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RESEARCH ARTICLE

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How much change in pelvic sagittal tilt can result in hip dislocation due to prosthetic impingement? A computer simulation study

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Abstract

Developing spinal pathologies and spinal fusion after total hip arthroplasty (THA) can result in increased pelvic retroversion (e.g., flat back deformity) or increased anterior pelvic tilt (caused by spinal stenosis, spinal fusion or other pathologies) while bending forward. This change in sagittal pelvic tilt (SPT) can result in prosthetic impingement and dislocation. Our aim was to determine the magnitude of SPT change that could lead to prosthetic impingement. We hypothesized that the magnitude of SPT change that could lead to THA dislocation is less than 10° and it varies for different hip motions. Hip motion was simulated in standing, sitting, sit-to-stand, bending forward, squatting and pivoting in Matlab software. The implant orientations and SPT angle were modified by 1° increments. The risk of prosthetic impingement in pivoting caused by increased pelvic retroversion (reciever operating characteristic [ROC] threshold as low as 1–3°) is higher than the risk of prosthetic impingement with increased pelvic anteversion (ROC threshold as low as 16–18°). Larger femoral heads decrease the risk of prosthetic impingement (odds ratio {OR}: 0.08 [932 mm head]; OR: 0.01 [36 mm head]; OR: 0.002 [40 mm head]). Femoral stems with a higher neck-shaft angle decrease the prosthetic impingement due to SPT change in motions requiring hip flexion (OR: 1.16 [132° stem]; OR: 4.94 [135° stem]). Our results show that overall, the risk of prosthetic impingement due to SPT change is low. In particular, this risk is very low when a larger diameter head is used and femoral offset and length are recreated to prevent bone on bone impingement.

KEYWORDS

computer modeling, hip arthroplasty, hip biomechanics

1 | INTRODUCTION

The importance of the preoperative sagittal pelvic tilt (SPT) assessment and its effect on the risk of total hip arthroplasty (THA) dislocation has been previously shown.[1-12] The magnitude of the SPT during different daily activities is personalized based on the patients' functional anatomy.[1,3-5,10,13-17] SPT changes with spinal pathologies as well as spinal surgeries, but there is limited evidence regarding the magnitude of SPT change that can increase the risk for postoperative THA dislocation. The criteria that is known is the spinal stiffness (SPT change less than 10°) that can increase the risk of dislocation.[17-19] The risk has been assessed by lateral lumbosacral radiographs in standing and sitting positions or advanced functional imaging techniques, such as bi-planer radiography (EOS; EOS imaging).

Computer simulation models that can predict risk are another method to study THA impingement in patients with spinal fusion or spinal pathologies. Computer simulation of hip motion is a research model which makes investigation of THA impingement possible. These models allow us to investigate replicable motion which is not readily available in motion analysis laboratories or clinical studies. These models can accurately predict the anatomical and functional orientation of the THA implants while modifying the simulation variables by only 1° at a time, which permits testing thousands of different scenarios with minimum cost.

Our purpose was to determine the magnitude of the SPT change caused by variable hip-spine positions that could lead to THA prosthetic impingement. We hypothesized that the magnitude of this SPT change is less than 10° but would be variable for different hip motions, different prosthetic femoral head sizes and stems with different femoral neck-shaft angles.

2 | METHODS

2.1 | Study setting

This study was conducted using a computer simulation of hip motions with THA implants. No human subjects were included in this study and the study was exempt from institutional review board. This project was conducted under National Institution of Health clinical investigator (K08) award.

2.2 | Computer model development

We developed our computer model with Matlab 2020a (Simscape—Multibody) (MathWorks). A deidentified pelvis and lower body computed tomography (CT) scan of a patient without previous lower extremity

