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Asymmetric hip kinematics during gait in patients with unilateral total hip arthroplasty: In vivo 3-dimensional motion analysis

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ABSTRACT

Asymmetric limb loading has been reported in unilateral total hip arthroplasty (THA) patients during gait. However, restoration of 3D motion symmetry of the hip following unilateral THA remains unclear. The purpose of this study was to investigate the in vivo 3D kinematics of the hip in unilateral THA patients during gait. Eight unilateral THA patients were evaluated for both hips during treadmill gait using a dual fluoroscopic imaging system. Reduced hip range of motion in sagittal plane, decreased peak hip extension and asymmetric pelvic rotation of the THA were observed. Furthermore, significant pelvic anterior/posterior tilt asymmetry, higher internal rotation (increased by 8.6° ± 4.6°) during stance phase and higher adduction (increased by 4.5° ± 3.2°) during swing phase of the THA were found in this cohort of patients. The results demonstrated that there was 3D motion asymmetry of the hip and pelvis in unilateral THA patients during gait. The data could provide insights into optimizing kinematics and to restoring normal hip function after THA.

1. Introduction

Total hip arthroplasty (THA) is a widely accepted surgical option for the patients suffering from degenerative arthritis when conservative treatments have failed to relief pain and to restore hip function. Although significant improvement in the hip functional capacity such as walking speed has been reported in THA patients (Long et al., 1993; Perron et al., 2000; Queen et al., 2011), asymmetric limb loading and joint moment during gait were also indicated (McCrory et al., 2001; Shakoor et al., 2003). Reduced range of hip flexion and decreased peak hip extension were detected between the implanted and non-implanted hip in THA patients (Ewen et al., 2012; Miki et al., 2004; Queen et al., 2013).

The majority of the previous studies on in-vivo three-dimensional (3D) kinematics of THA patients utilized skin-marker-based tracking techniques and suggested that asymmetrical loadings could contribute to long-term musculoskeletal problems (Beaulieu et al., 2010; Chiu et al., 2010; Madsen et al., 2004; McCrory et al., 2001; Nankaku et al., 2012, 2007). However, there was no data reported on hip motions in coronal and axial planes during gait due to the technical difficulties in measurements of 6 degrees of freedom (6DOF) hip kinematics (Stagni et al., 2005). Little is known about the differences in 6DOF in-vivo hip kinematics and 3D pelvic motion between the implanted and non-implanted side in unilateral THA patients.

The purpose of this study was to determine if contemporary THA could restore the hip and pelvic motion symmetry in unilateral THA patients. A combined dual fluoroscopic imaging system (DFIS) and CT based modeling technique (Lin et al., 2013; Tsai et al., 2013) was used to measure the hip and pelvic 6DOF kinematics during treadmill gait. The null hypothesis was that no significant difference in 3D hip and pelvic motion exists between implanted and non-implanted side during gait in unilateral THA patients.

2. Materials and methods

Eight well-functioning unilateral THA patients with no history of any surgical complication were included in this study with the institution's Internal Review Board approval. The median age was 59.0 years (± 8.4, range 47 to 69, Table 1). The median body height and weight were 168.9 cm (± 8.5, range 155.0 to 180.0) and 77.1 kg (± 13.0, range 60.0 to 95.0) with median BMI of 28.3 (± 3.7, range 20.7 to 30.9). These patients were implanted with a cementless metal on polyethylene THA (DJO Surgical, Encore Medical, Austin, Texas) through a posterior approach. The median follow-up time was 8.3 months (± 6.6, range 3.6 to 22.6) from surgical date.

