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Original Article

In vivo kinematics, component alignment and hardware variables influence on the liner-to-neck clearance during chair-rising after total hip arthroplasty

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A B S T R A C T

Background: There is an interest in quantifying dynamic hip kinematics before and after total hip arthroplasty (THA) during chair-rising: one of daily life activities.
Methods: The study consisted of 21 patients who underwent unilateral total hip arthroplasty for symptomatic osteoarthritis. We obtained continuous radiographs using a flat-panel X-ray detector while the participants rose from chair. We assessed the pre and postoperative hip joint's movements using three-dimensional-to-two-dimensional model-to-image registration techniques. We also measured minimum liner-to-neck distances at maximum hip flexion and extension as anterior and posterior liner-to-neck distances, respectively. Multivariate analyses were applied to determine which factors were associated with liner-to-neck distances.
Results: The cup inclination, cup anteversion, and stem anteversion averaged 37.4°, 23.1°, and 30.1°, respectively. Significantly larger maximum hip flexion angle (72°) was found during chair-rising after THA compared to that before THA (63°, $P < 0.01$). The anterior pelvic tilt at the maximum hip flexion after THA (3° of anterior tilt) was significantly ($P < 0.05$) anterior compared to that before THA (1° of posterior tilt). The anterior and posterior liner-to-neck distances averaged 12.3 mm and 8.1 mm, respectively, with a significant difference ($P < 0.01$). No liner-to-neck contact was found in any hips. In multivariate analysis, the hip flexion angle, cup inclination, stem anteversion and head diameter were significantly associated with the anterior liner-to-neck distance ($P < 0.05$), the hip extension angle, cup anteversion, neck length and with or without elevated rim were significantly associated with the posterior liner-to-neck distance ($P < 0.05$, 0.01, 0.05, 0.01, respectively).
Conclusion: This study indicates that well-positioned THA provide increased range of hip flexion with sufficient anterior liner-to-neck clearance during chair-rising. Dynamic hip kinematics, component position, and hardware variables significantly influenced on the liner-to-neck clearance under weight-bearing conditions.

1. Introduction

Osteoarthritis (OA) of the hip joint is a frequent cause of pain and functional disability during activities of daily living [1]. Total hip arthroplasty (THA) effectively provides pain relief, improves function, and promotes good long-term outcomes for patients with symptomatic OA [2]. The clinical success of THA enables patients to participate in fundamental daily activities, including chair-rising. However, to our knowledge, it is currently unclear how the weight-bearing kinematics of hips with end-stage OA change after THA. In a previous study, Hara et al. [3] quantified kinematics of OA

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hips and revealed that these patients had limited ranges of hip flexion and tilted the pelvis posteriorly at the maximum flexion during chair-rising than healthy subjects. Pathological hip kinematics could persist even after THA, which might affect postoperative functional outcomes. Chair-rising is a fundamental, common activity of daily living all over the world. Majority of the patients could perform chair-rising before and after THA. Because properly positioned implants should not dislocate during chair-rising, we could evaluate the pre and postoperative hip joint's movements in a safety manner while still obtaining important information. Therefore, our primary goal was to compare pre- and postoperative hip kinematics for the same subjects implanted with THA.

A previous report has analyzed sit-to-stand task after THA with video motion capture system providing valuable data [4]. However, lower reliability and higher error were found in the measurements of the hip's transverse plane due to soft tissue artifact [5]. The evaluation of hip kinematics under weight-bearing conditions has been achieved using three-dimensional (3D)-to-two-dimensional (2D) model-to-image registration techniques, with substantial accuracy for clinically relevant measurement scenarios [3,6,7]. Previous 3D kinematic analysis [7] and retrieval study [8] showed that asymptomatic liner-to-neck contact might occur frequently during activities of daily living in patients after THA. Recently, Dorr et al. [9] suggested the importance of the individual patient's functional position during daily activities to obtain impingement free functional positioning and reduce the rate of dislocation. Understanding how to maximize impingement-free range of motion (ROM) during weight-bearing activities could lead to improve surgical technique and minimize dislocation risk. However, the effects of hip kinematics, component alignment and hardware variables on the minimum distance between the acetabular liner and stem neck: liner-to-neck clearance, have not yet been reported sufficiently *in vivo*.

The purposes of the present study were to analyze dynamic hip kinematics during chair-rising before and after THA using 3D-to-2D model-to-image registration techniques. Specifically, the following questions were addressed: (1) How do the *in vivo* kinematics of prosthetic hips changed from those of OA hips in the same subjects? (2) Do the 3D reconstructed prosthetic hips show sufficient liner-to-neck clearance with influencing factors, based on patient-specific kinematics and component positioning and hardware variables?

