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原田, 知

出版情報：Kyushu University, 2021, 博士（医学）, 課程博士
バージョン：

The Journal of Arthroplasty xxx (2022) 1–8

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

Squatting After Total Hip Arthroplasty: Patient-Reported Outcomes and In Vivo Three-Dimensional Kinematic Study

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A R T I C L E I N F O

Article history:
Received 17 September 2021
Received in revised form
12 December 2021
Accepted 20 December 2021
Available online xxx

Keywords:
total hip arthroplasty
squat
patients-reported outcome
kinematics
pelvic tilt
liner-to-neck distance

A B S T R A C T

Background: Squatting is an important function for many daily activities, but has not been well documented after total hip arthroplasty (THA). This study investigated the participation rate of squatting and in vivo kinematics during squatting.
Methods: A survey questionnaire about squatting was mailed to patients who underwent primary THA and 328 patients returned acceptable responses. Additionally, 32 hips were evaluated for dynamic 3-dimensional kinematics of squatting using density-based image-matching techniques. Multivariate analyses were applied to determine which factors were associated with anterior liner-to-neck distance at maximum hip flexion.
Results: Patients who could easily squat significantly increased this ability postoperatively (23.5% vs 46%, $P < .01$). In 29.5% of the patients there was still no ability to squat after THA; the main reason was anxiety of dislocation (34.2%). Kinematic analysis revealed that maximum hip flexion averaged $80.7° \pm 12.3°$ with $12.8° \pm 10.7°$ of posterior pelvic tilt and 9.7 ± 3.0 mm of anterior liner-to-neck distance. Neither liner-to-neck, bone-to-bone, nor bone-to-implant contact was observed in any of the hips. Larger hip flexion and smaller cup anteversion were negatively associated with the anterior liner-to-neck distance at maximum hip flexion ($P < .05$).
Conclusion: Postoperatively, approximately 70% of patients squatted easily or with support. Anxiety of dislocation made patients avoid squatting after THA. In vivo squatting kinematics suggest no danger of impingement or subsequent dislocation, but excessively large hip flexion and small cup anteversion remain as risks.

Total hip arthroplasty (THA) is an effective treatment of end-stage hip osteoarthritis to restore patients' quality of life [1]. Long-term outcomes after THA have improved as a result of innovations in prostheses and surgical techniques [2–4]. THA is increasingly being performed in younger patients [5] who require a more active lifestyle [5–8]. Despite the widely recognized success of THA [2,3], there are still concerns about dislocation [9,10] as a major cause of revision [11–14]. The main mechanism of dislocation is prosthetic impingement during activities [15,16].

Squatting is a fundamental daily activity in many cultures as well as a basic movement for strengthening lower limb muscles [17–19]. Therefore, an inability to squat after hip surgery could impact younger and more active patients. However, there is little literature regarding squatting after THA, and even less is known about replaced hip biomechanics during squatting to confirm whether squatting can be performed safely.

This study aimed to investigate (1) the number of Asian patients who participated in squatting after THA as well as reasons given by those who did not participate in squatting, (2) patient-specific functional position while squatting under in vivo weight-bearing conditions using density-based image-matching techniques, and

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.arth.2021.12.028.

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https://doi.org/10.1016/j.arth.2021.12.028
0883-5403/

(3) the significant factors associated with minimum liner-to-neck distances during squatting as a risk of prosthetic impingement and dislocation.

Materials and Methods

Subjects

This study was approved by our Institutional Review Board (IRB number 30-91). Between February 2011 and December 2015, 543 Asian patients underwent primary cementless THA. All surgeries were performed via a posterolateral approach using combined anteversion of the stem and cup technique [11,16,20]. The combined anteversion technique was adopted to cope with the wide range of femoral anteversion of hip dysplasia [21]. The cup was placed according to stem anteversion so that combined anteversion ranged from 40° to 60° [11,16]. A cementless hemispherical press-fit cup, double wedge metaphyseal filling stem [22], and high cross-linked ultra-high molecular weight polyethylene liner (AMS and PerFix HA; Aeonian; Kyocera, Kyoto, Japan) were used. Of these, 499 satisfied the following inclusion criteria: (1) alive at the time of the survey, (2) >1 year since last surgery, (3) evaluation by a surgeon <1 year, (4) no revision surgery, and (5) no severe dementia or physical disorder unrelated to the hip joint that may lead to bed rest. The survey questionnaire was mailed to all patients, of which 328 patients (403 hips, 65.7%) completed and returned the questionnaire with written informed consent (Fig. 1).

