



Full length article

Effect of femoral offset and limb length discrepancy on hip joint muscle strength and gait trajectory after total hip arthroplasty

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ABSTRACT

Background: Femoral offset (FO) and limb length discrepancy (LLD) are important perioperative considerations when performing THA. Decreased FO prevents improvement of gait and muscle recovery and residual LLD has a prominent influence on patient satisfaction with THA, while few studies have investigated the relationship between FO and/or LLD and gait disturbances. We investigated the association between these two factors and hip muscle strength and the results of 3-D gait analysis after THA.

Methods: We evaluated 92 patients (including 20 patients who underwent gait analysis) in whom total hip arthroplasty was performed for unilateral severe osteoarthritis of the hip joint. FO and LLD were measured on a standard anteroposterior radiograph of the pelvis. Hip muscle strength was evaluated by isometric hip flexion (in the manner of straight leg raising test: SLR) and hip abduction strength. To evaluate 3-D walking trajectory, we used a portable gait analyzer.

Results: Reduction of global FO by > 5 mm after THA compared to the contralateral hip was associated with hip abductor muscle weakness. On the other hand, LLD ≤ 20 mm had no influence on hip abductor muscle strength and SLR strength. In gait analysis, SLR strength showed a significant difference between the sagittal plane symmetrical and asymmetrical groups.

Conclusion: Postoperative global FO > 5 mm less than that of the contralateral hip was associated with hip abductor muscle weakness. And, from the results of 3-D gait analysis, SLR weakness may increase gait asymmetry in the sagittal plane.

1. Introduction

Femoral offset (FO) and limb length discrepancy (LLD) are important perioperative considerations when performing total hip arthroplasty (THA). In particular, decreased FO is a concern because it may prevent improvement of gait and muscle recovery. Previous reports have indicated low abductor muscle strength [1–7] and poor hip function [8] compared to the healthy side in patients with decreased FO on the operated side. FO has commonly been defined as the distance between the center of rotation of the prosthetic femoral head and the long axis of the femur on radiographs [9]. However, this does not take into account changes caused by differences in positioning of the acetabular cup. The cup position is usually measured separately as the distance between the center of the prosthetic femoral head and a perpendicular line passing through the medial border of the ipsilateral

acetabular teardrop, and this is referred to as the cup offset [10]. Recently, it was proposed that global FO, which combines conventional FO and cup offset, should be used when evaluating the influence of FO on the clinical results of THA [9,11,12].

In patients with severe hip osteoarthritis, THA makes it possible to correct shortening of the leg resulting from destruction of the femoral head and acetabulum. Leg shortening that leads to marked LLD is more likely to occur in patients with OA due to developmental dysplasia of the hip (DDH). Generally, LLD can be completely corrected in patients with mild to moderate DDH (Crowe classes I or II), but complete restoration is challenging in patients with severe DDH. Although residual LLD has a prominent influence on patient satisfaction with THA, few studies have investigated the relationship between LLD and muscle strength and/or gait disturbance [14,15,21–24] [13–18].

Among the many methods for investigating gait, we used a portable

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gait analyzer based on inertial sensors to evaluate three-dimensional (3-D) changes of the walking trajectory. In patients with unilateral osteoarthritis of the hip, asymmetry of the walking trajectory is clearly observed in the coronal, sagittal and horizontal planes before THA, while the trajectory becomes symmetrical from 3 months or more postoperatively in many patients [19]. However, the walking trajectory does not become symmetrical after THA in a few patients with unilateral hip OA. In these patients, we hypothesized that global FO may be short and/or leg length may not have been corrected properly. Accordingly, we investigated the association between these two factors (global FO and LLD) and hip muscle strength and the results of 3-D gait analysis after THA.

2. Patients and methods

2.1. Subjects

This study was approved by our institutional review board, and informed consent was obtained from all of the patients. We evaluated 92 patients (including 20 patients who underwent gait analysis) in whom unilateral THA was performed with a minimum postoperative follow-up period of 12 months. All patients underwent regular review at our outpatient clinic from April 2016 to March 2017 and patients with functional, neurological, or morphological disorders affecting their gait were excluded from this study. Patients with adaptive soft tissue shortening, hip or knee joint contractures, ligamentous laxity, axial malalignment, abnormal foot mechanics, and torsion of the pelvis were also excluded from this study. All patients had a disease-free contralateral hip with radiological findings. The patients included 78 women and 14 men with a mean age of 70.5 years (range: 54–87 years) and the mean postoperative period was 6.8 years (range: 1 to 29 years). FO of the stem varied with each type of prosthesis as a result of attempts to optimize kinematics for individual patients based on preoperative radiographs. A posterior approach was employed in all cases, and further intraoperative assessment of FO and LLD was not done. The 20 patients who received THA from April 2016 to March 2017 also underwent gait analysis. They included 16 women and 4 men with a mean age of 67.1 years (range: 54–84 years). These patients underwent gait analysis and muscle strength testing at one year postoperatively.