2. Materials and methods

2.1. Subjects

This was a prospective longitudinal study. All patients provided informed consent before THA to participate in this study, which was approved by our institutional review board. Between August 2012 and October 2014, total 174 hips of 144 patients underwent primary cementless THA by two senior surgeons (Y.N. and S.H.). This study consisted of 21 patients agreed to participate in this study prior to surgery and met the following inclusion criteria: (1) no neuromuscular disorders; (2) no previous surgery of the analyzed hip; (3) no previous surgery or symptom of other joints or spine; and (4) non inflammatory arthritis. The 21 eligible OA patients, including 5 males and 16 females. 7 patients were primary OA and 14 patients were secondary OA due to developmental dysplasia of the hip (DDH). DDH was defined by a lateral center-edge of Wiberg less than 20° [10]. The major cause of THA is secondary OA due to acetabular dysplasia in female in Asian countries, which is different from that in Western countries [11]. According to the category of dysplasia severity [12], 4 hips were classified as borderline-mild DDH (15° ≤ lateral CEA < 25°), 5 hips were classified as moderate DDH (5° ≤ lateral CEA < 15°), 5 hips were classified as severe DDH (lateral CEA < 5°). Based on the migration magnitude of the femoral head relative to the inter-teardrop line [13], 10 hips were classified as Crowe type 1, 4 hips; type2. The average age at the time of THA was 67 ± 8 years (range, 56–84 years), the average height was 156 ± 9 cm (range, 137–173 cm), the average weight of 57 ± 12 kg (range, 40–89 kg), and the average body mass index (BMI) was 24 ± 4 kg/m^2 (range, 18–31 kg/m^2). There were no significant differences in age, height, weight and BMI between primary OA hips and DDH hips. According to the Kellgren–Lawrence scale [14], 5 hips were classified as grade III, 16 hips; grade IV. We prospectively analyzed the kinematics of hip joint immediately before and after THA. The average Harris hip score [15] was improved from 49 ± 14 (range, 15–81) to 92 ± 9 (range, 61–100) with 62 ± 11 months (range, 47–76 months) of the follow-up period. No patients had symptomatic lumbar disease before or after THA. No patients had a history of any complication after THA.

2.2. Implants

A cementless hemispherical press-fit cup, straight metaphyseal fit stem, and high cross-linked ultra-high molecular weight polyethylene liner (AMS and PerFix HA; Aeonian; Kyocera, Kyoto, Japan) were used. All femoral heads were alumina ceramic. The head size; 20 hips were 32 mm, one hips was 26 mm. There are 2 rim types in the Aeonian liner; one has a 15° elevated rim (elevated rim liner) to prevent dislocation of the femoral head, and the other does not (flat liner). The elevated rim liner was used in 11 hips, and the flat liner was used in 10 hips. For all hips implanted with the elevated rim liner, we recorded the location on the cup where the top of the elevated rim was placed.

2.3. Surgical technique

All operations were performed via a posterolateral approach. The femur was prepared first so that anteversion of the femur was known before cup placement [16]. Anteversion of the final broach was measured as the angle between the lower leg's axis and the trial stem's axis by flexing the knee and placing the tibia in a vertical position using a manual goniometer. Then, the cup was placed according to stem anteversion so that combined anteversion ranged from 40° to 60° [17]. Cup anteversion was defined as operative anteversion, following the method of Murray [18].

2.4. Analysis of kinematics

We essentially followed the method in accordance with previous reports [3,7,19]. Continuous radiographic images during chair-rising were recorded using a flat-panel X-ray detector (FPD; Ultimax-i; Toshiba, Tochigi, Japan) with an image area of 420 mm × 420 mm, resolution of 0.274 mm × 0.274 mm/pixel, 0.02 s pulse width, 80 kV and 360 mA and frame rate of 3.5 frames/s (Fig. 1) [3,19]. The patients rose from a seated position on a chair that had a height of 46.5 cm. Sequential movements were collected twice, because FPD provided a limited field of view. These radiographic images were taken before and after THA. As a result, a total of 394 radiographic images were used for the pre- and postoperative analyses (approximately 19 images on average for each subject). The patient could be exposed to a total of approximately 16 mGy of radiation does during the evaluation for continuous radiographic surveillance before and after THA, and gave informed consent of the risk of radiation exposure required. After the first and last radiograph images on the movement cycle were identified