Questionnaire

The details of the information collected by the survey questionnaire are as follows: (1) Each patient was asked if they could squat or not. They were asked to select from the following 4 items: (a) Yes, "easily possible," (b) Yes, "possible with some support," (c) No, "impossible," and (d) No, "have not tried." (2) Patients who answered "easily possible" and "possible with some support" were asked when they were able to squat after THA. They were asked to select from the following 5 items (a) <1 month, (b) 1-3 months, (d) 3-6 months, (d) 6-12 months, and (e) >12 months. (3) Patients who answered "impossible" and "have not tried" were asked to provide one reason from the following 6 items for not squatting: (a) hip pain, (b) weak muscle strength, (c) been told not to squat (restriction) by medical staff, (d) been told not to squat (restriction) by family and acquaintance, (e) anxiety about dislocation, and (f) others.

Kinematic Analysis

Thirty-two hips in 30 patients were included in this kinematic study from 211 patients who reported their ability to adopt a squatting position easily or with some support after THA. The protocol was approved by our Institutional Review Board, and all patients provided informed consent to participate in the present study. All demographic factors, including age at the time of surgery, gender, body mass index, diagnosis, follow-up duration, and Harris Hip Score [15] were obtained from the patients' medical records (Table 1). Lumbar lordosis angle immediately before THA averaged 61.8° ± 10.3° (range 45°-84°), indicating no flat back deformity or increased pelvic retroversion. No patients had a history of symptomatic lumbar disease before or after THA. Continuous radiographic images during squatting were recorded (Ultimax-i flat-panel X-ray detector [FPD] multipurpose system; Canon, Tochigi, Japan) with a field of view of 420 mm × 420 mm, resolution of 0.274 mm × 0.274 mm/pixel, 0.02-second pulse width, 80 kV and 360 mA, and frame rate of 3.5 frames/s (Fig. 2) [23–26].

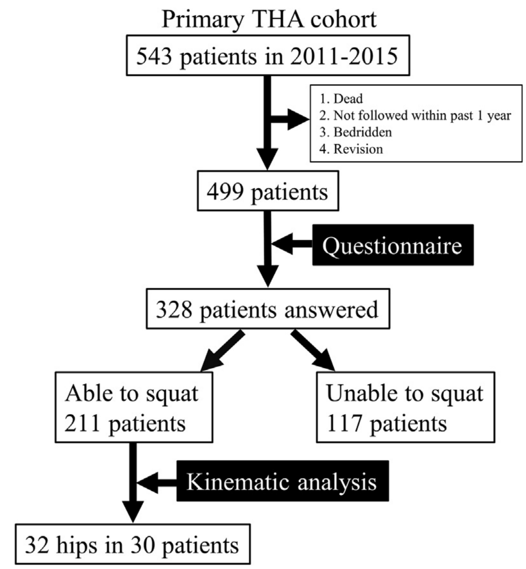

Fig. 1. Schematic representation of the study cohort inclusion process and study design. THA, total hip arthroplasty.

Each patient underwent computed tomography (CT; Aquilion; Canon) 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. Kinematics of both the hip joint and implant components were analyzed using density-based image-matching techniques [23–26]. These well-established techniques enabled accurate analysis of in vivo 3-dimensional (3D) joint kinematics based on 2D continuous radiographic images by matching 3D bone and implant models from CT and computer-aided design (CAD) data, respectively. 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. 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 in which the light source and projected plane parameters were set to be identical to the actual radiographic imaging conditions. Density-based digitally reconstructed radiographs of the pelvis and femur were matched with continuous radiographic

Table 1
Demographic and Radiographic Data for the Kinematic Study Cohort.

Thirty-two hips in 30 patients	
Age at surgery[a] (y)	62.9 ± 8.9 (47-78)
Gender (male; female), hips	14; 18
Body mass index[a] (kg/m^2)	22.8 ± 3.3 (18.8-32.2)
Diagnosis (OA; ONFH), hips	27; 5
Follow-up[a] (y)	7.4 ± 1.9 (5.4-8.9)
Preoperative Harris Hip Score[a]	48.5 ± 13.2 (27-81)
Postoperative Harris Hip Score[a]	95.6 ± 7.4 (62-100)
Cup size (46; 48; 50; 52; 54 mm)	2; 20; 8; 2
Stem size (9; 10; 11; 12; 13; 14)	1; 2; 8; 12; 8; 1
Ball diameter (26; 32 mm)	2; 30
Length of stem neck[a] (mm)	37.4 ± 3.2 (34-45)
Liner (elevated; flat)	20; 12
Cup inclination[a] (°)	38.1° ± 5.7° (27°-48°)
Cup anteversion[a] (°)	21.4° ± 8.2° (5°-40°)
Stem anteversion[a] (°)	29.8° ± 10.4° (2°-58°)

OA, osteoarthrosis; ONFH, osteonecrosis of the femoral head.
[a] The values are given as the mean ± standard deviations with the range in parentheses.