The patients were divided into the following 3 groups based on radiographic measurements: reduced FO group (reduced by > 5 mm on the operated side compared to the contralateral side), restored FO group (within 5 mm of that on the contralateral side), and increased FO group (increased by > 5 mm on the operated side compared to the contralateral side) (Fig. 1). A cut-off value of 5 mm was selected to divide the patients into groups because it was used in several previous studies [4,7,8]. Similarly, the patients were divided into 3 groups depending on the difference of limb length (LL) between the healthy and operated sides: undercorrected LL group (reduced by > 10 mm), restored LL group (within 10 mm), and overcorrected LL group (increased by > 10 mm) (Fig. 1). The distance of 10 mm was also selected on the basis of previous reports [13,14].

2.2. Radiographic assessment

Global FO and LLD were measured on a standard anteroposterior radiograph of the pelvis. During radiographic examination, the patient lay supine with both lower extremities in the neutral position for abduction or adduction and 15 degrees of internal rotation. The X-ray beam was centered on the symphysis pubis with a film focus distance of 115 cm [20]. For evaluation, the hip joint center was defined as the geometrical center of the femoral head/prosthetic femoral head. Global FO was calculated as the distance from the longitudinal axis of the femur to the center of the femoral head plus the distance from the center of the femoral head to a perpendicular line passing through the medial border of the ipsilateral teardrop point of the pelvis (Fig. 2). LL

was determined by drawing a line through the inferior borders of the teardrops (inter-teardrop line or Koehler line) and measuring the distance to the superior margin of the lesser trochanter [21]. A positive value indicated that FO or LL of the operated hip was greater than on the contralateral side, while a negative value indicated the opposite. Measurements were calibrated by using a 30-mm radiopaque standardized metal sphere to assess the magnification. A 1-mm precision scale was used.

2.3. Muscle strength test

The maximum voluntary bilateral hip flexion strength (straight leg raising: SLR) and abduction strength were measured with a hand-held dynamometer (Isoforce GT-300, OG Giken, Japan) during isometric contraction of the relevant muscles against manual resistance for 3 s. The subject rested in the supine position with both hip in the neutral position for flexion/extension and abduction/adduction. The dynamometer sensor was placed at the proximal border of the patella when assessing hip flexion. Similarly, the sensor was placed 5 cm above the proximal border of the lateral malleolus when assessing hip abduction. For comparison of muscle strength, the ratio between the operated side and the normal side (%) was determined in each patient.

2.4. Gait analysis

A portable gait rhythmograph (MG-M 1110, LSI Medience Co, Tokyo, Japan) was used for gait analysis. This small device ($8 \times 6 \times 2$ cm) only weighs 80 g and houses an accelerometer. Gait-induced acceleration is extracted from limb and trunk movements by using an automatic detection algorithm [22,23], allowing 3-D measurement of acceleration associated with voluntary limb and trunk movements, as well as acceleration induced by heel strike and toe-off when walking. The device was secured at the patient's waist using a belt. With the patient standing in the anatomical position, the three acceleration axes (X, Y, and Z) were oriented in the mediolateral, vertical, and anteroposterior directions, respectively. Thus, a positive X value represented acceleration to the left, a positive Y value indicated upward acceleration, and a positive Z value indicated forward acceleration. Data were collected at a sampling frequency of 100 Hz and stored on a microSD card in the device for subsequent analysis and recorded data were analyzed with MATLAB software (The MathWorks Inc., Natick, MA), which automatically estimates the principal axes, detects peak points, calculates 3-D motion trajectory, and performs 3-D visualization of gait symmetry/asymmetry without requiring manual tuning or input of subject-specific parameters [24]. The walking trajectory of a healthy young person is relatively symmetrical in the coronal, sagittal, and horizontal planes, while the trajectory forms a figure-8 in the coronal and horizontal planes. On the other hand, the walking trajectory of the preoperative patients was asymmetric in the coronal, sagittal, and horizontal planes, and the trajectory did not form a figure-8 in the coronal and horizontal plane (Fig. 3).