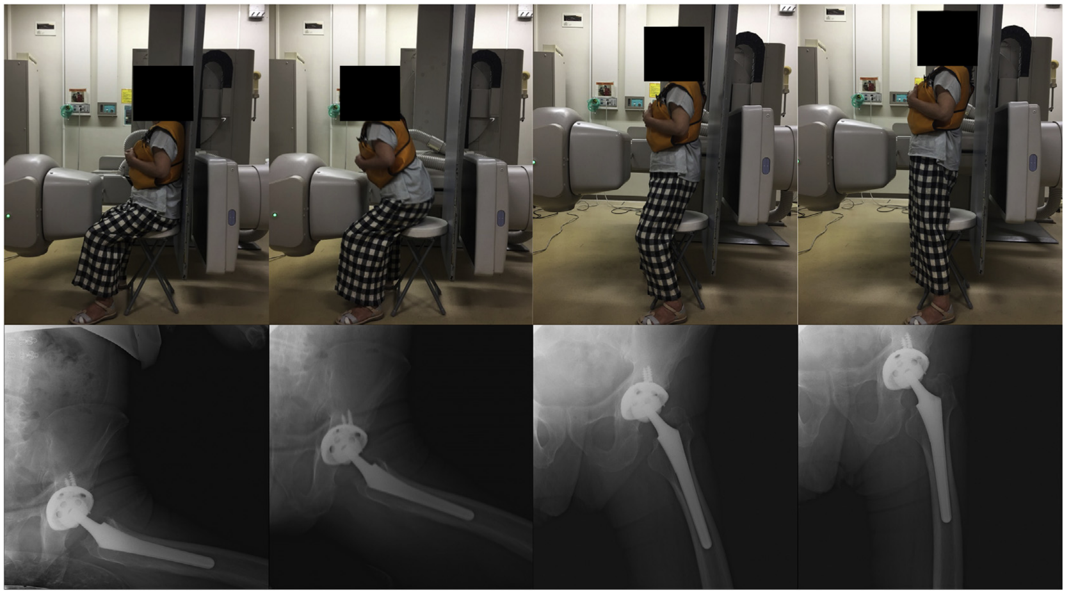

Fig. 1. Each subject rose from the chair with a height of 46.5 cm, and their hip motion was observed using a flat-panel X-ray detector.

among all frames, % movement cycle was calculated by the numbers of all analyzed radiographic images.

The 3D positions and orientations of the pelvis, acetabular cup, femur and femoral stem during the movement cycle were determined using density-based, 3D-to-2D model-to-image registration techniques (Fig. 2) [3,7,19]. Each patient underwent computed tomography (CT; Aquilion, Toshiba, Tochigi, Japan) with a 512 × 512 image matrix, a 0.35 × 0.35 pixel dim and a 1 mm thickness spanning from the superior edge of the pelvis to below the knee joint line. Anatomic coordinate systems of the pelvis and femur were embedded in each density-based volumetric bone model that was derived from CT data according to previous data [3,7,19]. The coordinate system of the pelvis was based on the anterior pelvic plane. The coordinate system of the femur was based on the center of the femoral head and the transepicondylar axis (TEA). To analyze the orientation of the stem relative to the acetabular cup, local coordinate systems to track implant movement were constructed for each implant. Computer simulation was performed to generate virtual digitally reconstructed radiographs (DRRs) in which the light source and projected plane parameters were set to be identical to the actual radiographic imaging conditions [3,7,19]. Density-based DRRs of the pelvis and femur were matched with continuous radiographic images that were acquired using the FPD (Fig. 2a–e). Projections of 3D computer-aided design (CAD) models of the acetabular cup and stem were also superimposed on 2D radiographic images (Fig. 2f). We defined the relative positions and orientation of the femur to the pelvis as hip movement. These movements were determined using Cardan/Euler angle system in x-y-z order (flexion/extension, adduction/abduction and internal rotation/external rotation) [6]. The accuracy of measured values