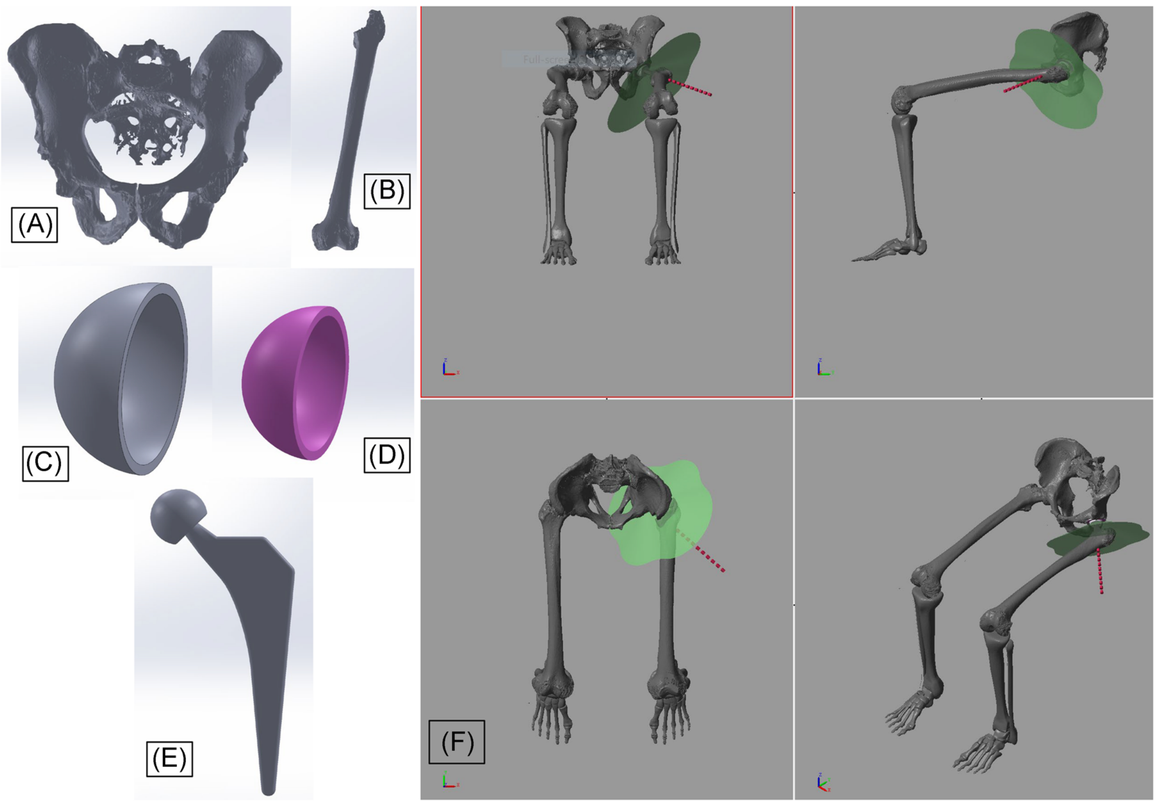

FIGURE 1 This figure shows how the computer simulation model. (A) pelvis computed tomography (CT) scan. (B) Femur CT scan. (C) Acetabular cup computer aided design (CAD) model. (D) Acetabular liner CAD model. (E) Femoral stem and prosthetic head CAD model. (F) Computer simulation of sitting motion [Color figure can be viewed at wileyonlinelibrary.com]

arthroplasty or fracture surgery was used to import the bony anatomy (pelvis, femur, tibia) into the model (Figure 1). The computer aided design models for the THA implant components (a full hemispherical acetabular cup without an elevated rim [best fit diameter = 56 m], polyethylene liner without an elevated rim and a triple-taper cementless stem with three different neck shaft angles [127°, 132°, 135°]) were designed in SolidWorks (Dassault Systèmes SolidWorks Corporation) and imported into the Matlab model. Acetabular cup and liner were placed in the acetabulum and the stem was placed in the proximal femur based on the anatomical orientation as defined below. The hip joint could move at the center of the acetabular cup in all directions (flexion/extension, abduction/adduction and internal/external rotation) and the knee joint could move into flexion and extension.

The polar axis (PA) represents the point on the prosthetic head where the line passing through the center of the prosthetic neck exits (Figure 2A). Motions of the femoral head inside the liner will produce a motion map with accurate coordinates and this map can be utilized to study the motions of the hip joint during daily activities. If PA moves closer to the edge of the polyethylene liner, the probability of prosthetic impingement and subsequent dislocation will increase (Figure 2A,B). Figure 3 shows the area inside a 28, 32, 36, and 40 mm liners. The red line shows when the prosthetic impingement between the trapezoidal femoral neck and polyethylene liner occurs. The blue line shows the 90% distance between the center and the edge of the polyethylene liner and represents our more conservative model. In mechanical engineering, the probability of error in calculation of the risk of prosthetic impingement increases when the PA passes the 90% distance line. Also, most dislocations that are due to bone on bone impingement would occur when the hip is closer to the end of the range of motion and PA crosses the blue line rather than at the red line, prosthetic impingement. We did our analysis separately for each of the blue and red lines (Figure 2B). As seen in Figure 3, the distance between the red line and blue line (safety region) increases with larger prosthetic femoral head diameters. This shows how larger femoral prosthetic heads lower the dislocation rate by increasing range of motion to impingement.

2.3 | Implant orientation measurement

Anatomical acetabular implant anteversion was calculated relative to the anterior pelvic plane (APP) (Figure 4).[1,7,20] Anatomical acetabular implant abduction was calculated relative to the horizontal plane

