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Three-dimensional kinematics and kinetics of getting into and out of a car in patients after total hip arthroplasty

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ABSTRACT

Background: In modern society, car usage is one of the most important activities of daily living. However, the three-dimensional (3D) mechanics of getting into and out of a car in total hip arthroplasty (THA) patients have not been studied.
Research question: This study aimed to elucidate the hip kinematics and kinetics of unilateral THA patients while getting into and out of a car.
Methods: 3D motion and ground reaction force data were collected for 40 unilateral primary THA and 30 control participants using motion capture of getting into and out of a car. Normalized joint power was used to determine the individual joint contribution and was calculated by dividing the power of each joint by the total lower-extremity power. These kinematic and kinetic data were compared between unilateral THA and control participants.
Results: When getting into the car using the surgical side as the pivot limb, the peak flexion, abduction angle, and normalized power of the pivot hip were significantly lower, and the normalized power of the contralateral ankle was significantly higher. The peak flexion and abduction angle of the pivot hip were significantly lower, and normalized contralateral hip power was significantly higher when getting out of the car. In getting into and out of the car using the contralateral side as the pivot limb, there was no significant difference in the range of motion (RoM) and normalized joint power.
Significance: The restoration of RoM and muscle strength in the surgical hip joint and adopting the normal side as the pivot limb may allow for a more appropriate balance in motion of getting into and out of a car, which will lead to safe mobility, assist in social participation, and improved quality of life.
Level of evidence: Level III, therapeutic study.

1. Introduction

Total hip arthroplasty (THA) is considered one of the most successful orthopedic procedures [1] performed on patients with osteoarthritis (OA). The ability to successfully perform common activities of daily living (ADLs) is important for safe mobility, social participation, and ultimately the quality of life. Patient perception of the replaced joint as a natural body part during ADLs is an ideal outcome after THA, and this perception is an important clinical outcome after THA [2].

In modern society, the use of cars is one of the most important ADLs. Shiomoto et al. report that getting into and out of a car significantly correlates with the perception of a natural joint [3]. Gait and stair ascent-descent mechanics are widely studied ADLs after THA [4–7]. However, to the best of our knowledge, analysis of the three-dimensional (3D) mechanics of getting into and out of a car has not been previously examined. Thus, the purpose of this study was to

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identify the kinematics and kinetics of THA patients in getting into and out of a car.

The present study aimed to address: (1) the differences in hip kinematics (time, range of motion [RoM]), and kinetics (moment, power) and (2) the differences in the contribution of the hip, knee, and ankle powers, between unilateral THA patients and control participants when getting into and out of a car.

2. Methods

2.1. Participants

All study participants were recruited between January 2020 and November 2021; they signed an institutional review board-approved (IRB number: 2019–323) informed consent. The recruited patients were at least two years past their unilateral primary THA for OA at our institution. All THAs were performed using a posterolateral approach, with a uniform protocol for postoperative rehabilitation [8]. Patients were excluded if they were unable to walk without an assistive device, had pain in more than one lower-extremity joint in either limb, had undergone prior lower-extremity arthroplasty, had radiographic Kellgren-Lawrence grade [9] 3 or 4 OA of the contralateral hip, or had undergone spinal surgery. Participants with a body mass index (BMI) over 30 were excluded because the anterior superior iliac spine (ASIS) markers could be hidden by the abdomen during hip flexion. Forty patients with unilateral THA (20 left-THA or L-THA [4 males and 16 females] and 20 right-THA or R-THA [4 males and 16 females]) were included (Table 1). Control participants (6 males and 24 females; Table 1) included 27 patients who had undergone upper limb surgery in our institution at least six months before recruitment and three staff members at our institution. The control participants were excluded if they were unable to walk without an assistive device, had pain in more than one lower-extremity joint of either limb, or had undergone prior lower-extremity arthroplasty or spine surgery.

2.2. Radiographic data

Leg length difference (LLD) and global femoral offset (GFO) before and after THA were assessed using anteroposterior radiographs of the pelvis as described previously [10,11].

Table 1
Comparison of demographics and radiographic data.

Parameters	L-THA (n = 20)	R-THA (n = 20)	Control (n = 30)
Age (y)	66.4 ± 6.8 (53–79)	67.4 ± 5.7 (59–77)	66.2 ± 7.5 (50–80)
Male/female, n (%)	4/16 (20/80)	4/16 (20/80)	6/24 (20/80)
Height (m)	1.56 ± 0.06 (1.44–1.67)	1.56 ± 0.07 (1.46–1.69)	1.56 ± 0.06 (1.47–1.69)
Weight (kg)	56.1 ± 7.6 (40–69)	56.6 ± 10.0 (41–73)	54.8 ± 8.0 (36.5–75)
BMI	23.1 ± 2.8 (17.5–27.8)	23.1 ± 2.6 (18.9–26.8)	22.4 ± 2.9 (15.4–27.5)
Follow-up duration (months)	68.9 ± 59.5 (24.0–205.2)	44.2 ± 32.2 (24.0–131.0)	
LLD (mm)	4.8 ± 2.7 (0–9.4)	4.4 ± 5.7 (0–24.2)	
Difference in GFO (mm)*	-1.8 ± 5.2 (−10.6–9.0)	-2.9 ± 9.4 (−27.0–13.5)	

Continuous values are expressed as mean ± standard deviation (range).
LLD, leg length discrepancy; GFO, global femoral offset; THA, total hip arthroplasty.
* Positive difference in GFO indicates that the postoperative GFO is more lateralized than the contralateral GFO in unilateral THA patients.

