing muscle function and minimizing polyethylene wear[74].

Use of robotic-arm-assisted surgery, facilitated by haptically guided reaming, can enable restoration of the native COR and improvement of component positioning[11,72], potentially reducing the need for intraoperative adjustments such as lateralizing the COR using an extended offset femoral stem[52]. Clement et al.[52] reported a significant decrease in acetabular offset and an increase in femoral offset, as well as significantly improved accuracy in component anteversion and overall alignment in a comparison of conventional manual THA with robotic-THA.

POTENTIAL FUTURE DIRECTION OF TRAVEL

The hipEOS software (EOS; EOS Imaging) has recently gained popularity as a low-dose imaging protocol utilizing biplanar standing weight-bearing X-rays for identification of anatomical landmarks in both sagittal and coronal planes. Use of this innovative approach can enable development of a 3D image of the pelvis while minimizing radiation exposure for the patient. Mainard et al.[25] reported improved accuracy in determining stem size using the biplanar 3D system with an error of ±1 in 84% (26 of 31 hips) of cases. In comparison, accuracy of 68% (21 out of 31 hips) was obtained with use of plain two-dimensional X-rays, reaching statistical significance ($P=0.04$). However, no significant difference was observed on the acetabular side.

Promising outcomes have also been reported with use of hipEOS software postoperatively for assessment of femoral component version. The results showed no significant difference compared with standard CT scans ($P=0.862$)[75]. In particular, measurements of femoral stem version showed strong correlation between the two imaging modalities (r=0.95; P<0.001), supporting the suitability of low dose biplanar radiography for postoperative assessment of THA while showing association with reduced exposure to radiation. Despite these encouraging findings, it is important to note that extensive research on the clinical application of hipEOS software has not yet been conducted, and conduct of additional high-quality studies will be necessary in order to confirm its efficacy and safety[25,26,76].

Research has also focused on the applicability of weight-bearing CT scans in hip and knee disorders[77,78] after the promising results achieved in foot and ankle surgery as a reliable and precise modality for measurement and analysis of bone position and deformities[79]. A cone-beam CT extremity scanner, which enables evaluation of joints under loading conditions while avoiding technical errors associated with plain X-rays such as rotational malalignment, is used in performance of this technique. Extension of this technology to hip and knee arthroplasty, potentially encompassing spino-pelvic evaluation would likely provide a definitive factor for validating the utilization of 3D CT-scans over 2D X-rays as the standard practice in primary THA.

CONCLUSION

While significant clinical improvement has not yet been confirmed[80], a considerable body of evidence provides support for the superior accuracy of preoperative CT-based 3D planning compared to 2D. There is mounting evidence indicating the multiple benefits for the hip arthroplasty surgeon. It can reduce the risk of intraoperative complications and facilitate informed decision-making during surgery. In addition, it can enable streamlining of implant stocks and enhancement of efficiency in the operating theatre in institutions, and ultimately show association with improved clinical outcomes.

Use of an intraoperative CT-based robotic-arm or navigation assistance can further enhance the accuracy of implant positioning while minimizing bone reaming. This technology has also been proven to support restoration of the native biomechanics of the hip and enables precise control of component positioning in order to optimize femoral stem anteversion, LL, and offset. Despite the undeniable advantages, there are also several limitations, including cost considerations and concerns regarding radiation exposure, which are currently a deterrent to its widespread application. However, if superior longer-term clinical outcomes were demonstrated, along with the development of innovative low-dose CT techniques, support for the routine use of CT-based planning and surgical execution in THA may increase in the future.

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Conflict of Interest

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