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Effect of Alteration in Hip Joint Alignment following Total Hip Arthroplasty on Hip Joint Contact Force during Gait

Kazutaka Hata[1]*, Yasuhiro Ishido[2], Kiyohiro Fukudome[3], Ryoji Kiyama[3], Masayuki Kawada[3], Tomohiro Nishi[1], Shintaro Nakatsuji[1], Kazunori Yone[3]

1. Doctoral Department, Course of Health Sciences, Graduate School of Health Sciences, Kagoshima University, Kagoshima, Japan,
2. Department of Medical Joint Materials, Graduate School of Medical and Dental Sciences, Kagoshima University, Kagoshima, Japan,
3. Department of Physical Therapy, School of Health Sciences, Faculty of Medicine, Kagoshima University, Kagoshima, Japan,

*Corresponding author: Kazutaka Hata, Doctoral Department, Course of Health Sciences, Graduate School of Health Sciences, Kagoshima University, Kagoshima, Japan, email address: kazutaka.93@gmail.com

Purpose

Investigation of the relationship between changes in hip-joint center and hip loading pre- and post- total hip arthroplasty (THA) is important in evaluating the effect of surgery on motor function. However, few longitudinal studies comparing pre- and post-THA have been reported. The purpose of this study was to determine the effect of changes in hip-joint center pre- and post-THA on the magnitude and direction of hip-joint contact force during the gait cycle, using a patient-specific musculoskeletal model.

Methods

The simulation program AnyBody was used to create musculoskeletal models incorporating patient specific hip-joint shape and hip-joint center position for 17 patients. The relationship between the displacement distance of the hip-joint center and the amount of change in hip-joint contact force was examined by correlation analysis.

Results

A decrease in the medial force ($p \leq 0.049$) and an increase in the anterior force ($p \leq 0.001$) acting on the hip joint were observed during gait post-THA compared to pre-THA. Mediolateral displacement of the hip-joint center post-THA compared to pre-THA was significantly positively correlated with the difference in anterior hip-joint contact force, and negatively to hip-joint medial contact force.

Conclusions

Longitudinal observations revealed the effects of change in hip-joint center position induced by THA on the hip-joint contact force during gait. Therefore, the change of hip-joint center position during THA can be an important factor for estimating the improvement of motor function following THA.

Key words: longitudinal study, gait analysis, musculoskeletal model, hip joint center

1. Introduction

Hip osteoarthritis (OA) induces significant functional impairments and joint pain, resulting in restricted mobility during activities of daily living. Total hip arthroplasty (THA) is one of the most common treatments for hip OA. Reconstruction of impaired hip-joint function can reduce pain and improve motor function and quality of life [16], [25]. A variety of studies have shown that notable functional improvement is observed until 6 months after surgery [23], [30], [37].

In THA hip reconstruction, acetabular implants are not always placed in the appropriate anatomical position due to the degree of acetabular deformity and bone loss, and the hip joint center (JC) position might change postoperatively. Previous cross-sectional studies have suggested that medial or inferior changes in the hip JC induced by THA reduce the hip joint contact force (JCF), while lateral or superior changes increase the hip JCF [7], [13], [24]. The lateral or superior changes in the hip JC after THA decrease the moment arm and the moment generating capacity of the abductor muscles, resulting in the increase in resultant hip JCF [11]. In particular, a superior hip JC induced by THA is considered as one risk factor for loosening of the acetabular component due to increased JCF on the hip [26]. Repeated exchip JCF during activity of daily living causes high stress on cup-bone interface, and decreases the endurance of implant material. These issues suggest the importance of the change in hip JCF magnitude and direction due to alteration of hip JC induced by THA.

Therefore, the quantification of the changes in the hip JCF induced by THA is important in order to evaluate the effect of surgery on motor function. In addition, knowledge of the relationship between changes in hip JC and hip JCF pre- and post-THA would be beneficial for surgeons and therapists engaged in the interventions for patients induced by THA. Previous study, reporting the relationship between the change in hip JC and hip JCF, were analyzed based on cross-sectional analysis. The hip JCF was affected by various patient characteristics including body mass index, age and so other parameters [12]. Thus, cross-sectional analysis necessarily cannot reveal the effect of change of the hip JC on the hip JCF during gait. Hip JCF is often used to estimate hip joint load, because it reflects anatomical joint structure, muscle tension force, and ground reaction force. Bergmann et al. [5] directly measured the *in vivo* JCF during gait using a strain gage inside the implant, and the magnitude and direction of the hip JCF were quantified. However, such mechanical investigations *in vivo* are uncommon as they require insertion of special implants and sophisticated measurement environment. In addition, direct measurements cannot utilize to investigate the hip JCF during gait in pre-THA patients. On the other hand, musculoskeletal model simulation using inverse dynamics is able to estimate hip JCF non-invasively, allowing comparison pre- and post- THA.