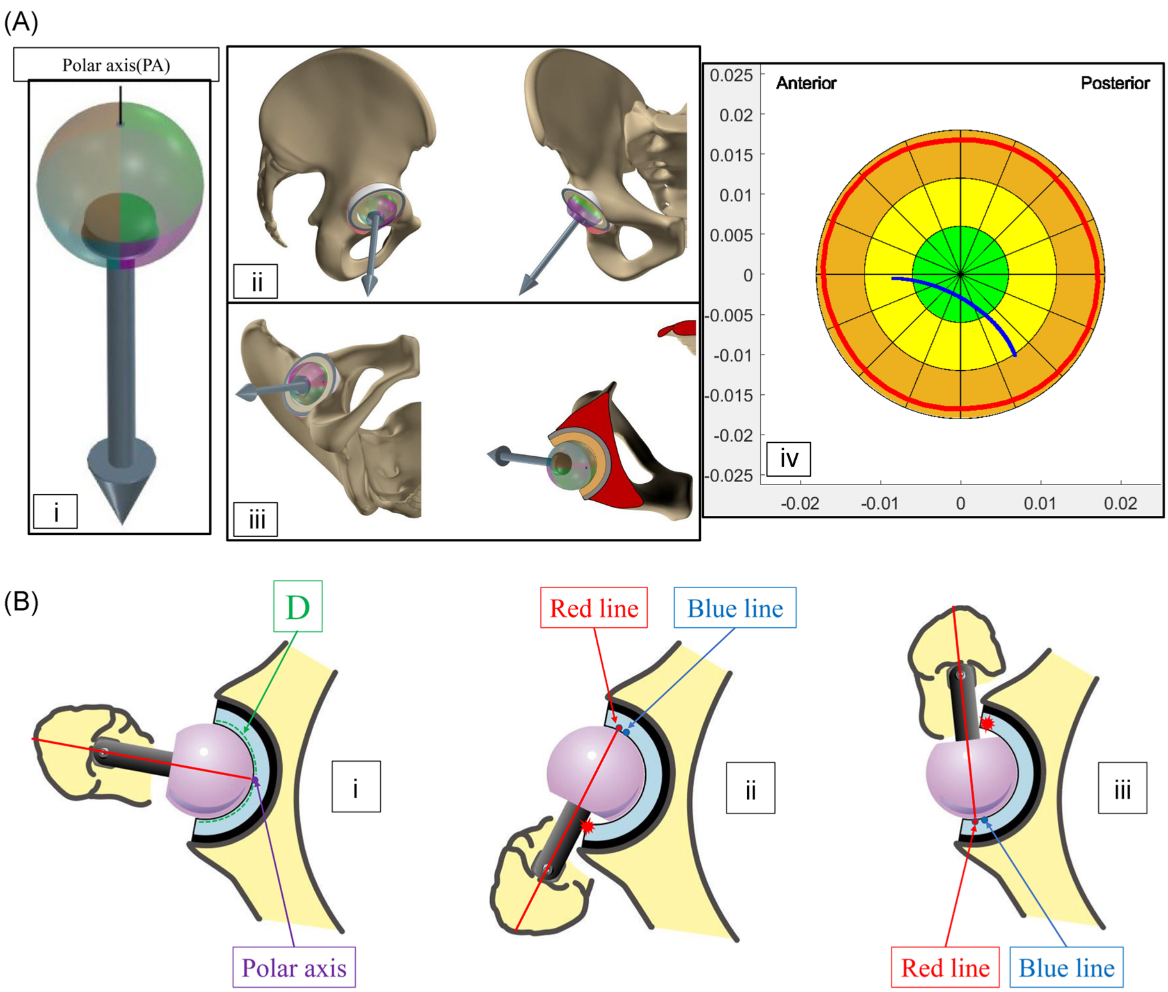

FIGURE 2 (A) Polar axis (PA) represents the point where the line passing through the center of the prosthetic neck exits the head. (B) Motions of the (B, C) PA inside the cup (D) can be mapped and studied

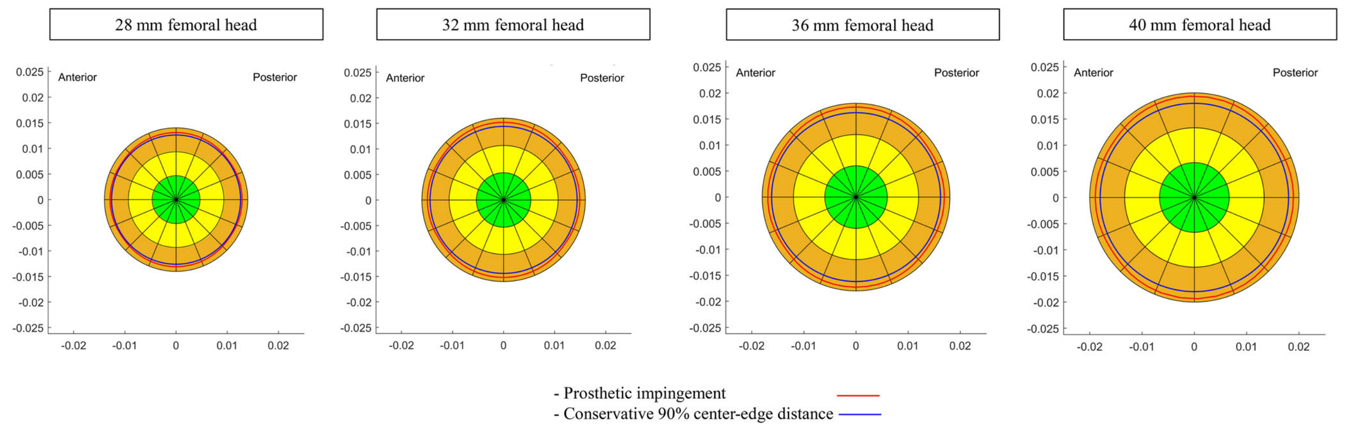

FIGURE 3 This figure shows the area inside 28, 32, 36, and 40 mm liners. Red line represents a true prosthetic impingement and blue line represents the 90% distance between the center and the edge of the liner