2.3. Data capture

A 10-camera VICON motion capture system with a sampling frequency of 100 Hz (VICON, Oxford Metrics Group, UK) and two force plates with a sampling frequency of 1000 Hz (AMTI, Waterton, MA, USA) were used. Each participant was provided form-fitting shorts and a shirt during testing; participants were barefoot during testing to control for footwear-associated changes in the ground reaction forces [12]. Reflective markers were placed on the lower body in accordance with the Plug-in-Gait configuration with anterior thigh and shank. A four-seater car (Subaru Stella DBA-RN2; Fig. 1) was dismantled to minimize the camera blind spot, leaving only the left front seat. In addition, four pulleys were attached to the car's bottom and the tires were removed to keep the car's bottom at a consistent height from the ground (Fig. 1). The maximum legroom and seat recline were used to avoid hiding the posterior superior iliac spine markers. The left forward pulley was mounted on the force plate (Fig. 2). Each participant was asked to perform the following movements in order: for getting into the car: raise the right lower limb, place the buttocks on the seat, and raise the left lower limb; for getting out of the car: raise the left lower limb, lift the buttocks off the seat, and raise the right lower limb at a self-selected speed (Fig. 1). Additionally, each participant was asked to avoid relying on upper limb support as much as possible throughout the two motions. After a minimum of three practice trials, participants repeated the motions until three trials suitable for data analysis were obtained [4].

2.4. Data processing

The getting into phase was defined as the period between standing on both legs to sitting in the car's passenger seat (Fig. 1). The start of the motion was defined as the time when the right knee marker started moving forward, and the end of the movement was defined as the time when both the right and left second metatarsal head and calcaneus markers stopped. The getting out phase was defined as the period between sitting in the car's passenger seat to standing on both legs. The upward movement of the left second metatarsal head or the calcaneus marker marked the start of the motion, and the end of the movement was the point at which the right knee marker stopped. The phase in which the patient stood on a single leg during either the getting into or out phase was defined as the single-leg phase. The arrival and departure of the right foot from the ground were simultaneously captured by two VICON VUE video cameras (VICON, Oxford Metrics Group, UK), and the arrival and departure of the right foot from the car's floor were determined by the reaction of the force plate on which the left forward pulley on the car's bottom was mounted (Fig. 2). The angles were time normalized to 100% of the getting into and out phase. The moments and powers were time normalized to 100% during the single-leg phase of the getting into and out phase, respectively. The marker trajectories were low-pass filtered using a Woltring filter with a cutoff frequency of 10 Hz. The joint angles, net internal moments, and power were calculated using the Plug-in Gait model. For lower limb joint kinematics, the Cardan rotation sequence was flexion-extension, adduction-abduction, internal-external rotation. The peak absolute power and the joint powers normalized to total lower extremity absolute power were calculated at the peak hip power production position of the pivot limb. The trial closest to the mean among the three trials was used for analysis [4,7]. Spatiotemporal variables were also calculated.

2.5. Statistical analysis

Statistical analysis was performed using JMP software v.14.0 (SAS Institute, Cary, NC, USA). The Student's t-test was used to compare the demographic, kinematic, and kinetic data between unilateral THA patients and control participants. The chi-square test was used to compare the effect of sex. Statistical significance was set as $P < .05$. Continuous variables were expressed as mean ± standard deviation. The power