2.5. Statistical analysis

Based on our hypothesis that uncorrected postoperative global FO and uncorrected LLD would each influence postoperative hip abductor muscle strength or SLR strength as single variables, analysis of variance (ANOVA) for parametric variables was used to compare differences among the 3 FO groups (reduced FO vs. restored FO vs. increased FO) with regard to the operated side / normal side ratio of hip abductor strength or the operated side / normal side ratio of SLR strength. Similarly, ANOVA was used to compare differences among the 3 LLD groups (undercorrected LL vs. restored LL vs. overcorrected LL) with regard to the operated side / normal side ratio of abductor strength or the operated side / normal side ratio of SLR strength. Second, the postoperative operated side / normal side ratio of hip abductor muscle

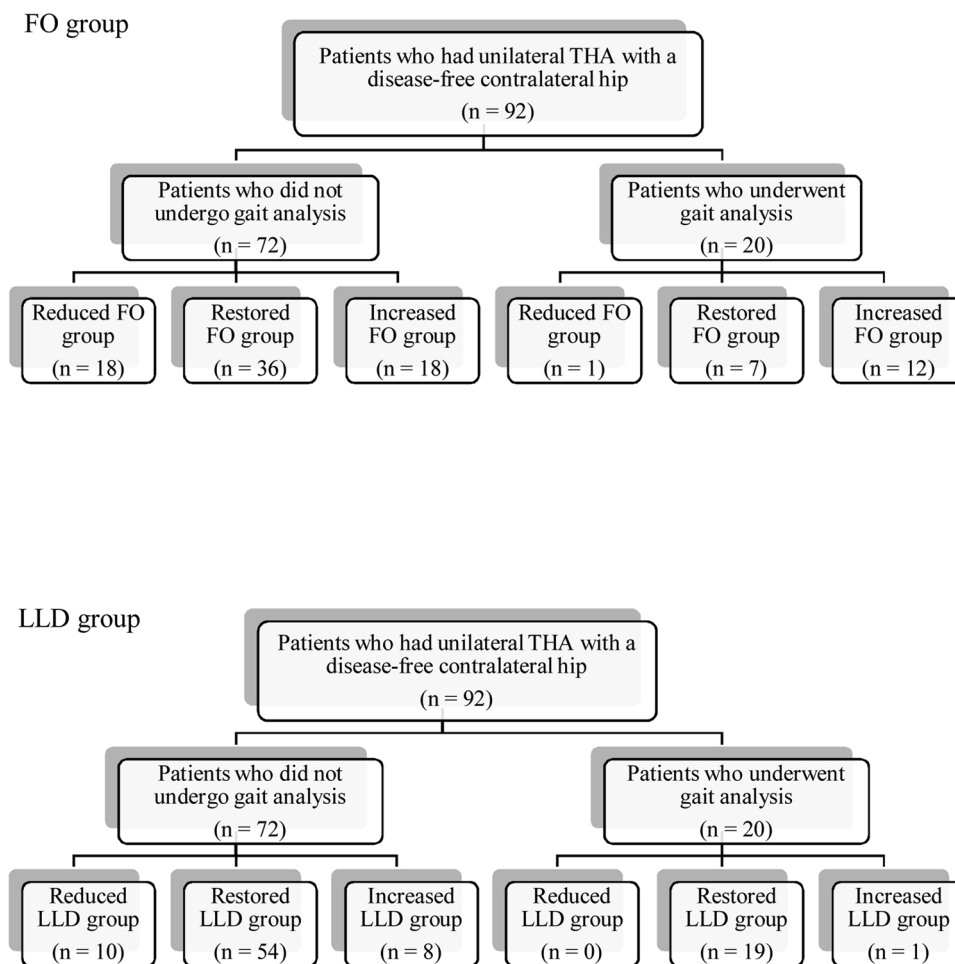


Fig. 1. Flow diagram for patients included.

