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SCIENTIFIC ARTICLE

Incidental findings detected on preoperative CT imaging obtained for robotic-assisted joint replacements: clinical importance and the effect on the scheduled arthroplasty

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Abstract

Objective To determine the type and frequency of incidental findings detected on preoperative computed tomography (CT) imaging obtained for robotic-assisted joint replacements and their effect on the planned arthroplasty.

Materials and methods All preoperative CT examinations performed for a robotic-assisted knee or total hip arthroplasty were obtained. This resulted in 1432 examinations performed between September 2016 and February 2020 at our institution. These examinations were initially interpreted by 1 of 9 fellowship-trained musculoskeletal radiologists. Using a diagnosis search, the examination reports were then reviewed to catalog all incidental findings and further classify as significant or non-significant findings. Demographic information was obtained. In those with significant findings, a chart review was performed to record the relevant workup, outcomes, and if the planned arthroplasty was affected.

Results Incidental findings were diagnosed in 740 (51.7%) patients. Of those with incidental findings, 41 (5.5%) were considered significant. A significant finding was more likely to be detected in males ($P = 0.007$) and on the hip protocol CT ($P = 0.014$). In 8 patients, these diagnoses resulted in either delay or cancelation of the arthroplasty. A planned total hip arthroplasty was more likely to be altered as compared to a knee arthroplasty ($P = 0.018$).

Conclusion Incidental findings are commonly detected by radiologists on preoperative CT imaging obtained for robotic-assisted joint replacement. Several were valuable findings and resulted in a delay or even cancelation of the planned arthroplasty after the detection of critical diagnoses, which if not identified may have resulted in devastating outcomes.

Keywords Robotic assisted · Knee arthroplasty · Total hip arthroplasty · Joint replacement · CT imaging · Incidental findings

Introduction

Total joint arthroplasty (TJA) is among the most common orthopedic procedures, reliably treating osteoarthritis-related pain [1–3]. Advancements in techniques, implant designs, and technologies of total hip (THA) and total knee arthroplasties (TKA), as well as the resurgence in unicompartmental knee arthroplasty (UKA), continue to improve outcomes and patient satisfaction while decreasing complications and readmission rates [4–6]. Nevertheless, factors outside of the surgeon's control, such as patient demographic and psychosocial issues, have been associated with decreased satisfaction following arthroplasty [7–10]. Additionally, 90-day readmissions following TJA create an enormous national healthcare economic burden, with approximately half of the annual expenses attributed to readmissions unrelated to the TJA [11, 12]. However, improvements in technique and implant positioning may mitigate the costs of revisions [13–17], which are responsible for the greatest readmission, post-acute care, and long-term expenses [12]. With the incidence of revision arthroplasties projected to increase over the next several decades [18, 19], there is an impetus to continue optimizing techniques and technologies to reduce revision and readmission rates following primary TJA.

Recently, robotic-assisted TJA utilizing preoperative imaging, in the form of radiographs and computed tomography (CT), has gained popularity as a method of improving precision [20–24]. Theoretically, improved implant positioning can

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lead to reduced complication rates, ultimately mitigating the economic burden [25, 26]. Conversely, there is concern that robotic technology may imply financial strain due to the preoperative imaging required [27]. Hassebrock and colleagues even suggested that preoperative advanced imaging is not benign and may create unnecessary workup of clinically insignificant incidental findings, incurring “hidden costs” [28]. Certainly, the utilization of robotic technologies has the potential of improved surgical technique and reduced complications, but the question remains whether it justifies exposing patients to radiation and creating unnecessary costs from incidental findings [25–29]. However, there is a paucity of literature investigating the benefits of preoperative CT imaging following the identification of significant incidental findings by radiologists, advancing patient care.

Therefore, the purpose of this study is to determine the type and frequency of incidental findings detected on the preoperative CT for robotic-assisted TJA and evaluate if any affected the planned surgery. The study aims to detail the significant incidental findings detected by radiologists and illustrates the ultimate benefit of CT to the patients, whose medical care was affected by these findings. If gone undetected, these findings could potentially have resulted in significant negative postsurgical outcomes.

Materials and methods

This study was performed in accordance with the ethical standards of our institutional research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Institutional review board approval was obtained for this retrospective study, and informed consent was waived. Our study complied with the Health Insurance Portability and Accountability Act.

Selection of study cohort

This retrospective study had a target population including all adult patients found by review of the radiology information system database to have had a CT examination performed for an indication of preoperative imaging for a robotic-assisted TKA, UKA, or THA. This search resulted in 1528 examinations performed between September 2016 and February 2020. Exclusion criteria included those examinations that were a repeat preoperative CT scan of the same extremity (i.e., technical scan errors) or those examinations performed for indications other than preoperative imaging for a robotic-assisted arthroplasty. Also, since the THA protocol CT includes the bilateral extremities, if a patient had the contralateral THA staged anytime during this period, that scan was excluded if performed. The final sample size resulted in 1432 patients and examinations.

Preoperative CT examination protocols

All 1432 preoperative CT examinations were performed in one hospital utilizing either a Philips 64 Brilliance CT scanner (Philips Medical Systems, Cleveland, OH) or a GE Optima CT660 CT scanner (General Electric Company, Milwaukee, WI). All scans used the following acquisition parameters: 120 kVp, 400 mA, and 0.5-s rotation time, and were done according to the specifications of the Mako robotic-arm assisted (MAKOplasty) surgery system (Stryker, Kalamazoo, MI).

The preoperative CT scan for a robotic-assisted THA at our institution includes 1-mm contiguous axial images obtained through the entire pelvis, scanned from the level of the iliac crests to 180 mm inferior to the lesser trochanters, including the bilateral hips. Also, 3-mm contiguous axial images are obtained through the bilateral knees. These parameters result in an inclusion of a portion of the lower intra-abdominal structures as well as visualization of all intra-pelvic structures (Fig. 1).

The preoperative CT scan for a robotic-assisted TKA or UKA at our institution includes 3-mm contiguous axial images through the unilateral hip (including the femoral head), 1-mm contiguous axial images through the unilateral knee (including 100 mm above and below the joint line), and 3-mm contiguous axial images through the unilateral ankle (including the talus and distal tibia), of the side of the planned surgery. Another unique requirement for the TKA/UKA CT protocol is that a radiopaque rod is placed, parallel to the lateral aspect of the entire lower extremity being scanned, that must be visible throughout all the hip, knee, and ankle axial CT images (Fig. 2). This rod is used to ensure the accuracy of the scan; if any motion is detected in the rod, this indicates patient movement during the scan, which would require the scan to be repeated.