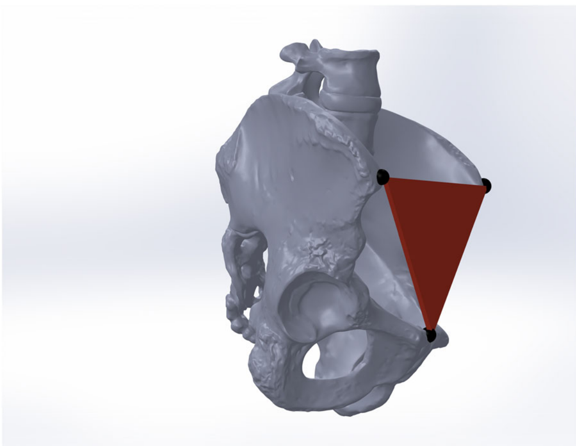

FIGURE 4 Anterior pelvic plane (APP) [Color figure can be viewed at wileyonlinelibrary.com]

that connected the hip center of rotation and was vertical to the APP. Anatomical femoral anteversion was calculated relative to the posterior femoral condylar plane. The functional acetabular implant orientation was measured relative to the horizontal (ground) and the vertical planes. If the APP was zero, the APP and vertical planes were parallel and the functional and anatomical cup orientations were similar. Functional femoral orientation was calculated as the angle between the femoral neck and the vertical plane in standing (Figure 5).

2.4 | Pelvic tilt and lower extremity parameters during simulated activities

In our model, we considered coronal and axial tilt as zero (except for pivoting) to standardize the sagittal measurement. The sagittal pelvic plane was considered zero when the APP was vertical. Posterior pelvic tilt was considered negative and anterior tilt positive. Table 1 shows the SPT in different motions as well as hip flexion, abduction and rotation as well as their range for this simulation. The SPT was then modified by 1° to a maximum of 45° for stand and sit and 35° for the other positions in both anterior and posterior directions. This range matches the extremes of pelvic tilts reported in the literature.[5,21-24]

2.5 | Motion simulation

The hip implant motion map is presented in Figure 1. The coordinates of the PA at its closest distance to the polyethylene edge during each motion were captured. For example, the colored dot for sit-to-stand represents the closest position of PA to the edge of the liner (Figure 6). MATLAB model was verified in silico with an independent model written in SolidWorks to compare the reference planes (anterior pelvic plane, horizontal, and vertical planes) and relative to each other.

2.6 | Variables

The main predictor was the SPT change for each of the six positions or motions. For the red line (true prosthetic impingement), the main categorical outcome variable was prosthetic impingement measured by the PA reaching the red line. For the more conservative model, the main outcome was the PA reaching the blue line. Other predicting variables included the anatomical acetabular cup anteversion (range: 5–30), the anatomical cup abduction (range: 40–60), the femoral neck anteversion, the prosthetic femoral head diameter, and the femoral stem neck-shaft angle. The implant orientation range was within the range of clinical use.

2.7 | Statistical analysis

The data was categorized into twelve groups based on the prosthetic femoral head diameter and femoral neck-shaft angle. Our model

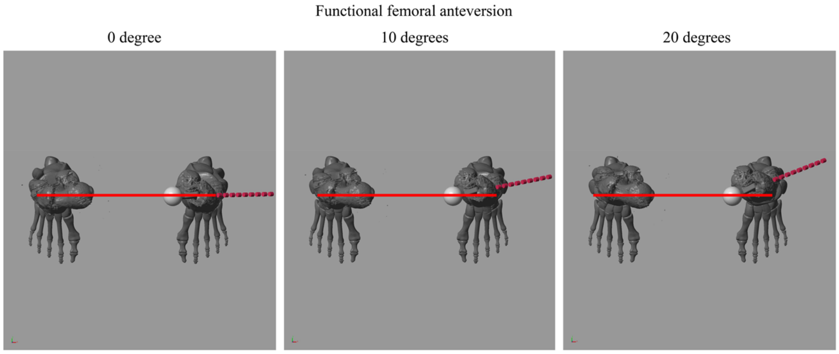

FIGURE 5 Functional femoral neck anteversion was measured relative to the vertical plane in standing [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Range of pelvic tilt and hip motions for the simulation

			Pelvic tilt				Hip motion	
Hip position	Body motion/ position	Degree of change in SPT	The sagittal tilt in standing and pivoting	The sagittal tilt in sitting, sit to stand, squatting and bending forward	Coronal	Axial	Flexion	Abduction
Extension	Standing	±45	0 (−45 to +45)	N/A	0	0	5 (±10)	0
	Pivoting	±35	−5 (−40 to +30)	N/A	0	50	0 (±10)	0
Flexion	Sitting	±45	N/A	−15 (−60 to +30)	0	0	65 (±10)	0
	Sit to stand	±35	N/A	10 (−25 to +45)	0	0	90 (±10)	0
	Squatting	±35	N/A	20 (−15 to +55)	0	0	100 (±10)	5
	Bend over	±35	N/A	50 (+15 to +85)	0	0	70 (±10)	5