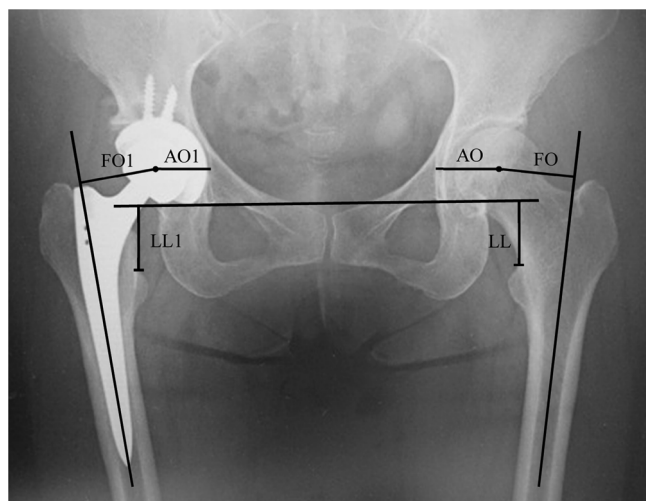


Fig. 2. Measurement of global FO and limb length.

To obtain global FO, the distance between the longitudinal axis of the femur and the center of the femoral head (FO1) was added to the distance from the center of the femoral head to a perpendicular line passing through the medial border of the ipsilateral teardrop point of the pelvis (AO1). Measurement was done on both sides, and global FO of the operated side (FO1 + AO1) was compared with that of the unoperated side (FO + AO). Limb length (LL) was obtained by drawing a line through the inferior aspects of the teardrops and measuring the distance to the superior margin of the lesser trochanter. Limb length on the operated side is designated as LL1 and that on the unoperated side is LL.

strength and the operated side / normal side ratio of SLR strength were compared among the three FO groups by post hoc analysis of covariance using Fisher's protected least significant difference (Fisher's PLSD) test, and the same comparison was done among the three LLD groups for the postoperative operated side / normal side ratio of hip abductor muscle strength and the operated side / normal side ratio of SLR strength. In addition, the mean postoperative duration and mean age at the time of the study were compared among the three FO groups and three LLD groups in the same way. Absolute frequencies of categorical data were compared between groups by the chi-square test, i.e., the restored FO group vs. the increased FO group and the restored LL group vs. the overcorrected LL group were compared between the symmetric gait and asymmetric gait categories by the chi-square test.

Statistical analysis was performed with StatView Ver. 5.0 software for Macintosh (SAS Institute Inc., North Carolina) and $p < 0.05$ was considered to indicate statistical significance.

3. Results

There were 19 patients (20.7 %; mean discrepancy of -11.0 mm) in the reduced FO group, 43 patients (46.7 %; mean discrepancy of 0.8 mm) in the restored FO group, and 30 patients (32.6 %; mean discrepancy of 9.7 mm) in the increased FO group. While there was no difference of the mean age at the time of the study among the three groups, there was a significant difference of the mean postoperative period between the reduced FO and increased FO groups, as well as between the reduced FO and restored FO groups.

