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Simulating movements of daily living in robot-assisted total hip arthroplasty with 3D modelling

A FEASIBILITY STUDY

W. S. Tung,
C. Donnelley,
A. Eslam Pour,
S. Tommasini,
D. Wiznia

From Yale University, New Haven, Connecticut, USA

Aims
Computer-assisted 3D preoperative planning software has the potential to improve postoperative stability in total hip arthroplasty (THA). Commonly, preoperative protocols simulate two functional positions (standing and relaxed sitting) but do not consider other common positions that may increase postoperative impingement and possible dislocation. This study investigates the feasibility of simulating commonly encountered positions, and positions with an increased risk of impingement, to lower postoperative impingement risk in a CT-based 3D model.

Methods
A robotic arm-assisted arthroplasty planning platform was used to investigate 11 patient positions. Data from 43 primary THAs were used for simulation. Sacral slope was retrieved from patient preoperative imaging, while angles of hip flexion/extension, hip external/internal rotation, and hip abduction/adduction for tested positions were derived from literature or estimated with a biomechanical model. The hip was placed in the described positions, and if impingement was detected by the software, inspection of the impingement type was performed.

Results
In flexion, an overall impingement rate of 2.3% was detected for flexed-seated, squatting, forward-bending, and criss-cross-sitting positions, and 4.7% for the ankle-over-knee position. In extension, most hips (60.5%) were found to impinge at or prior to 50° of external rotation (pivoting). Many of these impingement events were due to a prominent ischium. The mean maximum external rotation prior to impingement was 45.9° (15° to 80°) and 57.9° (20° to 90°) prior to prosthetic impingement. No impingement was found in standing, sitting, crossing ankles, seiza, and downward dog.

Conclusion
This study demonstrated that positions of daily living tested in a CT-based 3D model show high rates of impingement. Simulating additional positions through 3D modelling is a low-cost method of potentially improving outcomes without compromising patient safety. By incorporating CT-based 3D modelling of positions of daily living into routine preoperative protocols for THA, there is the potential to lower the risk of postoperative impingement events.

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Correspondence should be sent to Aidin Eslam Pour; email: aidin.eslampour@yale.edu

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Introduction
Hip impingement and dislocation following total hip arthroplasty (THA) is a well-documented postoperative complication.[1–6] Extant data suggest that robotic arm-assisted surgery and its related preoperative planning programs, which incorporate 3D pelvic tilt and hip motions, have the potential to

Table I. Intraoperative implant specifications (total n = 43).

Variable	Value
Stem neck angle (°), n (%)	
127	40 (93.0)
132	3 (7.0)
Liner type, n (%)	
X3	33 (76.7)
Modular Dual Mobility with X3	10 (23.3)
Femoral head size, n (%)	
32 mm for X3	1 (2.3)
36 mm for X3	12 (27.9)
40 mm for X3	20 (46.5)
46 mm for MDM with X3	9 (20.9)
48 mm for MDM with X3	1 (2.3)
Mean cup anteversion, ° (range)	17.5 (15 to 25)
Mean stem anteversion, ° (range)	18 (-5 to 40)

Cup inclination was set at 40° for all patients.

improve the stability of THA,[7–13] and are valuable in optimizing postoperative hip range of motion (ROM).[10,11] Such patient-specific CT-based 3D modelling data are particularly valuable, as recreating positions at high risk of impingement allow the surgeon to customize the position and orientation of a patient's implants to lower the risk of dislocation. Preoperatively, computer simulation models allow surgeons to incorporate sagittal pelvic tilt and hip motion data, and optimize the orientation and size of implants to reduce impingement. Intraoperatively, robotic- or computer-assisted navigation techniques improve the accuracy of acetabular component positioning and potentially reduce postoperative complications associated with impingement or edge loading.[8,9,14–16]

Most computer-assisted preoperative plans incorporate data from two functional positions: standing and relaxed sitting. However, other daily activities often associated with reported postoperative impingement and dislocation, such as getting out of a chair (flexed-seated position), bending forward to pick up objects (forward-bending position), crossing legs, or pivoting are missed in standard preoperative planning. Newly developed 3D modelling software now allows simulation of many hypothetical scenarios, including the above positions, where THA impingement or dislocation events may occur.

The purpose of this study, therefore, was to determine the feasibility of simulating additional positions of daily living using a 3D, CT-based preoperative planning software designed for robotic-assisted total hip arthroplasty. We hypothesized that simulating daily activities in addition to standing and relaxed sitting is not only feasible but would provide important data to assess prosthetic and bony impingement in THA.