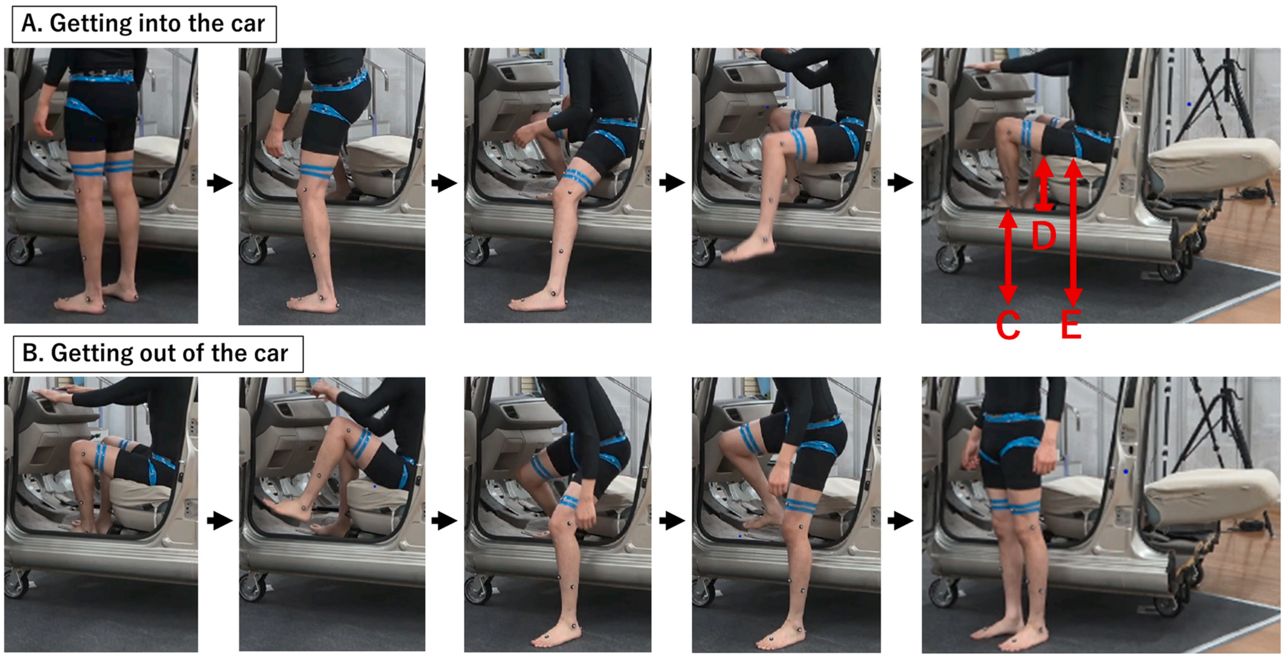

Fig. 1. A, The motion of getting into the car. B, The motion of getting out of the car, C, Ground to the top edge of the step, 330 mm; D, Car floor to the chair, 380 mm; E, Ground to the seat, 610 mm. Pre-dismantled car: Subaru's Stella DBA-RN2; weight 900 kg; Overall width, 1475 mm; Overall length, 3395 mm; Overall height, 1645 mm.

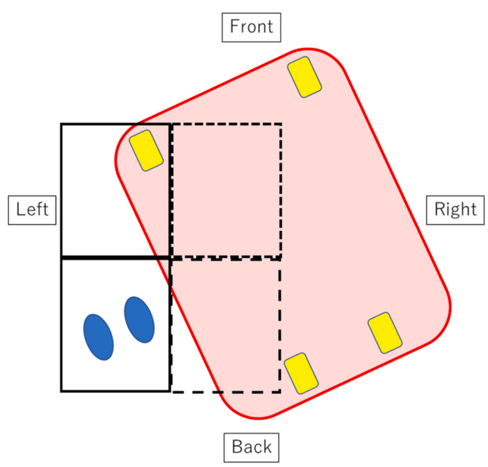

Fig. 2. Force plate and the dismantled car with only the passenger seat (left front seat) location. Solid black line, Used force plate; Dotted black line, Unused force plate; Red line, Dismantled car; Yellow zone, Pulleys attached to the bottom of the car; Blue zone, Starting foot position of the study participants.

analysis showed that a combined sample size of 40 provided 80% statistical power to detect a 0.39 difference in hip joint power between the two groups (assuming probability <0.05 and the standard deviation of 0.43) [4].

3. Results

3.1. Demographics and radiographic data

Demographic characteristics (age, sex, height, weight, and BMI) were similar between unilateral THA patients and the control participants ($P > .05$; Table 1). The follow-up duration and radiographic findings between L-THA and R-THA patients were also similar ($P > .05$; Table 1).

3.2. Spatiotemporal parameters

THA patients and control participants showed no significant difference in the time spent getting into and out of the car (Tables 2 and 3), while also showing a similar pattern of motion. The single-leg phase accounted for 25% of the getting into phase (onset at 5% of the task and finished at 30%) and 20% of the getting out of phase (onset at 75% of the task and finished at 90%) (Fig. 3).

4. Kinematics and kinetics parameters

4.1. Getting into the car

The peak flexion and abduction angles of the left hip were significantly lower than for control participants when using the surgical side as the pivot limb (L-THA, $P = .0033$ and.0002, respectively; Table 2 and Fig. 3). However, there were no significant differences in the angle when the contralateral side was used as the pivot limb (R-THA; Table 2 and Fig. 3). In the RoM of the surgical hip, the peak flexion angle was 56–105°, and the peak internal rotation angle in more than 90° of flexion was − 12–33°. No patient had more than 10° of adduction in more than 90° of flexion, regardless of the surgical side. The peak abduction moment (HAB), coronal generation power (CG), and total generation power (TG) of the left hip were significantly lower than those in the control participants when the surgical side was used as the pivot limb ($P = .045$,0.016, and.028, respectively; Table 2 and Fig. 3). On the other hand, the peak sagittal generation power (SG) and TG of the right hip were significantly lower, and the peak sagittal absorption power (SA) of the left hip was significantly higher than for control participants when the contralateral side was used as the pivot limb ($P = .046$,0.015, and.036, respectively; Table 2 and Fig. 3).

The TG of the pivot limb peaked in the swinging posture of the right lower limb in the initial single-leg phase, regardless of the surgical side. Compared to control participants, the absolute left hip power was significantly lower, and the absolute left ankle power was significantly higher when the surgical side was used as the pivot limb ($P = .028$ and.005, respectively; Table 2), and the normalized left hip power was

Table 2
Time, kinematics, and kinetics of getting into the car.