Both the hip and knee arthroplasty protocols require the legs to remain stationary throughout the entire scan and are performed with the patient supine and entering the CT gantry, feet first. Both protocols are also done without the use of intravenous or oral contrast and the images are obtained in seconds. Coronal, sagittal, and 3-dimensional reconstructions can also be obtained, if requested by the ordering orthopedic surgeon.

CT examination interpretations

All the CT examinations had been initially interpreted by 1 of 9 fellowship-trained musculoskeletal radiologists (clinical experience ranging from 2 to 33 years). These examinations were performed and interpreted in real-time, prior to any knowledge of this study.

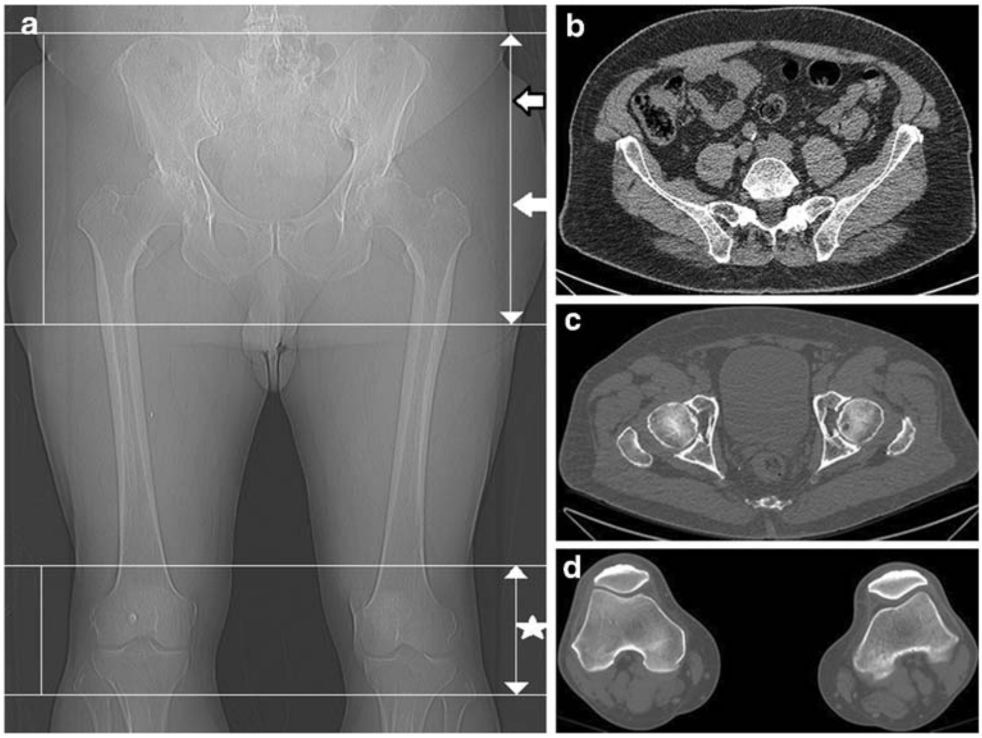

Fig. 1 Protocol for the preoperative computed tomography for a robotic-assisted total hip arthroplasty. **a** Coronal scout image demonstrates the range (horizontal and vertical lines with more superior arrowheads) of the 1-mm axial images obtained through the entire pelvis (black outlined white arrow) including the bilateral hips (solid white arrow), from the iliac crests to 180 mm inferior to the lesser trochanters. The more inferior range (horizontal and vertical lines with inferior arrowheads) shows the area of the 3-mm axial images obtained through the bilateral knees (star). **b** Axial image at the level of the black outlined white arrow in the scout demonstrates the intra-pelvic structures using soft tissue windows. **c** Axial image, in bone windows, at the level of the solid white arrow, shows the bilateral hips. **d** Axial image, also in bone windows, at the level of the star, displays the bilateral knees

Incidental findings categorization

Using a diagnosis search, the examination reports were then reviewed by one musculoskeletal radiologist with 11 years of clinical experience to catalog all incidental findings. The incidental findings were then further classified as significant or non-significant findings. Significant incidental findings were reserved for those that warranted further workup, those that could alter a planned surgery, and those that would require prompt notification of the ordering orthopedic surgeon. Demographic information about age and gender were recorded for these patients. A note was also made as to whether the incidental findings were from a THA protocol or TKA/UKA protocol preoperative CT. Finally, in those with significant findings, a chart review was also performed to record the additional workup performed, the outcomes, and if the planned arthroplasty was affected.

Statistical analysis

The association between the presence of a significant finding and the patient's age and gender was evaluated. Additionally, the association of the significant finding and whether it was from a THA protocol or TKA/UKA protocol preoperative CT was evaluated. Furthermore, in those in which the planned arthroplasty was altered due to a significant finding, any association between gender, age, or the type of preoperative CT protocol was assessed. The evaluations were performed using chi-square tests for categorical data and the 2-sided sample t test for numerical data. Given the samples' size, this would result in a power of 0.90 for most variables. Statistical significance was defined as a $P < 0.05$.

Results

Study group

Of the 1432 examinations, a total of 931 (65%) CT examinations were performed for either a TKA or UKA. A total of 501 (35%) were performed for a THA. Of those 1432 examinations, 825 (57.6%) were performed on women and 607 (42.4%) were performed on men. The age range was 26–95 years with a mean age of 65 (Table 1).