Methods

Study setting. Institutional Review Board approval (protocol ID #2000032304) was obtained from Yale University for this retrospective computer simulation study. Data from preoperative radiographs, CT scans, and 3D THA plans were extracted from the institution's electronic medical record (EMR) management system, EPIC Hyperspace (EPIC Systems Corporation, USA), and Stryker Smart Robotics MAKO Total Hip 4.0 (Stryker, USA) software archives. All figures were created with OpenSim 4.4 (Stanford University, USA) and Stryker Smart Robotics MAKO Total Hip 4.0.

Study population. All patients who underwent robotic arm-assisted primary THA for osteoarthritis, osteonecrosis, or inflammatory arthritis with a single surgeon at a single institution between 1 February 2021 and 30 September 2022 were considered. Patient pelvis CT scans and lateral lumbar radiographs in standing and relaxed sitting positions were obtained per the institution's routine preoperative protocol. Patients were excluded if there was incomplete preoperative imaging or 3D modelling information. All patients received a minimum of one-year follow-up, including recording any instability events.

Preoperative computer planning. An image-processed pelvis CT scan and data collected from lateral lumbar radiographs in standing and relaxed sitting positions for each patient were imported into the preoperative planning platform. Optimization of the acetabular implant size and orientation, centre of rotation, stem size and offset, and prosthetic head diameter to prevent prosthetic and bony impingement was performed per routine protocol for robotic arm-assisted THA. All patients received either a Stryker Trident X3[14] or a modular dual mobility (MDM) with X3 cup[15] along with an Accolade II stem.[16] In three hips, the stem neck angle was 132° (7%); in 40 patient hips, the stem neck angle was 127° (93%). One, 12, and 20 hips were provided with 32 mm, 36 mm, and 40 mm heads, respectively; the operating surgeon used the largest conventional head (36 mm) for the available polyethylene. Operating surgeons also chose a dual-mobility bearing surface option for ten patients who were believed to be at a higher risk for dislocation due to their hip-spine relationship. The cup inclination was set at 40° for all patients. The mean cup anteversion angle was 17.5° (15° to 25°), while the mean stem anteversion angle was 18° (-5° to 40°). Intraoperative implant specifications are summarized in Table I.

Simulation. To conduct this feasibility study, we used the robotic arm-assisted preoperative plans retrospectively, and the results were not used clinically. Two researchers (WS, CD) were trained by a Mako Product Specialist to simulate the positions on the platform. Common positions of postoperative impingement and dislocation derived from extant literature were used,[17] as defined in Table II. Tested motions included standing, relaxed sitting, pivoting (Figure 1), flexed seated position (Figure 2), squatting (Figure 3), forward bending (Figure 4), crossing ankle over the knee (Figure 5), crossing ankle over

Table II. Specifications of positions simulated in the study.

	Pelvic tilt			Hip motion		
Body motion/position	**Sagittal**	**Coronal**	**Axial**	**Flexion**	**External rotation**	**Abduction**
Extension						
Standing	Patient standing sacral slope	0°	0°	5°	0°	0°
Pivoting	5°	0°	0°	0°	50°	0°
Flexion						
Sitting	Patient sitting sacral slope	0°	0°	80°	0°	0°
Flex-seated	10°	0°	0°	80°	0°	0°
Squatting	5°	0°	0°	95°	0°	5°
Forward-bending	70°	0°	0°	20°	0°	5°
Crossing ankle over knee	-15°	0°	0°	100°	90°	15°
Crossing ankles	-15°	0°	0°	85°	50°	0°
Criss-cross sitting (Indian-style sitting)	7°	0°	0°	100°	75°	20°
Seiza (Japanese-style sitting)	0°	0°	0°	75°	0°	0°
Downward dog	20°	0°	0°	50°	0°	5°