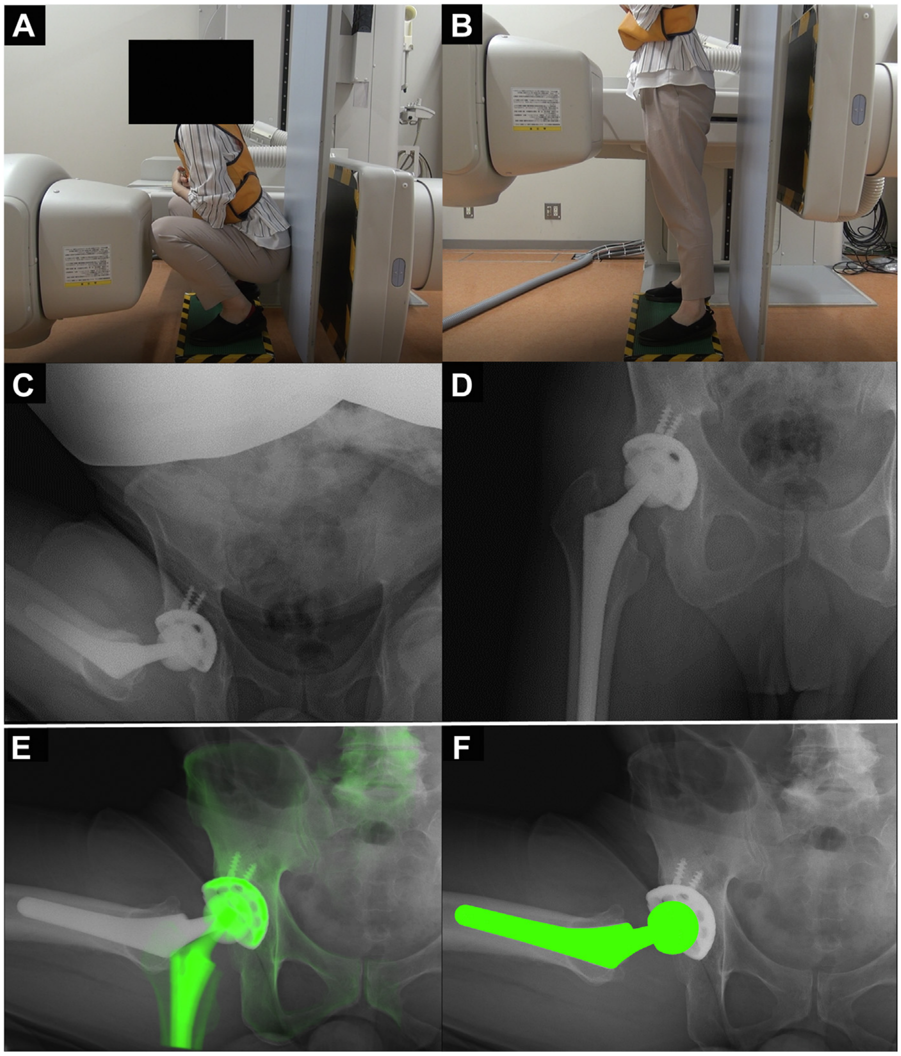

Fig. 2. Patients who had undergone total hip arthroplasty stood from a squat position with their heels down (A, B). Hip motions during squatting were captured using a flat-panel X-ray detector (C, D). Digitally reconstructed radiographs of the pelvis and acetabular cup (E) and computer-aided data of the femoral head and stem (F) were super-imposed on radiographic images.

images that were acquired using the FPD (Fig. 2). Projections of 3D CAD models of the acetabular cup and femoral stem were also superimposed on 2D radiographic images (Fig. 2). We defined the relative positions and orientation of the femur to the pelvis as hip movement. These movements were determined using a Cardan/Euler angle system in *x-y-z* order (flexion/extension, adduction/abduction, and internal rotation/external rotation) [23]. The accuracy of measured values was previously evaluated [24–27], and the root mean square errors 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.

Liner-to-Neck Distance

Using a CAD software program (CATIA V5; Dassault Systemes, Vélizy-Villacoublay, France) [25–27], the minimum distance between the polyethylene liner and stem neck (liner-to-neck distance) was measured on the anterior side at maximum hip flexion as the anterior liner-to-neck distance, and the minimum distance on the posterior side at the maximum hip extension as the posterior liner-to-neck distance (Fig. 3). In order to reveal associated risk factors of prosthetic impingement and dislocation, we examined 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, length of stem neck, and flat/elevated rim liner) on the anterior and posterior liner-to-neck distances. Furthermore, we examined the influence of individual pelvic tilt on hip kinematics and functional cup orientation during squatting [28].

