Femoral stem neck geometry determines hip range of motion shape

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HIP

Femoral stem neck geometry determines hip range of motion shape

A COMPUTER SIMULATION STUDY

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Aims

In computer simulations, the shape of the range of motion (ROM) of a stem with a cylindrical neck design will be a perfect cone. However, many modern stems have rectangular/oval-shaped necks. We hypothesized that the rectangular/oval stem neck will affect the shape of the ROM and the prosthetic impingement.

Methods

Total hip arthroplasty (THA) motion while standing and sitting was simulated using a MATLAB model (one stem with a cylindrical neck and one stem with a rectangular neck). The primary predictor was the geometry of the neck (cylindrical vs rectangular) and the main outcome was the shape of ROM based on the prosthetic impingement between the neck and the liner. The secondary outcome was the difference in the ROM provided by each neck geometry and the effect of the pelvic tilt on this ROM. Multiple regression was used to analyze the data.

Results

The stem with a rectangular neck has increased internal and external rotation with a quatrefoil cross-section compared to a cone in a cylindrical neck. Modification of the cup orientation and pelvic tilt affected the direction of projection of the cone or quatrefoil shape. The mean increase in internal rotation with a rectangular neck was 3.4° (0° to 7.9°; $p < 0.001$); for external rotation, it was 2.8° (0.5° to 7.8°; $p < 0.001$).

Conclusion

Our study shows the importance of attention to femoral implant design for the assessment of prosthetic impingement. Any universal mathematical model or computer simulation that ignores each stem's unique neck geometry will provide inaccurate predictions of prosthetic impingement.

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Keywords: Stem neck geometry, Hip arthroplasty, Computer simulation

Article focus

- Many researchers have investigated the prosthetic impingement between the neck of the femoral stem and edge of the polyethylene liner, and provided universal mathematical or computer modelling to predict this impingement. In most of these models, the stem neck is always considered round.
- This computer simulation study focuses on the difference in the shape of range of motion (ROM) between a stem with a round neck and a stem with a rectangular/oval-shaped neck. It investigates the shape of ROM as well as the effect of neck geometry on the internal and external rotation of the hip in different daily activities.

Key messages

- The shape of the ROM of a hip arthroplasty stem with a cylindrical neck design will be a cone. Many modern stems have rectangular/oval-shaped

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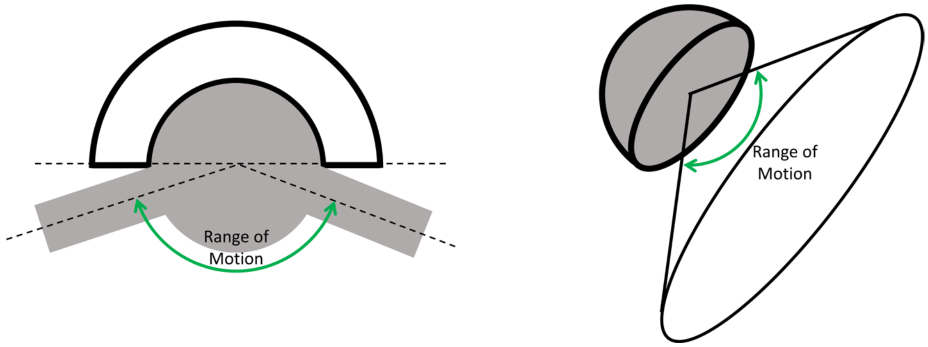

Fig. 1

The motion of a stem with a cylindrical neck design that produces a perfect cone.

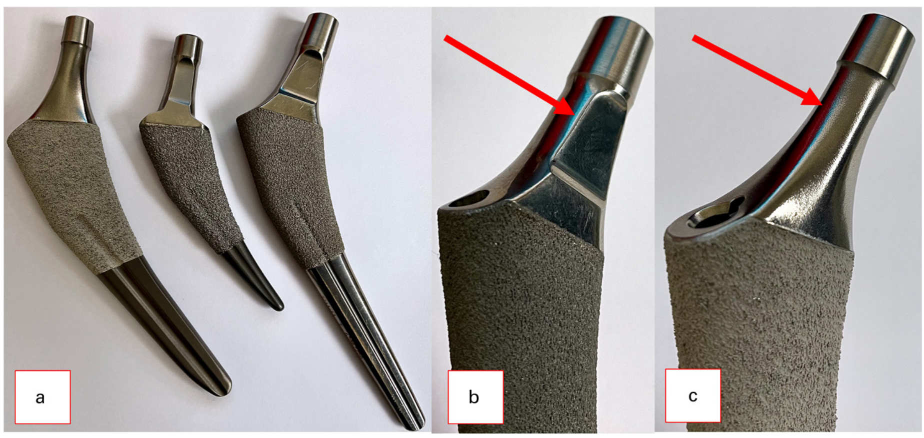

Fig. 2

a) Different femoral stems with different neck designs. b) Trapezoidal neck design with anterior and posterior cut-offs to increase the range of motion. c) Cylindrical neck design.

necks and the shape of the ROM will not be a perfect cone.