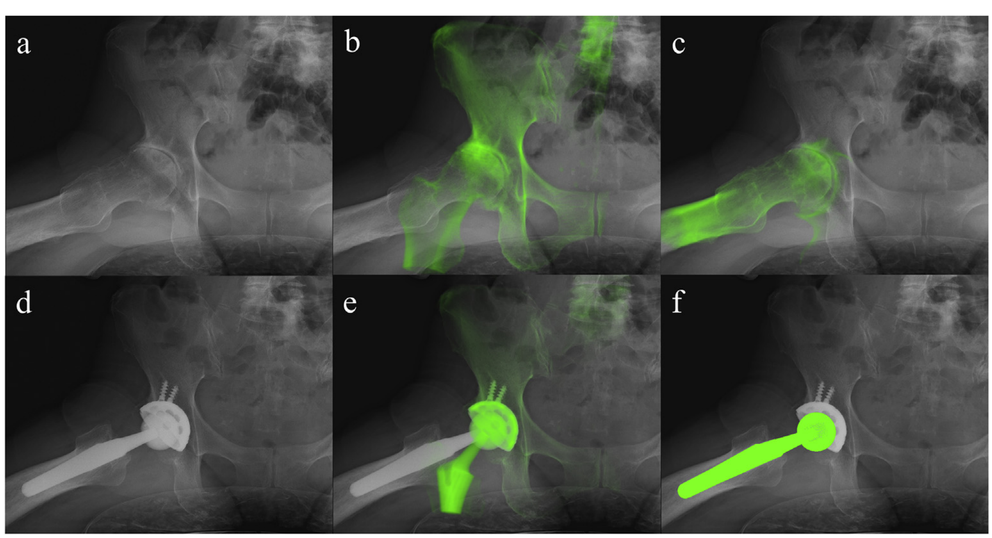

Fig. 2. Hip motions during chair-rising before THA were captured as periodic radiographic images using a flat-panel detector (a). Digitally reconstructed radiographs of the pelvis (b) and femur (c) were compared with continuous radiographic images before THA. Replaced hip motions were also captured as periodic radiographic images using a flat-panel detector (d). Digitally reconstructed radiographs of the pelvis and acetabular cup (e) and projections of 3D computer-aided data of the femoral head and stem (f) were superimposed on 2D radiographic images.

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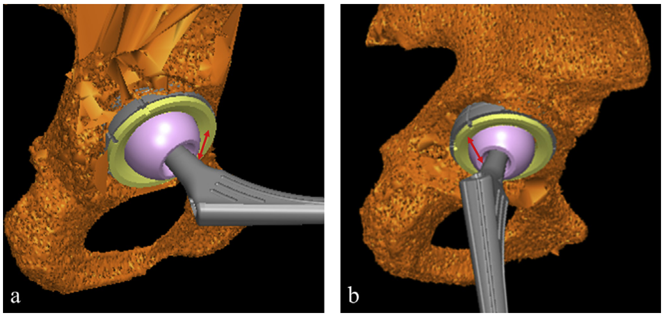

Fig. 3. The minimum distance on the anterior side at the maximum hip flexion as the anterior liner-to-neck distance (a), and the minimum distance on the posterior side at the maximum hip extension as the posterior liner-to-neck distance (b).

were previous evaluated [3,7,19], and the root mean square errors (RMSE) for bone/implant movement were 0.36/0.43 mm for in-plane translation, 0.37/0.48 mm for out-of-plane translation and 0.48°/0.52° for rotation.

2.5. Orientation of components

The orientations of the acetabular cup and stem were measured using postoperative CT data. Cup inclination was measured as the angle of abduction using the inter-tear-drop line as the baseline (radiographic inclination). Cup anteversion was measured as the angle of anteversion in the sagittal plane (operative anteversion) [18]. Femoral anteversion was measured as the angle of anteversion between the prosthetic femoral neck and TEA [17]. Combined anteversion was calculated as the sum of cup and stem anteversions [17]. We evaluated whether the cup positions were within the safe zones defined by Lewinnek et al. [20] and Elkins et al. [21] as the cup positions of anteversion of 5°–25° and 5°–40° with inclination of 30°–50° and 30°–55°, respectively.

2.6. Liner-to-neck distance

We measured the minimum distance between liner and the stem neck (liner-to-neck distance) using a CAD software program (CATIA V5; Dassault Systemes, Vélizy-Villacoublay, France) [7,22]. We measured the minimum distance on the anterior side at the maximum hip flexion as the anterior liner-to-neck distance (Fig. 3a), and the minimum distance on the posterior side at the maximum hip extension as the posterior liner-to-neck distance (Fig. 3b). We also investigated the influence of hip kinematics (flexion/extension, adduction/abduction and internal/external rotation) and orientation of the components (cup inclination, cup anteversion and stem anteversion) and implants (head size, neck length and flat/elevated rim liner) on the anterior and posterior liner-to-neck distances.

2.7. Statistical analysis

Statistical analyses were performed using JMP software version 12.0 (SAS Institute, Cary, NC, USA). All data were tested for normality with the Shapiro–Wilk test, and for homoscedasticity with the Levene's test. Normally distributed variables were evaluated with a Student-*t* test or a paired *t*-test. Non-normally distributed variables were evaluated with the Wilcoxon rank-sum test. The levels of association between liner-to-neck distance and factors: hip kinematics, orientation of components and neck length, were examined using Pearson's correlation coefficients and Spearman's correlation coefficients. Stepwise linear multiple-regression models were used to determine the hip kinematics and orientations of the components and implant. Statistical significance was set as $P < 0.05$. Values are expressed as mean ± standard deviation. A power analysis indicated that a sample size of 21 patients would provide 80% statistical power detecting a 6.4° difference in absolute value of ROM between before and after THA. This assumes a probability value of less than 0.05 and a standard deviation of 10°.