Orientation of Components

Orientations of the cup and stem were measured using postoperative CT. Cup inclination was measured as the angle of abduction using the inter-tear-drop line as the baseline (radiographic inclination). Cup anteversion was measured based on functional pelvic plane (radiographic anteversion) [29]. Femoral anteversion was measured as the angle of anteversion between the prosthetic femoral neck and the transepicondylar axis [11]. Cup inclination and anteversion, stem anteversion and combined anteversion are summarized in Table 1. Twenty-two hips (70%) were in the safe zone defined by Lewinnek et al [30]. Sixteen hips (50%) showed cup position within the target zone: combined anteversion of 40°-60° and cup inclination of 30°-50° [11,16,30].

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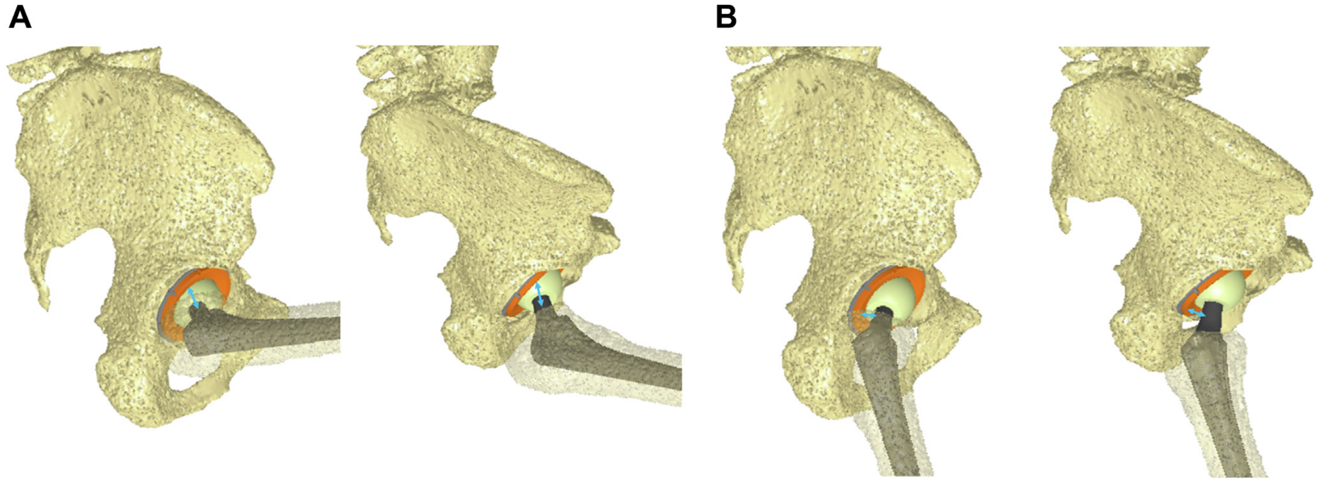

Fig. 3. Minimum distance on the anterior side at the maximum hip flexion as the anterior liner-to-neck distance (A), and minimum distance on the posterior side at the minimum hip flexion as the posterior liner-to-neck distance (B). (Left: lateral view, Right: oblique view).

Statistical Analysis

Statistical analyses were performed using JMP software v.14.0 (SAS Institute, Cary, NC). Normally distributed variables were evaluated with Student's *t*-test. Non-normally distributed variables were evaluated with the Wilcoxon rank-sum test. A multiple linear regression analysis using a stepwise variable entry method was performed to determine the risk factors associated with liner-to-neck distance. Hip kinematics, orientation of components, and implants were used in the multivariate logistic regression model. Statistical significance was set as $P < .05$. Values are expressed as mean ± standard deviation.

Results

Patient-Reported Outcomes

The number of patients who answered "easily possible" increased from 77 (23.5%) preoperatively to 151 (46.0%) postoperatively ($P < .001$; Fig. 4A). Meanwhile, the number of patients who could not squat decreased from 69 (21.0%) preoperatively to 45 (13.7%) postoperatively ($P < .001$). Ninety-seven patients (29.5%) either could not or had not tried to squat after THA. The most common period when patients could squat after THA surgery was 3-6 months (Fig. 4B). The most common cause of inability to squat before THA was pain, which decreased from 76 patients (64.9%) preoperatively to 8 patients (6.8%) postoperatively ($P < .01$; Fig. 4C). The most common cause of inability to squat after THA was anxiety about dislocation (40 patients, 34.2%), followed by weakness of muscle strength (24.7%), others included knee pain/back pain (17.1%), restriction by medical stuff (10.3%), and family and friends (6.8%).