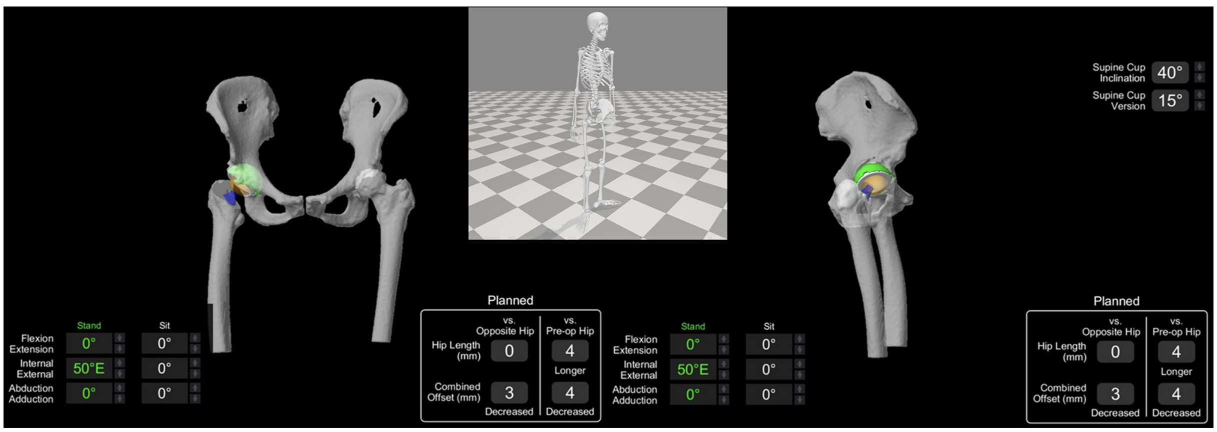

Fig. 1

Pivoting position using estimated anterior pelvic plane (APP) values.

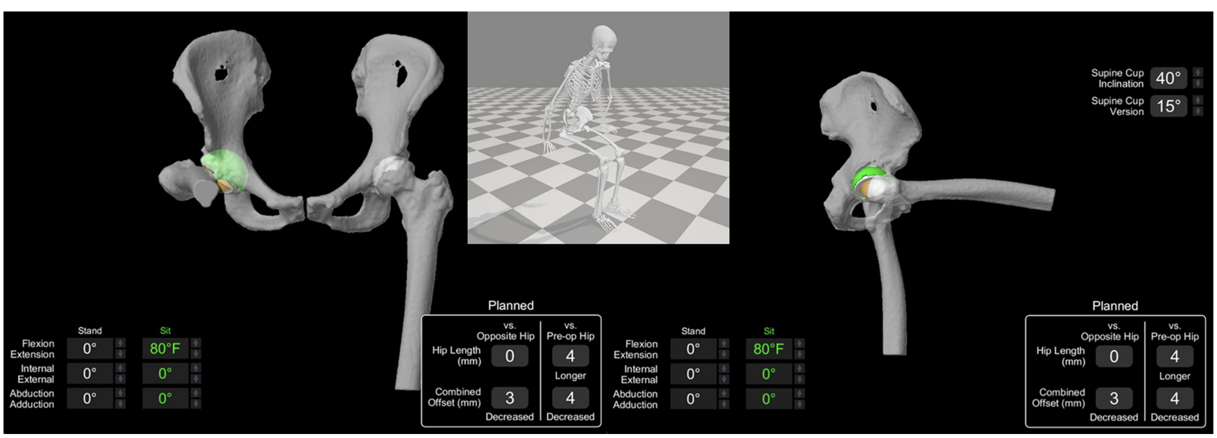

Fig. 2

Flex-seated position using estimated anterior pelvic plane (APP) values.

ankle (Figure 6), criss-cross sitting (Indian-style sitting) (Figure 7), Seiza sitting (Japanese-style sitting) (Figure 8), and downward dog position (Figure 9). The software requires a minimum of four variables for simulation: sacral slope (SS) or anterior pelvic plane (APP) for sagittal pelvic tilt, hip flexion or extension, hip internal or external