Abbreviation: SPT, sagittal pelvic tilt.

provided 974,688 different scenrios for motions (pivoting, sit-to-stand, squating and bending forward) and 1,249,248 different scenarios for positions (standing, sitting). All the continuous variables were described using the mean, mean difference, *SD*, and 95% confidence interval. Normal distribution of the values was checked by Shapiro–Wilk normality test for each series of measurements. A univariate logistic regression model analyzed each of the predicting variables seperately which showed a significant effect of the predicting variables on the prosthetic impingement for them. A multiple logitic regression model was used to analyze the effect of the change in the acetabular and femoral anteversion angles as well as other variables on the motion pattern of the hip in different daily activities. The Hosmer-Lemeshow goodness-of-fit test was used to test our logistic regression model. Multicollinearity was tested using

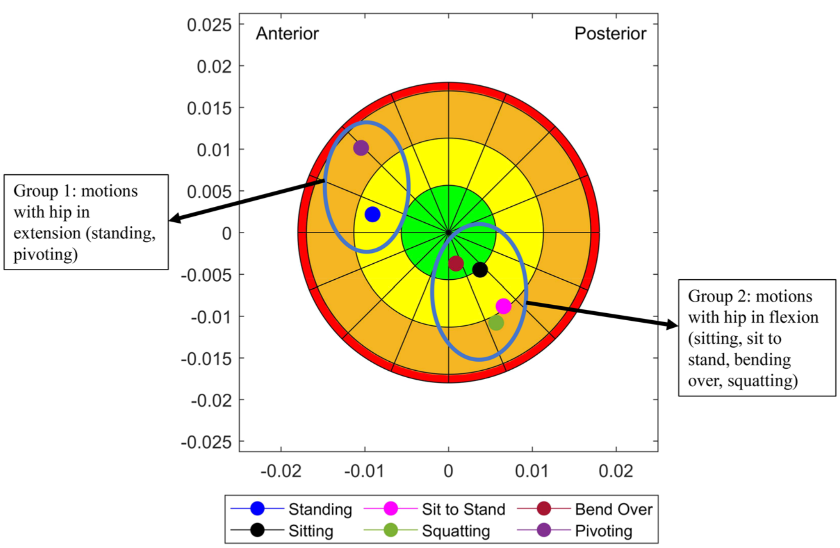

FIGURE 6 This figure shows the motion simulation map. Each colored dot on the map shows the closest distance of the PA to the edge of the liner for each of the tested motions. For example, the colored dot which represents sit-to-stand, represents the closest position of PA to the edge of the liner during this motion when the pelvis is at this maximum anterior tilt, right before the patient gets up from the sitting position. PA, polar axis

TABLE 2 Results of logistic regression for pivoting (red line-true impingement)

	Logistic regression—pivoting				Number of observations = 974,688 LR $\chi^2(9)$ = 1120053.26 Prob $>\chi^2$ = 0.0000 Pseudo R^2 = 0.9285	
	Odds ratio	Coefficient	Standard error	p Value	95% Confidence Interval	
Change in SPT angle	2.769	−1.018	0.0049	<0.0001	−1.028	−1.009
Head diameter effect as compared to head with 28 mm diameter						
32 mm	0.08	−2.522	0.0273	<0.0001	−2.575	−2.469
36 mm	0.01	−4.539	0.0329	<0.0001	−4.604	−4.475
40 mm	0.002	−6.157	0.0385	<0.0001	−6.233	−6.0819
Femoral stem neck angle effect as compared to stem with 127° neck angle						
Stem with 132° neck angle	0.014	−4.224	0.0294	<0.0001	−4.282	−4.167
Stem with 135° neck angle	0.001	−6.792	0.039	<0.0001	−6.869	−6.716
Cup abduction angle	1.73	0.548	0.002	<0.0001	0.543	0.554
Cup anteversion angle	3.59	1.278	0.006	<0.0001	1.266	1.291
Femoral anteversion angle	2.94	1.079	0.006	<0.0001	1.069	1.091

Abbreviations: LR, likelihood ratio; SPT, sagittal pelvic tilt.

collinearity test in Stata. There was no multicollinearity (individual vif for variables = 1; average model vif = 1). Reciever operating characteristic (ROC) curve was used to determine the SPT change that could result in prosthetic impingement for each prosthetic femoral head diameter and stem neck-shaft angle seperately. The significance level was set at less than 0.05. The data was analyzed with Stata 16.0 MP (StataCorp LP). Simulation software accumulated the data from simulation in a file with .csv format which was imported to Stata for our analysis.