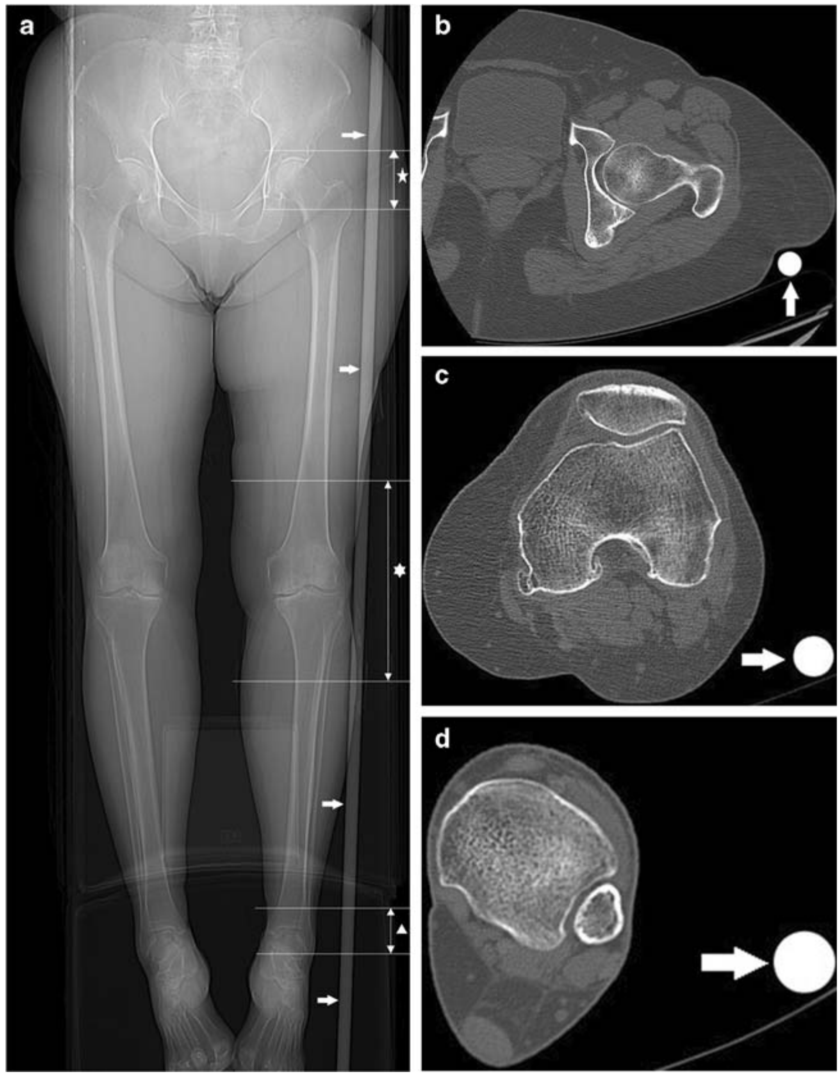

Fig. 2 Protocol for the preoperative computed tomography for a robotic-assisted left total knee or unicompartmental knee arthroplasty. **a** Coronal scout image demonstrates the ranges (3 sets of horizontal and vertical lines with arrowheads) of the 3-mm axial images through the left hip, including femoral head (star), 1-mm axial images through the left knee, including 100 mm above and below the joint line (asterisk), and 3-mm axial images through the left ankle, including talus and distal tibia (triangle). Also, note the radiopaque rod (arrows) that is placed parallel to the lateral aspect of the entire lower leg. **b** Axial image at the level of the star from the scout demonstrates the left hip in bone windows with a small portion of the lower intra-pelvic structures. Also, note the radiopaque rod (arrow). **c** Axial image in bone windows, at the level of the asterisk, shows the left knee with a radiopaque rod (arrow). **d** Axial image in bone windows, at the level of the triangle, displays the left ankle with a rod (arrow)

All incidental findings

Incidental findings were identified in 740 (51.7%) of the 1432 preoperative CT examinations. The majority of these incidental findings were diverticulosis (47.2%, $n = 349$), prostatic enlargement (12%, $n = 89$), fat-containing inguinal or umbilical hernias (10.2%, $n = 76$), intramuscular lipomas (10.1%, $n = 75$), and uterine fibroids (9.1%, $n = 67$) (Table 2).

Table 1 Patient demographics and preop CT protocol type associations among all preop CT exams, among those with significant incidental findings, and among those with an altered surgery

		All preop CT exams performed ($N = 1432$)	Significant incidental findings ($n = 41$)	*P* value	Altered surgery ($n = 8$)	*P* value
THA		501 (35%)	22 (53.7%)	0.014 (C)	6 (75%)	0.018 (C)
TKA/UKA		931 (65%)	19 (46.3%)		2 (25%)	
Gender	Female	825 (57.6%)	15 (36.6%)	0.007 (C)	4 (50%)	0.664 (C)
	Male	607 (42.4%)	26 (63.4%)		4 (50%)	
Age, years (mean ± SD)		65 ± 10.3	68 ± 10.9	0.089 (T)	72 ± 11.5	0.129 (T)

CT, computed tomography; *Preop*, preoperative; *THA*, total hip arthroplasty; *TKA*, total knee arthroplasty; *UKA*, unicompartmental knee arthroplasty. Categorical data is represented as frequency (percent of column). Numerical data is represented as the mean ± standard deviation (SD). C indicates the χ^2 test and *T* indicates 2-sided sample *t* test.

Table 2 Catalog of the type and percentage of all incidental findings among all preoperative CT examinations

Incidental findings (total n = 740)	Number of CT exams with incidental finding (total n = 740)	Percentage among those scans with incidental findings (n = 740) (%)	Percentage of total CT scans (N = 1432) with incidental finding (%)
Diverticulosis	349	47.2	24.4
Prostate enlargement	89	12.0	6.2
Intramuscular lipoma	75	10.1	5.2
Uterine fibroid	67	9.1	4.7
Fat-containing inguinal hernia	44	5.9	3.1
Fat-containing umbilical hernia	32	4.3	2.2
Anterior talofibular ligament tear	14	1.9	1.0
Hydrocele	12	1.6	0.8
Bladder wall thickening*	5	0.7	0.3
Atypical lipomatous tumor/liposarcoma*	4	0.5	0.3
Iliac artery aneurysm*	4	0.4	0.3
Soft tissue fluid collection*	4	0.4	0.3
Bowel-containing inguinal hernia*	3	0.4	0.2
Lymphadenopathy*	3	0.4	0.2
Avascular necrosis (not joint for arthroplasty)*	3	0.4	0.2
Abdominal aortic aneurysm*	3	0.4	0.2
Peroneal tenosynovitis	3	0.4	0.2
Bladder diverticulum	2	0.3	0.1
Bladder calculi	2	0.3	0.1
Adnexal solid mass*	2	0.3	0.1
Ovarian cyst	2	0.3	0.1
Renal cyst	2	0.3	0.1
Horseshoe kidney	2	0.3	0.1
Spinal hardware loosening*	2	0.3	0.1
Suspicious uterine mass*	1	0.1	0.1
Diverticulitis*	1	0.1	0.1
Bowel-containing umbilical hernia*	1	0.1	0.1
Ostomy bowel-containing hernia*	1	0.1	0.1
Retroperitoneal mass*	1	0.1	0.1
Suspicious osseous lesion*	1	0.1	0.1
L4 vertebral body compression fracture*	1	0.1	0.1
Popliteal artery aneurysm*	1	0.1	0.1
Posterior tibial tenosynovitis	1	0.1	0.1
Achilles tendon partial-thickness tear	1	0.1	0.1
Cholelithiasis	1	0.1	0.1
Renal calculi	1	0.1	0.1