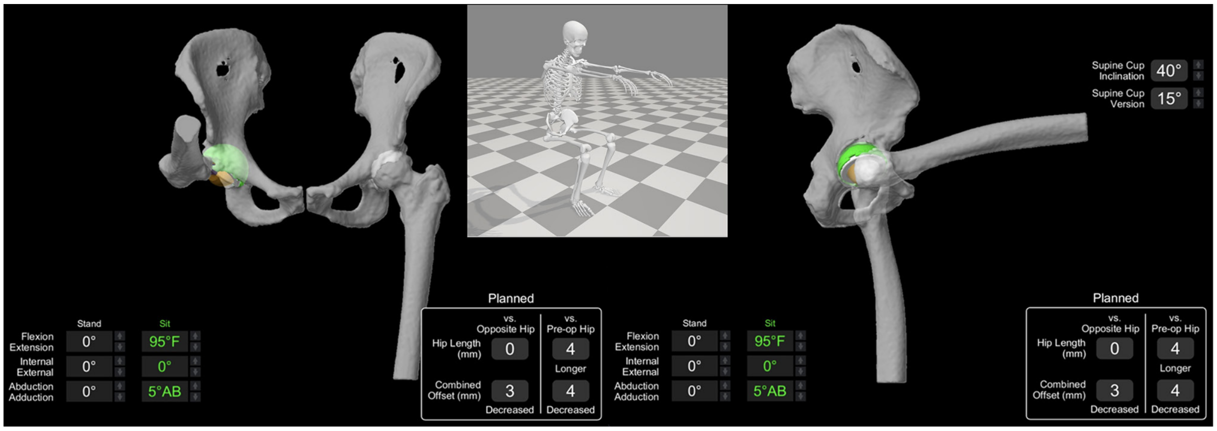

Fig. 3

Squatting position using estimated anterior pelvic plane (APP) values.

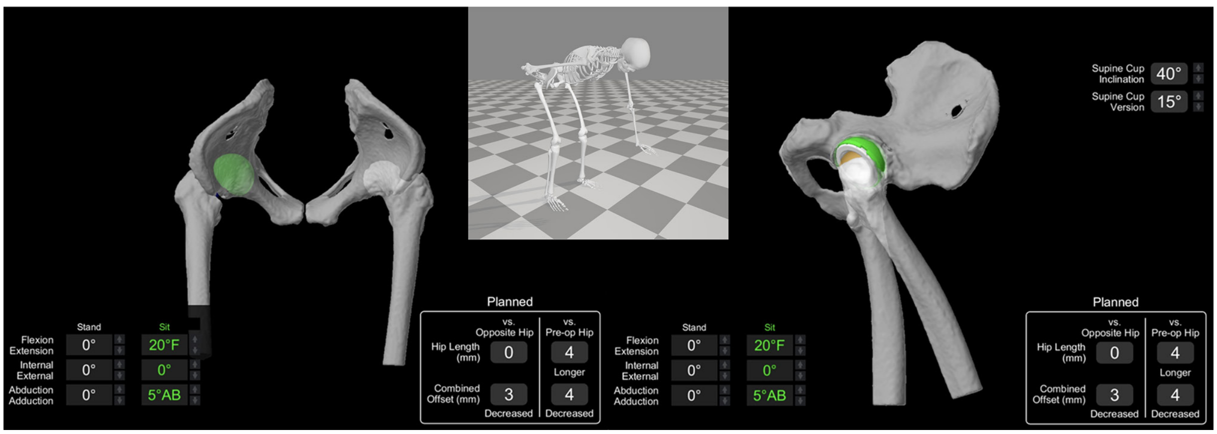

Fig. 4

Forward-bending position using estimated anterior pelvic plane (APP) values.

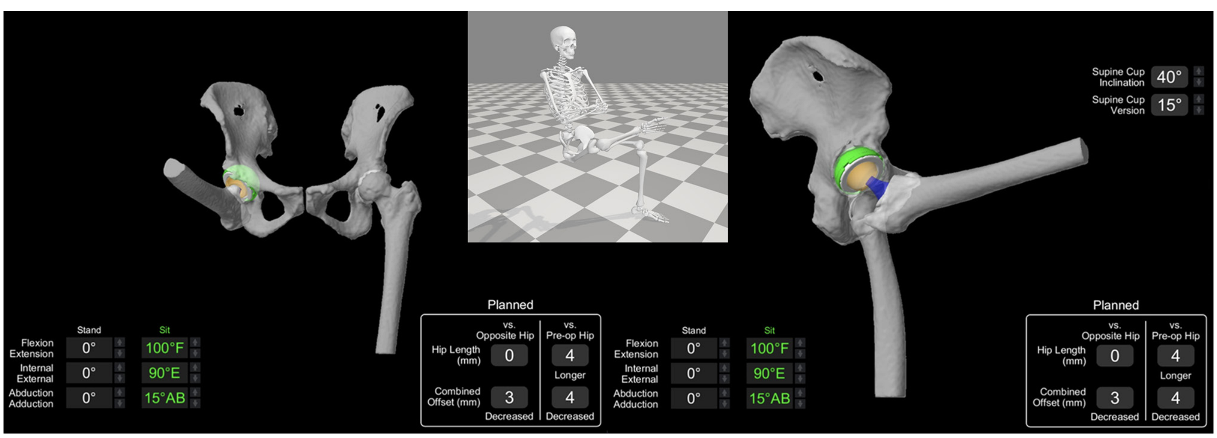

Fig. 5

Crossing ankle over knee position using estimated anterior pelvic plane (APP) values.