Parameters	L-THA (n = 20)	R-THA (n = 20)	Control (n = 30)
Time (s)	3.5 ± 0.7 (2.5–5.3)	3.4 ± 0.6 (2.4–4.4)	3.4 ± 0.5 (2.3–4.3)
Left hip peak angle			
Flexion (°)	82 ± 10 (56–98)[a]	87 ± 9 (74–106)	90 ± 8 (73–105)[a]
Extension (°)	-4 ± 9 (−18–20)	-1 ± 10 (−156–24)	-5 ± 7 (−18–11)
Adduction (°)	10 ± 4 (1–19)	10 ± 5 (1–20)	10 ± 5 (2–20)
Abduction (°)	33 ± 10 (8–53)[a]	38 ± 5 (30–50)	41 ± 5 (30–52)[a]
Internal rotation (°)	16 ± 6 (5–31)	15 ± 7 (2–25)	13 ± 9 (−1–40)
External rotation (°)	14 ± 6 (6–24)	18 ± 10 (5–37)	18 ± 8 (6–31)
Right hip peak angle			
Flexion (°)	91 ± 5 (80–100)	88 ± 10 (75–105)	91 ± 7 (77–108)
Extension (°)	-9 ± 12 (−37–20)	-10 ± 7 (−20–7)	-8 ± 7 (−23–5)
Adduction (°)	10 ± 6 (0–21)	9 ± 5 (2–19)	9 ± 4 (3–19)
Abduction (°)	24 ± 13 (8–52)	19 ± 12 (−6–42)	19 ± 10 (−7–41)
Internal rotation (°)	13 ± 7 (2–26)	15 ± 10 (−1–33)	15 ± 92 (−1–35)
External rotation (°)	23 ± 9 (4–38)	14 ± 11 (−14–37)	19 ± 9 (3–47)
Left hip peak moment (Nm/kg)			
Flexion moment (HF1)[*]	0.17 ± 0.20 (−0.23–0.58)	0.20 ± 0.17 (−0.10–0.44)	0.22 ± 0.18 (−0.18–0.55)
Flexion moment (HF2)[*]	0.24 ± 0.24 (−0.23–0.69)	0.26 ± 0.24 (−0.29–0.80)	0.26 ± 0.24 (−0.30–0.71)
Abduction moment (HAB)[*]	0.63 ± 0.20 (0.34–1.08)[a]	0.74 ± 0.17 (0.46–1.07)	0.74 ± 0.17 (0.45–1.04)[a]
Internal rotation moment (HIR)[*]	0.13 ± 0.09 (−0.06–0.31)	0.13 ± 0.06 (0.03–0.26)	0.13 ± 0.05 (0.05–0.25)
Right hip peak moment (Nm/kg)			
Flexion moment (HF1)[*]	0.21 ± 0.06 (0.09–0.35)	0.22 ± 0.06 (0.11–0.42)	0.23 ± 0.07 (0.05–0.36)
Flexion moment (HF2)[*]	0.38 ± 0.07 (0.24–0.52)	0.39 ± 0.09 (0.24–0.66)	0.36 ± 0.07 (0.20–0.50)
Abduction moment (HAB)[*]	0.23 ± 0.07 (0.10–0.37)	0.23 ± 0.06 (0.12–0.35)	0.26 ± 0.08 (0.10–0.43)
Internal rotation moment (HIR)[*]	0.11 ± 0.03 (0.07–0.19)	0.10 ± 0.02 (0.05–0.14)	0.04 ± 0.05 (−0.04–0.16)
Left hip peak power (W/kg)			
Sagittal absorption power (SA)[*]	0.06 ± 0.08 (−0.07–0.25)	0.14 ± 0.16 (−0.02–0.50)[b]	0.07 ± 0.06 (−0.004–0.22)[b]
Coronal generation power (CG)[*]	0.40 ± 0.17 (0.12–0.72)[a]	0.56 ± 0.24 (0.04–1.06)	0.52 ± 0.16 (0.23–0.80)[a]
Total generation power (TG)[*]	0.39 ± 0.19 (0.11–0.77)[a]	0.49 ± 0.23 (0.12–1.05)	0.50 ± 0.17 (0.21–0.76)[a]
Absolute hip power	0.39 ± 0.19 (0.11–0.77)[a]	0.50 ± 0.22 (0.17–1.05)	0.50 ± 0.17 (0.21–0.76)[a]
Absolute knee power	0.11 ± 0.09 (0.03–0.31)	0.14 ± 0.12 (0.02–0.50)	0.13 ± 0.09 (0.001–0.39)
Absolute ankle power	0.22 ± 0.18 (0.04–0.86)[a]	0.09 ± 0.06 (0.02–0.23)	0.11 ± 0.07 (0.02–0.29)[a]
Normalized hip power	0.19 ± 0.09 (0.04–0.36)[a]	0.26 ± 0.08 (0.14–0.42)	0.24 ± 0.07 (0.13–0.43)[a]
Normalized knee power	0.05 ± 0.03 (0.01–0.14)	0.07 ± 0.06 (0.02–0.25)	0.06 ± 0.04 (0.005–0.14)
Normalized ankle power	0.11 ± 0.08 (0.02–0.38)[a]	0.05 ± 0.03 (0.01–0.10)	0.05 ± 0.03 (0.01–0.12)[a]
Right hip peak power (W/g)			
Sagittal generation power (SG)[*]	0.71 ± 0.26 (0.33–1.39)	0.63 ± 0.19 (0.33–1.15)[b]	0.75 ± 0.21 (0.46–1.19)[b]
Sagittal absorption power (SA)[*]	0.46 ± 0.16 (0.20–0.83)	0.39 ± 0.14 (0.15–0.65)	0.46 ± 0.15 (0.17–0.77)
Axial generation power (AG)[*]	0.11 ± 0.05 (0.05–0.21)	0.10 ± 0.04 (0.03–0.18)	0.11 ± 0.05 (0.05–0.24)
Total generation power (TG)[*]	0.72 ± 0.27 (0.25–1.37)	0.62 ± 0.20 (0.31–1.19)[b]	0.76 ± 0.21 (0.45–1.21)[b]
Total absorption power (TA)[*]	0.41 ± 0.13 (0.17–0.67)	0.37 ± 0.11 (0.19–0.57)	0.42 ± 0.14 (0.18–0.71)
Absolute hip power	0.72 ± 0.27 (0.25–1.37)	0.62 ± 0.20 (0.31–1.19)[b]	0.77 ± 0.21 (0.45–1.21)[b]
Absolute knee power	0.58 ± 0.29 (0.29–1.16)	0.47 ± 0.15 (0.29–0.78)	0.57 ± 0.25 (0.18–1.30)
Absolute ankle power	0.06 ± 0.03 (0.02–0.14)	0.04 ± 0.02 (0.007–0.11)	0.06 ± 0.04 (0.01–0.18)
Normalized hip power	0.35 ± 0.10 (0.17–0.48)	0.33 ± 0.07 (0.21–0.46)	0.36 ± 0.07 (0.25–0.49)
Normalized knee power	0.27 ± 0.09 (0.13–0.46)	0.26 ± 0.07 (0.13–0.38)	0.26 ± 0.08 (0.09–0.45)
Normalized ankle power	0.03 ± 0.01 (0.007–0.06)	0.02 ± 0.01 (0.003–0.05)	0.03 ± 0.02 (0.005–0.10)