3. Results

3.1. Kinematics of hip joint

The maximum anterior and posterior pelvic tilt angles (anterior −, posterior +) after THA (−11.7 ± 7.1° [range, −31.1–0.7° and 14.5 ± 5.5° [range, 3.2–30.0°], respectively) changed significantly ($P = 0.001$, 0.036, respectively) compared with those before THA (−6.3 ± 9.8° [range, −31.1–13.6°] and 19.0 ± 9.7° [range, −2–40.6°], respectively) (Fig. 4a, Table 1). In both pre- and post-THA, maximum femoral flexion angles were observed at the sitting position. The maximum femoral flexion angle after THA (74.4 ± 6.2° [range, 62.8–90.3°]) was significantly ($P = .028$) increased than that before THA (70.0 ± 5.8° [range, 58.9–79.5°]) (Fig. 4b). In both pre- and post-THA, maximum hip flexion angles were observed during the chair-rising motion (25%, 20%, respectively). The maximum hip flexion angle before THA (62.8 ± 12.7° [range, 38.6–93.5°]) was significantly ($P < .001$) increased than that after THA (72.0 ± 8.8° [range, 59.6–94.1°]) (Fig. 4c, Table 1). The pelvic tilt angle at the maximum hip flexion after THA (−3.3 ± 9.5° [range, −30.7–10.2°]) was significantly ($P = 0.017$) anterior to that before THA (1.2 ± 10.4° [range, −27.6–21.9°]) (Table 2). There were no significant differences in maximum and minimum pelvic, maximum femoral and hip kinematics before THA between primary OA hips and DDH hips ($P = 0.248$, 0.737, 0.439, 0.625, respectively).

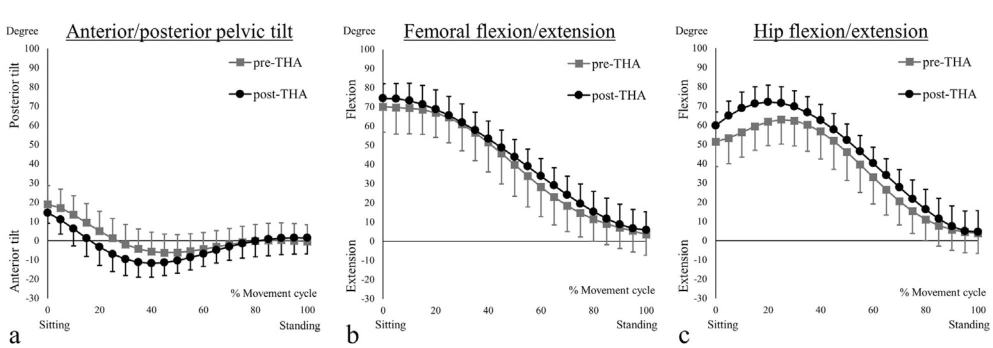

Fig. 4. Pelvic tilt (a), femoral flexion/extension (b), and hip flexion/extension angles (c) in pre-THA (gray lines) and post-THA (black lines). The error bars represent the standard deviation. THA: total hip arthroplasty.

Table 1
The maximum and minimum angles of the pelvic tilt (posterior +, anterior −) and hip flexion/extension (flexion+, extension −) were compared between pre- and post-THA.

	Maximum pelvic tilt (°)	Minimum pelvic tilt (°)	Maximum hip flexion (°)	Minimum hip flexion (°)
Pre-THA	19.0 (9.7)	−6.3 (9.8)	62.8 (12.7)	3.9 (10.6)
Post-THA	14.5 (5.5) *	−11.7 (7.1) *	72.0 (8.8) *	4.5 (11.0)

The values are expressed as the mean (standard deviation). * Significant difference compared with pre-THA ($P < 0.05$).
THA: total hip arthroplasty.

Table 2
The pelvic tilt (posterior +, anterior −), hip adduction/abduction (adduction +, abduction −), and internal/external hip rotation (internal +, external −) angles at the maximum hip flexion were compared between pre- and post-THA.

	Maximum hip flexion (°)	Pelvic tilt (°)	Hip adduction/abduction (°)	Internal/external hip rotation (°)
Pre-THA	62.8 (12.7)	1.2 (10.4)	0.4 (12.4)	−14.0 (10.8)
Post-THA	72.0 (8.8) *	−3.3 (9.5) *	1.3 (8.4)	−16.8 (12.8)

The values are expressed as the mean (standard deviation). * Significant difference compared with pre-THA ($P < 0.05$).
THA: total hip arthroplasty.

