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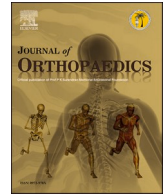
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Trendelenburg gait after total hip arthroplasty due to reduced muscle contraction of the hip abductors and extensors

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ABSTRACT

Background: Despite experiencing pain relief and improved activities of daily living after total hip arthroplasty (THA) for osteoarthritis of the hip, a Trendelenburg gait may be observed in some patients. The concentric and eccentric contraction patterns of hip muscles in a Trendelenburg gait are not well understood.

Methods: This study included 89 patients (28 males and 61 females, mean age 66.5 ± 8.4 years, mean post-operative period 1.3 ± 0.4 years) after unilateral THA without functional impairment on the contralateral side. Gait analysis utilized a three-dimensional motion capture system to assess pelvis and hip angles, hip moment, and hip power. A Trendelenburg gait was defined as positive when nonoperative pelvic descent occurred at 30 % of the gait cycle, equivalent to mid-stance. Patients were classified into Trendelenburg gait-positive and -negative groups for statistical analysis. Unpaired *t*-test and chi-square test were used to compare the two groups. Multiple regression analysis was conducted to identify factors associated with the presence of a Trendelenburg gait.

Results: A Trendelenburg gait was observed in 24 patients (27 %). Multiple regression analysis indicated that abduction ($p < 0.01$) and extension ($p = 0.03$) of hip joint power were significant determining of a Trendelenburg gait. Patients with a Trendelenburg gait exhibited reduced eccentric contraction of the hip abductor muscles and decreased concentric contraction of hip extensor muscles during early to mid-stance of their gait.

Conclusion: Centrifugal contraction of hip abductor muscles and diminished eccentric contractility of hip extensor muscles appear crucial for hip stabilization mechanisms during gait after THA.

1. Introduction

Osteoarthritis (OA) is a prevalent chronic condition causing pain and dysfunction, affecting approximately 4 %–9 % of adults aged 45 and older.^{1,2} Total hip arthroplasty (THA) has emerged as the most effective treatment for OA of the hip joint, providing pain relief, improved gait, and restoration of daily activities.^{3–5} Gait function after THA typically returns to or surpasses preoperative levels in terms of gait speed and stride length by 12 months postoperatively.⁶ However, abnormal gait patterns^{7,8} such as restricted hip extension and adduction angles,⁹ reduced hip abduction moment,¹⁰ Trendelenburg gait^{11,12} or trunk movements abnormalities¹³ may persist. Gait function is a critical clinical outcome desired by patients for improvement¹⁴ and strongly influences postoperative satisfaction.¹⁵

One of the notable abnormal gaits after total hip arthroplasty (THA) is the Trendelenburg gait, attributed to weakness in the hip abductor

muscles.^{11,12} Mjaaland et al. reported a decrease in Trendelenburg gait incidence from 44 % before THA to approximately 25 % at 12 months after THA, though it persisted at 16 % by 24 months.¹⁶ This abnormal gait increases energy expenditure due to lateral trunk movements during gait,¹⁷ leading to decreased physical activity.¹⁸ While static one-legged standing posture has been studied,¹⁹ the dynamic contraction pattern of the hip abductor muscles during Trendelenburg-positive gait remain unclear. Normally, eccentric contraction during mid-stance phase contributes to hip joint stability,²⁰ underscoring the importance of evaluating hip abductor muscle contraction patterns under dynamic conditions.

This study aimed to explore: 1) the impact of hip abduction moment on gait after THA, and 2) the contraction patterns of hip abductor and extensor muscles during Trendelenburg gait. We hypothesized that implant placement affecting the abduction moment arm contributes to reduced hip abduction moment, potentially influencing the presence of Trendelenburg gait.