Continuous values are expressed as mean ± standard deviation (range).
THA, total hip arthroplasty; Normalized power, % absolute joint power of total limb absolute power.
[a] $p < .05$ for the comparison between L-THA patients and control participants.
[b] $p < .05$ for the comparison between R-THA patients and control participants.
[*] Peak hip moment and peak hip power were listed when these values were > 0.10 in at least one of the three groups.

significantly lower, and the normalized left ankle power was significantly higher ($P = .046$ and.002, respectively; Table 2). On the other hand, there was no significant difference in the normalized joint power when the contralateral side was used as the pivot limb (Table 2), although the absolute right hip power was significantly lower ($P = .015$; Table 2).

4.2. *Getting out of the car*

The peak flexion and abduction angles of the left hip were significantly lower than the control participants when the surgical side was used as the pivot limb (L-THA, $P = .0008$ and.0004, respectively; Table 3 and Fig. 3); However, there were no significant differences in the angle when the contralateral side was used as the pivot limb (R-THA; Table 2 and Fig. 3). In the RoM of the surgical hip, the peak flexion angle was 55–106°, and the peak internal rotation angle in more than 90° of flexion was 6–24°. The peak internal rotation angles in more than 10° of adduction and more than 90° of flexion were − 1–4°. The moment and power of both hips were comparable with the control participants, regardless of the surgical side (Table 3 and Fig. 3).

The TG of the pivot limb peaked in the posture immediately after the right foot left the car's floor in the initial single-leg phase, regardless of the surgical side. The absolute left hip power was lower; however, the difference was not significant when the surgical side was used as the pivot limb ($P = .068$; Table 3); other absolute joint powers were not significantly different (Table 3). The normalized right hip power was significantly higher ($P = .033$; Table 3); there were no significant differences in other normalized joint powers (Table 3). On the other hand, all absolute joint powers and the normalized joint powers were comparable when the contralateral side was used as the pivot limb (Table 3).

5. Discussion

Gait analysis of THA patients has been well documented [4–7]. However, to the best of our knowledge, dynamic analysis of getting into and out of a car has not been previously examined. This study allowed the assessment of the 3D mechanics of the hip, knee, and ankle in THA

Table 3
Time, kinematics, and kinetics of getting out of the car.