*Indicates those considered significant incidental findings (also bolded)

Significant incident findings

Of those with incidental findings, 41 (5.5%) were considered significant. These included diagnoses such as abdominal and pelvic masses, acute diverticulitis, bowel-containing hernias, suspicious osseous or soft tissue masses of the extremities, and vascular aneurysms (Table 2) (Figs. 3, 4, 5, 6, and 7). Of those 41 examinations, 15 (36.6%) were identified in female patients and 26 (63.4%) in male patients. The age range was 42–89 years with a mean age of 68. Additionally, a slim majority of significant findings were in the THA protocol (22) versus the TKA/UKA protocol (19) CT examinations (Table 1). Only 22% (9 of 41) patients

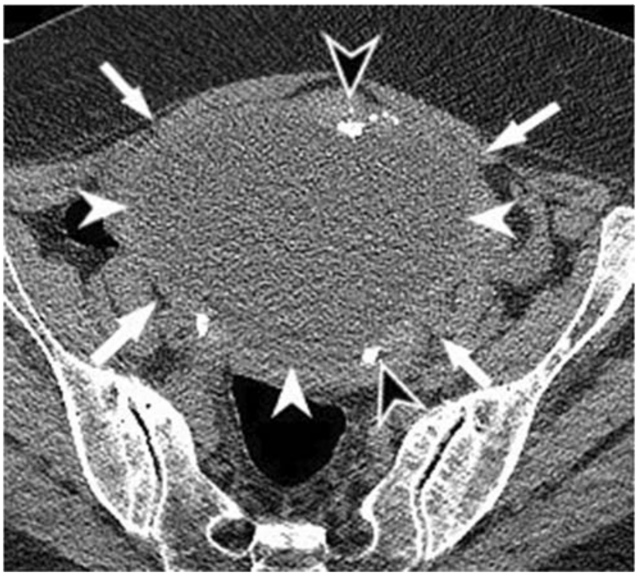

Fig. 3 Computed tomography axial image, in soft tissue windows, at the level of the pelvis, from a 74-year-old female undergoing the preoperative left total hip arthroplasty protocol computed tomography demonstrates an enlarged uterus (arrows) with hypodense irregular endometrial thickening (white arrowheads), with peripheral calcifications (black arrowheads). The final diagnosis was metastatic papillary carcinoma resulting in a cancelation of the planned left total hip arthroplasty

required further imaging to better evaluate their incidental finding.

Fig. 4 Computed tomography axial image, in soft tissue windows, at the level of the left hip of a 52-year-old male undergoing a preoperative left total knee arthroplasty protocol computed tomography. The image shows a left quadriceps intramuscular complex lipomatous lesion (arrows) with internal nodular soft tissue components (arrowhead). The final diagnosis following an excisional biopsy was an atypical lipomatous tumor with a cancelation of the scheduled left total knee arthroplasty

Fig. 5 Soft tissue window, axial computed tomography image of a 73-year-old male undergoing a preoperative right total hip arthroplasty protocol computed tomography demonstrates a 5.5-cm abdominal aortic aneurysm (arrows). Prompt endovascular repair was subsequently performed resulting in a delay of the scheduled right total hip arthroplasty

Altered scheduled arthroplasty

A total of 8 of the 41 examinations (19.5%) with significant findings resulted in an alteration of a scheduled arthroplasty. Three resulted in a complete surgery cancelation and 5 led to a delay of the planned arthroplasty surgical date. The mean surgical date delay was 134.2 days with a range of 36–302

Fig. 6 Axial image, in soft tissue windows, of an 89-year-old female undergoing a preoperative left total knee arthroplasty protocol computed tomography displays a large right inguinal (arrows) hernia containing multiple small bowel loops (arrowheads) without obstruction. The scheduled left total knee arthroplasty was delayed

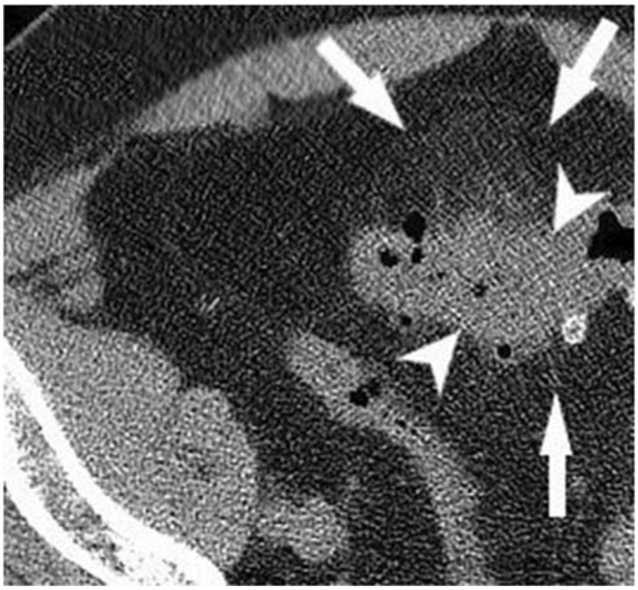

Fig. 7 Axial, soft tissue window, computed tomography image from a 51-year-old male undergoing a preoperative right total knee arthroplasty protocol computed tomography shows findings of acute diverticulitis of the sigmoid colon including bowel wall thickening (arrowheads) and adjacent mesenteric inflammatory fat stranding surrounding the diverticuli (arrows). The patient underwent treatment with antibiotics and the planned left total knee arthroplasty was performed as scheduled

days. Of those 8 examinations, 4 (50%) were from women and 4 (50%) were from men. The age range was 52–89 years with a mean age of 72. Furthermore, 6 (75%) were from THA protocol CT examinations and 2 (25%) were from TKA protocol CT examinations (Table 1).