Kinematics and Liner-to-Neck Distance

Maximum and minimum hip flexion angles were 80.7° ± 12.3° and 1.6° ± 8.3°, respectively (Table 2). Sagittal pelvic tilt angles (anterior −, posterior +) at maximum and minimum hip flexion angles averaged 12.8° ± 10.7° and −0.2° ± 7.4° and varied between patients with 8.7°-16.3° and −2.9° to 2.6° (95% confidence interval), respectively. The posterior pelvic tilt at maximum hip flexion was significantly correlated with pelvic tilt at minimum hip flexion ($\rho = 0.4$, $P = .01$; Fig. 5A) and maximum hip flexion ($\rho = 0.39$, $P = .02$; Fig. 5B). Functional cup anteversion (anteversion +, retroversion −) at maximum and minimum hip flexion angles averaged 35.8° ± 13.8° and 22.1° ± 11.3°, respectively. Functional cup orientation at maximum hip flexion significantly depends on pelvic orientation relative to the ground ($\rho = 0.5$, $P < .01$) and cup orientation relative to the pelvis ($\rho = 0.6$, $P < .01$).

The minimum anterior and posterior liner-to-neck distances averaged 9.7 ± 3.0 mm (3.1-16.6) and 6.4 ± 3.4 mm (1.7-12.6), respectively. Liner-to-neck, bone-to-bone, or bone-to-implant contact was not observed in any hips. The anterior liner-to-neck distance at maximum hip flexion was significantly larger than the

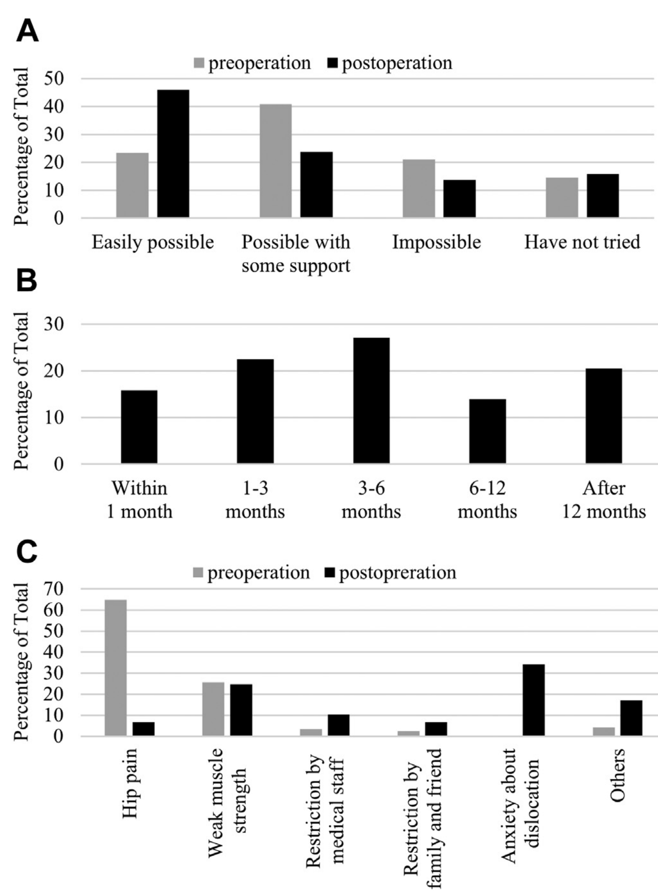

Fig. 4. Bar graphs illustrating the distributions for answers to the questionnaire.

Table 2
Hip Adduction/Abduction and Internal/External Angles, Pelvic Tilt, Obliquity, and Rotation Angles, and Functional Cup Anteversion and Abduction Angles at Maximum and Minimum Hip Flexion/Extension.

Parameters	Maximum Hip Flexion	Minimum Hip Flexion	*P*-Value
Hip flexion/extension (°)(flexion +, extension −)	80.7° ± 12.3°	1.6° ± 8.3°	<.01[a]
Hip adduction/abduction (°)(abduction +, adduction −)	7.3° ± 5.4°	3.6° ± 3.1°	<.01[a]
Hip internal/external rotation (°)(internal +, external −)	−22.7° ± 11.3°	−10.0° ± 6.5°	<.01[a]
Sagittal pelvic tilt (°)(posterior +, anterior −)	12.8° ± 10.7°	−0.2° ± 7.4°	<.01[a]
Coronal pelvic obliquity (°)(abduction +, adduction −)	−0.9° ± 4.7°	−0.8° ± 2.6°	.52
Axial pelvic rotation (°)(internal +, external −)	1.5° ± 9.3°	3.2° ± 4.8°	.09
Functional cup anteversion (°)(anteversion +, retroversion −)	35.8° ± 13.8°	22.1° ± 11.3°	<.01[a]

The values are given as the mean ± standard deviations.
[a] *P*-values indicate statistically significant differences ($P < .05$).

posterior liner-to-neck distance at minimum hip flexion ($P < .01$). Maximum hip flexion during squatting ($\rho = -0.51$, $P < .01$; Fig. 5C) and cup anteversion ($\rho = 0.42$, $P = .01$; Fig. 5D) was significantly correlated with anterior liner-to-neck distance at maximum hip flexion. Twelve hips with the flat liner (8.4 ± 3.9 mm, 2.3-12.6) had a significantly higher posterior liner-to-neck distance at minimum hip flexion than 20 hips with the elevated liner (4.6 ± 2.2 mm, 1.7-10.3, $P < .01$).