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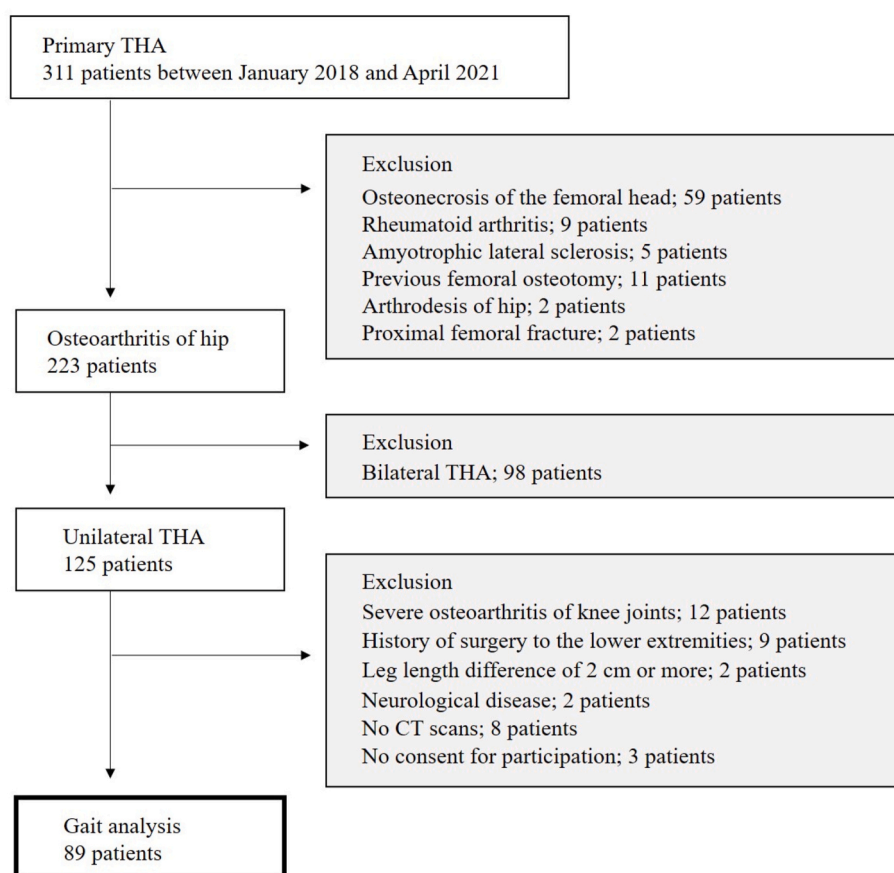


Fig. 1. Schematic representation of the study cohort.

2. Materials and methods

2.1. Patients

This retrospective cohort study followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines²¹ and was approved by the ethics committee of our university hospital (ID number: 2020-395). Signed informed consent was obtained from all patients.

Of the 311 patients who underwent primary THA at our university hospital between January 2018 and April 2021, 223 had undergone primary THA for hip OA. Of these, 125 patients (29 males and 96 females, average age 67.2 ± 8.3 years, range 43–79 years) had a healthy contralateral hip and were at least 12 months post THA (average follow-up of 1.3 ± 0.4 years, range 1.1–2.6 years). Exclusion criteria included: 1) severe lower back or knee OA, 2) history of lower extremity fractures or surgeries, 3) leg length discrepancy (LLD) of 2 cm or more, 4) lack of pre- or postoperative CT scans, 5) neurological diseases, 6) dementia, and 7) inability to walk or perform measurement tasks independently. Ultimately, 89 patients met the inclusion criteria (Fig. 1).

2.2. Gait analysis

Gait analysis was performed using a 3D motion analysis system with 10 infrared cameras (VICON Vero 2.2; Vicon Motion Systems, Oxford, UK) at a sampling rate of 100 Hz. Ground reaction forces were recorded using six embedded force platforms (AMTI; Watertown, MA, USA) at a sampling rate of 1000 Hz.²² Data collection and synchronization were managed using VICON Clinical Manager (VCM) software (Vicon Nexus 2; Vicon Motion System Ltd., Oxford, UK) and MATLAB 2019a (MathWorks Ltd., Massachusetts, USA).

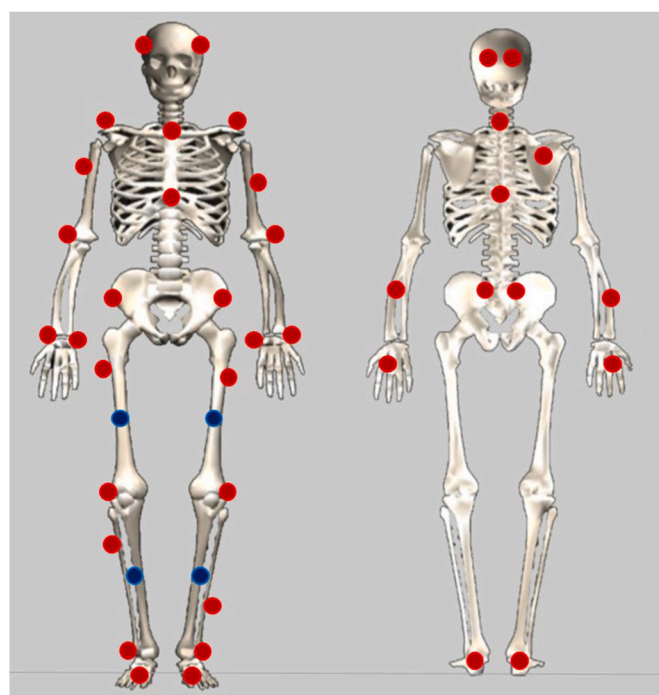


Fig. 2. Reflective marker placement: 39 reflective markers (red marks) for the plug-in-gait full-body model and 4 reflective markers (blue marks) for the SCoRE-and-SARA model were affixed to the body for measurement.