DDH hips showed significantly (P = 0.015, 0.005, respectively) smaller maximum and minimum pelvic tilt angles after THA (12.5 ± 4.8° [range, 3.2–18.9°] and −14.6 ± 6.3° [range, −31.1–4.5°], respectively) compared with primary OA hips (18.5 ± 4.9° [range, 10.8–25.0°] and −6.0 ± 4.9° [range, −14.8–0.7°]). There were no significant differences in femoral and hip kinematics after THA between primary OA hips and DDH hips (P = 0.681, 0.537, respectively).

3.2. Orientation of components

The cup inclination and cup anteversion averaged 37.4 ± 4.3° (range, 30.0–46.8°) and 23.1 ± 8.8° (range, 9.7–35.8°), respectively. The cup positions within the safe zones by Lewinnek et al. [22] and Elkins et al. [23] were 14 hips (67%) and 21 hips (100%), respectively. The stem anteversion averaged 30.1 ± 14.3° (range, 6.7–60.7°), and the combined anteversion averaged 53.1 ± 15.7° (range, 21.2–76.9°). There were no significant differences in cup anteversion, cup inclination and stem anteversion between hips with flat and elevated liners (P = 0.156, 0.096, 0.117, respectively). The combined anteversion in hips with elevated liner (45.7 ± 15.8° [range, 21.2–70.9°]) was significantly (P = 0.021) smaller than hips with flat liner (61.4 ± 12.4° [range, 45.2–76.9°]).

3.3. Liner-to-neck distance

The minimum anterior and posterior liner-to-neck distances averaged 12.3 ± 2.7 mm (range, 6.1–17.6 mm) and 8.1 ± 3.0 mm (range, 2.8–14.3 mm), respectively. The anterior liner-to-neck distance was significantly larger than the posterior liner-to-neck distance ($P < 0.001$). There was no liner-to-neck contact during chair-rising in any hips.

In univariate analysis, no factor significantly influenced the anterior liner-to-neck distance (Table 3). However, multivariate analysis showed that the larger hip flexion angle, smaller cup inclination, smaller stem anteversion and use of 26 mm head were negatively associated with the anterior liner-to-neck distance (P = 0.028, 0.041, 0.007, 0.006, respectively) (Table 4). In univariate analysis, the posterior liner-to-neck distance with elevated rim liner (6.9 ± 3.1 mm [range, 2.8–14.0 mm]) was significantly ($P < 0.05$) smaller than that with flat liner (9.5 ± 2.6 mm [range, 5.6–14.3 mm]). Multivariate analysis showed that the larger hip extension angle, larger cup anteversion, shorter neck length and use of an elevated rim liner were negatively associated with the posterior liner-to-neck distance (P = 0.015, 0.001, 0.008, 0.001, respectively) (Table 5). Larger cup anteversion was most negatively sensitive to the posterior liner-to-neck distance than use of elevated rim liner, shorter neck length and larger hip extension angle (Table 5).

Table 3
Univariate analysis of factors that influenced the anterior and posterior liner-to-neck distance.

	P-value	
	Anterior liner-to-neck distance	Posterior liner-to-neck distance
Kinematics of the hip joint		
Flexion/extension	0.580	0.070
Adduction/abduction	0.941	0.423
Internal/external rotation	0.500	0.420
Orientation of the components		
Cup anteversion	0.236	0.209
Cup inclination	0.674	0.311
Stem anteversion	0.243	0.412
Implants		
Head size (26 mm vs. 32 mm)	0.216	0.934
Neck length	0.663	0.242
Liner (flat vs. elevated)	NA	0.049*

NA; not applicable.
* P-values indicate statistically significant differences ($P < 0.05$).

Table 4
Multivariate analysis of factors influencing the anterior liner-to-neck distance.

	β-value	Negative effect	P-value
Kinematics of the hip joint			
Flexion	−0.52	Large ROM	0.028*
Internal rotation	0.33		0.123
Orientation of the components			
Cup anteversion	0.37		0.055
Cup inclination	0.48	Small angle	0.041*
Stem anteversion	0.58	Small angle	0.007*
Implants			
Head size (26 mm vs. 32 mm)	−0.68	Using 26 mm head	0.006*

The variables were selected using a stepwise multiple regression analysis. β is standard regression coefficient.
* P-values indicate statistically significant differences ($P < 0.05$). ROM: range of motion.

4. Discussion

This study examined the dynamic kinematics of the hip joint during chair-rising before and after THA. The maximum hip flexion during chair-rising significantly improved from 63° before THA to

Table 5
Multivariate analysis of factors influencing the posterior liner-to-neck distance.