Multivariate analyses showed that larger hip flexion angle and smaller cup anteversion were negatively associated with the anterior liner-to-neck distance ($P < .01$; Table 3); larger stem anteversion and use of the elevated rim liner were negatively associated with posterior liner-to-neck distance ($P < .01$; Table 4).

Discussion

This study first examined the participation rate for squatting after THA. To the best of our knowledge, few studies have looked at squatting ability. Significant improvement in squatting ability was found after THA with most patients being able to achieve squatting

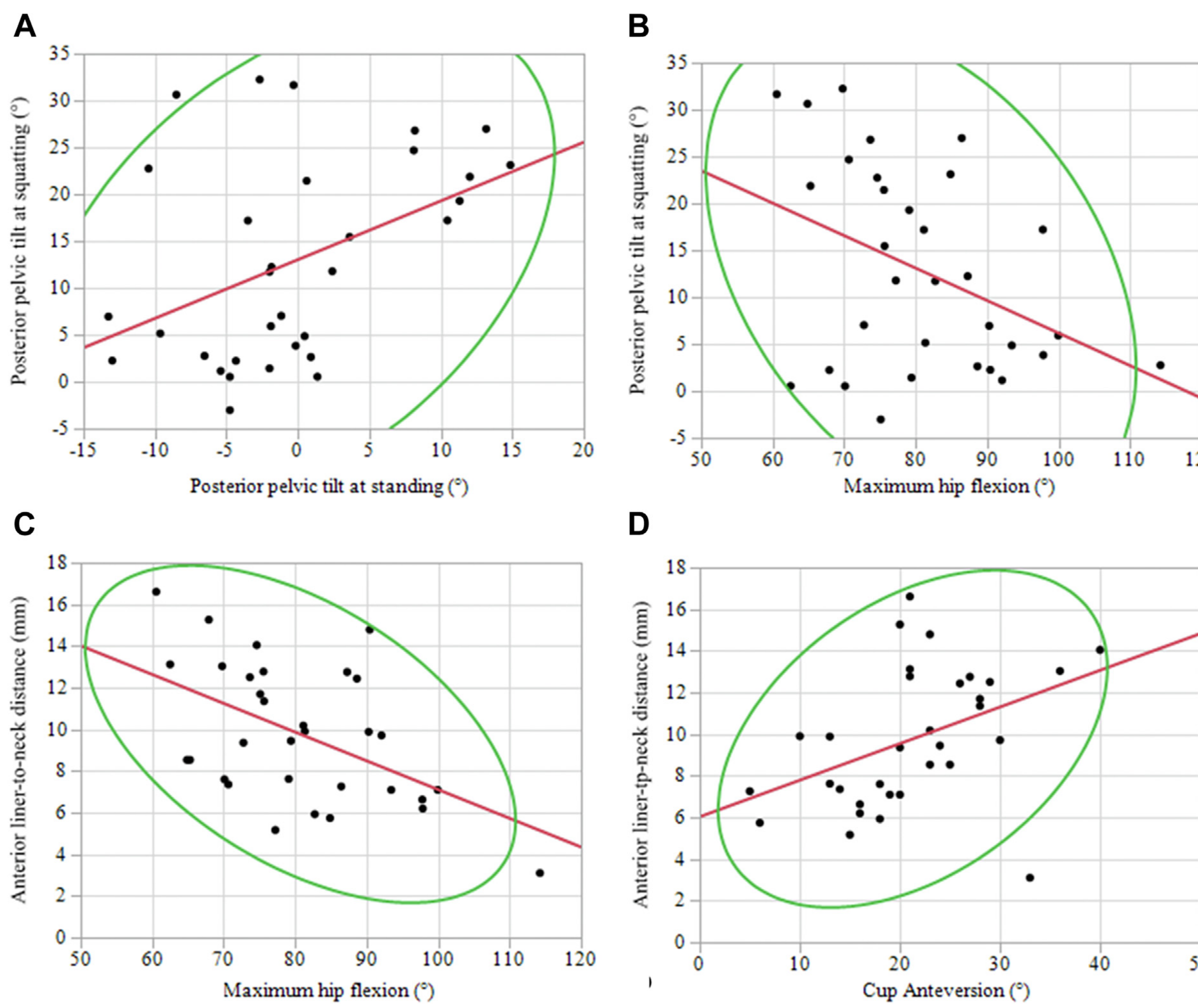

Fig. 5. Posterior pelvic tilt at squatting was significantly correlated with the pelvic tilt at standing (A) and maximum hip flexion at squatting (B). Anterior liner-to-neck distance at maximum hip flexion were significantly correlated with the maximum hip flexion at squatting (C) and cup anteversion (D).