Concerning LLD, there were 10 patients (10.9 %; mean discrepancy

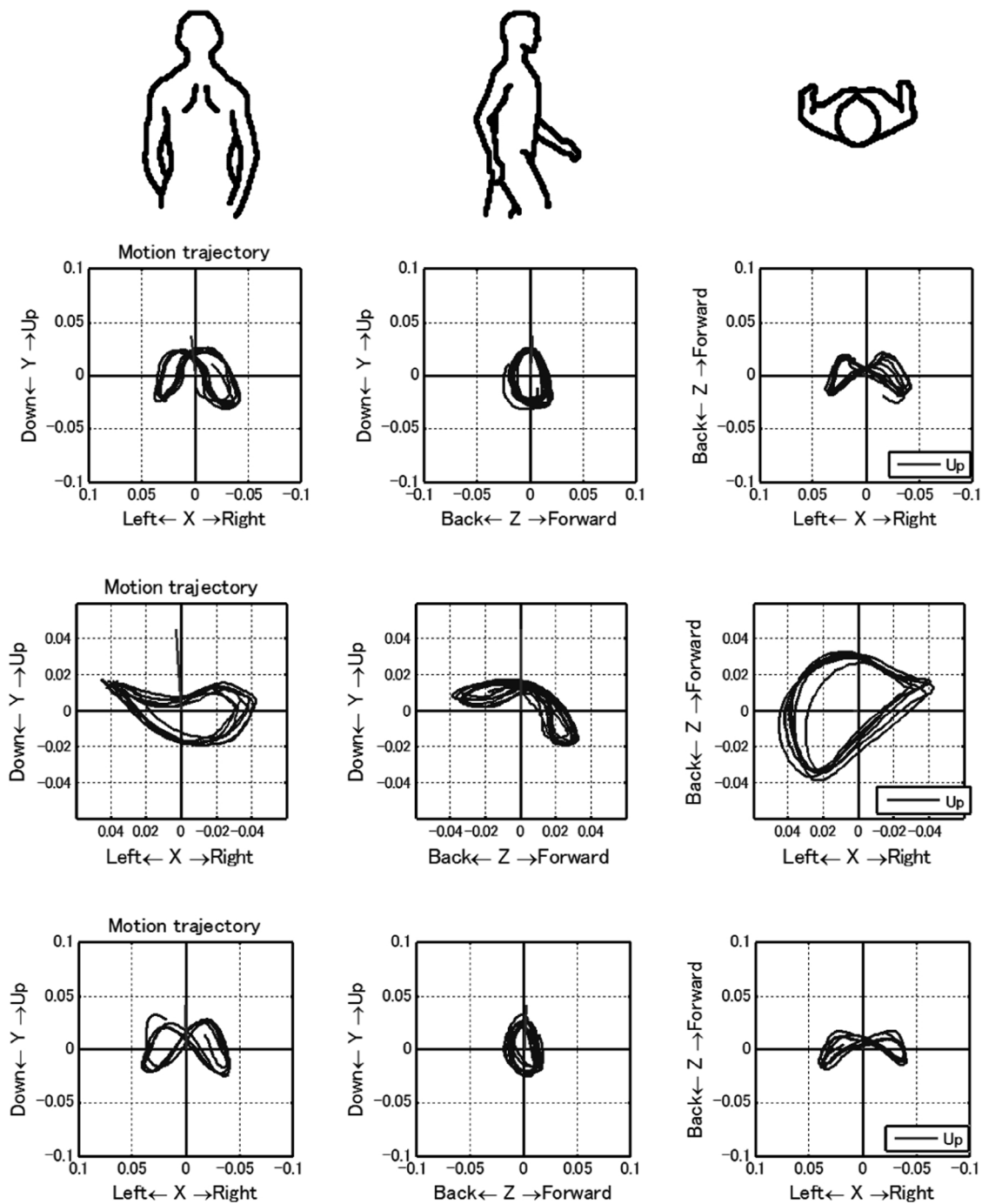


Fig. 3. Walking trajectory.

Lt. row: coronal plane, Middle row: sagittal plane, Rt. row: horizontal plane

Upper row: The walking trajectory of healthy young person. That is symmetrical in the coronal, sagittal, and horizontal planes, while the trajectory forms a figure-8 in the coronal and horizontal planes. On the sagittal plane, the trajectory draws a symmetrical circle.

Middle row: The walking trajectory of the preoperative patient who has right osteoarthritis of the hip. That was asymmetric in the coronal, sagittal, and horizontal planes, and the trajectory did not form a figure-8 in the coronal and horizontal planes.

Lower row: Post-THA walking trajectory of the patient also shown in the middle row. The walking trajectory has become symmetrical, like that of the healthy person in the upper row.

of -17.2 mm) in the undercorrected LL group, 73 patients (79.3 %; mean discrepancy of 0.9 mm) in the restored LL group, and 9 patients (9.8 %; mean discrepancy of 13.0 mm) in the overcorrected LL group. Only 3 patients had an LLD ≥ 20 mm, and all 3 patients were in the undercorrected LL group (Table 1).

The patients who underwent gait analysis included 1 patient (discrepancy of -9.3 mm) from the reduced FO group, 7 patients (mean

discrepancy of 1.2 mm) from the restored FO group, and 12 patients (mean discrepancy of 10.2 mm) from the increased FO group. With respect to LLD, no patient underwent gait analysis in the undercorrected LL group, while it was done in 19 patients (mean discrepancy of 0.6 mm) from the restored LL group and 1 patient (discrepancy of 13.0 mm) from the overcorrected LL group (Table 1).

Table 1
Patients demographics.