Each patient received a computerized tomography (CT) scan (Sensation 64, Siemens, Germany) from the L5 vertebra to the mid-femur for creation of surface models of the acetabular cup, femoral stem, the femur and the hip bone of both the implanted and non-implanted sides (Fig. 1) using a protocol established previously

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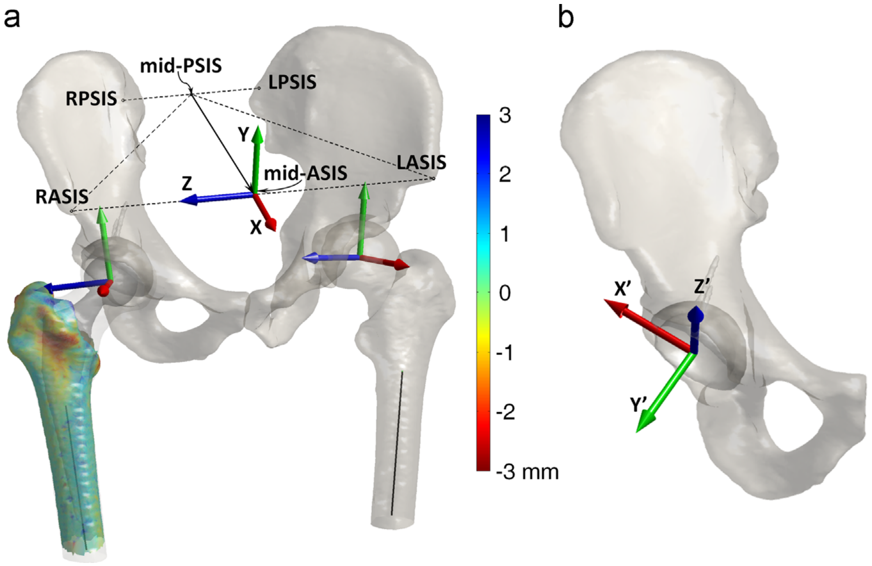

Fig. 1. (a) Three-dimensional pelvic models of a unilateral THA patient reconstructed from CT images. The pelvic coordinate was determined with left (L) and right (R) anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). The vector from the middle point of the left and right posterior superior iliac spines (mid-PSIS) to the middle point of the left and right anterior superior iliac spines (mid-ASIS) represents the walking director. Native femoral coordinate system was defined using the femoral head center and the long axis of the femoral shaft. The native femur was then mirrored and aligned with the remaining femoral bone to copy the native femoral coordinate to the implanted femur. The color on the implanted femur indicated the minimum distance between the native and implanted femurs. (b) A cup coordinate system was defined for describing the movement of the femoral head relative to the cup during gait. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Demographic data of the 8 unilateral THA patients. Median (MED), average (AVG), and standard deviation (SD) were calculated.

Patient	Gender	TKA side	Age (year)	Mass (kg)	Height (cm)	BMI	Follow-up (month)
1	F	L	69	60	170	20.7	22.6
2	F	R	63	73	155	30.2	9.7
3	F	R	54	64	165	23.5	16.2
4	F	L	55	82	163	30.9	6.8
5	M	R	64	95	178	30.1	13.6
6	M	L	47	91	175	29.5	5.8
7	F	R	66	71	168	25.2	3.6
8	M	L	48	88	180	27.1	4.4
MED	–	–	59.0	77.1	168.9	28.3	8.3
AVG	–	–	58.3	77.8	169.2	27.1	10.3
SD	–	–	8.4	13.0	8.5	3.7	6.6

(Tsai et al., 2013). Two pelvic local coordinate systems were defined for each hip (Tsai et al., 2014a) to describe the hip joint rotations (Fig. 1a) and the femoral head translations relative to the acetabular cup (Fig. 1b), respectively. For the femur, a femoral local coordinate system was constructed on the non-implanted femur. The origin of the native femur was set at the center of the femoral head (Fig. 2a). The femoral y-axis was parallel to the long axis of the proximal femoral shaft. The x-axis was vertical to the plane formed by the y-axis and the center of the femoral head. To determine the anatomic coordinate system of the implanted femur, the native femur together with the coordinate system was mirrored with respect to the sagittal plane (x–y plane). The mirrored femur was then aligned with the remaining femur of the implanted side using a point to surface registration technique (Tsai et al., 2014b). The aligned coordinate system was then considered as the femoral coordinate of the implanted side. A 3D deviation analysis on the mirrored native femur and the implanted femur showed that the average (AVG) ± standard deviation (SD) of the distances in between was 0.58 ± 0.11 mm for the proximal femur (Fig. 1a).