Parameters	L-THA (n = 20)	R-THA (n = 20)	Control (n = 30)
Time (s)	3.3 ± 0.6 (2.5–4.3)	3.4 ± 0.7 (2.3–4.9)	3.4 ± 0.6 (2.4–5.1)
Left hip peak angle			
Flexion (°)	83 ± 10 (55–98)[a]	90 ± 11 (64–106)	92 ± 7 (77–105)[a]
Extension (°)	-7 ± 9 (−21–15)	-9 ± 11 (−24–15)	-9 ± 7 (−31–5)
Adduction (°)	9 ± 6 (0–18)	9 ± 4 (1–15)	9 ± 4 (3–17)
Abduction (°)	30 ± 10 (6–49)[a]	35 ± 6 (23–51)	37 ± 4 (30–44)[a]
Internal rotation (°)	14 ± 6 (2–23)	13 ± 6 (−3–21)	12 ± 10 (−1–36)
External rotation (°)	14 ± 5 (5–21)	16 ± 10 (1–40)	17 ± 7 (5–44)
Right hip peak angle			
Flexion (°)	89 ± 7 (76–104)	85 ± 12 (63–106)	90 ± 9 (69–111)
Extension (°)	-9 ± 7 (−24–8)	-11 ± 8 (−28–3)	-8 ± 11 (−32–23)
Adduction (°)	10 ± 6 (2–21)	10 ± 5 (3–20)	10 ± 5 (1–26)
Abduction (°)	28 ± 11 (14–52)	23 ± 10 (−2–38)	27 ± 8 (1–38)
Internal rotation (°)	17 ± 7 (6–27)	13 ± 8 (0–27)	16 ± 7 (4–34)
External rotation (°)	14 ± 11 (−17–31)	11 ± 6 (0–23)	13 ± 8 (1–36)
Left hip peak moment (Nm/kg)			
Extension moment (HE)[*]	0.37 ± 0.32 (−0.13–1.02)	0.43 ± 0.26 (−0.08–0.96)	0.45 ± 0.38 (−0.18–1.25)
Abduction moment (HAB)[*]	0.72 ± 0.24 (0.19–1.20)	0.65 ± 0.15 (0.46–1.11)	0.71 ± 0.20 (0.39–1.11)
Right hip peak moment (Nm/kg)[*]			
Flexion moment (HF1)[*]	0.29 ± 0.09 (0.14–0.46)	0.23 ± 0.11 (0.02–0.39)	0.26 ± 0.09 (0.04–0.48)
Flexion moment (HF2)[*]	0.16 ± 0.13 (−0.11–0.39)	0.17 ± 0.09 (−0.09–0.28)	0.20 ± 0.09 (−0.03–0.40)
Abduction moment (HAB)[*]	0.22 ± 0.09 (0.09–0.46)	0.23 ± 0.05 (0.11–0.31)	0.24 ± 0.06 (0.14–0.39)
Internal rotation moment (HIR)[*]	0.11 ± 0.03 (0.06–0.19)	0.10 ± 0.03 (0.03–0.14)	0,10 ± 0.03 (0.03–0.18)
Left hip peak power (W/kg)			
Sagittal generation power (SG)[*]	0.27 ± 0.25 (−0.008–0.81)	0.48 ± 0.42 (0.001–1.74)	0.44 ± 0.44 (−0.06–1.45)
Coronal absorption power (CA)[*]	0.44 ± 0.25 (0.11–1.11)	0.43 ± 0.09 (0.22–0.64)	0.51 ± 0.23 (0.23–1.37)
Total generation power (TG)[*]	0.24 ± 0.22 (−0.09–0.75)	0.42 ± 0.38 (−0.11–1.41)	0.43 ± 0.51 (−0.30–1.62)
Total absorption power (TA)[*]	0.43 ± 0.26 (0.07–1.09)	0.42 ± 0.14 (0.15–0.67)	0.43 ± 0.25 (−0.08–1.07)
Absolute hip power	0.31 ± 0.18 (0.03–0.75)	0.46 ± 0.34 (0.15–1.41)	0.51 ± 0.45 (0.06–1.62)
Absolute knee power	0.14 ± 0.10 (0.01–0.40)	0.18 ± 0.10 (0.03–0.46)	0.20 ± 0.17 (0.03–0.68)
Absolute ankle power	0.18 ± 0.08 0.06–0.32)	0.17 ± 0.12 (0.03–0.53)	0.16 ± 0.11 (0.02–0.51)
Normalized hip power	0.21 ± 0.11 (0.02–0.41)	0.27 ± 0.12 (0.13–0.52)	0.25 ± 0.16 (0.04–0.58)
Normalized knee power	0.09 ± 0.05 (0.003–0.19)	0.11 ± 0.06 (0.02–0.24)	0.10 ± 0.07 (0.02–0.28)
Normalized ankle power	0.12 ± 0.04 (0.05–0.17)	0.11 ± 0.06 (0.03–0.27)	0.10 ± 0.06 (0.006–0.25)
Right hip peak power (W/g)			
Sagittal generation power (SG)[*]	0.43 ± 0.19 (0.02–0.81)	0.28 ± 0.19 (0.003–0.69)	0.34 ± 0.18 (0.06–0.78)
Sagittal absorption power (SA)[*]	0.57 ± 0.42 (−0.006–1.50)	0.51 ± 0.25 (0.07–0.94)	0.65 ± 0.33 (−0.02–1.53)
Coronal absorption power (CA)[*]	0.18 ± 0.09 (0.05–0.37)	0.17 ± 0.12 (0.03–0.59)	0.18 ± 0.10 (−0.09–0.36)
Axial generation power (AG)[*]	0.11 ± 0.11 (−0.05–0.35)	0.11 ± 0.06 (0.0003–0.19)	0.13 ± 0.11 (−0.05–0.35)
Axial absorption power (AA)[*]	0.21 ± 0.16 (0.001–0.50)	0.13 ± 0.09 (0.01–0.38)	0.19 ± 0.14 (0.01–0.50)
Total generation power (TG)[*]	0.33 ± 0.19 (−0.03–0.74)	0.17 ± 0.15 (−0.07–0.53)	0.26 ± 0.20 (−0.01–0.90)
Total absorption power (TA)[*]	0.59 ± 0.40 (−0.02–1.47)	0.51 ± 0.27 (0.03–0.94)	0.64 ± 0.33 (0.008–1.48)
Absolute hip power	0.36 ± 0.16 (0.09–0.74)	0.23 ± 0.13 (0.06–0.53)	0.34 ± 0.17 (0.07–0.90)
Absolute knee power	0.47 ± 0.26 (0.13–1.09)	0.48 ± 0.29 (0.03–1.10)	0.59 ± 0.34 (0.12–1.75)
Absolute ankle power	0.07 ± 0.04 (0.01–0.13)	0.06 ± 0.02 (0.03–0.11)	0.07 ± 0.03 (0.02–0.18)
Normalized hip power	0.24 ± 0.10 (0.10–0.40)[a]	0.16 ± 0.09 (0.06–0.40)	0.19 ± 0.07 (0.05–0.37)[a]
Normalized knee power	0.30 ± 0.11 (0.13–0.55)	0.31 ± 0.17 (0.04–0.55)	0.32 ± 0.15 (0.11–0.71)
Normalized ankle power	0.05 ± 0.03 (0.005–0.11)	0.04 ± 0.02 (0.02–008)	0.04 ± 0.02 (0.01–0.12)