Global FO	Reduced	Restored	Increased
Number of patients (male / female)	19 (6 / 13)	43 (4 / 39)	30 (4 / 26)
Mean age (y.o.)	68.8	72.3	69.1
Mean discrepancy (mm)	-11	0.8	9.7
Mean postoperative duration (yrs)	9.5	6.2	4.1
LLD	Undercorrected	Restored	Overcorrected
Number of patients (male / female)	10 (3 / 7)	73 (9 / 64)	9 (2 / 7)
Mean age (y.o.)	69.8	70.8	68.6
Mean discrepancy (mm)	-17.2	0.9	13
Mean postoperative duration (yrs)	5.5	6	8.4
Twenty patients who underwent gait analysis			
Global FO	Reduced	Restored	Increased
Number of patients (male / female)	1 (1 / 0)	7 (1 / 6)	12 (2 / 10)
Mean age (y.o.)	54	69.9	66.5
Mean discrepancy (mm)	-9.3	1.2	10.2
LLD	Undercorrected	Restored	Overcorrected
Number of patients (male / female)	-	19 (4 / 15)	1 (0 / 1)
Mean age (y.o.)	-	66.9	69
Mean discrepancy (mm)	-	0.6	13.0

3.1. Muscle strength

The mean operated side / normal side ratio (%) of abductor muscle strength was 90.4 %, in the reduced FO group, 95.9 % in the restored FO group, and 103.7 % in the increased FO group. There was a significant difference of abductor muscle strength between the reduced and restored FO groups ($P < 0.05$), as well as between the reduced and increased FO groups ($P < 0.01$) (Fig. 4). Mean operated side / normal side ratio (%) of SLR muscle strength was 89.1 % in the reduced FO group, 98.4 % in the restored FO group, and 96.5 % in the increased FO group, showing no significant differences (Fig. 4). With respect to the relationship between LLD and muscle strength, the mean operated side / normal side ratio (%) of abductor muscle strength was 103.6 % in the undercorrected LL group, 100.0 % in the restored LL group, and 100.9 % in the overcorrected LL group, while the mean operated side / normal side ratio (%) of SLR muscle strength was 90.1 %, 96.6 %, and 96.5 %, respectively (Fig. 5). Both abductor and SLR strength were not influenced by LLD. Thus, there was no influence on hip abductor muscle strength and SLR muscle strength in the 3 patients with LLD ≥ 20 mm.

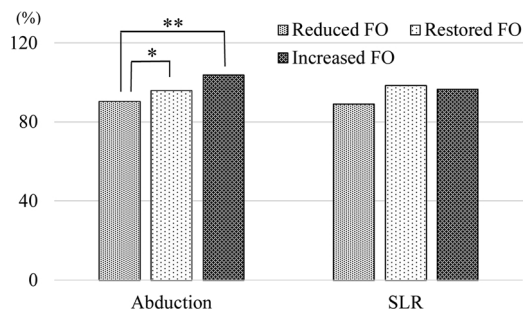


Fig. 4. Comparison of the mean operated side / normal side ratio of abductor muscle strength and SLR strength among the reduced FO, restored FO, and increased FO groups. A significant difference was recognized between the reduced FO and restored FO groups (*, $P < 0.05$), as well as between the reduced FO and increased FO groups (**, $P < 0.01$).

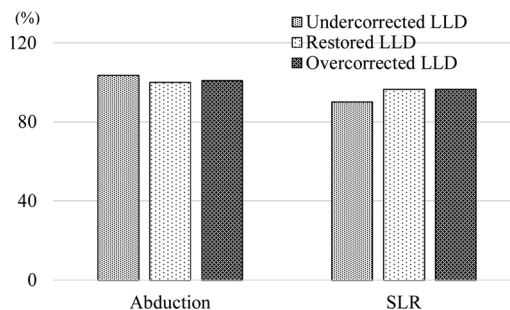


Fig. 5. Comparison of the mean operated side / normal side ratio of abductor muscle strength and SLR strength among the reduced LLD, restored LLD, and increased LLD groups.