3 | RESULTS

The results of the regression model for true impingement are presented in Tables 2-4. As shown in the table, stems with lower neck-shaft angles increase the chance of posterior impingement and anterior dislocation in pivoting motion (132° neck-shaft angle coefficient: −4.2 compared to 127° neck-shaft angle; 135° neck-shaft angle coefficient: −6.7 compared to 127° neck-shaft angle) ($p < .0001$). Stems with lower neck-shaft angles are more protective against posterior

TABLE 3 Results of logistic regression for sit-to-stand (red line-true impingement)

	Logistic regression—sit-to-stand				Number of observations = 974,688 LR $\chi^2(9)$ = 43900.32 Prob $>\chi 2$ = 0.0000 Pseudo R^2 = 0.966	
	Odds ratio	Coefficient	Standard error	p Value	95% Confidence interval	
Change in SPT angle	21.6	3.073	0.112	<0.0001	2.853	3.293
Head diameter effect as compared to head with 28 mm diameter						
32 mm	4.84	−12.239	0.471	<0.0001	−13.161	−11.316
36 mm	3.42	−21.797	0.812	<0.0001	−23.389	−20.205
40 mm	9.84	−29.949	1.111	<0.0001	−32.126	−27.774
Femoral stem neck angle effect as compared to stem with 127° neck angle						
Stem with 132° neck angle	4.36	29.105	1.165	<0.0001	26.82	31.389
Stem with 135° neck angle	1.22	46.255	1.743	<0.0001	42.839	49.67
Cup abduction angle	0.009	−4.632	0.169	<0.0001	−4.964	−4.301
Cup anteversion angle	0.046	−3.075	0.112	<0.0001	−3.295	−2.855
Femoral anteversion angle	0.131	−2.031	0.075	<0.0001	−2.179	−1.884

Abbreviations: LR, likelihood ratio; SPT, sagittal pelvic tilt.

TABLE 4 Results of logistic regression for squatting (red line-true impingement)

	Logistic regression—squatting				Number of observations = 974,688 LR $\chi^2(9)$ = 278557.36 Prob > χ^2 = 0.0000 Pseudo R^2 = 0.949	
	Odds ratio	Coefficient	Standard error	*p* Value	95% Confidence interval	
Change in SPT angle	4.543	1.513	0.019	<0.0001	1.479	1.549
Head diameter effect as compared to head with 28 mm diameter						
32 mm	0.001	−8.165	0.108	<0.0001	−8.378	−7.952
36 mm	3.16	−14.966	0.183	<0.0001	−15.326	−14.605
40 mm	1.3	−20.463	0.246	<0.0001	−20.948	−19.979
Femoral stem neck angle effect as compared to stem with 127° neck angle						
Stem with 132° neck angle	1.16	18.566	0.228	<0.0001	18.119	19.014
Stem with 135° neck angle	4.94	29.229	0.347	<0.0001	28.548	29.91
Cup abduction angle	0.038	−3.261	0.039	<0.0001	−3.337	−3.186
Cup anteversion angle	0.268	−1.314	0.016	<0.0001	−1.345	−1.283
Femoral anteversion angle	0.392	−0.935	0.012	<0.0001	−0.959	−0.912

Abbreviations: LR, likelihood ratio; SPT, sagittal pelvic tilt.

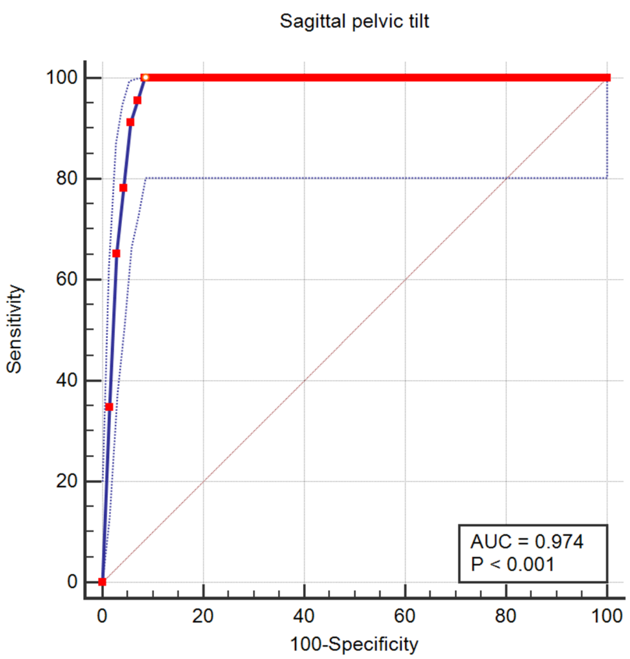

FIGURE 7 This figure shows the sample ROC curve for sit-to-stand motion using a 28-mm prosthetic head and a stem with 127° neck-shaft angle. AUC, area under the ROC curve; ROC, rreceiver operating characteristic [Color figure can be viewed at wileyonlinelibrary.com]

dislocation in sit-to-stand and squatting (132° neck-shaft angle coefficient: 29.1 compared to 127° neck-shaft angle; 135° neck-shaft angle coefficient: 46.2 compared to 127° neck-shaft angle) (p < .0001).