Continuous values are expressed as mean ± standard deviation (range).
THA, total hip arthroplasty; Normalized power, % absolute joint power of total limb absolute power.
[b] $p < .05$ for the comparison between R-THA patients and control participants.
[a] $p < .05$ for the comparison between L-THA patients and control participants.
[*] Peak hip moment and peak hip power were listed when these values were > 0.10 in at least one of the three groups.

patients while getting into or out of a car in comparison with age, sex, and physique-matched control participants. Overall, these findings indicated that this was a low dislocation risk motion within the required RoM of the ADLs [13,14]. However, there were differences in hip joint angle, moment, and power between the surgical side of unilateral THA patients and the same side of control participants. Additionally, the compensatory changes in the contralateral hip joint power and the ipsilateral ankle joint power were different.

5.1. Getting into the car

The peak flexion and abduction angles, HAB, CG of the abductor, and TG of the surgical hip were significantly lower than those in the control participants when the surgical side was used as the pivot limb (L-THA). In contrast, the contralateral hip angle, moment, and power were comparable with the control participants. The gluteus medius is the primary hip abductor muscle, given its role in maintaining a level pelvis and preventing hip adduction and femoral internal rotation during single limb support [15,16]. Recent studies report a higher gluteus medius activity in single-leg standing with contralateral limb motion (hip flexion, extension, or abduction) [17]. The motion of getting into a car involves single-leg standing with flexion and abduction of the contralateral hip, which may place a higher load on the gluteus medius. The posterolateral approach used for all THAs in the present study results in a minute invasion of the midline muscles, suggesting that the observed findings may reflect preoperative muscle weakness caused by persistent effects of OA [7,18]. The contribution of the surgical hip to the total lower-extremity power was significantly lower, and the contribution of the surgical side ankle was significantly higher. Previous gait analyses have shown greater ankle power and increases in ankle energy relative to hip energy in THA patients [6,19,20]. When getting into a car using the surgical side as the pivot limb, the ankle may provide a large percentage of compensatory power compared with the hip, and this compensatory role may be reduced when the hip can produce more power, especially from the hip abductor (e.g., the gluteus medius).

The angles and moments of both hips were comparable. The SG of the flexors, the TG, and the absolute power of the surgical hip were significantly lower, and the SA of the flexors in the contralateral hip was