	β-value	Negative effect	P-value
Kinematics of the hip joint			
Extension	−0.41	Large ROM	0.015*
Orientation of the components			
Cup anteversion	−0.60	Large angle	0.001*
Implants			
Neck length	0.42	Short neck	0.008*
Liner (flat vs. elevated)	0.58	Using elevated rim liner	0.001*

The variables were selected using a stepwise multiple regression analysis. β is standard regression coefficient.
* *P*-values indicate statistically significant differences ($P < 0.05$). ROM: range of motion.

72° after THA. The previous study found that maximum hip flexion angles during chair-rising in healthy subjects averaged 81° [22]. Therefore, THA improved the maximum hip flexion during chair-rising compared with same patients in pre-THA OA hips, in spite of the residual limited range of hip flexion compared with healthy hips. The pelvic tilt angle at the maximum hip flexion during chair-rising came to 3° of anterior tilt after THA compared with 1° of posterior tilt before THA. In the previous study by Hara et al. [3], OA patients showed larger posterior pelvic tilt angles maximum hip flexion during chair-rising than healthy subjects. During chair-rising, to move the center of gravity forward, the pelvis must be tilted anteriorly, but the pelvis of the OA hips showed difficultly achieving anterior tilt because of the limited functional range of hip flexion compared to the normal hips [3]. As a result of this study, we found that THA increased the ROM in hip joint during chair-rising and made it easy to tilt the pelvis anterior during chair-rising.

Liner-to-neck contact is a recognized risk factor for increased rates of dislocation accelerated wear, linear fractures, and decreased lifespan of implants [8,23]. Estimation of liner-to-neck distance under dynamic weight-bearing conditions using 3D-to-2D model-to-image registration techniques could provide useful information for hip surgeons because dislocation caused by liner-to-neck contact may occur during postural changes [24]. Dorr et al. [9] recently described that the surgeon needs to consider the individual patient's functional position which occurs during daily activities, including impingement prone activities such as chair-rising. However, to our knowledge, there has been no detailed information of the liner-to-neck clearance during chair-rising. Using four-dimensional patient-specific analysis, Miki et al. [23] found prosthesis impingement to be related to instability at least in 6 of 10 hips with dislocation after primary THA. The present study showed that there was no liner-to-neck contact, and sufficient anterior and posterior liner-to-neck clearance occurred during chair-rising in patients with well-positioned THA. Increased maximum hip flexion after THA was found with 12.3 mm on average of minimum anterior liner-to-neck distance at maximum hip flexion was found during chair-rising after THA. Koyanagi et al. [6] previously described liner-to-neck clearance less than 10° as the cautionary value for prosthetic impingement. Komiyama et al. recently [22] reported sufficient liner-to-neck clearance (10.9 mm and 35° on average) at the maximum hip flexion (81° on average) during squatting after THA, which were slightly smaller than 12.3 mm on average of anterior liner-to-neck distance at the maximum flexion (72° on average) during chair-rising in this study. They did not focus on evaluation of influencing factors on liner-to-neck clearance during squatting due to smaller number of subjects [22] compared to the present study. The present study with a greater statistical reliability could reveal the influence of multiple factors on the liner-to-neck clearance under *in vivo* weight-bearing conditions. To our knowledge, no study has been published evaluating the influence of dynamic hip kinematics, component position, and hardware variables on the liner-to-neck clearance under *in vivo* weight-bearing conditions. Even in the same chair-rising activity, patient-specific ROM (degrees of hip flexion and extension), which native flexibility, posture habit, muscle strength, and especially residual soft tissue contractures could contribute to, demonstrated significant influence on both the anterior and posterior liner-to-neck clearance. Multivariate analysis performed in this study showed that the larger hip flexion angle, smaller cup inclination, smaller stem anteversion and use of 26 mm head were negative factors of the anterior liner-to-neck distance at the maximum hip flexion. This result is generally in agreement with previous simulation study by D′ Lima et al. [25]. They reported that acetabular abduction angles of less than 45°, smaller femoral anteversion and lower head-neck ratios (i.e. small head size) decreased prosthetic impingement-free ROM. They also said that this decreased ROM can be countered by increasing femoral anteversion. Geieret et al. [26] found that larger stem anteversion, cup anteversion and head size lead to larger prosthetic impingement free-ROM. Sariali et al. [27] reported that the jumping distance: the degree of lateral translation of the femoral head center required for dislocation to occur, increased as the femoral head diameter increased. Stem anteversion (30° on average) in the present study was larger than that in past studies (10°−23° on average) [16,28] possibly because of many secondary OA cases due to DDH in our Asian cohort study. Generally, DDH promotes large femoral anteversion, and subsequent stem anteversion is large [29]. Between primary OA hips and DDH hips, there are significant differences in the pelvic tilt angles after THA while no significant differences in those before THA. Further investigation will be necessary to understand the relationship between pelvic kinematics and demographic data including especially primary disease, gender, age, at operation, body weight, and pre-operative stage of OA. In this study, the anterior liner-to-neck distance was significantly larger than the posterior liner-to-neck distance. Larger anterior clearance should be kept to ensure further deeply hip flexed posture, hip abduction and internal rotation avoiding anterior prosthetic impingement because a posterolateral approach for THA retain tension in anterior soft tissues and most dislocations occur in the posterior direction. Therefore, the hip surgeon should be more aware that smaller cup inclination, stem anteversion and head size could lead to decrease anterior liner-to-neck clearance during chair-rising especially in patients with larger hip flexion angle. In terms of posterior liner-to-neck distance at the maximum hip extension, the present study showed that the larger hip extension angle, larger cup anteversion, shorter neck length and use of an elevated rim liner were negatively associated factors. This result also showed the same trend to previous reports [7,8,30] that focused on the prosthetic impingement. In retrieval analysis, Marchetti et al. [8] showed that posterior prosthetic impingement was associated with use of elevated rim liner. Sato et al. [30] reported that the larger cup anteversion decreased the posterior liner-to-neck distance *in vitro* replaced 3D CAD bone model simulation study. Hara et al. [7] reported that significantly larger cup anteversion was seen in hips with posterior prosthetic impingement compared with hips without posterior prosthetic impingement during golf swing. They also reported that elevated rim liner was used in all hips with posterior prosthetic impingement. The short neck length leads to a decrease in the oscillation angle, so it is considered to be related to liner-to-neck clearance. In this study, the posterior liner-to-neck distance at maximum hip extension: 8.1 mm on average, were significantly smaller than the anterior liner-to-neck distance at maximum hip flexion: 12.3 mm on average. Although we found no posterior liner-to-neck contact in the present study, patients with a large hip extension angle may require additional caution regarding cup anteversion, neck length and use of an elevated rim liner during procedure. We selected a flat liner in hips with sufficient posterior stable range of movement at internal rotation in 90° of flexion. This study showed that the combined anteversion in hips with elevated liner was significantly smaller than hips with flat liner. These results indicated that decreased value of combined anteversion could provide surgeons concern of posterior dislocation during procedure. Other studies have reported that an elevated liner significantly decreased the rate of posterior dislocation [31,32] and reduced the range of motion by 30% with a risk for posterior liner-to-neck contact [33] compared to a flat liner. Understanding how *in vivo* patient-specific kinematics and component positioning may influence liner-to-neck clearance during activities in patients after THA can ultimately lead to improved functional ROM and implants lifespan.