- The shape of ROM of each stem has to be considered for computer-assisted preoperative planning to prevent prosthetic impingement and dislocation. Rectangular/oval-shaped necks will provide more external and internal rotation prior to impingement.
- Universal mathematical formulae or computer simulations that ignore the specific neck geometry for each stem are inaccurate.

Strengths and limitations

- This study is performed using a verified MATLAB simulation model, which could investigate the ROM with different prosthetic head diameters as well as different activities in standing and sitting positions.
- This study does not include bone-on-bone impingement as the goal is to assess prosthetic impingement only. Bone-on-bone impingement would not affect the maximum prosthetic ROM simulation between two different neck geometries.

Introduction

The hip prosthetic range of motion (ROM) is defined as the maximum ROM of the prosthetic femoral head inside the acetabular liner before impingement between the edge of the liner and the prosthetic femoral neck. Researchers have investigated prosthetic ROM to understand prosthetic impingement and total hip arthroplasty (THA) dislocation.[1-13] In most of these studies, the motions of a cylindrical femoral neck and prosthetic head ball are mated against a hemispheric acetabular liner. This combination will produce a perfect cone with its apex located at the centre of rotation (Figure 1). The investigators of these papers have mainly focused on the effect of the diameter of the prosthetic head on prosthetic ROM, or the effect of the offset of the femoral stem on ROM prior to bony impingement. Some investigators have introduced mathematical models and formulae to calculate the ROM based on this perfect cone.[3-6,14] Table I shows the commonly used femoral stems for primary and revision THA and their different neck geometrical designs. As this table shows, not all modern stems have a cylindrical neck design. Many

Table I. This table shows some of the commonly used stems for primary and revision total hip arthroplasty.

Manufacturer	Femoral stems with rectangular/oval neck design	Femoral stems with cylindrical neck design
	Primary total hip arthroplasty stems	
Zimmer-Biomet	ML taper, Taperloc, Taperloc Microplasty, Wagner cone, Avenir complete	Avenir legacy
Stryker		Accolade, Accolade 2, Exeter, Anato, Securefit
Smith & Nephew	Anthology, CPCS, Echelon	SL plus, Synergy
Depuy-Johnson & Johnson	Corail, Actis, Summit, Tri-lock	
	Revision total hip arthroplasty stems	
Zimmer-Biomet	Arcos	Wagner, ZMR
Stryker		Restoration modular
Smith & Nephew		Echelon
Depuy-Johnson & Johnson	Corail, Reclaim	

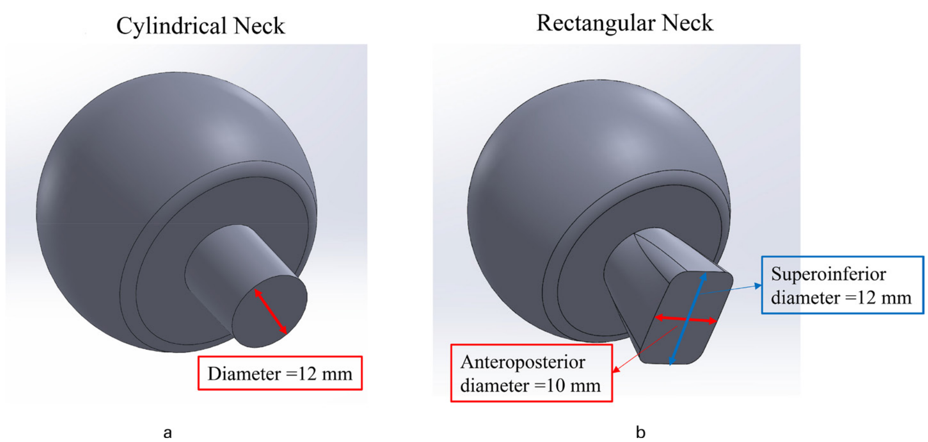

Fig. 3

Femoral stem necks with a) cylindrical and b) rectangular designs.