All 3 patients with complete arthroplasty cancelations were diagnosed with an incidental malignancy, 2 requiring oncologic surgery. This included a 74-year-old female who was found to have a suspicious uterine mass on her preoperative THA CT (Fig. 3). A pelvic ultrasound was then performed demonstrating an enlarged uterus with endometrial irregularity. A subsequent PET/CT showed hypermetabolism throughout the uterus/myometrium and within adjacent lymph nodes. The final diagnosis following a total hysterectomy and bilateral salpingo-oophorectomy was metastatic papillary carcinoma. Another patient was a 64-year-old male who was diagnosed with a suspicious right hamstring intramuscular lipomatous mass on a preoperative THA CT, which was suspected to be an atypical lipomatous tumor versus a liposarcoma. This arthroplasty was also canceled without further imaging or workup. Additionally, a 52-year-old male was found to have a suspicious left quadriceps intramuscular lipomatous mass on a preoperative TKA CT, which was also suspected to be an atypical lipomatous tumor versus a liposarcoma (Fig. 4). A subsequent MRI pelvis confirmed an atypical lipomatous tumor versus a liposarcoma. The final diagnosis following an excisional biopsy was an atypical lipomatous tumor.

One patient with a 302-day surgical delay was a 73-year-old male who required prompt endovascular surgery to repair a 5.5-cm abdominal aortic aneurysm found on his preoperative THA CT (Fig. 5) and confirmed with a CT angiogram. Another 89-year-old female's arthroplasty was delayed due to a bowel-containing right inguinal hernia discovered on a preoperative TKA CT (Fig. 6). The patient deferred repair of the hernia and the arthroplasty was performed after a 50-day delay. A 71-year-old female was found to have a new compression fracture of L4 on a preoperative THA CT. The patient was treated conservatively and the arthroplasty was performed after a delay of 36 days. Additionally, an 84-year-old female was found to have a complex abdominal wall fluid collection on a preoperative THA CT. She was monitored clinically as it was favored to represent a resolving hematoma. Her arthroplasty was completed after a 219-day delay. Finally, a 68-year-old male was found to have a suspicious right quadriceps intramuscular lipomatous mass on a preoperative THA CT, which was suspected to be a liposarcoma. A subsequent MRI of the right femur confirmed an atypical lipomatous tumor versus a liposarcoma. The final diagnosis following an ultrasound-guided biopsy was an atypical lipomatous tumor. This mass was eventually excised after a successful THA was performed following a delay of 64 days. The final surgical pathology was also consistent with an atypical lipomatous tumor.

Statistical significance

A statistically significant difference was seen demonstrating males to be more likely than females to have a significant incidental finding as compared to all patients obtaining a preoperative CT for robotic-assisted arthroplasty ($P = 0.007$). Additionally, a significant incidental finding is more likely to be found on the THA protocol CT as compared to the TKA/UKA protocol CT ($P = 0.014$) (Table 1). Finally, a planned THA was more likely to be delayed or canceled as compared to a TKA ($P = 0.018$) (Table 1).

Age comparisons

Compared to the entire study cohort, the average ages for both those with significant incidental findings and those whose planned surgeries that were altered were greater, albeit statistically insignificant (Table 1).

Discussion

In this large study, we retrospectively evaluated over 1400 preoperative CT examinations obtained for robotic-assisted THA, TKA, or UKA, at a large healthcare system (5 hospitals, 50 clinic locations) with a largely captured patient population under one electronic medical record. Our findings demonstrated that not only are incidental findings commonly identified on the preoperative CT examinations (51.7%) but also many are significant incidental findings (5.5%). Ultimately, the vast majority did not require any further imaging which may further characterize the value equation. However, some of the significant findings resulted in a required delay or even cancelation of the planned surgery due to the discovery of ominous diagnoses, which if had gone undetected, may have resulted in significant negative outcomes. This is the first investigation of the authors' knowledge to evaluate such a large patient population.

Overall, we found that males are more likely than females to have a significant incidental finding. Additionally, these significant incidental findings are more likely to be found on the THA protocol CT as compared to the TKA/UKA protocol CT and furthermore, a planned THA was more likely to be delayed or canceled as compared to a TKA. Given that the preoperative THA protocol CT includes imaging of the lower abdomen, the entire pelvis, and large portions of the bilateral lower extremities (Fig. 1), this lends itself to discovering a larger number of incidental findings. This also may suggest that a preoperative CT is preferred over preoperative radiographs, especially in a male undergoing a robotic-assisted THA. In practice, such inclination has been evident as we have grown more comfortable with the robotic workflow. Clinicians have been ordering fewer repeat radiographs in the office once a surgery decision is delineated, assuming a patient has any prior imaging in our system.

In the 41 patients with significant incidental findings, only 9 (22%) went on to further advanced imaging, including 4 of the 8 patients with an altered scheduled arthroplasty. Although Hassebrock et al. suggested "significant additional costs" related to the unnecessary workup of incidental findings [28], our study demonstrates that the majority of the significant incidental findings are managed without the need for any costly imaging. Yet, their discovery by a dedicated radiologist interpretation may have resulted in actual healthcare savings by preventing more costly future workups and management. Even in the patients who required advanced imaging, such as the complex uterine mass (Fig. 3) and the abdominal aortic aneurysm (Fig. 5), the cost related to a few additional imaging studies is minuscule when compared to the potential healthcare costs related to surgical management, chemotherapy, multiple consultations, intensive care unit admissions, etcetera, that could have ensued if these incidental findings were not detected. Given the known complications, if the endometrial carcinoma or liposarcoma had resulted in wide-spread metastases or if the aneurysm had ruptured, the spiraling expense is obvious. Furthermore, had the aneurysm not been identified it could have potentially ruptured intraoperatively or shortly after the placement of the scheduled THA.

In the present cohort of patients, there were significant incidental findings identified that did not result in an alteration of the scheduled arthroplasty but yet may have benefitted patient care. In regard to the 2 additional patients with bowel-containing inguinal hernias and the patient with acute diverticulitis (Fig. 7), although their scheduled arthroplasty was not affected, their clinical course was perhaps significantly altered. Had these diagnoses gone undetected and untreated before the planned arthroplasty, the known associated devastating complications such as bowel strangulation or incarceration, bowel perforation or the development of a pericolonic abscess may have occurred. This again illustrates scenarios leading to higher postoperative morbidity or even mortality, especially if sepsis ensued.