Recent studies have reported the benefit of the musculoskeletal model with patient-specific geometry to estimate the JCF in patients with joint deformity [20], [27]. Generic musculoskeletal models are based on healthy subjects, and it cannot adequately reflect the anatomical structure in patients with joint deformity. Therefore, the musculoskeletal model with a patient-specific geometry allows more appropriate estimation of the kinetics during gait compared to analysis using a typically generic musculoskeletal model. Gait analysis using a patient-specific musculoskeletal model could reveal the relationship between changes in the hip JC and hip JCF. However, previous studies have focused on post-THA, with few longitudinal studies comparing pre- and post-THA. The lack of study analyzing the change in hip JCF induced by THA would be mainly due to the difficulty in adaptation of the musculoskeletal model to the deformed hip joint with generic scaling methods by normal bone geometry [21], [27]. Therefore, there is a lack of knowledge regarding the relationship between changes in the hip JC and hip JCF during gait pre- and post-THA.

The purpose of this study was to determine the effect of change in the hip JC induced by THA surgery on the JCF on the hip joint during gait by longitudinal study, using a patient-specific musculoskeletal model. We hypothesized that the amount of change in the hip JC at THA correlates with the amount of change in the magnitude and direction of the hip JCF vector.

2. Materials and methods

2.1. Participants

Sixteen women and one man (age, 61.7 ± 8.5 years; weight, 56.3 ± 7.0 kg; height, 1.547 ± 0.052 m; mean ± standard deviation) with hip OA participated in this study. The severity of hip OA is classified into four stages (pre-OA, initial, advanced, and terminal stages) according to the guidelines of the Japanese Orthopaedic Association [31]. The severity of all patients was terminal. All patients underwent primary unilateral total hip arthroplasty with a lateral approach (9 right-sided THA and 8 left-sided THA). Participants with other neurological or orthopedic diseases and previous surgical intervention or lower extremity trauma such as fractures that could interfere with walking were excluded. This study was approved by the Ethics Committee of Kagoshima University Hospital (Approval Number: 26 -37). According to the principles established in the Helsinki Declaration, written informed consent was obtained from all patients.

2.2. Musculoskeletal modeling

We developed a patient-specific musculoskeletal model based on three-dimensional (3D) computed tomography (CT) data of bilateral hip joint and compared the hip JCF during gait pre- and post-THA. The Twente Lower Extremity Model 2.0 (TLEM) implemented in the AnyBody Modeling System v. 6.0 (AnyBody, AnyBody Technology, Aalborg, Denmark), a musculoskeletal simulation software package, was used to create a musculoskeletal model that incorporated each patient's specific hip-joint shape and hip JC position pre- and post-THA [9].

TLEM consists of a head, thorax, lumbar spine, and both lower limbs. Segments of the lower limb are connected at the hip, knee, and ankle joints. The hip joint is defined by a spherical joint with 3 degrees of freedom, and the total degrees of freedom of the model is 32. The model contains 57 actuators with 173 muscle–tendon elements, described by Hill-type muscle model [6], [22]. Pelvis and bilateral femur shape data obtained from preoperative and postoperative 3D-CT were imported into AnyBody, and a custom scaling function was used to define 30 reference point landmarks at the same sites on the pelvis and bilateral femurs of the 3D-CT and TLEM [2]. The bone shape of TLEM was morphed so that the reference points of the CT data and TLEM were matched as closely as possible, and the pelvic and femoral shapes specific to the subjects were implemented in TLEM (Figure 1a) [3]. Another bone shape was morphed from the default bone shape in TLEM by each patient's anthropometric data. The muscle attachments were repositioned based on the results of morphing and scaling of the bone geometry.