To evaluate the effects of THA on the leg length discrepancy, the positions of the geometric rotation centers of the THA components were measured and compared with that of the contralateral non-implanted hip. The difference between the positions of the cup component center and the contralateral bony acetabular cup center along the superior/inferior direction in the pelvic coordinate system was calculated and considered as vertical elevation or depression of the cup. The difference between the positions of the femoral head center and the stem head center along the long axis of the femur was also quantified and considered as changes in femoral vertical offset. The combined effect of both of the THA component translations was considered as leg length discrepancy.

Each THA patient performed level walking on a treadmill at self-selected speed under the DFIS (BV Pulsera, Phillips Medical, USA) surveillance using snapshots (with an 8 ms pulse width, 60–80 kV and 0.042–0.066 mA s). The same walking speed was set when testing the implanted and non-implanted hips of the same patient. Two treadmill gait trials for each hip were recorded. Two thin pressure sensors (force sensor resistor, Interlink Electronics, Camarillo, CA) were fixed to the bottom of shoes to determine the heel strike and toe off during the treadmill gait (Chen et al., 2012). Images of the hips at an upright standing position were captured as a reference. On average, each patient was exposed to an effective dose of 9.1 mSv (range 8.7 to 9.6) from both the CT and dual fluoroscopy procedures.

The 2D fluoroscopic images and the 3D subject-specific hip models were imported into a virtual DFIS environment for determination of hip positions. The hip models were registered when its projection on the virtual image intensifiers best matches the fluoroscopic outlines of the actual hip (Lin et al., 2013; Tsai et al., 2013). The hip rotation angles were calculated following ISB recommendation (Wu et al., 2002) (Fig. 1a). The 3D vector from the origin of the acetabulum to the center of the femoral head in the acetabular coordinate system was defined as the hip translation (Fig. 1b). Pelvic obliquity (drop/lift), axial rotation and anterior/posterior (A/P) tilt were determined with respect to the walking direction and ground horizon. The walking direction on the treadmill was determined by averaging the vectors from the middle point of the left and right posterior superior iliac spines (mid-PSIS) to the middle point of the left and right anterior superior iliac spines (mid-ASIS) throughout the gait (Fig. 1a). The range of motion (ROM) of hip rotations and femoral head translations of both implanted and non-implanted hips during gait were also calculated.

Wilcoxon singed-rank test was performed to determine if there is a significant difference in the hip motion during gait by comparing the 6DOF kinematic throughout gait cycle between non-implant and implanted sides ($\alpha = 0.05$).

3. Results

No significant cup elevation and femoral stem vertical translation were found with respect to the contralateral non-implanted leg (Table 2). However, significant leg lengthening by 4.6 ± 3.0 mm ($p = 0.008$) in the implanted side was determined (Table 2). The median ± standard deviation of walking speeds of all the unilateral THA patients was 3.1 ± 0.6 (range 2.4 to 4.2) km/h.

Significantly higher hip internal rotation during the stance phase (Fig. 2h) and significantly higher hip adduction during the