Joint replacement surgeries of the hip and knee are of the most common surgeries performed in the USA for the highly effective treatment of osteoarthritis and as such mainly consist of an elderly population in whom several common medical conditions may coexist [30–34]. The number of these arthroplasties performed annually continues to steadily rise due to the increasing life expectancy and the associated high prevalence of osteoarthritis. It is estimated that by 2030, up to nearly 3.5 million TKAs and 600,000 THAs will be performed in the USA [31, 35–38]. UKA has also gained popularity in the treatment of isolated medial compartment osteoarthritis of the knee and now constitutes approximately 8%–10% of all knee arthroplasties performed in the USA [20]. This procedure is no longer limited to the elderly with a more limited lifespan. UKA has become an excellent choice among younger and active individuals with unicompartmental osteoarthritis who elect to delay or avoid a TKA [39]. This increased popularity is due to its many unique advantages over a TKA including a less-invasive surgery with increased preservation of the native knee structures, a faster recovery period, improved range of motion, less intraoperative blood loss, decreased costs, lower morbidity and mortality, and overall improved patient satisfaction [40–42]. While the reproducibility of this procedure has been variable in the registries, many would contend that this more challenging procedure has less room for error and best suited for robotic assistance.

Joint arthroplasty surgical techniques and instrumentation have evolved tremendously over recent decades. This is largely due to the desire to correct for human technical errors in an attempt to improve patient outcomes, decrease revision rates, and lower the overall economic burden. Modern technology, through the use of robotic-assistance, has been instrumental in facilitating significant advancements [23, 43]. Multiple studies have demonstrated that robotic-assisted joint replacement allows for an improved precision of implant positioning for THA, TKA, and UKA when compared to conventional jig-based techniques [20, 21, 42, 44]. By using a preoperative CT for surgical planning, a unique 3-dimensional model of the patient's anatomy can act as a roadmap, which allows for greater accuracy in the precision of bone cuts and component placement [30, 45]. This perfected accuracy permits the restoration of biomechanics by improvements in the precision of bone resection, implant positioning, and bone coverage resulting in a restoration of a desired target alignment [22, 43, 46]. The improved preparation of the bone and resultant enhancements in implant positioning and safeguards allows for next level adjustments to surgical techniques [22, 46, 47]. Such custom fit to the patient's distinctive anatomy results in a preservation of the periarticular soft tissues, which equates to decreased postoperative inflammation, pain, and swelling [22]. Furthermore, an overall reduction of perioperative and postoperative complications and improved arthroplasty component positioning leads to improved patient satisfaction, improved patient outcomes, increased implant longevity, and reduced revision rates [44, 48, 49] which translates to a reduction of healthcare costs and the overall economic burden.

The increased radiation exposure as a result of the required preoperative CT scan has been cited as a limitation to the adoption of robotic-assisted joint arthroplasty. The typical mean effective radiation dose for these CT protocols is equal to approximately 4.8 mSv. However, this is only 2.5–3 times the radiation dose of typically acquired orthopedic radiographs including that of a complete hip or knee series and oftentimes, these radiographs must be repeated due to the patient's size or technical factors further decreasing this dose difference [41, 43, 50]. Additionally, newer CT technologies emit lower radiation doses [41]. While some authors have highlighted the concern of clinically relevant radiation dosage, others have noted the risks associated with this single CT scan for preoperative mapping have been overstated and the benefits of robotics likely outweigh this risk, should any exist [50, 51]. The dual benefit of both the precise pre-surgical plan and the benefit of detecting these incidental diagnoses by detailed anatomic review and radiologist interpretation may favor the use of CT by clinicians, payers, and patients despite the inconveniences.

Given the continually increasing rate of robotic-assisted arthroplasties performed, radiologists are more frequently tasked with interpreting these preoperative CT examinations ordered by the performing orthopedic surgeons. However, in our experience, these studies are often viewed as a formality only, rather than for diagnostic purposes, used solely for the purposes of surgical planning with little attention given to the actual findings by the radiologist or the surgeon. Furthermore, Abdelfadeel and colleagues, in their study of 176 patients, found no incidental findings that resulted in a change in management [52]. They also suggested that the radiologist professional component and therefore the evaluation of these studies by a trained imaging specialist could be eliminated to help reduce costs, although they themselves report that the professional fee is only approximately 10% of the overall CT examination total cost. The findings of our large study bring to light the importance of these preoperative CT examinations to both the interpreting radiologist and the ordering surgeon, to be aware of the benefits of these significant incidental findings and the potential consequences if these findings are not identified by a trained imaging specialist.

We recognize several limitations of this study. First, given the timeframe of the study, there was no mid-term follow-up of those with non-significant findings that may have later become significant. An appreciation of longer-term clinical data may show that even the discovery of some non-significant incidental findings could be beneficial once recognized if they eventually become significant and are acted upon more expeditiously. Additionally, since these CT protocols are limited to only axial imaging and without the use of intravenous or oral contrast, there may have been additional incidental findings that were potentially undetectable. Thirdly, given the large number of cases included in this study, it was not feasible to go back and re-review all the images to determine if any other findings were missed by the interpreting musculoskeletal radiologists. A future prospective study could be performed doing a head-to-head comparison of those undergoing preoperative radiographs versus those undergoing preoperative CT. This could be used to determine the long-term morbidity and mortality related to potentially missed diagnoses by utilizing preoperative radiographs rather than CT.

In conclusion, incidental findings are commonly detected by radiologists on preoperative CT imaging obtained by orthopedic surgeons for robotic-assisted joint replacement. Several were significant findings that were more likely to be found in males and on preoperative CT imaging for THA. Furthermore, some of these resulted in a delay or even cancelation of the planned arthroplasty, more commonly a THA. The detection of these significant incidental findings may suggest that despite the slight increased radiation dose of CT as compared to radiographs, the benefit of reporting these incidental findings by a radiologist may favor the use of CT and especially in men having a THA. If gone undetected, some of these patients may have had significant negative outcomes following the arthroplasty that could have otherwise been avoided.

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Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was waived.

Conflict of interest The authors declare that they have no conflict of interest.