3.2. Gait trajectory

At 1 year postoperatively, 70 % of patients showed symmetrical gait trajectory in the coronal plane, while 80 % were symmetrical in the sagittal plane and 80 % in the horizontal plane. The patients were grouped by determining whether the gait trajectory became symmetrical or remained asymmetrical in each plane. With respect to muscle strength, the mean operated side / normal side ratio (%) of abductor muscle strength was 95.4 % in the coronal plane symmetrical group and 96.6 % in the coronal plane asymmetrical group. Similarly, the mean operated side / normal side ratio (%) of abductor muscle strength was 97.4 % versus 89.1 % in the sagittal plane symmetrical and asymmetrical groups and 96.8 % versus 91.6 % in the horizontal plane symmetrical and asymmetrical groups. There were no significant differences of abductor muscle strength between the symmetrical and asymmetrical groups (Fig. 6). The mean operated side / normal side ratio (%) of SLR strength was 100.8 % in the coronal plane symmetrical group and 99.4 % in the asymmetrical group. Similarly, the mean operated side / normal side ratio (%) of SLR strength was 100.3 % versus 88.4 % in the sagittal plane symmetrical and asymmetrical groups and 100.7 % versus 98.9 % in the horizontal plane symmetrical and asymmetrical groups. SLR strength showed a significant difference between the sagittal plane symmetrical and asymmetrical groups ($P < 0.05$) (Fig. 6).

As only one patient showed a decrease of FO compared with the contralateral side, the relationship between FO and gait trajectory was examined by comparison of the restored and increased FO groups. There was no significant difference of global FO between the symmetrical and asymmetrical groups (Table 2). Similarly, only one patient showed an overcorrection of FO compared with the contralateral side, the relationship between LLD and gait trajectory was examined by

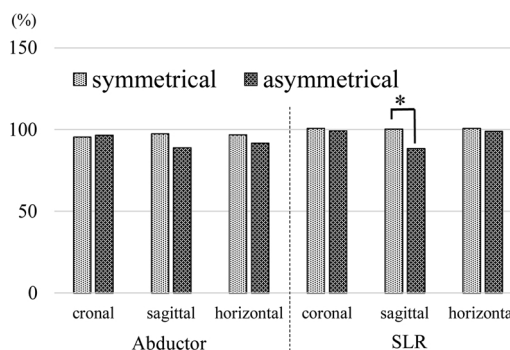


Fig. 6. Comparison of the mean operated side / normal side ratio of abductor muscle strength and SLR strength among gait symmetrical group and gait asymmetrical group. There was a significant difference of SLR strength between the symmetrical and asymmetrical sagittal plane groups (*, $P < 0.05$).

Table 2
The relationships between global FO and gait trajectory, as well as LLD and gait trajectory.

3D surface	Symmetrical / Asymmetrical	Global FO			LLD		
		Reduced FO	Restored FO	Increased FO	Uncorrected LLD	Restored LLD	Overcorrected LLD
Coronal	Symmetrical (n)	0	6	8	0	14	0
	Asymmetrical (n)	1	1	4	0	5	1
	P value	0.2			0.12		
Sagittal	Symmetrical (n)	0	5	11	0	15	1
	Asymmetrical (n)	1	2	1	0	4	0
	P value	0.07			0.61		
Horizontal	Symmetrical (n)	0	5	11	0	15	1
	Asymmetrical (n)	1	2	1	0	4	0
	P value	0.07			0.61		

comparison of the restored and overcorrected LL groups. There was no significant difference of LLD between the symmetrical and asymmetrical groups (Table 2).

4. Discussion

Several investigators have reported FO is related to abductor muscle strength [1–7]. Mahmood et al. [5] reported that reduction of global FO by > 5 mm after THA was negatively associated with abductor muscle strength on the operated side, and they also reported that restoration or an increment of global FO were associated with better results. Chamnongkitch et al. [7] found that the deficit of abductor isometric strength was 9% in high FO patients and 25 % in low FO patients compared to the intact limb, and they concluded that a slightly increased FO may be effective for enhancing hip abductor muscle function and ambulatory balance after THA. Furthermore, Cassidy et al. [8] reported that the WOMAC physical activity subscale was worse in patients with reduced global FO and they speculated that this was the result of abductor muscle weakness. We also showed that postoperative global FO > 5 mm less than that of the contralateral hip was associated with hip abductor muscle weakness. During single-limb standing, adequate hip abductor muscle strength is essential to control pelvic obliquity and maintain upright balance of the trunk. Assuming that all other factors remain constant, THA patients with restored or increased FO should be able to generate sufficient hip abductor muscle torque to maintain appropriate pelvic obliquity and an upright trunk posture, while this will be problematic for patients with reduced FO. It is unclear whether or not maintenance of pelvic balance during single-limb standing is directly linked to the presence or absence of truncal sway while walking, but it has been inferred that truncal sway leads to a smaller stride and slower walking speed. On the other hand, marked leg length (LL) inequality after THA is a major cause of patient dissatisfaction due to abnormal gait mechanics that lead to knee and back pain, early prosthesis loosening, and revision surgery [13]. Beard et al. [14] reported that patients with a LL difference > 10 mm at three years of follow-up had significantly worse Oxford hip scores. In addition, Renkawitz et al. [15] reported that residual LL and an FO difference > 10 mm were associated with significant differences of patient-related outcome scores and/or changes of gait symmetry. Moreover, Lai et al. [16] found marked reduction of walking speed and stride length on the affected side in patients with a discrepancy > 20 mm after THA, and they stated that correcting unilateral lower limb discrepancy in patients with congenital hip dislocation by THA is useful for improving walking efficiency and gait symmetry in the frontal plane. On the other hand, Benedetti et al. [17] concluded that limb lengthening of up to 20 mm did not significantly alter kinematic symmetry and loading on the hips during level walking or ascending stairs, and they considered that correction of discrepancies up to 20 mm by using an insole seems to be unjustified from a biomechanical viewpoint. Liu et al. [18] stated that full correction of LLD was not always necessary or desirable in patients with unilateral severe DDH since the extent of leg lengthening was