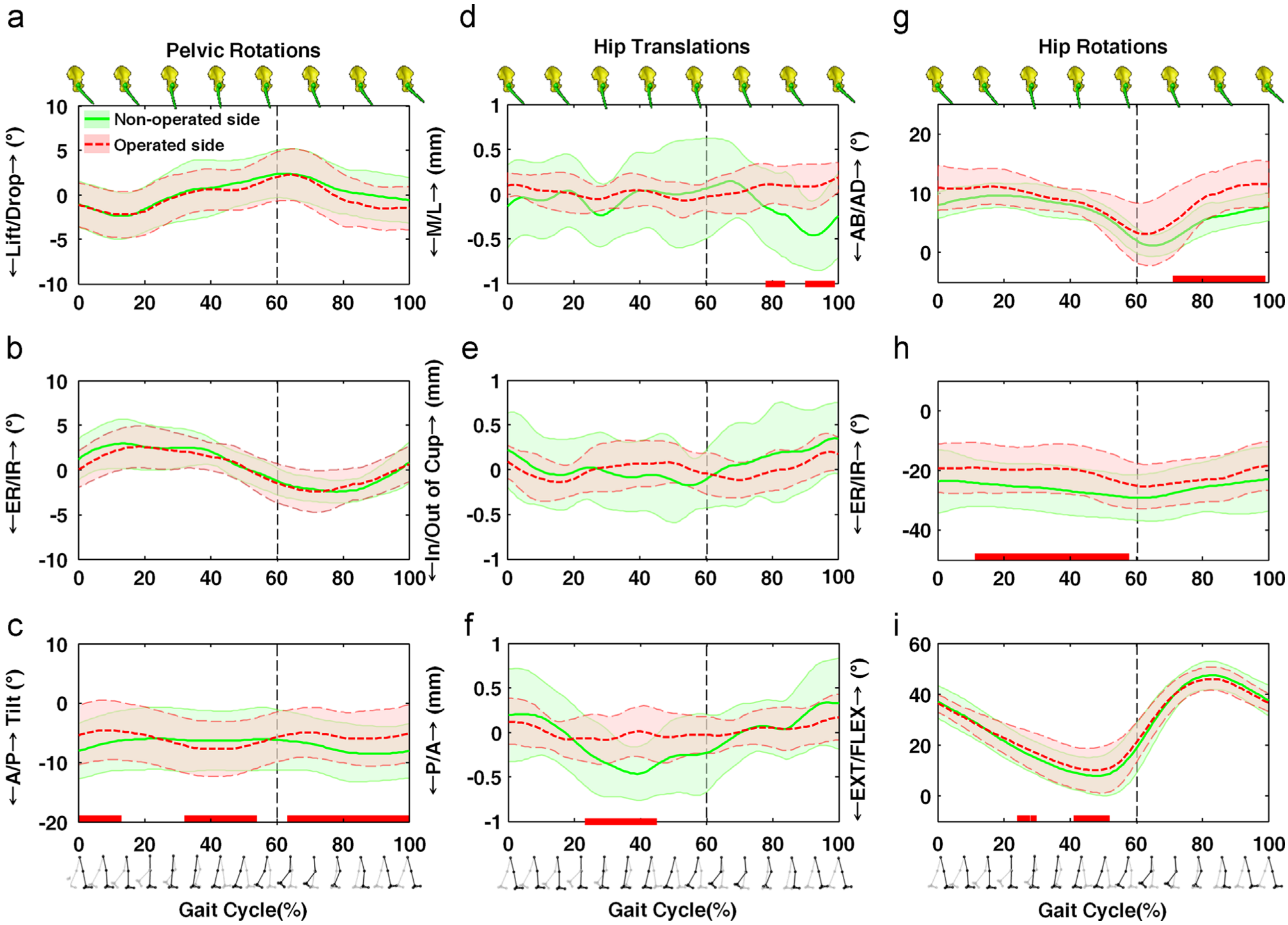

Fig. 2. Average and standard deviation of the pelvic lift/drop (a), pelvic external/internal rotation (ER/IR, (b)), anterior/posterior (A/P) tilt (c), medial/lateral (M/L) translation (d), in/out of cup translation (e), A/P translations (f), hip abduction/adduction (AB/AD, (g)), hip ER/IR (h), and hip flexion/extension (EXT/FLEX, (i)) for the operated and non-operated hips in unilateral THA patients during gait. Red bars on the horizontal axes (Gait Cycle %) indicate statistical significant difference between the limbs. Gray dashed vertical lines denote toe-off. Significant differences in hip rotations, hip translations and pelvic A/P tilt between implanted and non-implanted sides during gait were observed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Median (MED), average (AVG) and standard deviations (SD) of cup vertical elevation, femoral vertical translation and leg length discrepancy with respect to the contralateral non-implanted hip were shown. Wilcoxon signed-rank test was performed. No significant difference was found in component translations, while significant leg lengthening by 4.6 ± 3.0 mm in the implanted side was determined.