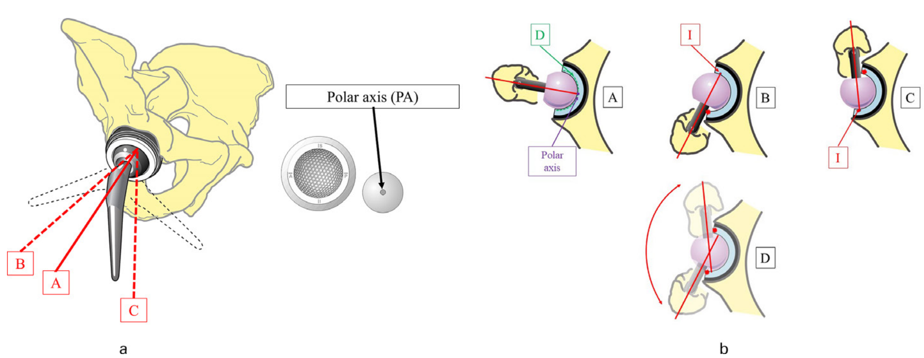

Fig. 4

a) Design of the model. A line that passes through the centre of the neck is used to study the motions of the prosthetic head relative to polyethylene. The hip is in a neutral position (A), extension (B), and flexion (C). b) The motions of the head inside the polyethylene liner. A: The head and liner are parallel, and the polar axis is at the centre of the liner. B: Maximum external rotation to impingement (I). C: Maximum internal rotation to impingement (I). D: Maximum prosthetic range of motion (oscillation angle).

modern stems have trapezoidal/oval neck designs with smaller anteroposterior (AP) diameter compared to superoinferior diameter. These stems improve the head-neck ratio of the prosthetic femoral neck against impingement during internal and external rotation (Figure 2). The shape of the hip ROM with this implant design will not be a perfect cone, which changes the results of the computer simulations performed for the optimal orientation of the implants, as it can substantially affect the internal and external rotation of the hip prior to prosthetic impingement.

In this study, we investigated the shape of the ROM for femoral stems with a rectangular/oval neck design, specifically the difference in ROM before impingement in internal and external rotation, by using a rectangular/oval neck design compared to a cylindrical design.

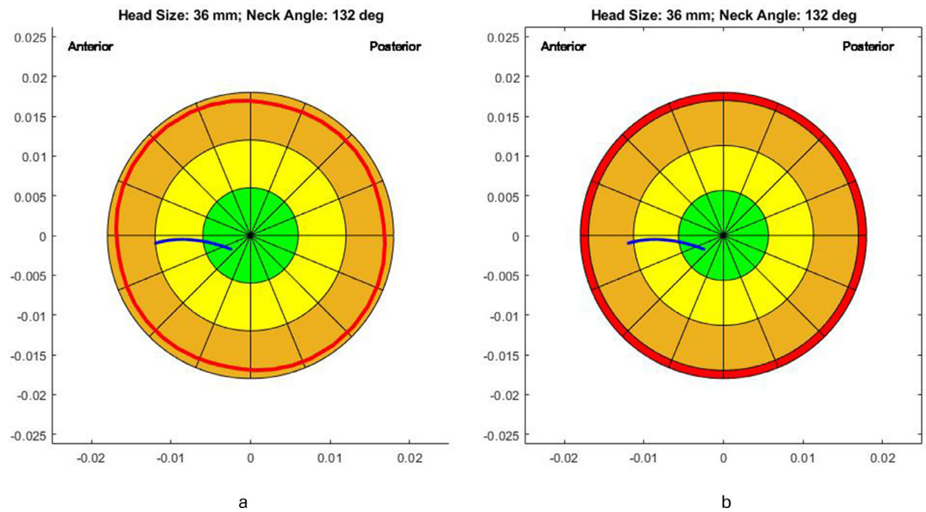

Fig. 5

The motions of the prosthetic head inside a 36 mm liner. a) The red line shows prosthetic impingement when a stem with a rectangular neck is used. b) The red line shows prosthetic impingement when a stem with a cylindrical neck is used.