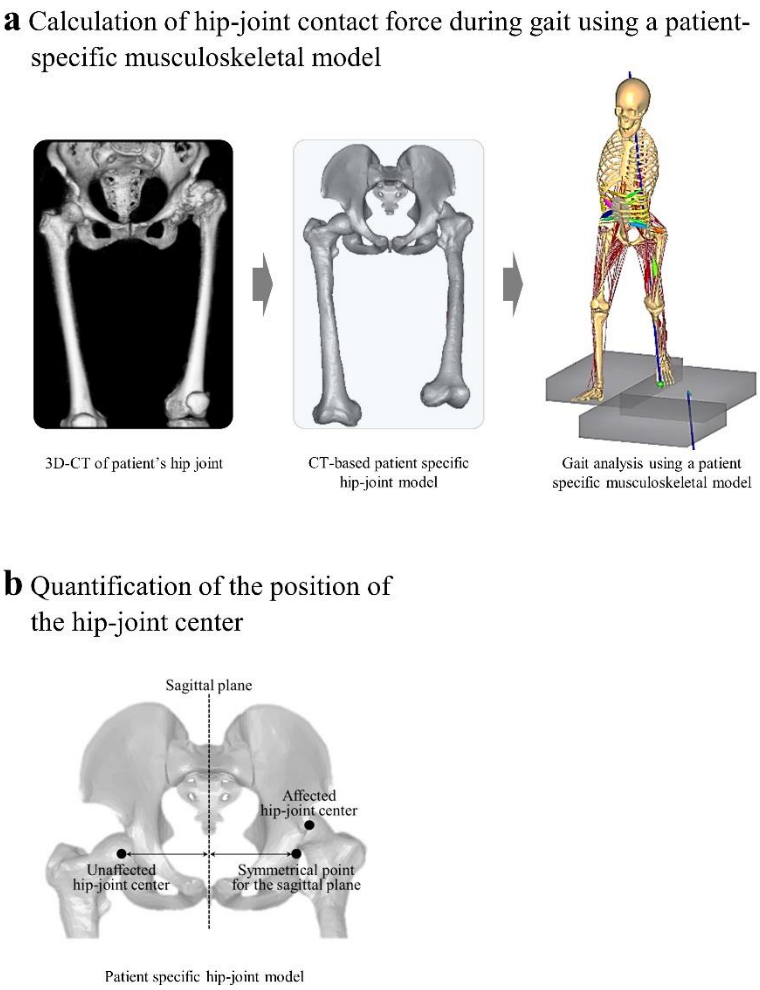

Figure 1 — a Hip-joint contact forces were estimated by gait analysis using a musculoskeletal model (AnyBody) with a patient's specific hip-joint shapes and hip-joint center position defined based on 3D-CT data. b The affected hip-joint center position was calculated as the position relative to the symmetrical point for the sagittal plane of the unaffected hip-joint center.

2.3. Experimental protocol

The hip JC position on the affected side pre- and post-THA was calculated using 3D preoperative planning software for THA (ZedView 6.5 Standard LEO 237, LEXY, Tokyo, Japan). The sphere closest to the 3D reconstruction of the femoral head or the hip prosthesis head was fitted, and the center coordinates of the sphere were calculated as hip JC [32]. The affected hip JC position was calculated as the position relative to the symmetrical point of the unaffected hip JC for the sagittal plane in the anteroposterior (A/P), superior-inferior (S/I), and mediolateral (M/L) directions (anterior, superior, and medial as positive; Figure 1b). Then, the absolute difference, along the three planes, between preoperative and postoperative hip JC location (Diff-JC) was calculated.

Gait analysis was performed twice, 1 or 2 days before THA and approximately 6 months after surgery (184.0 ± 24.1 days). The subject walked barefoot at a self-selected speed along a 10-meter walking path without a walking aid or physical support at least 10 times [27]. Trajectories of 28 markers placed on the participant's torso, pelvis, and bilateral lower extremities, according to the Plug-in Gait model [10] were recorded at 100 Hz using a 3D motion capture system consisting of 7 cameras (VICON, Oxford Metrics, UK). Ground reaction forces were recorded at 1000 Hz using 2 force plates (AMTI Inc., Watertown, MA, USA). Marker trajectories and ground reaction forces were processed using a Butterworth low-pass filter with cutoff frequencies of 5 and 12 Hz, respectively [35]. Gait cycle events (initial contact, toe off) was determined from ground reaction force and the trajectory of heel marker, and the one gait cycle stepping on the force plate in the middle of each trial were analyzed. Data for five gait cycles were used for further analysis. Gait speed and step length were calculated using the coordinate data of the trajectories of heel markers.

The kinematic and kinetic data obtained from the motion capture system and the force plates were input to AnyBody, and the lower limb joint angle, muscle tension, and JCF during gait were calculated using the inverse dynamics and optimization method (Figure 1a) [9]. Optimization was performed to minimize the total load of the muscle, indicated by the sum of the cube of the ratio of muscle output in the maximum muscle force of each muscle [14], [17].