rotation, and hip abduction or adduction in degrees. For simulation of standing and relaxed sitting positions, patients' SS angle measured by the operating surgeon were retrieved from lateral lumbar radiographs and rounded to the nearest degree. All other positions used an estimated sagittal pelvic tilt, as we did not have the static radiological imaging for the tested positions to measure the sagittal pelvic tilt. Reported ranges and estimations made

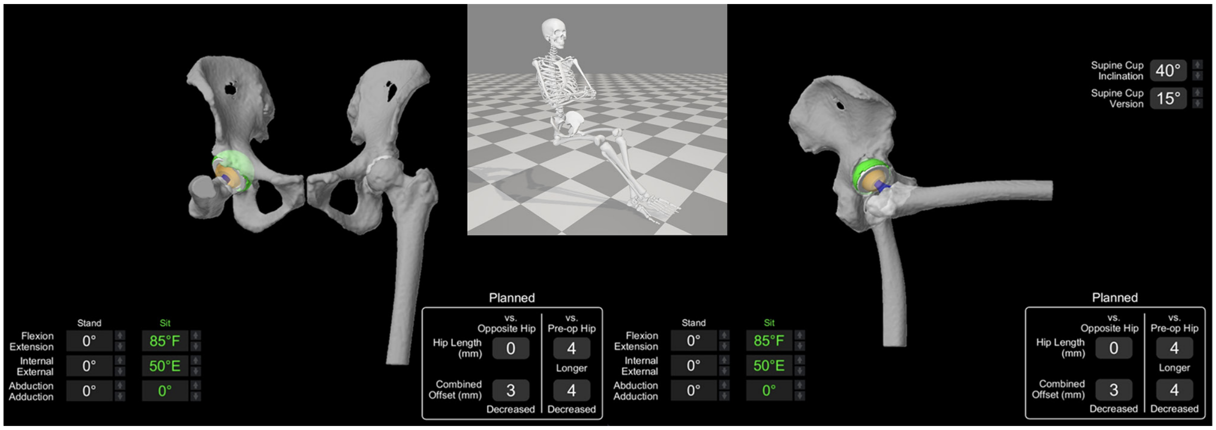

Fig. 6

Crossing ankles position using estimated anterior pelvic plane (APP) values.

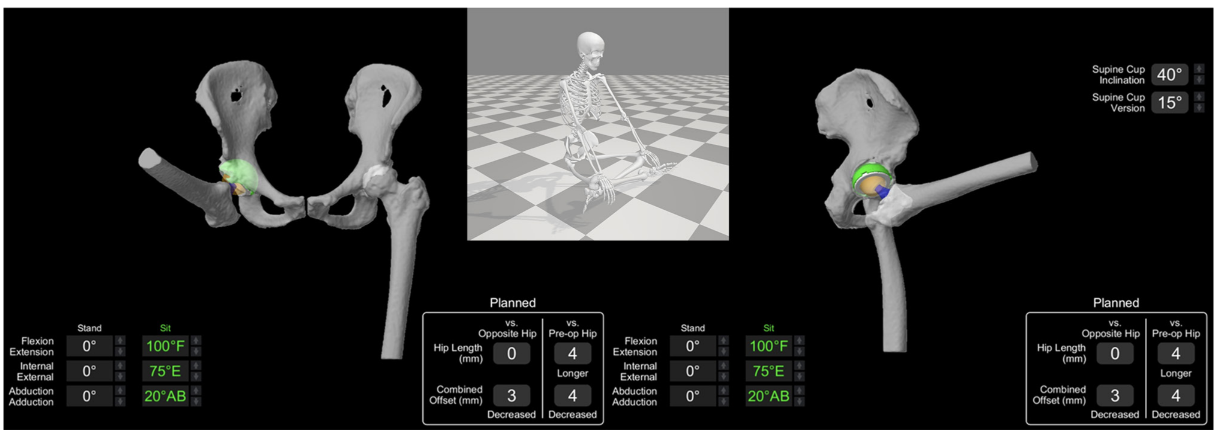

Fig. 7

Criss-cross (Indian-style) sitting position using estimated anterior pelvic plane (APP) values.