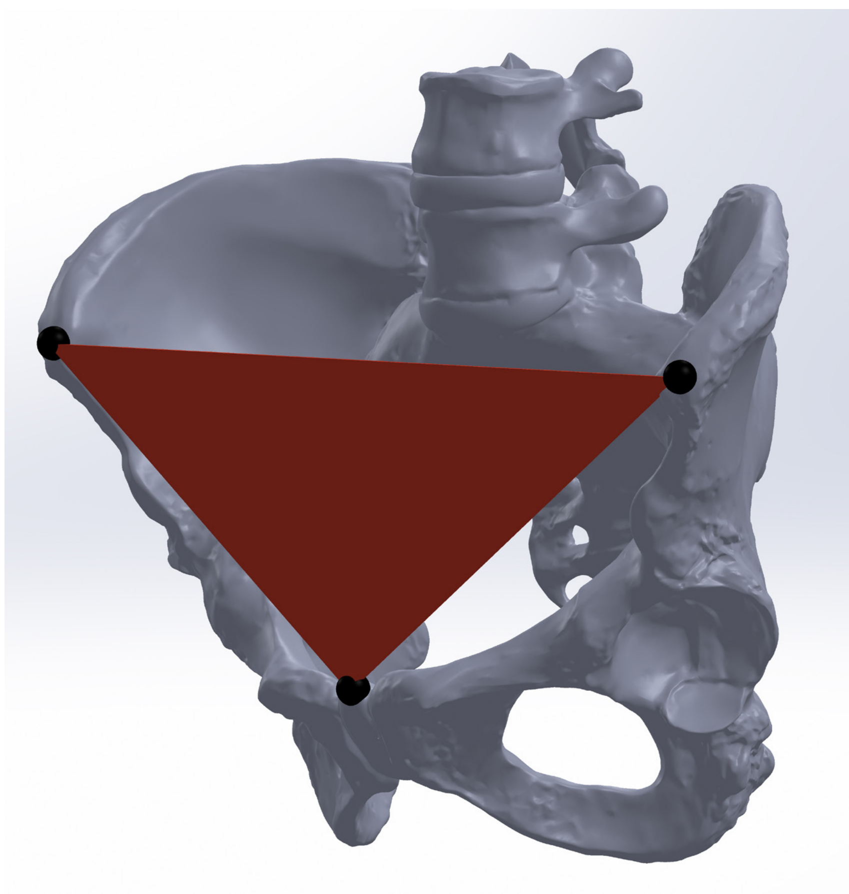

Fig. 6

The anterior pelvic plane is a plane that connects the two anterior superior iliac spines and symphysis pubis.

We hypothesized that the shape of the ROM for stems with the rectangular/oval neck design is not a perfect cone due to the non-circular neck cross-section, and this design improves impingement-free internal and external rotation compared to stems with a cylindrical neck. We also hypothesized that sagittal pelvic tilt and

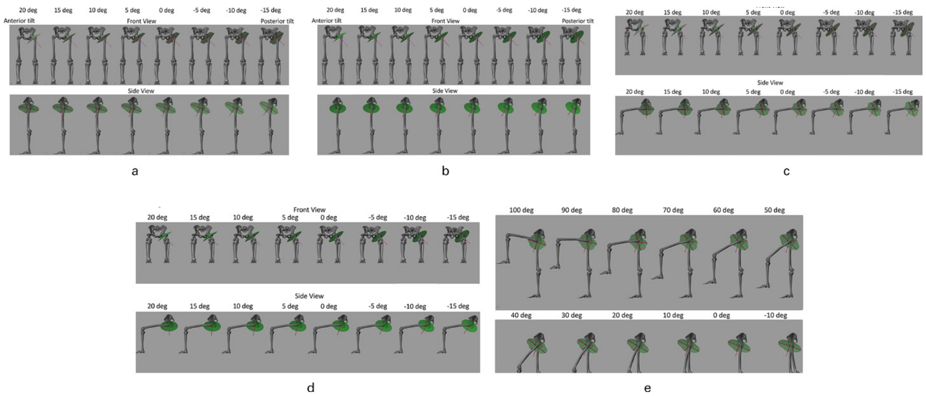

Fig. 7

a) and b) Front and side views of the pelvis and hip in the standing position with a rectangular neck (a) quatrefoil-shaped range of motion (ROM)) and a cylindrical neck (b) cone-shaped ROM). The direction of the spatial projection of the ROM changes with the pelvic tilt and anatomical cup orientation. c) and d) Front and side views of the pelvis and hip in the sitting position with a rectangular neck (c) quatrefoil-shaped ROM) and a cylindrical neck (d) cone-shaped ROM). e) Front and side views of the pelvis and hip in the standing position with a rectangular neck. The quatrefoil-shaped ROM rotates clockwise and anticlockwise with hip flexion and extension.

hip flexion affect the spatial orientation of the projected ROM during different daily activities.