Table 3
Multivariate Analysis of Factors Influencing the Anterior Liner-to-Neck Distance.

	β-Value	Negative Effect	*P*-Value
Kinematics of the hip joint			
Flexion	−0.15	Large ROM	<.01[a]
Adduction			.85
Internal rotation			.72
Orientation of the components			
Cup anteversion	0.12	Small angle	.03[a]
Cup inclination	0.13		.11
Stem anteversion			.60
Hardware variables			
Head size (26 mm vs 32 mm)			.62
Length of stem neck			.97
Liner (flat vs elevated)			.21

The variables were selected using a stepwise multiple regression analysis. β is the standard regression coefficient.
ROM, range of motion.
[a] *P*-values indicate statistically significant differences ($P < .05$).

easily or with some support. The main reason for avoiding squatting was anxiety of dislocation. Therefore, a patient's ability to squat may exceed their own expectation.

Dislocation can occur mainly after impingement between the 2 components during postural changes [31]. Dorr et al and Malik et al recently described how a surgeon needs to consider a patient's functional position, including impingement prone activities such as squatting [32]. Maximum hip flexion during squatting after THA (81° on average) was smaller than in normal subjects (95°-102°) [33,34]. In terms of severely degenerative osteoarthritic hips immediately before THA, 68° on average of maximum hip flexion was reported during squatting [24,35], which is significantly less than in patients after THA. Therefore, residual soft tissue contracture may decrease maximum range of hip flexion under in vivo weight-bearing even after THA. Alternately, lumbar stiffness due to degenerative changes or surgical fusion with pelvic fixation could cause decreased pelvic motion during postural changes requiring a larger range of hip flexion [28]. Therefore, patient-specific optimal orientation based on functional pelvic tilt has been recently proposed in planning THA [36]. When patients squatted, the pelvis tilted posteriorly an average of 12.5°, and the functional cup anteversion changed from 22.1° to 35.8° on average. The pelvises of healthy subjects and patients with end-stage hip osteoarthritis were tilted posteriorly during squatting by 11.7° and 18°, respectively [24]. The pelvic tilt of patients after THA was approximately 7° more anterior than before THA for the same patients without spinal disease [25], which is generally consistent with the 12.8° of posterior pelvic tilt in this study. On the contrary, a previous kinematic study using a coordinate system based on the neutral standing position demonstrated 25.7° of posterior pelvic tilt during squatting after THA [27]. The discrepancy could be explained by different coordinate systems, squatting postures, and spinal diseases. Multiple studies report that a 1° pelvic tilt changes the functional cup anteversion by 0.7°-0.8° [37,38]. However, the pelvis rotated not only anteroposteriorly, but also obliquely and axially during actual squatting motion, possibly affecting the ratio derived from in vivo data. Furthermore, Snijders et al [36] demonstrated that the 3D effect of functional pelvic tilt is specific to the initial acetabular cup orientation and thus to each THA patient, supporting the results of our study. Functional cup orientation significantly depended on pelvic orientation relative to the ground and cup orientation relative to the pelvis. Posterior pelvic tilt at maximum hip flexion varied greatly among individuals and was significantly correlated with pelvic tilt at standing and maximum hip flexion at squatting. Consistent with previous studies [28,35], a significantly larger maximum hip flexion was required in patients with a smaller posterior pelvic tilt at squatting. It is important to understand how in vivo patient-specific kinematic characteristics and component positioning affect functional cup orientation and liner-to-neck clearance, which may allow for a more active lifestyle.