Table III. Baseline demographic data (n = 43).

Variable	Value
Mean age, yrs (range)	58 (32 to 89)
Sex, n (%)	
Male hips	21 (48.8)
Female hips	22 (51.2)
Mean standing sacral slope, ° (range)	39.67 (8 to 65)
Mean sitting sacral slope, ° (range)	16.35 (0 to 50)

using a biomechanical model rounded to the nearest fifth degree were used for the additionally tested positions in this study.[17]

Observed impingement was divided into three categories: prosthetic (implant-to-implant), implant-to-bone, and bone-to-bone. If impingement was identified by the software, a red marking would highlight the location of contact. A thorough visual inspection by rotation on all axes was required to determine the type of impingement; this was recorded for each occurrence along with the degree in which it occurred. For pivoting, the type of impingement encountered first was recorded along with the degree of rotation at which it occurred.

Impingement involving small islands of osteophytes were excluded if intraoperative removal was guaranteed. In scenarios where osteophytes could not be fully removed intraoperatively, 5° towards the direction of rotation was added to ensure true impingement. When bone-to-bone impingement occurred first, the maximum rotation prior to impingement was documented.

Statistical analysis. Descriptive statistics were used to summarize the rate of impingement in each of the 11 positions simulated.

Results

A total of 43 hips were available for simulation, with patient demographics detailed in Table III. All patients received a unilateral primary THA, except for one who received a staged bilateral primary THA. All surgeries were performed via posterior approach in the lateral decubitus position successfully, without any reported instability events in the first postoperative year. Of the 11

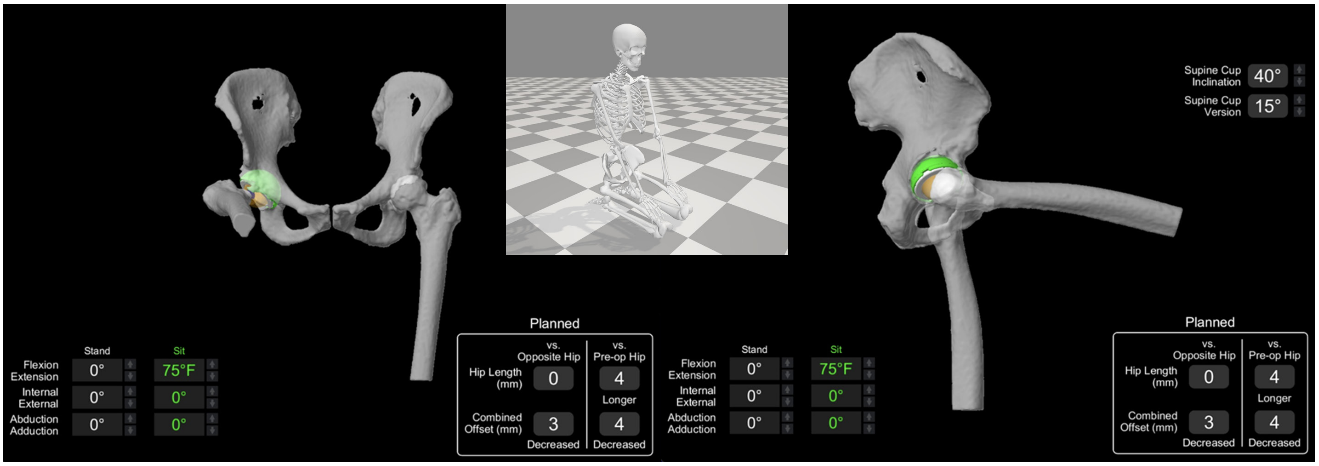

Fig. 8

Seiza (Japanese-style) position with estimated anterior pelvic plane (APP) values.