Hip JCF was calculated in the femoral coordinate system defined according to the recommendations of the International Society of Biomechanics and normalized by body weight (BW) [38]. The hip JCF vector was defined as the JCF vector acting from the femoral head to the pelvis (Figure 2). The gait cycle was divided into an initial double-limb support phase (IDS), a single-limb support phase (SST), and a terminal double-limb support phase (TDS) [28]. The resultant force of the hip JCF vector in each phase was calculated and the maximum value was used as the representative value. In addition, the A/P, S/I, and M/L components, and the inclination angles of the vector of the maximum hip JCF in each gait phase were determined (Figure 2). The difference in magnitude of each component of the hip JCF pre- and post-THA (Diff-JCF) was also calculated.

2.4. Statistical analysis

We compared the gait speed, bilateral step length, bilateral hip flexion, extension, abduction, and adduction angles, hip JC position and hip JCF of the affected side, and the inclination angles of the maximum hip JCF vector of the affected side pre- and post-surgery, to analyze the kinematic and kinetic changes following THA. All variables were examined for normality using the Shapiro-Wilk test, and if a normal distribution could be assumed, the paired-samples t-test was used, otherwise, the Wilcoxon signed-rank test was used. The effect size r was also calculated [8].

Effect of the displacement of hip JC provided by THA on change in hip JCF was examined by correlation analysis between Diff-JC (A/P, S/I, and M/L) and Diff-JCF (A/P, S/I, and M/L), pre- and post-THA. Correlation analysis was performed by Pearson's product-moment correlation coefficient or Spearman's rank correlation coefficient based on the results of the Shapiro-Wilk test. All statistical analyses were performed using SPSS statistics 26.0 (IBM, US) with a significance level of <5%. Effect size was classified into small (r = 0.10), medium (r = 0.30), and large (r = 0.50), according to a previous study [8].