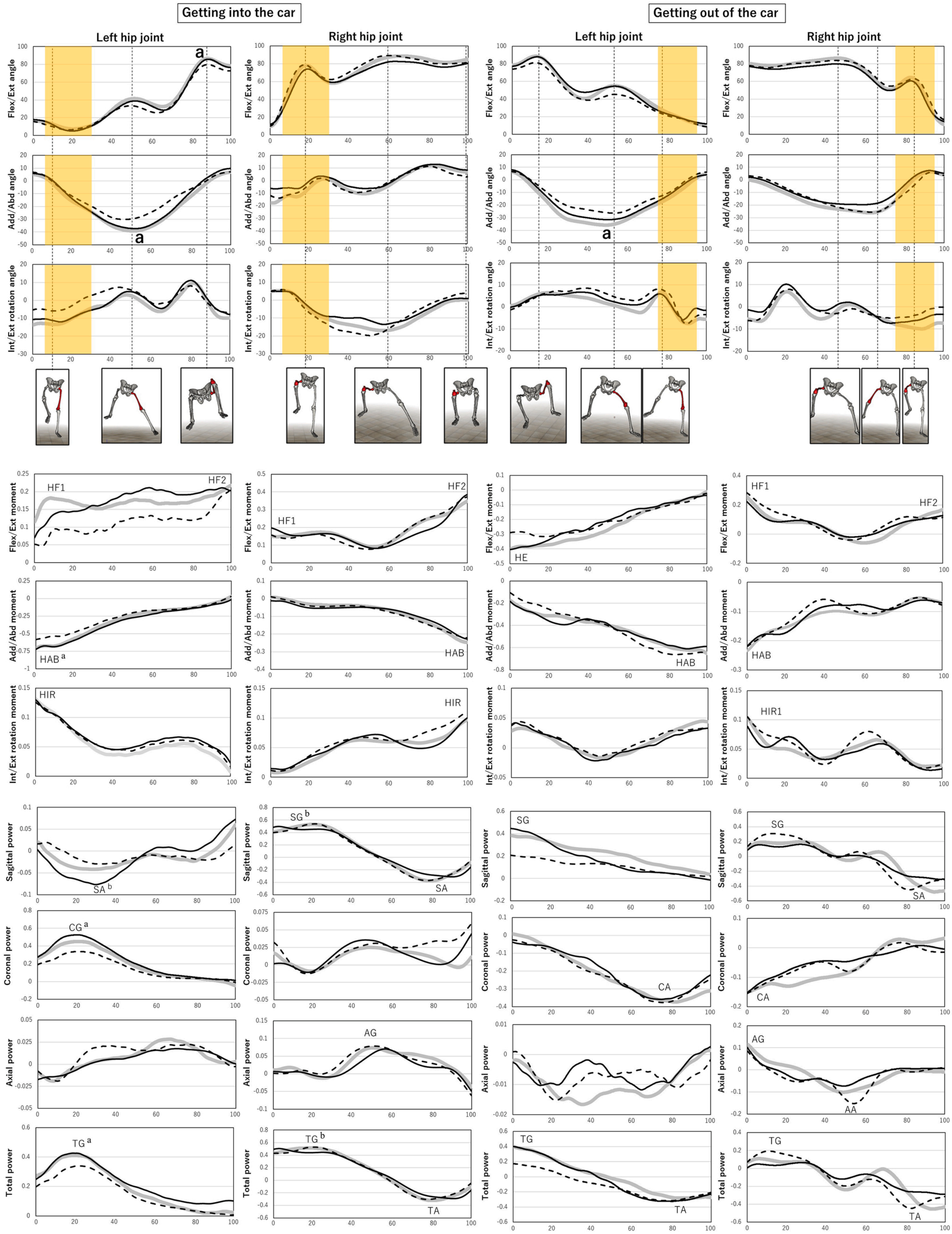

Fig. 3. Range of motion, kinetics, and kinematics in getting into and out of the car. Dotted black line, Left-THA patients (L-THA); Solid black line, Right-THA patients (R-THA); Thick gray line, control participant; Yellow zone, Single-leg phase; HF, Flexion moment; HE, Extension moment; HAD, Adduction moment; HAB, Abduction moment; HIR, Internal rotation moment; HER, External rotation moment; SG, Sagittal generation power; SA, Sagittal absorption power; CG, Coronal generation power; CA, Coronal absorption power; AG, Axial generation power; AA, Axial absorption power; TG, Total generation power; TA, Total absorption power. [a] $P < .05$ for the comparison between L-THA patients and control participants. [b] $P < .05$ for the comparison between R-THA patients and control participants.

significantly higher than those in control participants when the contralateral side was used as the pivot limb (R-THA). These results indicate a shift in power production in the sagittal plane from the surgical hip to the contralateral hip; however, there was no significant difference in individual joint contributions to the total lower-extremity power. The getting into the car motion, using the contralateral side as the pivot limb (R-THA), may be preferable to the surgical side (L-THA) because the kinematics and kinetics in the former mimic those of the control participants more closely.

5.2. Getting out of the car

The peak flexion and abduction angles of the surgical hip were significantly lower than the control participants when the surgical side was used as the pivot limb. There was no significant difference in moment and power, while the absolute hip power on the surgical side was lower in THA patients. The contribution of the contralateral hip to total lower-extremity power was significantly higher, which may compensate for the lower power of the surgical hip. Previous studies have identified an increased risk of OA and joint arthroplasty of the contralateral hip or knee in THA patients [21,22], possibly because of the increased mechanical demand on the contralateral joints to compensate for the lost power in the surgical joint while walking or using stairs [23,24].

The angle, moment, and power of both hips were comparable, and there was no significant difference in the individual joint contributions to the total lower-extremity power when the contralateral side was used as the pivot limb. The getting out of the car motion using the contralateral side as the pivot limb (R-THA) may be preferable to using the surgical side (L-THA) because the kinematics and kinetics of the former more closely mimic those in the control participants.

6. Limitations

The present study was limited to active THA patients who were pain-free in all other lower-extremity joints, those who could walk without an assistive device, and no patient was taller than 170 cm in this Asian cohort. Additionally, participants with a BMI over 30 were excluded to improve the visibility of the ASIS markers. Therefore, these results could suffer from selection bias and may not be generalizable to a wide range of body forms, age groups, or health statuses. However, the non-reliance on the upper limbs for support and adequate pelvic tracking allowed accurate assessment of the load on the joints and the joint angles of the lower limbs. Second, the follow-up duration after THA was not tightly controlled. This variable was tested for difference between the patient groups, with none found. However, a wide range of durations was present, with a wide range of variability within both groups, which may account for the lack of a significant difference. Third, control participants included fully healed patients who received upper-limb surgery more than 6 months ago. Because all participants were asked to avoid relying on upper limb support, the movement did not involve any additional stabilization from the upper limbs. Forth, while the technique of shifting to a unilateral stance and "stepping" into and out of a car as evaluated in this study is common, some THA patients with inadequate muscle strength sat on the seat and sequentially brought the right (in a left passenger seat) and then the left leg into the car while getting into and the reverse sequence when getting out. Fifth, the thigh and soft tissue compression when sitting may affect the location of the thigh markers. However, this should not impact the kinetic determinations for the early part of getting into and the later part of getting out of a car, including the single-leg phase. Finally, this study focused on the kinetics only in the single-leg phase because there were no force plates in the car.

7. Conclusion

Even high-functioning unilateral THA patients have limited RoM and power production in the surgical hip; they compensate for this loss by producing power in other joints, especially when the surgical side is the pivot limb, which may damage those joints. Therefore, restoration of the surgical hip's RoM and muscle strength and adopting the normal side as the pivot limb may enable a more balanced motion.

Author statement

Each author certifies that he has no commercial associations that might pose a conflict of interest in connection with the submitted article. Each author certifies that his institution approved the human protocol for this investigation and that all investigation was conducted in conformity with ethical principles of research. This work was performed at the Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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