Methods

Study setting. Our study did not include any human subjects, and the study was exempt from review by the institutional review board. This project was conducted under a National Institutes of Health (NIH) clinical investigator (K08) award.

Computer model development. We imported a deidentified pelvis and lower body CT scan of a male patient without a previous lower limb arthroplasty or fracture surgery into our computer simulation model (MATLAB 2020a; Simscape/Multibody; MathWorks, USA). Computer-aided design (CAD) models for the THA implant components (a full hemispherical acetabular component without an elevated rim (best fit diameter: 56 mm), a polyethylene liner without an elevated outer rim or an inner chamfered rim and femoral head (diameter: 28 mm, 32 mm, 36 mm, 40 mm), and a triple taper cementless stem with three different neck shaft angles (127°, 132°, 135°)) were designed in SolidWorks (Dassault Systèmes SolidWorks Corporation, USA). The diameter of the cylindrical neck was 12 mm. The neck dimension of the stem with a trapezoidal neck was 10 mm × 12 mm (Figure 3). These sizes were chosen based on the average dimensions of the prosthetic neck immediately below the trunnion area, measured by caliper for a few uncemented stems (Zimmer-Biomet Taperloc Microplasty, Zimmer-Biomet, USA; Zimmer-Biomet M-L Taper; Stryker Accolade-2, Stryker, USA). For the bearing surface diameter, we chose 28 mm, 32 mm, 36 mm, and 40 mm prosthetic heads and liners. These CAD models were imported into the MATLAB model to construct a prosthetic THA. The hip joint could move in all directions (flexion/extension, abduction/adduction, and internal/external rotation), and the knee joint could move by flexion and extension.

To simplify the understanding of the model, readers can imagine a line passing through the centre of the prosthetic femoral neck and the centre of the prosthetic femoral head (Figures 4a and 4b). The point on the femoral head where this line exits is the polar axis (PA). Motion of the femoral head inside the liner is captured for each stem. Figures 5a and 5b show the area inside a 36 mm liner while walking with a stem with a trapezoidal neck (Figure 5a) and a stem with a cylindrical neck (Figure 5b). The red line in each figure represents when prosthetic impingement between the femoral neck and polyethylene liner occurs. By following the motions of the line passing through the femoral stem neck axis (Figures 4a and 4b), we can draw the shape of the range of motion for each stem. We developed an independent model in SolidWorks to verify the MATLAB model in silico.

Implant orientation measurement. Anatomical acetabular implant anteversion was calculated relative to the anterior pelvic plane (APP) (Figure 6). Anatomical acetabular implant abduction was calculated relative to the horizontal plane that connected the hip centre of rotation and was vertical to the APP. Anatomical femoral anteversion was calculated relative to the posterior femoral condylar plane. Functional femoral anteversion was calculated relative to the vertical plane.

Pelvic tilt and lower limb parameters during activities. We considered coronal and axial tilt as zero 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 was considered positive. Hip motion and sagittal pelvic tilt were simulated in standing and sitting positions. The magnitude of hip external rotation was measured at different degrees of hip flexion (-10°, 0°, 10°, 45°, 90°). The magnitude of hip internal rotation was measured at 90° and 110° of hip flexion.

Table II. This table shows the difference in range of motion (flexion) between the cone-shaped range of motion (cylindrical neck) and quatrefoil-shaped range of motion (trapezoidal neck). In this table, the acetabular abduction angle is 40° and anteversion is 20°, while the femoral stem anteversion is 20°.