The cutoff points from the ROC curve (Figure 7) is presented in Table 5. Despite evaluating range of motion extremes of anterior and posterior pelvic retroversion, no prosthetic impingement (neither true prosthetic impingement represented by red line or conservative measurements represented by blue line) occurred in standing and bending forward to pick up an object. The PA stays close to the center while the patient is bending forward to pick up an object (Figure 6). Prosthetic impingement in the sitting position could only occur if the pelvis was significantly anteverted in stems with 135° neck-shaft angle with smaller diameter heads. Anterior pelvic tilt in the sitting position is extremely rare as patients usually have posterior pelvic tilt in sitting.

The risk of prosthetic impingement in standing with pelvic retroversion is much higher with a 28 mm head on a stem with a 127° neck-shaft angle. Prosthetic Impingement while pivoting would occur if there was more pelvis retroversion than 3° (red line-true prosthetic impingement) or even just 1° (Blue line-conservative estimate). These numbers are 11° and 6° when a 40 mm prosthetic femoral head is used with a stem with 135° neck-shaft angle.

A second example is sit-to-stand and squatting motions, where no prosthetic impingement occurred when either a 36 and 40 mm heads were used with a stem with a 127°neck-shaft angle (Table 3).

4 | DISCUSSION

In this study, we determined the amount of change in SPT (caused by spinal pathology or surgical spinal fusion) after THA that could result in prosthetic impingement. We used two models, one with true prosthetic impingement and one with a conservative measurement (blue line). Our results showed that patients with spinal pathologies and fusion are more prone to anterior dislocation as opposed to posterior dislocation shown by the result of the ROC curve analysis. The risk of prosthetic impingement caused by SPT change due to pelvic retroversion while pivoting (threshold in ROC curve as low as 1–3°) on a hip is much less than the risk of prosthetic impingement caused by increased pelvic

TABLE 5 Results of the ROC (receiver operating characteristic) curve

		Head sized	28 mm			32 mm			36 mm			40 mm		
		Neck-shaft angle	127°	132°	135°	127°	132°	135°	127°	132°	135°	127°	132°	135°
Standing	True impingement	Cutoff point	Dislocation due to prosthetic impingement does not occur even with conservative approach											
		AUC												
	Conservative	Cutoff point												
		AUC												
Pivoting	True impingement	Cutoff point	−3	−6	−8	−4	−7	−9	−5	−9	−10	−6	−9	−11
		AUC	0.948	0.948	0.946	0.945	0.943	0.941	0.942	0.939	0.937	0.939	0.936	0.934
	Conservative	Cutoff point	−1	−4	−6	−1	−4	−6	−1	−4	−6	−1	−4	−6
		AUC	0.953	0.952	0.951	0.953	0.952	0.951	0.953	0.952	0.951	0.953	0.952	0.951
Sitting	True impingement	Cutoff point	None	None	43	None	None	45	None	None	None	None	None	None
		AUC			0.983			0.989						
	Conservative	Cutoff point	None	43	41	None	43	41	None	42	41	None	43	41
		AUC		0.983	0.974		0.983	0.974		0.983	0.974		0.983	0.974
Sit-to-stand	True impingement	Cutoff point	32	28	25	35	30	27	None	31	28	None	33	30
		AUC	0.974	0.952	0.94	0.993	0.96	0.948		0.969	0.954		0.977	0.96
	Conservative	Cutoff point	29	25	24	29	26	24	29	26	24	29	26	24
		AUC	0.956	0.942	0.936	0.956	0.942	0.936	0.956	0.942	0.936	0.956	0.942	0.936
Squatting	True impingement	Cutoff point	26	21	19	28	24	21	30	25	22	31	26	24
		AUC	0.913	0.908	0.951	0.945	0.92	0.911	0.965	0.929	0.915	0.973	0.937	0.929
	Conservative	Cutoff point	22	18	16	22	18	16	22	18	16	22	18	16
		AUC	0.917	0.909	0.912	0.917	0.909	0.912	0.917	0.909	0.912	0.917	0.909	0.912
Bending forward	True impingement	Cutoff point	Dislocation due to prosthetic impingement does not occur even with conservative approach											
		AUC												
	Conservative	Cutoff point												
		AUC												

Abbreviation: AUC, area under the ROC curve.

anteversion during sit-to-stand, squatting or bending forward (threshold in ROC curve as low as 16–18°). This probability is influenced by stems with different neck-shaft angles or a larger diameter prosthetic head. Stems with a lower neck-shaft angle lower the risk of prosthetic impingement in sit-to-stand, squatting or bending forward but increase the risk of prosthetic impingement while pivoting. Larger femoral head sizes protected against prosthetic impingement at all hip or pelvis positions. Our data confirms previous observations regarding late THA dislocation.