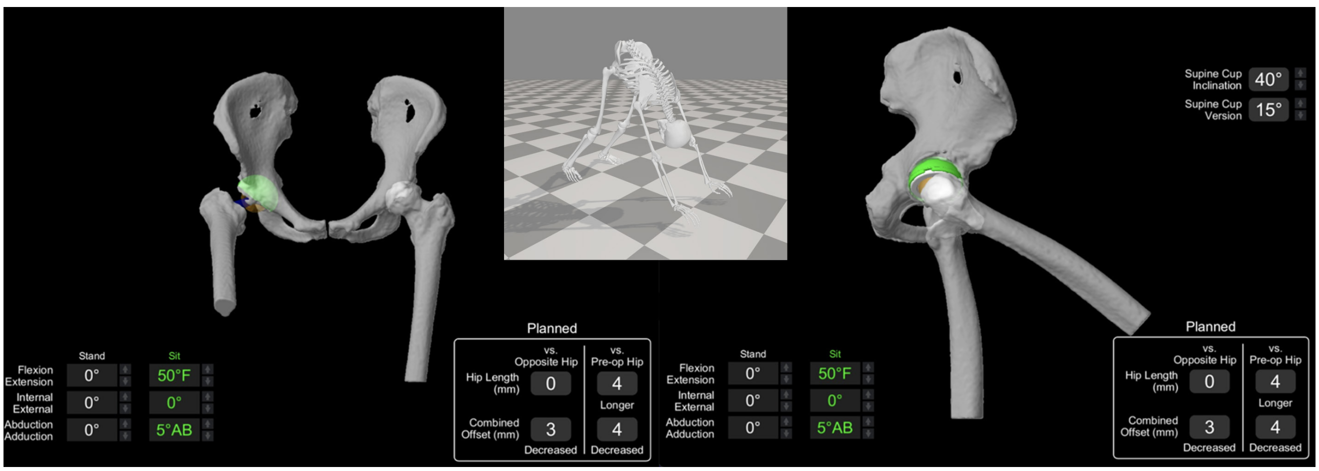

Fig. 9

Downward dog position with estimated anterior pelvic plane (APP) values.

positions of daily living, no impingement was found in standing, relaxed sitting, crossing ankles, seiza (a formal, traditional way of Japanese sitting), or downward dog positions. Apart from pivoting, all other occurrences of impingement occurred in three patients in flexion positions: one patient with three bone-to-bone impingement events and two other patients with bone-to-implant impingement events (Table IV). This resulted in an impingement rate of 2.3% for the flexed sitting, squatting, forward-bending, and criss-cross sitting positions, and 4.7% for the ankle-over-knee position. No prosthetic impingement was found.

Impingement found in pivoting was evaluated separately. Of the 43 hips, 26 (60.5%) impingement events were found at or prior to 50°. In 50° of external rotation 19 hips (44.2%) were found to have a combination of two or three types of impingements. Of those, 14 hips (32.6%) were found to have all three types of impingement: bone-to-bone, bone-to-implant, and prosthetic, while five (11.6%) had a combination of implant-to-bone and bone-to-bone impingement (Table IV). Six hips (14.0%) had implant-to-bone impingement exclusively. One hip (2.3%) had prosthetic impingement exclusively at 50°. The first occurrence of impingement of any type for each hip was also recorded and defined. Overall, 20 (46.5%) of the first impingement events were implant-to-bone, followed by 11 (25.6%) combined events, seven (16.3%) bone-to-bone events, and five (11.6%) prosthetic events (Table IV). The mean maximum external rotation prior to any type of impingement was 45.9° (15° to 80°) and 57.9° (20° to 90°) before prosthetic impingement. No prosthetic impingement was recorded within the allowable range on Total Hip 4.0 for two of the 43 hips (4.7%).

Discussion

To the best of our knowledge, this is the first study to investigate the feasibility of simulating positions of daily

Table IV. Tabulation of impingement events. Impingement was not found in any of the other simulated positions of daily living.

Type of impingement, n (%)	Extension		Flexion				
	Pivoting	**First impingement in external rotation**	**Flex-seated**	**Squatting**	**Bending over**	**Crossing ankle over knee**	**Criss-cross sitting**
Bone-to-bone	0	7 (16.3)	1 (2.3)	1 (2.3)	1 (2.3)	0	0
Implant-to-bone	6 (14.0)	20 (46.5)	0	0	0	2 (4.7)	1 (2.3)
Prosthetic	1 (2.3)	5 (11.6)	0	0	0	0	0
Combination	19 (44.2)	11 (25.6)	0	0	0	0	0

living beyond standing and relaxed sitting positions in a CT-based 3D model. Of the nine additional positions investigated in this study, pivoting had the highest impingement rate. All impingement events found in other positions were in three patients with large osteophytes, a prominent anterior-inferior iliac spine (AIIS), or a large proximal femur. While the expected maximum impingement-free external hip rotation is approximately 50° (pivoting),[18] 60.5% of the patients were shown to have impingement prior to or at 50° of rotation. Given a lower estimation of 40° of maximum external rotation,[19] 19 patients (44.2%) still had some sort of impingement. In addition, an overwhelming number of patients (72.1%) had exclusive, or a combination involving, implant-to-bone impingement as their first impingement event. Many of these events can be attributed to a prominent ischium.