Head size, mm	NSA, °	ER (-10°)			ER (0°)			ER (10°)			ER (45°)			ER (90°)			IR (90°)			IR (110°)		
		Cone	Q	Diff	Cone	Q	Diff	Cone	Q	Diff	Cone	Q	Diff	Cone	Q	Diff	Cone	Q	Diff	Cone	Q	Diff
28	127	31.1	31.6	0.5	43.1	44.7	1.6	56.5	57.8	1.3	96.1	98.2	2.0	101.0	103.6	2.6	47.4	51.6	4.2	33.4	34.2	0.8
32	127	32.9	34.9	2.0	45.2	46.9	1.7	58.7	61.1	2.4	98.3	100.9	2.6	102.5	105.0	2.5	49.0	54.5	5.5	35.0	36.4	1.4
36	127	34.7	36.0	1.3	47.1	49.1	2.0	60.8	63.3	2.5	100.2	102.3	2.0	104.0	106.4	2.3	50.5	56.7	6.2	36.4	37.8	1.4
40	127	36.3	38.2	1.9	48.8	51.3	2.5	62.7	65.5	2.7	102.1	105.0	2.9	105.4	107.7	2.3	51.8	58.2	6.4	37.7	39.3	1.5
28	132	36.2	37.1	0.9	49.5	51.3	1.7	63.9	65.5	1.5	103.0	105.0	2.0	102.5	105.0	2.5	47.1	50.9	3.8	30.5	30.5	0.0
32	132	38.3	39.3	1.0	51.7	53.5	1.7	66.4	68.7	2.3	105.4	107.7	2.3	104.2	107.7	3.5	48.8	53.8	5.0	32.3	32.7	0.4
36	132	40.3	41.5	1.2	53.9	55.6	1.7	68.7	72.0	3.3	107.6	110.5	2.9	105.8	109.1	3.3	50.4	57.5	7.1	33.9	34.9	1.0
40	132	41.9	43.6	1.7	55.7	58.9	3.2	70.8	73.1	2.3	109.5	111.8	2.3	107.2	109.1	1.9	51.8	59.6	7.9	35.3	36.4	1.0
28	135	39.6	40.4	0.8	53.7	54.5	0.9	68.9	70.9	2.0	107.6	109.1	1.5	103.5	105.0	1.5	46.8	50.2	3.4	28.4	28.4	-0.1
32	135	41.8	42.5	0.8	56.1	58.9	2.8	71.6	74.2	2.6	110.0	111.8	1.8	105.3	107.7	2.5	48.5	55.3	6.8	30.3	30.5	0.2
36	135	43.9	45.8	2.0	58.4	61.1	2.7	74.1	76.4	2.3	112.4	115.9	3.5	106.9	110.5	3.5	50.2	57.5	7.3	32.1	32.7	0.7
40	135	45.6	48.0	2.4	60.3	63.3	2.9	76.4	79.6	3.3	114.5	118.6	4.1	108.4	110.5	2.0	51.6	58.9	7.3	33.6	34.2	0.6

ER, external rotation; IR, internal rotation; NSA, neck shaft angle; Q, quatrefoil.

Table III. The results of multiple regression analysis with external rotation as the outcome variable. Number of observations = 360.

Variable	Coefficient	SE	t	p > t	95% CI
Neck design (compared to cylindrical neck)					
Trapezoidal	2.165	0.176	12.24	< 0.001	1.818 to 2.514
Stem neck-shaft angle (compared to stem with 127° neck angle)					
132°	5.775	0.216	26.65	< 0.001	5.349 to 6.202
135°	9.644	0.216	44.5	< 0.001	9.218 to 10.071
Head diameter (compared to 28 mm head)					
32 mm	2.481	0.25	9.92	< 0.001	1.989 to 2.974
36 mm	4.704	0.25	18.8	< 0.001	4.212 to 5.196
40 mm	6.525	0.25	26.08	< 0.001	6.033 to 7.018
Hip flexion (compared to -10° of hip extension)					
0°	13.77	0.279	49.22	< 0.001	13.22 to 14.321
10°	28.559	0.279	102.09	< 0.001	28.009 to 29.109
45°	67.505	0.279	241.3	< 0.001	66.956 to 68.055
90°	66.832	0.279	238.89	< 0.001	66.281 to 67.382
Femoral stem anteversion (compared to 0° of anteversion)					
10° anteversion	-9.983	0.217	-46.07	< 0.001	-10.41 to -9.558
20° anteversion	-19.975	0.217	-92.18	< 0.001	-20.401 to -19.548

CI, confidence interval; SE, standard error.

Table IV. The results of multiple regression analysis with internal rotation as the outcome variable. Number of observations = 144.