This study has limitations. This study focused only on prosthetic impingement. The zone between the red line (true prosthetic impingement) and blue line (conservative measurement) simulated an area in where the risk of bone on bone impingement would be higher. It is impossible to conduct a study similar to this with a very large sample size as bony impingement and anatomy are patient specific. Our model assumes that the patient will not actively rotate the lower extremity either internally or externally more than 5–10° from its original relaxed position (other than pivoting). This is a common assumption in all the computer simulations as it is not possible to predict patients' motion patterns during all activities. All the computer simulations consider a range for pelvic tilt as well as lower extremity motions based on the data published in the literature. We used one pelvis and lower extremity CT scan from a male patient. The anatomical shape and size of the pelvis is individualized and is affected by gender. But the anatomical and functional orientations of the acetabular implant are always measured relative to the anterior pelvic plane and is not affected by size of the pelvic or femoral bone. Similarly, the effect of the anterior and posterior pelvic tilt on the functional cup orientation is independent of the size or shape of the pelvis or gender of the patient, as all the measurements are based on the angle between the anterior pelvic plane and horizontal plane. For example, 10° of anterior pelvic tilt is similar for men and women with pelvic structures of different shapes and sizes. We acknowledge that bony coverage and anatomy may influence the surgeons' decisions regarding the size of the implants or the offset to prevent bony impingement; however, these considerations do not affect the prosthetic impingement.

As our knowledge regarding the hip-spine relation grows, more questions arise. As clinicians, we need to know how much change in the hip-spine biomechanical relation can be tolerated in THA patients with spinal pathologies or spinal fusion. Researchers have previously shown the importance of hip-spine relation in THA dislocation risk[1,4,7-9,11,14,15,20,25] and preoperative planning using computer simulation is investigated to optimize implant position and reduce the risk of postoperative dislocation.[26-29] Many patients develop spinal pathologies or undergo spinal fusion before or after THA and both arthroplasty and spine surgeons are consulted about the risk of THA dislocation associated with this spinal pathology and surgery. Spinal pathologies and fusion can potentially increase the risk of THA dislocation.[1,4,7-9,11,14,15,20,25] The ultimate effect of any phenomenon in the spine whether it is a fusion surgery, stiffness or a pathology will be on the magnitude of the sagittal pelvic tilt during daily activities. In some cases, this will be more pelvic retroversion in standing position and in other cases, it might change the anterior pelvic tilt in activities, such as sitting or squatting. However, the rate of THA dislocation is rather low in arthroplasty registries.[30-34] This means that most patients do not sustain THA dislocation despite having different hip-spine biomechanics. This shows that some level of tolerance exists to prevent THA dislocation which might be due to the use of larger femoral head sizes or the use of adjacent anatomical structures to compensate for the lost range of motion in the spine. Knowing the level of this tolerance can help hip and spine surgeons with perioperative planning and their discussion regarding the risk of THA dislocation with patients. Computer simulation can help with this task. The hip joint is a hemisphere within a hemisphere and its motion as well as orientation of the implants relative to each other and can be accurately predicted during any activities as well the risk of prosthetic impingement. Non-prosthetic impingement, including bone on bone and bone, soft tissue and bone on prosthesis impingements, depend on the size and shape of the pelvic anatomy and proximal femur and are less predictable.

In this study, the cutoff points from the ROC curve clearly showed less tolerance for increased posterior pelvic tilt in standing and pivoting, as even a small change in pelvic posterior tilt can potentially result in posterior prosthetic impingement and anterior dislocation especially if a 28 mm head is used. Increased posterior pelvic tilt occurs in flat back deformity (most spondylolisthesis, failed lumbar spine fusion or degenerative lumbar spine disease), or in patients with low pelvic incidence. Our model showed more tolerance for increased anterior pelvic tilt in sitting, sit-to-stand, squatting and bending forward. Dislocation due to anterior prosthetic impingement did not occur in sitting position (not sit-to-stand) unless the pelvis was anteriorly tilted around 30°. The pelvis is usually tilted posteriorly or is neutral in the sitting position (not while bending forward to get out of chair) and 30° of anterior tilt is extremely rare in these cases. In bending forward motion, prosthetic impingement did not occur in neither of the two models (true prosthetic impingement and conservative assessment) even when the pelvis was tilted forward 85°. This is consistent with possible anterior bone-on-bone impingement or lack of offset or length restoration as the cause of dislocation in this position. Increased anterior pelvic tilt occurs with lumbar hyperlordosis (high pelvic incidence), some patients with isthmic spondylolisthesis or surgical fusion. Overall, the risk of anterior prosthetic impingement is low with an increase in anterior pelvic tilt up to 21°. Most patients will overall tolerate the SPT changes caused by spinal pathologies when larger femoral heads (36 and 40 mm) are used during surgery. Our simulation shows the significant effect that femoral neck-shaft angle has on prosthetic impingement and the tolerance for SPT changes similar to the previously published paper by Shoji et al.[35]

5 | CONCLUSION

Our results show an overall low prosthetic impingement risk with SPT changes when a larger diameter prosthetic head is used during surgery as well as when offset and length are restored to prevent bony impingement.

AUTHOR CONTRIBUTIONS

Aidin Eslam Pour planned and designed the study, performed data acquisition, analysis and interpretation, and drafted the original article. Ran Schwarzkopf contributed to the study design, data analysis and interpretation and drafting the original article as well as critically revising it. Manan P. Anjaria and Kunj Paresh kumar Patel made the Matlab model, performed data acquisition, data interpretation, and took part in drafting the article. Lawrence D. Dorr and Jean Yves Lazennec contributed to the study design, data interpretation, and critically revising it.

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