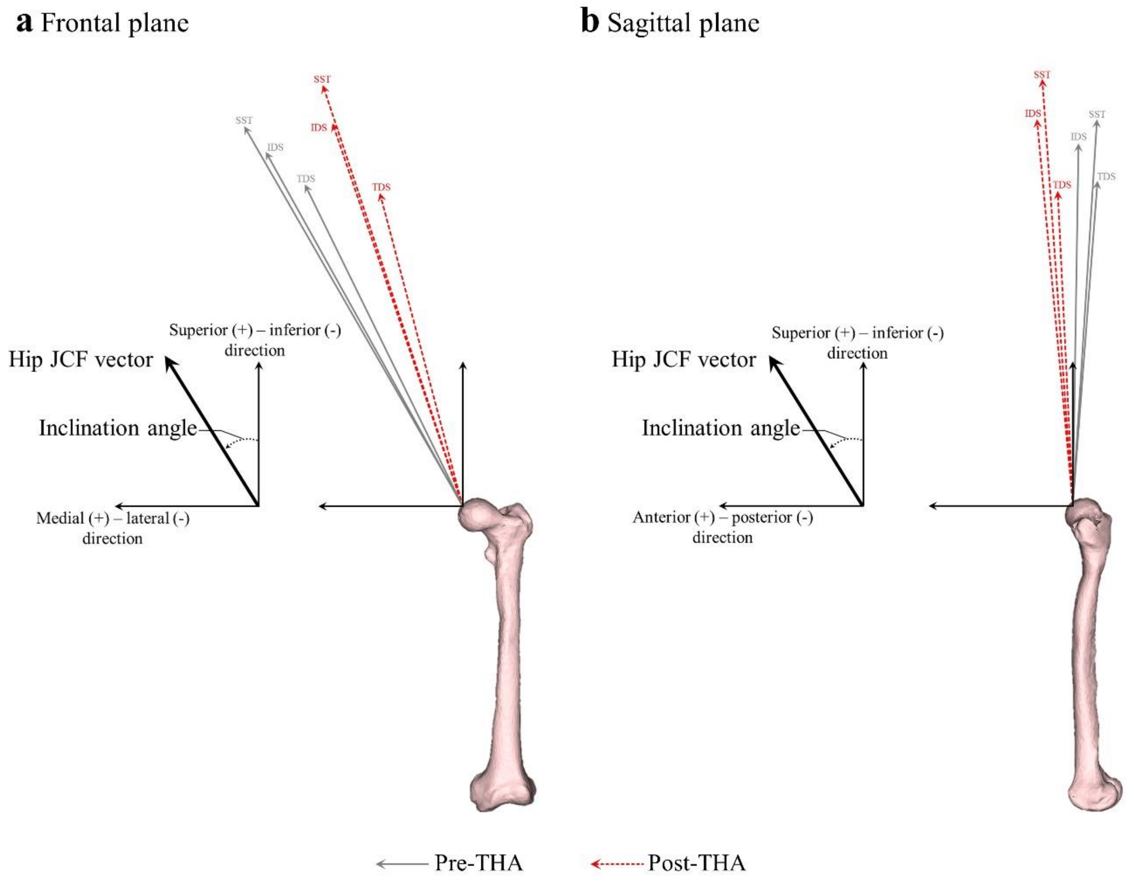

Figure 2 — Hip-joint contact force (JCF) vectors and the inclination angles (positive medial and anterior inclination) of the vector in the femoral coordinate system (positive superior, medial, and anterior) pre- (gray-solid line) and post- (red-dashed line) total hip arthroplasty (THA) during each phase of the gait cycle; IDS - initial double-limb support phase, SST - single-limb support phase, TDS - terminal double-limb support phase: a) frontal plane; b) sagittal plane.

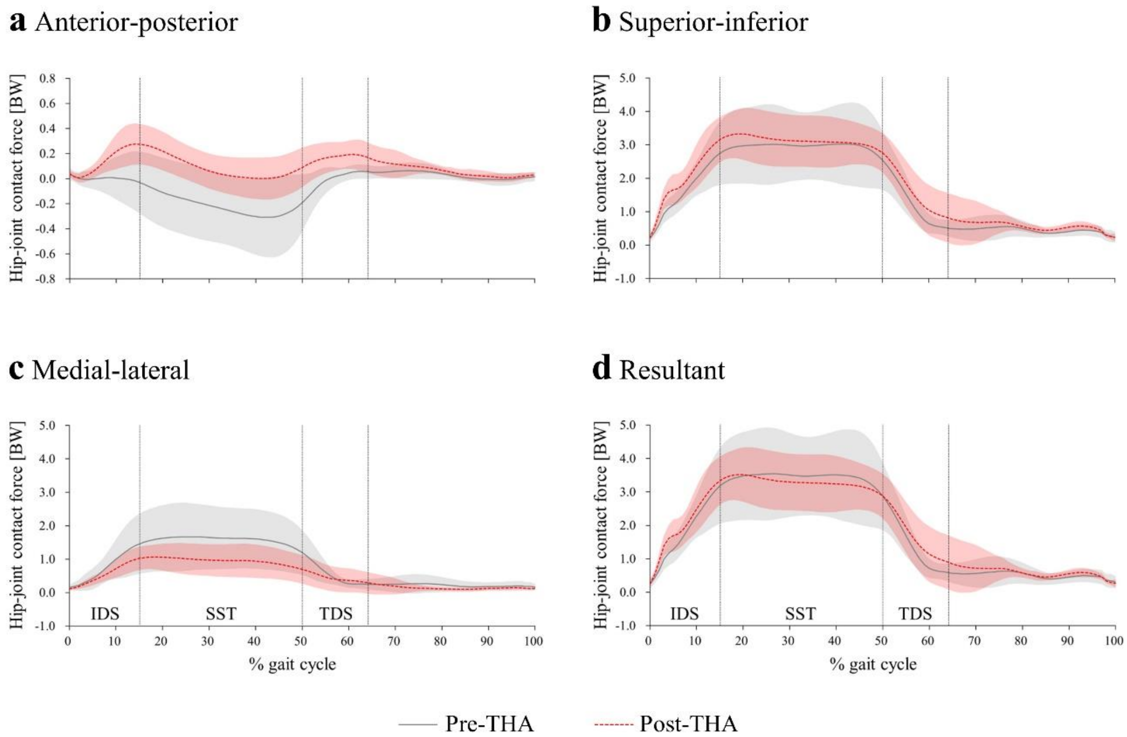

Figure 3 — The components of hip-joint contact force (a: anterior-posterior, b: superior-inferior, c: medial-lateral) and resultant force (d) pre- (gray-solid line) and post- (red-dashed line) total hip arthroplasty (THA) expressed as body weight (BW) through the gait cycle (mean ± SD); IDS - initial double-limb support phase, SST - single-limb support phase, TDS - terminal double-limb support phase.

3. Results

3.1. Gait speed and kinematics

Gait speed ($p = 0.015$) and step length ($p < 0.001$) were significantly increased post-THA (Table1). The maximum flexion and extension angle of the affected hip joint during gait were also significantly increased post-THA (flexion angle, $p = 0.030$; extension angle, $p = 0.028$; Table1), but there were no significant changes in the maximum hip abduction and adduction angle (abduction angle, $p = 0.078$; adduction angle, $p = 0.210$; Table1).