Variable	Coefficient	SE	t	p > t	95% CI
Neck design (compared to cylindrical neck)					
Trapezoidal	3.328	0.302	11.01	< 0.001	2.73 to 3.926
Stem neck-shaft angle (compared to stem with 127° neck angle)					
132°	-1.52	0.37	-4.1	< 0.001	-2.251 to -0.787
135°	-2.646	0.37	-7.14	< 0.001	-3.378 to -1.913
Head diameter (compared to 28 mm head)					
32 mm	2.378	0.427	5.56	< 0.001	1.531 to 3.224
36 mm	4.289	0.427	10.03	< 0.001	3.443 to 5.135
40 mm	5.712	0.427	13.36	< 0.001	4.865 to 6.557
Hip flexion (compared to 90° of hip extension)					
110°	-18.786	0.302	-62.13	< 0.001	-19.384 to -18.189
Femoral stem anteversion (compared to 0° of anteversion)					
10° anteversion	9.978	0.37	26.94	< 0.001	9.245 to 10.71
20° anteversion	19.99	0.37	53.98	< 0.001	19.258 to 20.722

CI, confidence interval; SE, standard error.

Statistical analysis. Continuous variables were described using the mean, mean difference, standard deviation (SD), and 95% confidence interval (CI). Normal distribution of the values was checked by the Shapiro-Wilk normality test for each series of measurements. To analyze the effects of the neck design on the internal and external rotation, a multiple regression model was used to analyze the data. The primary predictor was the shape of the neck. The primary predictor was the geometry of the neck (cylindrical vs rectangular) and the main outcome was the shape of range of motion (ROM) based on the prosthetic impingement between the neck and the liner. The secondary outcome was the difference in the ROM provided by each neck geometry and the effect of pelvic tilt on this ROM. Other predictors in the model included anatomical cup abduction and anteversion, head diameter, stem neck-shaft angle, and the degree of hip flexion. The significance level was set at $p < 0.05$. The data were analyzed with Stata 16.0 MP (StataCorp, USA).

Results

Figures 7a and 7d show the shape of the prosthetic ROM in standing and sitting positions with different degrees of sagittal pelvic tilt. As seen in these figures, the shape of the prosthetic ROM is a quatrefoil similar to a four-leaf clover when a femoral stem with a rectangular neck is used (Figure 7), compared to a perfect cone created by a stem with a cylindrical neck (Figures 7b and 7d). Posterior pelvic tilt and an increase in anatomical cup anteversion shifted the direction of the ROM projection anteriorly (Figures 7a and 7b). However, anterior pelvic tilt and cup retroversion shift the projection posteriorly. With different degrees of hip flexion, the quatrefoil-shaped ROM rotates around its axis clockwise or counterclockwise depending on the operative side (Figure 7e). Posterior pelvic tilt has the same effect as hip extension, while anterior pelvic tilt has the same effect as hip flexion.

Table II shows the differences in internal and external rotations between stems with rectangular and cylindrical necks with different prosthetic head diameters. Using a larger-head diameter increases the head-neck ratio in the anterior and posterior aspects of the neck with a trapezoidal design, where the diameter of the neck is narrower, which is different from a stem with a cylindrical neck design. For example, when using a 36 mm head, the head-neck ratio in a stem with a cylindrical neck design is always 3 (36/12) compared with the head-neck ratio in a stem with a trapezoidal neck design (3 in superior and inferior aspects (36/12) vs 3.6 in anterior and posterior aspects (36/10)). This difference results in increased internal and external rotation of the hip in different motions, which produces the quatrefoil shape. The overall mean increase in internal rotation with a rectangular neck was 3.4° (0° to 7.9°; $p < 0.001$); with external rotation, it was 2.8° (0.5° to 7.8°; $p < 0.001$). Using a head with a larger diameter improves the internal and external rotation in either neck design, but its effect was more significant in trapezoidal neck design due to the change in the head-neck ratio. Tables III and IV show the results of the multiple regression. As shown in these two tables, the trapezoidal neck design increased the internal rotation (coefficient = 3.328, $p < 0.001$) and the external rotation (coefficient = 2.165, $p < 0.001$) compared to the cylindrical neck design when adjusting for the other variables in the model.

Discussion

We investigated prosthetic hip ROM at the articular level using a polar coordination system, which allows an accurate assessment of the effects of implant orientation and pelvic tilt. Our investigation shows a significant difference in the shape of the ROM between a femoral stem with a cylindrical neck design and a rectangular neck design. The spatial projection of the shape created by the ROM of each design depends on the anatomical acetabular implant orientation and the pelvic tilt. The flexion of the hip joint and pelvic tilt during different daily activities will determine the direction in which the projected shape rotates around its axis. The neck design affects the recommended range for the proposed safe zone for acetabular and femoral implants to provide an optimal ROM free of prosthetic impingement. The use of stems with a trapezoidal neck will widen the range for the safe zone for implant orientation.