The reasons for postoperative dislocations after total hip arthroplasty are multifactorial, including surgical approach,[1] soft-tissue concerns, and impingement. When prosthetic impingement occurs, or when the neck impinges on a bony prominence, a lever mechanism is created providing a pathway to dislocation.[2,3] Avoiding impingement in all positions of daily living can be difficult to determine intraoperatively and is often based solely on tactile feedback in standard positions of hip flexion, extension, internal, and external rotation. Personalizing implant size, position, and orientation based on a patient's SS and testing for impingement with modelling may be useful in lowering the risk of impingement and possible dislocation. The ability to simulate activities of daily living in addition to standing and relaxed sitting positions at a low cost, and almost effortlessly, without compromising patient safety makes for a compelling reason for 3D-based modelling to become a preoperative standard.

This feasibility study has demonstrated that the preoperative planning platforms can be effectively used to detect impingement in additional positions of daily living. Although impingement was not observed in most scenarios tested, these simulations can aid in validating implant position and orientation preoperatively. Simulation software gives its operator the opportunity to place patient hips into a variety of positions, a chance to make the necessary adjustments to components, and the potential to avoid postoperative impingement risks. The inclusion of additional positions, known to have an increased risk of impingement and dislocation in routine preoperative planning protocol, has the potential to alleviate anxiety and uncertainty for both the patient and the surgeon around postoperative hip impingement and dislocation risks. As advances in robotic arm-assisted and computer-guided surgical techniques in THA continue to be developed, this study can be used as a starting point for future research that employs technology to improve postoperative patient outcomes.

There are limitations to this investigation. Primarily, it is retrospective in nature and, as a feasibility study, contains only a small cohort of patients. Additionally, while there have been many advances in robotic arm-assisted total hip preoperative planning software, the current versions do not allow variations in coronal or axial pelvic tilts. These movements are likely important, as previous computer simulations have shown the effect of these variables on prosthetic impingement.[17–19] Lastly, aggregated estimates from published papers were used to simulate the additional positions of daily life. Although these estimates were reported by experienced orthopaedic surgeons and averaged for each position, these numbers do not necessarily represent how a particular patient may move, but still constitute level V evidence.

Despite these limitations, this investigation has demonstrated a novel expansion of preoperative templating using advanced imaging to optimize implant positioning in THA. The values used for tested positions were based on previously published literature, and these values can be different for each patient. Future research may include a larger cohort with longer follow-up in addition to advances in templating software and assessments of cost-effectiveness.

In this study, the feasibility of simulating positions of daily life and positions that may be related to an increased impingement risk was investigated with CT-based 3D modelling. At present, commercially available preoperative planning software primarily focuses on standing and relaxed sitting positions to identify impingement. Our findings demonstrate the feasibility of incorporating additional movements – which patients commonly use in their daily lives or for leisure activities – into these software platforms. Preoperative planning software provides a low-cost, ethical way to detect possible impingement in an array of positions with the change of a few variables. By incorporating more positions into the routine preoperative protocol for THAs, there is the potential to lower the risk of postoperative impingement events.

Take home message

- At present, commercially available preoperative planning software primarily focuses on standing and relaxed sitting positions to identify impingement.
- Our findings demonstrate the feasibility of incorporating additional movements, which patients commonly use in their daily lives or for leisure activities, into these software platforms.

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Author information:
- W. S. Tung, BS, Research Fellow
- C. Donnelley, MD, Orthopaedic Surgery Resident
- A. Eslam Pour, MD, MS, FAAOS, Orthopaedic Surgeon
- S. Tommasini, PhD, Research Scientist
- D. Wiznia, MD, MS, Orthopaedic Surgeon
Department of Orthopaedics & Rehabilitation, Yale University, New Haven, Connecticut, USA.

Author contributions:
- W. S. Tung: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.
- C. Donnelley: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Validation, Project administration.
- A. Eslam Pour: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Validation.
- S. Tommasini: Project administration, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.
- D. Wiznia: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision.

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