3.2. Position of the hip-joint center

Hip JC of the affected side pre-THA was displaced laterally by 7.25 ± 8.49 mm, superiorly by 3.96 ± 7.69 mm, and slightly anteriorly by 2.21 ± 4.94 mm compared to the unaffected side due to hip-joint deformity (Table 1). THA moved the hip JC medially by 11.65 ± 5.61 mm and posteriorly by 4.93 ± 2.97 mm ($p < 0.001$, Table 1). THA also moved the hip JC inferiorly by 1.75 ± 5.93 mm, but showed no significant difference ($p = 0.254$, Table 1).

3.3. Hip-joint contact force and vector inclination angle

The waveform of the A/P component of the hip JCF in the affected side during the stance phase showed a maximum value in the posterior component pre-THA and showed a bimodal anterior peak post-THA (Figure 3a). The A/P component of hip JCF changed direction significantly from posterior to anterior post-THA ($p \leq 0.001$, Table 2), and resulted in alteration of the inclination angle of hip JCF vector in the sagittal plane from posterior to anterior ($p < 0.001$, Table 2).

The waveform of the M/L component of hip JCF showed that the acetabulum received medial force during the stance phase (Figure 3c), and the medial force significantly decreased post-THA compared with pre-THA ($p \leq 0.049$, Table 2). As a result, the inclination angle of the hip JCF vector at the frontal plane significantly decreased and changed vertically after surgery ($p \leq 0.004$, Table 2). The effect size of the changes in each component of the hip JCF was 0.477–0.878 (Table 2), and that of the change in the vector inclination angle was 0.695–0.852 (Table 2); effect size was large. On the other hand, the Resultant and S/I component waveforms of hip JCF showed maximum values at SST (Figure 3a and d), with no significant changes following THA in any phase ($p > 0.062$, Table 2).

Table 1 Gait parameters, kinematics, and hip-joint center position of affected side pre- and post-THA

	Pre-THA	Post-THA	*p*-value	Effect size r
Gait parameters				
Gait speed (m/s)	0.74 ± 0.19	0.84 ± 0.23	**0.015**	0.591
Step length of unaffected side (m)	0.43 ± 0.07	0.48 ± 0.08	**0.001**	0.709
Step length of affected side (m)	0.43 ± 0.09	0.49 ± 0.08	**<0.001**	0.775
Maximum hip-joint flexion angle (°)				
Unaffected side	23.80 ± 9.42	16.59 ± 5.40	**0.002**	0.690
Affected side	14.69 ± 7.69	18.60 ± 4.19	**0.030**	0.513
Maximum hip-joint extension angle (°)				
Unaffected side	12.02 ± 9.56	16.71 ± 9.13	**0.025**	0.526
Affected side	5.12 ± 9.33	10.10 ± 8.18	**0.028**	0.516
Maximum hip-joint abduction angle (°)				
Unaffected side	1.88 ± 3.52	2.13 ± 2.72	0.768	0.075
Affected side	0.86 ± 3.57	2.88 ± 3.51	0.078	0.425
Maximum hip-joint adduction angle (°)				
Unaffected side	4.36 ± 3.98	5.01 ± 2.70	0.496	0.172
Affected side	4.76 ± 3.66	3.25 ± 3.10	0.210	0.310
Hip-joint center position of affected side (mm)				
A/P direction	2.21 ± 4.94	-2.72 ± 4.58	**<0.001**	0.856
S/I direction	3.96 ± 7.69	2.20 ± 7.31	0.254	0.284
M/L direction	-7.25 ± 8.49	4.40 ± 7.14	**<0.001**	0.901

Values are mean ± standard deviation.

Bold indicates significant correlation p < 0.05.

THA, Total hip arthroplasty.

A/P, Anterior (+)/Posterior (-); S/I, Superior (+)/Inferior (-); M/L, Medial (+)/Lateral (-).

3.4. Relationship between change in hip-joint center and change in hip-joint contact force

The M/L component of Diff-JC was significantly positively correlated with the A/P component of Diff-JCF in IDS (r = 0.514, p = 0.035) and SST (r = 0.599, p = 0.011), and significantly negatively correlated with the M/L component throughout stance phase (r = -0.815 to -0.787, $p < 0.001$, Table 3). Shifting of hip JC in the M/L direction induced by THA increased the anterior force and reduced the medial force on hip JCF. On the other hand, the A/P and S/I components of Diff-JC post-THA were not significantly correlated with Diff-JCF (r = -0.429 to 0.446, $p \geq 0.073$, Table 3).