Our study has limitations. We did not include bone-on-bone impingement in this model, as the purpose of the study was to examine the shape of prosthetic ROM based on prosthetic impingement. Bone-on-bone impingement is dependent on the surgeon restoring hip length and offsetting and removing the osteophytes, as well as each patient's bony anatomy. This finding would not affect the prosthetic ROM. Additionally, we did not simulate the pelvis and hip motions in squatting, bending forward, or pivoting, as it would not affect the shape of the ROM. Other motions mainly affect the spatial projection of the ROM and not its shape. Our study was limited to neutral coronal and axial tilt to facilitate the simulation, but coronal tilt and axial rotation of the pelvis can affect the spatial projection of the prosthetic ROM. Our CAD model for liners has a flat edge without a skirt or elevated rims. Elevated rim/skirt designs for liners will affect the results of any computer model, as shown in previous studies.[14–18]

To lower the dislocation rate, patients need to have an impingement-free ROM for different daily activities. Investigators have published their results of computer simulation and mathematical formulae for hip prosthetic ROM with optimal acetabular angles and a cylindrical femoral neck design. The maximum arc of motion of the prosthetic neck from inside the liner before prosthetic impingement occurs is defined as the oscillation angle.[6,14] If the oscillation angle can be maximized, the chance of prosthetic impingement and THA dislocation will decrease. Yoshimine et al[6] published their mathematical analysis using a flat surface cup and a stem with a cylindrical neck, and proposed a formula to calculate the oscillation angle for each patient to determine the best orientation for the acetabular implant. In this model, there are two cones: one represents abduction/adduction, and the second represents internal/external rotation. Another mathematical formula by Ellison[3] considered cylindrical, rectangular/oval, and free-form shapes for the prosthetic neck at the point of impingement. Ellison's formula might be more accurate than the method used by Yoshimine et al,[6] however neither of these methods considered 3D pelvic tilt or hip flexion and extension during different daily activities.

The effect of the shape on ROM has been investigated previously. Hariri et al[19] investigated the effect of the shape of the modular prosthetic neck on the ROM. They focused on the version of the neck of one stem with a modular neck design (anteverted, straight, retroverted) (Kinectiv; Zimmer-Biomet) and the length of the neck in a study performed with saw bones. In this study, this stem with a particular design was not compared to a stem with a cylindrical neck design. However, other authors have shown the effect of the prosthetic neck design on the ROM. Barack et al[20] studied the effect of stem neck design both using computer modelling and in clinical practice among patients who underwent revision THA. They included two stems: one with an anteverted, long cylindrical neck and a large taper; and the second with a straight neck with a trapezoidal design and a smaller taper. They showed a higher dislocation rate with a lower arc of motion in stems with a cylindrical design than in stems with a trapezoidal design. In a study similar to our paper, Higashi et al[21] investigated the effect of femoral neck design on hip ROM. In their study, the maximum oscillation angle increased by increasing the head diameter and changing the neck design, similar to our study findings. However, neither of these papers investigated the effect of pelvic tilt or different degrees of hip flexion on the ROM, or the shape of the ROM, as we did in our study.

Our findings confirm those of previously published studies regarding the important effects of prosthetic neck design and head size on the ROM. Those extra few degrees of internal and external rotation can be the difference between a stable hip and hip that sustains dislocation during daily activities. However, our findings also show the shape of this ROM and the effect of pelvic tilt on its spatial projection during different activities. One common assumption might be to orient the acetabular implant in a way that the projected cone covers the patient ROM to prevent prosthetic impingement. Such an assumption will be wrong, as our results show that the spatial projection of the ROM shape (even if it is considered a cone-shaped ROM) is affected significantly by pelvic tilt. Thus, a dedicated simulation will be required for each patient and each implant.

In conclusion, prosthetic ROM is related to the prosthetic femoral neck design as well as the 3D pelvic tilt and unique functional anatomy of the hip in each patient. No universal formula can be produced to accurately predict or optimize the prosthetic ROM. Not only are the results of computer simulations for the prevention of prosthetic impingement stem-specific, but they are also patient-specific. Using stems with a trapezoidal design can increase the ranges of internal and external rotation prior to impingement, especially if a larger femoral head diameter is used. Bony impingement will affect the shape of the ROM, but this effect is dependent on the surgeon, recreating offset and length, as well as medialization of the acetabular implant and not the prosthetic design.

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