Abbreviations CT, computed tomography; THA, total hip arthroplasty; TJA, total joint arthroplasty; TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty

References

1. Fingar KR, Stocks C, Weiss AJ, Steiner CA. Most frequent operating room procedures performed in U.S. hospitals, 2003-2012: Statistical Brief #186. In: Healthcare Cost and Utilization Project (HCUP) Statistical Briefs. Agency for Healthcare Research and Quality: Rockville (MD); 2006.
2. Gademan MG, Hofstede SN, Vliet Vlieland TP, Nelissen RG, Marang-van de Mheen PJ. Indication criteria for total hip or knee arthroplasty in osteoarthritis: a state-of-the-science overview. BMC Musculoskelet Disord. 2016;17(1):463.
3. Quintana JM, Arostegui I, Escobar A, Azkarate J, Goenaga JI, Lafuente I. Prevalence of knee and hip osteoarthritis and the appropriateness of joint replacement in an older population. Arch Intern Med. 2008;168(14):1576–84.
4. Lim SJ, Jang SP, Kim DW, Moon YW, Park YS. Primary ceramic-on-ceramic total hip arthroplasty using a 32-mm ceramic head with a titanium-alloy sleeve. Clin Orthop Relat Res. 2015;473(12): 3781–7.
5. Sobieraj M, Marwin S. Ultra-high-molecular-weight polyethylene (UHMWPE) in total joint arthroplasty. Bull Hosp Jt Dis. 2013;76(1):38–46.
6. Delaunay CP, Putman S, Puliero B, Begin M, Migaud H, Bonnomet F. Cementless total hip arthroplasty with metasul bearings provides good results in active young patients: a concise followup. Clin Orthop Relat Res. 2016;474(10):2126–33.
7. Clement ND, Bardgett M, Weir D, Holland J, Gerrand C, Deehan DJ. Three groups of dissatisfied patients exist after total knee arthroplasty: early, persistent, and late. Bone Joint J. 2018;100-B(2):161–9.
8. Farooq H, Deckard ER, Ziemba-Davis M, Madsen A, Meneghini RM. Predictors of patient satisfaction following primary total knee arthroplasty: results from a traditional statistical model and a machine learning algorithm. J Arthroplasty. 2020;35(11):3123–30. https://doi.org/10.1016/j.arth.2020.05.077.
9. Guofeng C, Chen Y, Rong W, Ruiyu L, Kunzheng W. Patients with metabolic syndrome have a greater rate of complications after arthroplasty: a systematic review and meta-analysis. Bone Joint Res. 2020;9(3):120–9.
10. Lostak J, Gallo J, Zapletalova J. Patient satisfaction after total knee arthroplasty. analysis of pre-operative and peri-operative parameters influencing results in 826 patients. Acta Chir Orthop Traumatol Cech. 2016;83(2):94–101.
11. Kurtz SM, Lau EC, Ong KL, Adler EM, Kolisek FR, Manley MT. Which clinical and patient factors influence the national economic burden of hospital readmissions after total joint arthroplasty? Clin Orthop Relat Res. 2017;475(12):2926–37.
12. Phillips JLH, Rondon AJ, Vannello C, Fillingham YA, Austin MS, Courtney PM. How much does a readmission cost the bundle following primary hip and knee arthroplasty? J Arthroplasty. 2019;34(5):819–23.
13. Benson JR, Govindarajan M, Muir JM, Lamb IR, Sculco PK. Surgical approach and reaming depth influence the direction and magnitude of acetabular center of rotation changes during total hip arthroplasty. Arthroplast Today. 2020;6(3):414–21.
14. Khasian M, Meccia BA, LaCour MT, Komistek RD. A validated forward solution dynamics mathematical model of the knee joint: can it be an effective alternative for implant evaluation? J Arthroplasty. 2020;35(11):3289–99. https://doi.org/10.1016/j.arth.2020.06.017.
15. Kia M, Wright TM, Cross MB, et al. Femoral component external rotation affects knee biomechanics: a computational model of posterior-stabilized TKA. Clin Orthop Relat Res. 2018;476(1): 113–23.
16. Pincus D, Jenkinson R, Paterson M, Leroux T, Ravi B. Association between surgical approach and major surgical complications in patients undergoing total hip arthroplasty. JAMA. 2020;323(11): 1070–6.
17. Rassir R, Nolte PA, van der Lugt JCT, Nelissen R, Sierevelt IN, Verra WC. No differences in cost-effectiveness and short-term functional outcomes between cemented and uncemented total knee arthroplasty. BMC Musculoskelet Disord. 2020;21(1):448.
18. Klug A, Gramlich Y, Rudert M, et al. The projected volume of primary and revision total knee arthroplasty will place an immense burden on future heath care systems over the next 30 years. Knee Surg Sports Traumatol Arthrosc. 2020;15:1–12. https://doi.org/10.1007/s00167-020-06154-7.
19. Schwartz AM, Farley KX, Guild GN, Bradbury TL Jr. Projections and epidemiology of revision hip and knee arthroplasty in the United States to 2030. J Arthroplasty. 2020;35(6S):S79–85.
20. Bell SW, Anthony I, Jones B, MacLean A, Rowe P, Blyth M. Improved accuracy of component positioning with robotic-assisted unicompartmental knee arthroplasty: data from a prospective, randomized controlled study. J Bone Joint Surg Am. 2016;98(8):627–35.
21. Conditt MA, Roche MW. Minimally invasive robotic-arm-guided unicompartmental knee arthroplasty. J Bone Joint Surg Am. 2009;91(Suppl 1):63–8.
22. Kayani B, Haddad FS. Robotic total knee arthroplasty: clinical outcomes and directions for future research. Bone Joint Res. 2019;8(10):438–42.
23. Kayani B, Konan S, Ayuob A, Ayyad S, Haddad FS. The current role of robotics in total hip arthroplasty. EFORT Open Rev. 2019;4(11):618–25.
24. Nodzo SR, Chang CC, Carroll KM, et al. Intraoperative placement of total hip arthroplasty components with robotic-arm assisted technology correlates with postoperative implant position: a CT-based study. Bone Joint J. 2018;100-B(10):1303–9.
25. Cotter EJ, Wang J, Illgen RL. Comparative cost analysis of robotic-assisted and jig-based manual primary total knee arthroplasty. J Knee Surg. 2020. https://doi.org/10.1055/s-0040-1713895.
26. Waddell BS, Carroll K, Jerabek S. Technology in arthroplasty: are we improving value? Curr Rev Musculoskelet Med. 2017;10(3): 378–87.
27. Chen AF, Kazarian GS, Jessop GW, Makhdom A. Robotic technology in orthopaedic surgery. J Bone Joint Surg Am. 2018;100(22):1984–92.
28. Hassebrock JD, Makovicka JL, Clarke HD, Spangehl MJ, Beauchamp CP, Schwartz AJ. Frequency, cost, and clinical

significance of incidental findings on preoperative planning images for computer-assisted total joint arthroplasty. J Arthroplasty. 2020;35(4):945–9. e1.