Liner-to-neck contact is a recognized risk factor for increased rates of dislocation accelerated wear, linear fractures, and decreased lifespan of implants [9,39]. In addition to pelvic and functional cup orientation, 3D estimation of liner-to-neck distance under dynamic conditions could provide useful information. However, we found only a few reports that quantified the liner-to-neck distance [25,26]. Consistent with previous studies [40,41], manual placement of the cup in this study resulted in 30% and 55% of outliers from the safe zone defined by Lewinnek et al [30] and our target zone [11,16]. As a result, larger hip flexion angle and smaller cup anteversion were negatively associated with the anterior liner-to-neck distance. Previous computer simulation studies also show that anteversion of cup and stem substantially affects hip flexion range and is critical for avoidance of posterior dislocation after THA [13,42]. However, current patients still achieved sufficient anterior clearance without impingement while squatting. The pelvis moves an average of 12.8° posteriorly with squatting, and this posterior motion opens the cup to provide 9.7 mm of anterior line-to-neck distance on average. In vivo squatting kinematics seem safe against component impingement and dislocation, but the excessively larger hip flexion and smaller cup anteversion still remain risks. In particular, anterior clearance should be maintained, ensuring further unintentional deeply hip flexed, abducted, and internally rotated posture, thus avoiding prosthetic impingement because most dislocations occur in the posterior direction in a posterolateral approach. These data may be beneficial for advising patients after THA regarding postoperative squatting activities in daily life.

In terms of posterior liner-to-neck distance at minimum hip flexion, larger stem anteversion and use of elevated rim liner were negatively associated factors. This result showed the same trend to previous reports that focused on prosthetic impingement [26]. Vigdorchik et al [43] demonstrated that prosthetic impingement occurred at extension in models with a lipped liner. Based on an in vitro replaced 3D CAD bone model simulation study, Sato et al [44] showed that anteversion of the larger cup decreased posterior liner-to-neck distance. Hara et al reported that larger cup anteversion and use of an elevated rim liner were seen in hips with posterior prosthetic impingement compared with hips without impingement during golf swing [26]. Marchetti et al [9] performed a retrieval analysis of 416 acetabular cups in 311 cases and reported that contact was found in 214 of 416 explants (51.4%). In the present study evaluating squatting movements, neither liner-to-neck,

Table 4
Multivariate Analysis of Factors Influencing the Posterior Liner-to-Neck Distance.

	β-Value	Negative Effect	*P*-Value
Kinematics of the hip joint			
Flexion			.41
Adduction			.27
Internal rotation	0.18		.06
Orientation of the components			
Cup anteversion	−0.09		.11
Cup inclination	0		.88
Stem anteversion	−0.10	Large angle	<.03[a]
Hardware variables			
Head size (26 mm vs 32 mm)			.57
Length of stem neck			.94
Liner (flat vs elevated)	−1.4	Use of elevated liner	<.01[a]

The variables were selected using a stepwise multiple regression analysis. β is standard regression coefficient.
[a] *P*-values indicate statistically significant differences ($P < .05$).

bone-to-bone, nor bone-to-implant contact was observed in any hips. However, increased pelvic retroversion was not included in this cohort with −2.9° to 2.6° (95% CI) at a standing pelvic tilt. Patients with larger hip extension due to, for example, flat back deformity may require additional caution regarding stem anteversion and the use of an elevated rim liner as well as cup anteversion during the procedure. When using standard cementless stems, stem anteversion correlates with patient-specific femoral anteversion [45]. Therefore, during preoperative planning, in cases where femoral anteversion is excessively large, adjustment of stem anteversion using changeable neck or cone types should be considered.

The present study had several limitations. First, the number of patients was small. However, significant influencing factors on in vivo liner-to-neck distances were identified in this 3D kinematic study. Second, the present study analyzed only a single component design. Although the design is similar to that of many other components currently available, the results could differ. Third, this study was conducted on Asian patients with shorter stature and lower body weight compared to the average Westerner. Although this study is not directly applicable to THA with a head size larger than 32 mm, our results can still be useful because larger heads increase the impingement-free arc of hip motion [46]. Finally, we only evaluated the kinematics of the hip joint during squatting. Specific postures provide activity-dependent hip kinematics and liner-to-neck clearance.

Conclusions

Based on patient-reported outcomes, 29.5% of patients still could not or did not try to squat postoperatively, with the main reason being anxiety about dislocation. In vivo squatting kinematics seem safe against impingement and subsequent dislocation, but extremely large hip flexion and small cup anteversion remain risks. These results may help surgeons to understand the effect of an individual's replaced hip kinematics and component alignment on the liner-to-neck clearance during squatting.

Acknowledgments

This study was supported by the Grants-in-Aid for Scientific Research of Japan Society for the Promotion of Science (Grant Number 19K09652). The authors thank Goro Motomura, Satoshi Ikemura, Masanori Fujii, Taishi Sato, Shinya Kawahara, Daisuke Hara, Keisuke Komiyama, Kyohei Shiomoto, Masato Kiyohara, and Tetsunari Harada from the Department of Orthopedic Surgery, Faculty of Medical Sciences, Kyushu University and Motoji Yamamoto, Yoshihiko Furuta, and Koki Honda from the Department of Medical-Engineering Collaboration for Healthy Longevity, Kyushu University for providing helpful advice and suggestions during the course of this study.

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