Patient	1	2	3	4	5	6	7	8	MED	AVG	SD	p value
Cup vertical Elevation (mm)	2.5	3.2	0.9	−2.4	−0.2	−1.3	−3.0	−1.3	−0.7	−0.2	2.2	0.813
Femoral vertical translation (mm)	9.8	9.7	9.3	−1.4	0.0	5.1	−0.1	2.7	3.9	4.4	4.8	0.078
Leg length discrepancy (mm)	7.3	6.5	8.4	0.9	0.2	6.3	2.9	4.0	5.2	4.6	3.0	**0.008***

swing phase (Fig. 2g) of gait cycle were observed in the implanted side than the contralateral non-implanted side. The average increases in hip rotation and hip adduction after THA, when there are significant differences between the hips (Fig. 2g and h), were 8.6° ± 4.6° and 4.5° ± 3.2° (Table 3), respectively. In addition, the implanted hips had significantly less extension at around 50% gait cycle (Fig. 2i). The femoral head of the non-implanted hips had larger range of translation along all directions than the implanted hips during gait (Fig. 2d–f). Significantly larger medial translation in terminal swing phase at ~80% and ~95% gait cycle (Fig. 2d) and larger posterior translation at ~25% and ~45% of gait cycle (Fig. 2f) were observed in the non-implanted femoral heads.

Table 3
Median (MED), average (AVG) and standard deviations (SD) of the differences in pelvic posterior/anterior (P/A) tilt angle, hip adduction/abduction (AD/AB) and interior rotation/exterior rotation (IR/ER) angles between implanted and non-implanted hip during treadmill gait when there are significant differences in between (Fig. 2).

Patient	1	2	3	4	5	6	7	8	MED	AVG	SD
Pelvic P/A Tilt (°)	1.9	1.4	2.8	1.7	3.4	2.4	4.1	0.7	2.2	2.3	1.1
Hip AD/AB (°)	5.2	9.4	8.6	3.0	4.7	1.9	0.9	2.0	3.9	4.5	3.2
Hip IR/ER (°)	9.6	18.4	11.1	5.9	7.5	6.6	3.2	6.6	7.1	8.6	4.6

The pelvic A/P tilt of the implanted side significantly deviated from that of the contralateral side (Fig. 2c) in the first double support phase (0% to 13%) and late of single leg stance phase during gait (32% to 54%). The implanted sides showed significantly increased pelvic posterior tilt with respect to the non-implanted sides in the swing phase during gait (Fig. 2c). The non-implanted sides showed more pelvic drop during the late swing phase when using the contralateral implanted leg as the supporting leg

Table 4
Range of motion (ROM) of hip rotations and femoral head excursions along different directions between implanted and non-implanted hips during treadmill gait were listed for each THA patient. Femoral head translations along anterior/posterior (A/P), medial/lateral (M/L), and in/out-of-the-cup (I/O) directions were reported. Median (MED), average (AVG) and standard deviation (SD) across subjects were calculated. Wilcoxon paired singed-rank test was performed. No significant difference was found in the hip rotation ROM between implanted and non-implanted hips. However, significant smaller femoral head translation ranges were observed in implanted hips along all directions.