Table 2 Maximum hip-joint contact force and vector inclination angle on the affected side during the stance phase pre- and post-THA

	Phase in gait cycle	Pre-THA	Post-THA	*p*-value	Effect size r
Maximum of hip-joint contact force (BW)					
Resultant	IDS	3.11 ± 1.07	3.03 ± 0.73	0.586	0.054
	SST	3.81 ± 1.34	3.87 ± 0.71	0.906	0.029
	TDS	3.01 ± 1.44	2.73 ± 0.60	0.435	0.189
A/P component	IDS	-0.03 ± 0.24	0.27 ± 0.14	**0.001**	0.803
	SST	-0.17 ± 0.38	0.25 ± 0.16	**0.001**	0.832
	TDS	-0.22 ± 0.33	0.12 ± 0.16	**<0.001**	0.878
S/I component	IDS	2.70 ± 0.92	2.86 ± 0.70	0.637	0.119
	SST	3.25 ± 1.17	3.64 ± 0.67	0.062	0.454
	TDS	2.67 ± 1.28	2.63 ± 0.52	0.554	0.144
M/L component	IDS	1.38 ± 0.84	0.93 ± 0.32	**0.049**	0.477
	SST	1.78 ± 0.97	1.21 ± 0.44	**0.028**	0.534
	TDS	1.24 ± 0.82	0.66 ± 0.40	**0.009**	0.637
Inclination angles of hip-joint contact force vector (°)					
Angle in frontal plane	IDS	25.75 ± 10.80	17.87 ± 4.64	**0.004**	0.695
	SST	27.74 ± 10.71	18.14 ± 5.44	**0.001**	0.832
	TDS	23.51 ± 10.37	13.03 ± 6.02	**<0.001**	0.771
Angle in sagittal plane	IDS	-0.57 ± 4.59	5.28 ± 2.01	**<0.001**	0.808
	SST	-2.31 ± 4.68	3.93 ± 2.32	**<0.001**	0.781
	TDS	-4.15 ± 3.23	2.52 ± 3.41	**<0.001**	0.852

Values are mean ± standard deviation.
Bold indicates significant correlation $p < 0.05$.
THA, Total hip arthroplasty.
A/P, Anterior (+)/Posterior (-); S/I, Superior (+)/Inferior (-); M/L, Medial (+)/Lateral (-).
IDS, Initial double-limb support phase; SST, Single-limb support phase; TDS, Terminal double-limb support phase.

4. Discussion

The purpose of this study was to clarify the effects of hip JC alteration pre- and post-THA on the load acting on the hip joint. Simulation using a patient-specific musculoskeletal model to estimate the hip JCF during gait showed that the medial component of the hip JCF significantly decreased, and the A/P component changed direction from posterior to anterior after surgery. As a result, the direction of the hip JCF vector changed in the vertical in the frontal plane, and anterior in the sagittal plane. In addition, the change in A/P and M/L hip JCF was found to be significantly correlated with the amount of change in hip JC position, thus supporting our hypothesis. The strong point of this study is that it revealed the effects of change in hip JC position induced by THA on the hip JCF during gait through longitudinal observation.

Table 3 Relationship between change in hip joint center position and change in joint contact force on the affected side post-THA

Variables	Phase in gait cycle	Diff-JC					
		A/P direction		S/I direction		M/L direction	
		Correlation coefficient	*p*-value	Correlation coefficient	*p*-value	Correlation coefficient	*p*-value
Diff-JCF							
A/P component	IDS	0.302	0.238	-0.007	0.978	0.514	**0.035**
	SST	0.263	0.308	0.029	0.911	0.599	**0.011**
	TDS	0.407	0.105	0.064	0.808	0.444	0.074
S/I component	IDS	0.234	0.366	-0.194	0.456	-0.428	0.087
	SST	0.115	0.660	-0.272	0.291	-0.238	0.358
	TDS	0.120	0.646	-0.382	0.130	-0.407	0.105
M/L component	IDS	0.404	0.107	-0.289	0.260	-0.787	**<0.001**
	SST	0.446	0.073	-0.328	0.198	-0.800	**<0.001**
	TDS	0.383	0.130	-0.429	0.086	-0.815	**<0.001**

Values are correlation coefficient.
0.00–0.19 "Very weak", 0.20–0.39 "Weak", 0.40–0.59 "Moderate", 0.60–0.79 "Strong", 0.80–.0 "Very strong".
Bold indicates significant correlation $p < 0.05$.
THA, Total hip arthroplasty.
A/P, Anterior (+)/Posterior (-); S/I, Superior (+)/Inferior (-); M/L, Medial (+)/Lateral (-).
IDS, Initial double-limb support phase; SST, Single-limb support phase; TDS, Terminal double-limb support phase.
Diff-JC, Difference in preoperative and postoperative hip-joint center location of the affected side.
Diff-JCF, Difference in preoperative and postoperative hip-joint contact force of the affected side.