The present study has several limitations. First, the study was certainly limited by the small number of subjects. Hips with significant malalignment could demonstrate liner-to-neck contact or smaller liner-to-neck distances. However, significant differences between pre- and postoperative kinematics and influencing factors on liner-to-neck clearance were identified in this study. Second, the present study analyzed only a single component design: a hemispherical press-fit cup and straight metaphyseal fit stem. Although the design is similar to that of many other components currently available, the results could differ. Third, sequential movements during chair-rising were collected twice, because even the large FPD that was used in this study provided a limited field of view (FOV). Development of mobile fluoroscopy is expected to achieve quite a large FOV. Forth, a single-plane FPD is used present study. Bi-plane imaging has higher measurement accuracy for out-of-plane translation theoretically [34]. Importantly, none of the uncertainty would bias our measures to show increased range of replaced hip flexion with sufficient anterior liner-to-neck clearance during chair-rising. Finally, we only evaluated the kinematics of the hip joint during chair-rising. Specific postures provide activity-dependent hip kinematics and liner-to-neck clearance. Therefore, additional analyses including different postures, e.g. stair-climbing and walking, could be helpful for the hip surgeon and physical therapist to detect risks of impingement and dislocation, and counsel patients about activities after THA.

5. Conclusion

We analyzed dynamic hip kinematics before and after THA and the liner-to-neck clearance during chair-rising, using 3D-to-2D model-to-image registration techniques. Well-positioned THA components provide an increased range of hip flexion with sufficient anterior liner-to-neck clearance during chair-rising. Dynamic hip kinematics (maximum hip flexion and extension), component position (cup inclination, cup anteversion and stem anteversion) and hardware variables (neck length, with or without elevated liner and head diameter) significantly influenced on the liner-to-neck clearance under weight-bearing conditions. These results may help surgeons to understand the effect of individuals hip kinematics, component alignment and hardware variables on the liner-to-neck clearance, leading to improve surgical technique and maximize impingement-free ROM under weight-bearing conditions.

Conflicts of interest

The authors declare no conflicts of interest associated with this manuscript.

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