Patient		1	2	3	4	5	6	7	8	MED	AVG	SD	*p* Value
F/E ROM (°)	Native	37.3	38.6	34.1	42.6	42.2	49.0	43.8	44.0	42.4	41.5	4.6	0.148
	THA	34.7	29.0	41.2	43.0	34.0	41.1	34.1	46.3	37.9	37.9	5.8	
AD/AB ROM (°)	Native	6.1	11.7	7.3	10.3	8.8	14.5	10.5	11.9	10.4	10.2	2.7	0.844
	THA	9.7	4.0	8.9	13.4	12.9	9.6	9.2	13.5	9.7	10.1	3.2	
IR/ER ROM (°)	Native	12.9	8.9	12.0	5.5	9.8	15.6	8.4	7.3	9.4	10.1	3.3	0.945
	THA	10.8	8.7	22.7	11.9	12.3	7.5	6.4	7.2	9.8	10.9	5.2	
A/P translation range (mm)	Native	1.4	1.2	1.2	1.4	1.1	1.1	0.9	1.8	1.2	1.3	0.3	**0.008***
	THA	0.4	0.8	0.6	0.9	0.8	0.8	0.9	0.8	0.8	0.7	0.2	
M/L translation range (mm)	Native	1.1	1.4	1.1	1.4	0.9	1.4	1.1	1.6	1.3	1.2	0.2	**0.008***
	THA	0.4	0.7	0.5	0.7	0.8	0.5	0.5	0.6	0.6	0.6	0.1	
I/O Translation range (mm)	Native	1.8	1.9	0.9	1.4	0.6	1.3	0.7	2.0	1.4	1.3	0.6	**0.039***
	THA	0.5	0.9	0.6	0.8	0.8	1.0	0.7	0.7	0.8	0.7	0.2	

(Fig. 2a). No significant difference was found in pelvic axial rotation between sides in unilateral THA patient (Fig. 2b).

The range of the femoral head translations of the THAs was significantly smaller than that of the non-implanted hips in A/P (0.75 mm vs. 1.28 mm, $p=0.008$, Table 4), medial/lateral (M/L, 0.60 mm vs. 1.23 mm, $p=0.008$), and in/out-of-the-cup directions (I/O, 0.74 mm vs. 1.30 mm, $p=0.039$, Table 4). The deviations of the femoral head translations in THAs were also smaller than those of the non-implanted hips (Table 4). The flexion/extension ROMs during the gait were similar between the implanted and non-implant hips (37.9° ± 5.8° vs. 41.5° ± 4.6°, $p=0.148$, Table 4). The average ROM in hip adduction/abduction was also similar (~10°) for both sides while the implanted hip had higher variation (3.2° vs. 2.7°, Table 4). Similar amount of around 10° ROM was measured in the hip internal/external rotation for both hips with higher deviation in the implanted hips than the non-implanted hip (5.2° vs. 3.3°, Table 4).

4. Discussion

This study investigated the in-vivo hip kinematics in unilateral THA patients during treadmill gait. Asymmetric hip and pelvic motions were found between the implanted and non-implanted hips. Significantly higher hip internal rotation during the stance phase and significantly higher hip adduction during the swing phase of gait cycle were observed in the implanted side than the contralateral non-implanted side. Significant asymmetric pelvic anterior/posterior tilt was also measured during gait. These data rejected the null hypothesis of no difference in the hip and pelvic motions between sides in unilateral THA patients.

Several studies reported reduction in hip ROM in sagittal plane in THA patients during gait, however the comparison was made using healthy people as control (Beaulieu et al., 2010; Bennett et al., 2008; Ewen et al., 2012; Madsen et al., 2004; Nankaku et al., 2007; Perron et al., 2000). There are also reports on reduced hip ROM in sagittal plane and decreased peak hip extension during gait were observed between limbs at 1 year after unilateral THA (Miki et al., 2004; Queen et al., 2013). No significant differences were found in pelvic tilt, rotation ROM and obliquity between sides in unilateral THA patients during gait (Miki et al., 2004). In this study, reduced hip flexion/extension ROM (Table 4), decreased peak hip extension (Fig. 2i) and symmetric pelvic rotation during gait were observed.

However, no significant differences in hip rotations on transverse and frontal planes between limbs were reported in literature (Miki et al., 2004; Queen et al., 2013). Asymmetric hip rotations during gait, in terms of higher hip internal rotation during the stance phase and higher hip adduction during the swing phase were observed in this cohort of unilateral THA patients. Significant differences in pelvic anterior/posterior tilt were observed between sides during gait in this study. More pelvic drop was measured during the late swing phase in the non-implanted side when using the implanted leg for support (Fig. 2a).