Previous studies report that gait speed and step length are increased significantly by 6 months post-THA compared with pre-THA [30], [36]. Similarly, the present study showed a significant increase in gait speed and step length after surgery. The flexion and extension angle of the operated hip join was significantly increased post-THA, and this alteration contributed to the increase in gait speed and step length.

The maximum resultant force in hip JCF post-THA was 3.87 ± 0.71 BW, and the maximum inclination angle was about 18° medially in the frontal plane and about 5° anteriorly in the sagittal plane. Skubich et al. report that the hip JCF reached 4.04 BW during gait using musculoskeletal model simulation in healthy subjects [35]. Bergmann et al. also report that the direction of the hip JCF vector inclined medially, 13–21°, in the frontal plane and slightly anteriorly, -1–11°, in the sagittal plane post-THA following analysis *in vivo* [4]. Our results were consistent with those reported by previous studies, both pre- and post-THA.

The hip JCF inclined anteriorly and the medial JCF decreased post-THA in the present study. Previous studies report that the frontal and sagittal JCF vector angles in hip JCF are influenced by the anatomical structure of the hip [40] and that increased medial force and decreased anterior component are observed in hip malformation compared with healthy subjects [19], [34]. Lateral migration of the hip JC decreases the abductor moment arm and consequently increase the hip JCF [11].

Approximately a 5° increase in the hip extension angle during gait, an anterior tilt of the hip JCF vector, and a greater than 0.3 BW increase in anterior hip JCF were observed in affected side post-THA. Change in the hip extension angle during gait post-THA would also impose an effect on the direction and magnitude of the hip JCF vector in the sagittal plane. A previous study reported that a 2° increase in hip extension angle during gait leads to an increase of 0.2 BW in the anterior hip JCF [29]. Meanwhile, a significant relation between the displacement distance of hip JC post-THA and the increase in the A/P hip JCF was observed in this study. These results indicate the importance of the alteration of the position of hip JC following THA for hip-joint load and gait function.

Current results showed that participants could walk with increased speed and step length post-THA without an increasing the magnitude of the Resultant of hip JCF [18]. Change in hip JC position following THA would increase the moment arm of the hip abductor muscles, allowing hip muscle to efficiently generate joint moments during gait. These alterations induced with change in hip JC position post-THA might contribute to the increased gait speed without excessive hip JCF [1], [13]. Therefore, alteration of the hip JC position induced by THA would provide benefit to gait function in patients hip OA. Otherwise, several limitations should be noted in this study. The small sample size and recruitment of THA patients with a lateral approach might make it difficult to generalize the present results [33], [39]. The magnitude and direction of the hip JCF post-THA in the current study were similar to a previous study, but the accuracy was less reliable than for *in vivo* measurement using an implant [15]. We also did not analyze factors affecting the hip JCF during gait, such as muscle strength, muscle tension force, and femur neck length and angle. On the other hand, contrary to our expectations and previous studies, no significant change in the vertical direction of hip JC position was observed in this study. These issues should be addressed in the further study.

5. Conclusions

In conclusion, a significant relationship among the displacement distance of M/L hip JC following THA, a decrease in the M/L force, and an increase in A/P hip JCF were found in this study. These results suggest that the change of hip JC position induced by THA can be an important factor for estimating the improvement of motor function in rehabilitation patients post-THA. Therefore, due attention should be paid to changes in the individual hip JC position in patients post-THA.

Acknowledgments

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Figure Captions

Figure 1 — **a** Hip-joint contact forces were estimated by gait analysis using a musculoskeletal model (AnyBody) with a patient's specific hip-joint shapes and hip-joint center position defined based on 3D-CT data. **b** The affected hip-joint center position was calculated as the position relative to the symmetrical point for the sagittal plane of the unaffected hip-joint center.

Figure 2 — Hip-joint contact force (JCF) vectors and the inclination angles (positive medial and anterior inclination) of the vector in the femoral coordinate system (positive superior, medial, and anterior) pre- (gray-solid line) and post- (red-dashed line) total hip arthroplasty (THA) during each phase of the gait cycle; IDS - initial double-limb support phase, SST - single-limb support phase, TDS - terminal double-limb support phase: a) frontal plane; b) sagittal plane.

Figure 3 — The components of hip-joint contact force (a: anterior-posterior, b: superior-inferior, c: medial-lateral) and resultant force (d) pre- (gray-solid line) and post- (red-dashed line) total hip arthroplasty (THA) expressed as body weight (BW) through the gait cycle (mean ± SD); IDS - initial double-limb support phase, SST - single-limb support phase, TDS - terminal double-limb support phase.