negatively correlated with abductor strength. Our study also showed no differences of hip abductor strength and SLR strength, when LLD was < 20 mm.

One of the notable points of this study was investigation of both FO and LLD, as well as the influence of abductor muscle and SLR strength on gait trajectory, which have not been reported previously. Thus, we hypothesized that the asymmetric walking trajectory occurs in patients with either inappropriate global FO or incorrect leg length adjustments after undergoing THA; or that it occurs in patients that display both of these features. The results of our gait analysis determined that patients with an FO of less than 5 mm had decreased abductor strength on that side of the body. However, a 10 % decrease in abductor strength did not affect the asymmetrical trajectory for the coronal, sagittal, or horizontal planes. Also, an LLD of 20 mm or less did not influence the walking trajectory for any of the three planes. On the other hand, this gait analysis identified a significant difference ($P < 0.05$) of SLR strength between the sagittal plane symmetrical group and asymmetrical group. SLR strength is important for generating sufficient forward thrust when walking. Accordingly, SLR strength influences the stride length and strength of the lower limb forward swing, suggesting that SLR weakness will lead to asymmetry of gait trajectory in the sagittal plane.

We also found limitations in this study. First off, there were only a few cases of patients who underwent gait analysis in each of these groups: reduced FO, undercorrected LL, and overcorrected LL. Initially, all patients who underwent gait analysis had recently undergone THA performed by the same surgeon; this may have been the reason for lack of variation in either FO or LLD among the patients. Therefore, we decided to include patients that were previously operated on by other surgeons to increase the variety of implants, global FO, and LLD; the increased variety allowed us to study the relationships between muscle strength and either global FO or LLD. Even though we expanded our criteria to include a wider variety of implants, there was still a bias towards the types of THA implants used in this study because the implant selection was typically based on the surgeon's preference and previous implant experiences. After we expanded our criteria to include cases of THA performed by multiple surgeons who used implants of various designs with differing offsets, we were then able to include patients with different measurements of postoperative FO and LLD. If decreased FO, decreased LLD, or increased LLD is indeed an obstacle to exerting muscular strength, then that difference becomes more pronounced as the postoperative duration increases. Thus, it will be much more useful to evaluate the influence of FO and LLD measurements several years after surgery. In addition, many Japanese patients undergoing THA due to osteoarthritis of the hip also have underlying acetabular dysplasia; since both sides of the hips are often affected, few patients have healthy contralateral hip joints. Therefore, to enroll patients who did not have an acetabular dysplasia on the contralateral side and only needed THA on one side, it was necessary to extend the postoperative period past one year. As a result, the postoperative period that ranged from 1 to 29 years was quite large for this study. Lastly, we were not able to include cases with either uncorrected global FO or

uncontrolled leg length in our three-dimensional gait analysis, but we plan to include these types of cases in our future studies.

In conclusion, reduction of global FO by > 5 mm after THA compared to the contralateral hip was associated with hip abductor muscle weakness. On the other hand, LLD \leq 20 mm had no influence on hip abductor muscle strength and SLR strength. The results of 3-D gait analysis suggested that SLR weakness may increase gait asymmetry in the sagittal plane.

Declaration of competing Interest

The authors declare that they have no conflict of interest.

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