29. Yeroushalmi D, Feng J, Nherera L, Trueman P, Schwarzkopf R. Early economic analysis of robotic-assisted unicondylar knee arthroplasty may be cost effective in patients with end-stage osteoarthritis. J Knee Surg. 2020. https://doi.org/10.1055/s-0040-1712088.
30. Kayani B, Konan S, Pietrzak JRT, Haddad FS. Iatrogenic bone and soft tissue trauma in robotic-arm assisted total knee arthroplasty compared with conventional jig-based total knee arthroplasty: a prospective cohort study and validation of a new classification system. J Arthroplasty. 2018;33(8):2496–501.
31. Khalil LS, Darrith B, Franovic S, Davis JJ, Weir RM, Banka TR. Patient-Reported Outcomes Measurement Information System (PROMIS) Global Health Short Forms demonstrate responsiveness in patients undergoing knee arthroplasty. J Arthroplasty. 2020;35(6):1540–4.
32. Mallon S, Bussis K, Beswick Z, North WT, Soliman SB. Ultrasonographic and radiographic findings of polyethylene component displacement with severe metallosis and metal-induced synovitis following total knee arthroplasty. Knee. 2019;26(4):941–50.
33. North WT, Mehran N, Davis JJ, Silverton CD, Weir RM, Laker MW. Topical vs intravenous tranexamic acid in primary total hip arthroplasty: a double-blind, randomized controlled trial. J Arthroplasty. 2016;31(5):1022–6.
34. Srivastava K, Bozic KJ, Silverton C, Nelson AJ, Makhni EC, Davis JJ. Reconsidering strategies for managing chronic periprosthetic joint infection in total knee arthroplasty: using decision analytics to find the optimal strategy between one-stage and two-stage total knee revision. J Bone Joint Surg Am. 2019;101(1):14–24.
35. Arnholdt J, Kamawal Y, Holzapfel BM, Ripp A, Rudert M, Steinert AF. Evaluation of implant fit and frontal plane alignment after bi-compartmental knee arthroplasty using patient-specific instruments and implants. Arch Med Sci. 2018;14(6):1424–31.
36. Aujla RS, Esler CN. Total knee arthroplasty for osteoarthritis in patients less than fifty-five years of age: a systematic review. J Arthroplasty. 2017;32(8):2598–603. e1.
37. Kurtz S, Ong K, Lau E, Mowat F, Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am. 2007;89(4):780–5.
38. Netravali NA, Shen F, Park Y, Bargar WL. A perspective on robotic assistance for knee arthroplasty. Adv Orthop. 2013;2013:970703.
39. Citak M, Suero EM, Citak M, et al. Unicompartmental knee arthroplasty: is robotic technology more accurate than conventional technique? Knee. 2013;20(4):268–71.
40. Jennings JM, Kleeman-Forsthuber LT, Bolognesi MP. Medial unicompartmental arthroplasty of the knee. J Am Acad Orthop Surg. 2019;27(5):166–76.
41. Lonner JH, Klement MR. Robotic-assisted medial unicompartmental knee arthroplasty: options and outcomes. J Am Acad Orthop Surg. 2019;27(5):e207–e14.
42. Pearle AD, van der List JP, Lee L, Coon TM, Borus TA, Roche MW. Survivorship and patient satisfaction of robotic-assisted medial unicompartmental knee arthroplasty at a minimum two-year follow-up. Knee. 2017;24(2):419–28.
43. Tarwala R, Dorr LD. Robotic assisted total hip arthroplasty using the MAKO platform. Curr Rev Musculoskelet Med. 2011;4(3):151–6.
44. Sousa PL, Sculco PK, Mayman DJ, Jerabek SA, Ast MP, Chalmers BP. Robots in the operating room during hip and knee arthroplasty. Curr Rev Musculoskelet Med. 2020;13(3):309–17.
45. Hampp EL, Chughtai M, Scholl LY, et al. Robotic-arm assisted total knee arthroplasty demonstrated greater accuracy and precision to plan compared with manual techniques. J Knee Surg. 2019;32(3):239–50.
46. Grau L, Lingamfelter M, Ponzio D, et al. Robotic arm assisted total knee arthroplasty workflow optimization, operative times and learning curve. Arthroplast Today. 2019;5(4):465–70.
47. Dorr LD, Wan Z, Malik A, Zhu J, Dastane M, Deshmane P. A comparison of surgeon estimation and computed tomographic measurement of femoral component anteversion in cementless total hip arthroplasty. J Bone Joint Surg Am. 2009;91(11):2598–604.
48. Marchand RC, Sodhi N, Khlopas A, et al. Patient satisfaction outcomes after robotic arm-assisted total knee arthroplasty: a short-term evaluation. J Knee Surg. 2017;30(9):849–53.
49. Qin J, Xu Z, Dai J, et al. New technique: practical procedure of robotic arm-assisted (MAKO) total hip arthroplasty. Ann Transl Med. 2018;6(18):364.
50. Ponzio DY, Lonner JH. Preoperative mapping in unicompartmental knee arthroplasty using computed tomography scans is associated with radiation exposure and carries high cost. J Arthroplasty. 2015;30(6):964–7.
51. Miller LE. Letter to the Editor on "Preoperative mapping in unicompartmental knee arthroplasty using computed tomography scans is associated with radiation exposure and carries high cost". J Arthroplasty. 2016;31(5):1130.
52. Abdelfadeel W, Houston N, Star A, Saxena A, Hozack WJ. CT planning studies for robotic total knee arthroplasty. Bone Joint J. 2020;102-B(6_Supple_A):79–84.