Various factors could contribute to the asymmetric hip motion observed in this study. The better conformity of the hip implant articulations than the non-implant hip might be the cause of the smaller range of femoral head translation in the THAs. Previous study reported that leg length discrepancy correlates with gait abnormalities and asymmetry (Kaufman et al., 1996). A leg length discrepancy of more than 2 cm can result in gait asymmetry which was greater than that in the normal population (Kaufman et al., 1996; Lai et al., 2001). Although significant leg length discrepancy of the implanted side by 5 mm (Table 2) was found in this cohort of THA patients, the leg lengthening of each of the THA patients less than 2 cm is not likely to significantly influence gait symmetry.

The altered hip motion after THA may lead to altered post-operative function of the hip. As previous study reported that internal rotation gait may be a compensation for children with femoral deformities to achieve the abduction moment arm needed for walking (Arnold et al., 1997). The internal rotation gait of THA patients might be an adaptation to increase abduction capacity during gait due to the abductor muscle weakness after THA. The significantly more anterior pelvic tilt of the implanted hip at around 50% gait cycle (Fig. 2) could compensate the decreased peak of hip extension. The contralateral pelvic drop during stance phase and the hip adduction during swing phase in the implanted side, the same trend with Trendelenburg (1998) sign, could be due to abductor muscle weakness. The relatively less hip rotation ROMs in THAs might be due to scar tissue constrains resulted from the operation. Since the THA surgical approach makes separation of the hip muscles to expose the acetabulum and the femoral head, certain amount of damage to the hip muscles is likely despite the surgical repair at the conclusion of the surgery. The asymmetric gait after THA could alter the lower limb dynamics and induce mechanical problems of adjacent joints in long term (Chiu et al., 2010; McCrory et al., 2001; Nankaku et al., 2012). Therefore, restoration of the gait symmetry following THA is important to improve the longevity of the surgery.

The results of the current study need to be interpreted in light of several limitations. There were a relatively small number of patients recruited in this study due to radiation exposure concern. Despite this, statistically significant differences in the hip and pelvic motion were observed. There was large range of post-operative follow-up time, age, walking speed, body height and weight in THA patients recruited in this study. However, the same trend of asymmetry hip and pelvic motion between the implanted and non-implanted was found in each individual THA patient (Table 3). The hip motion during the treadmill gait may differ from level walking on the ground, although previous studies showed similarities of hip kinematics between normal walking and treadmill walking (Riley et al., 2007). The unilateral THA may affect the kinematics of the pelvis during gait since the pelvic bones are interrelated as a segment. However, the comparison between the operated and non-operated pelvis could still be helpful in understanding the difference in pelvic motion when walking with implanted and non-implanted legs. Symmetric geometry between the left and the right femur was assumed to map the coordinate system. Therefore, patients with femoral deformity were precluded in this study. This study included only one surgical approach and one THA design. Since posterior approach was chosen in the study, the effect of other surgical approaches on the hip kinematics during gait was not determined. As different surgical approach and THA designs may influence the hip function, the current findings might not be generalized to other THA patients using different surgical approach. Further studies are required to investigate the effects of surgical technique, component positioning, THA design, and rehabilitation regimen on in-vivo THA kinematics during functional activities.

In summary, asymmetry hip and pelvic motion persisted in in-vivo unilateral THA patients during gait. Significantly higher hip internal rotation during stance phase and higher hip adduction during swing phase were observed in the implanted side of unilateral THA patients. The results of the current study suggested that the hip and pelvic motion symmetry during gait was not restored in patients with unilateral THA. Further studies are required to investigate the potential effects of THA designs, component positioning and rehabilitation regimes on optimizing in-vivo THA kinematics during functional activities.

Declarations

Competing interests: None declared.

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Ethical approval: Research protocol has been reviewed and approved by Massachusetts General Hospital IRB.

Conflict of interest statement

The authors of this manuscript have nothing to disclose that would bias our work.

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