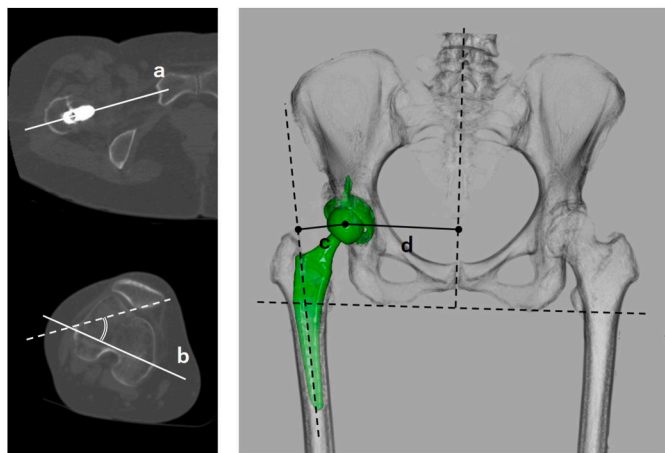


Fig. 3. Hip joint alignment measurements: Stem anteversion was defined as the angle between the femoral neck axis (a) and the transepicondylar axis (b). Global offset was the sum of the femoral offset (c) and the acetabular offset (d).

Participants wore elastic motion capture bodysuits with 9.5 mm diameter reflective markers placed at 43 locations on the body, following the plug-in-gait full body model and SCoRE-and-SARA protocols^{23,24} (Fig. 2). They were instructed to gait at a self-selected comfortable speed, and three successful gait trials were recorded. A rigid link model was created using the VICON Plug-in-Gait Full Body Ai Functional Model and SCoRE-and-SARA data. The arithmetic mean from the three trials was used, with data time-normalized to a 100 % gait cycle. Gait parameters analyzed included gait speed, cadence, stride time, step time, stride length, and step length. Kinematic data included hip joint abduction moment and hip joint power, analyzed in the sagittal, frontal, and horizontal planes.

A Trendelenburg gait was defined as a contralateral pelvic lean during the mid-stance phase (30 % of the gait cycle).^{11,12,25} It was considered positive if the operated pelvic lean angle was positive and the contralateral pelvic lean angle was negative at 30 % of the gait cycle.^{26,27} Pelvic lean angles were evaluated simultaneously for both the operated and contralateral sides in the frontal plane. Maximum hip joint angles (flexion-extension/adduction-abduction), hip joint moments (extension/abduction), and hip joint power (extension/abduction) were calculated for the period between 10 % (load-response phase) and 30 % (mid-stance phase) of the gait cycle.

2.3. Surgical procedures and components position

All surgeries were performed using a posterolateral approach with the combined anteversion technique for the stem and cup,²⁸ which accommodates the wide range of femoral anteversion in hip dysplasia.²⁹ The acetabular cup position was assessed from pre- and postoperative x-ray images. The cup height was defined as the distance from the head center to the interteardrop line.³⁰ Acetabular cup inclination was measured as the angle of abduction using the interteardrop line as the baseline (radiographic inclination), and anteversion was measured as the angle in the sagittal plane (operative anteversion).³¹ The positions were normalized by calculating the pre- and postoperative ratios (%) from their respective values.

2.4. CT imaging

CT scans were taken from the fourth lumbar vertebra to the knee, including the distal femoral condyles. Pre- and postoperative hip joint measurements were taken using SYNAPSE VINCENT software (Fujifilm, Tokyo, Japan). Measurements included femoral and postoperative stem anteversions, and femoral and acetabular offsets³¹ (Fig. 3). Stem anteversion was defined as the angle between the femoral neck axis and the

Table 1
Relation between peak hip abduction moment and each factors.

	Average ± SD (range)	correlation coefficient	p- value
Patient characteristics			
Age (years)	66.5 ± 8.4 (43–79)	−0.21	0.18
Gender (male/female) ^b	28/61		0.72
BMI (kg/m ²)	24.0 ± 4.1 (15.8–39.7)	−0.32	0.04 ^a
Follow-up duration (years)	1.3 ± 0.4 (1.1–2.6)	0.22	0.13
LLD (mm)	7.1 ± 4.6 (2.1–18.2)	0.38	0.35
VAS Pain (mm)	2.9 ± 8.5 (0–30)	0.25	0.22
Gait parameters			
Gait speed (m/sec)	1.1 ± 0.2 (0.6–1.7)	0.34	0.03 ^a
Cadence (steps/min)	114 ± 12 (77–146)	0.23	0.14
Stride time (sec)	1.1 ± 0.2 (0.8–1.6)	−0.18	0.25
Step time (sec)	0.5 ± 0.1 (0.5–0.8)	−0.11	0.52
Stride length (m)	1.1 ± 0.2 (0.6–1.4)	0.24	0.13
Step length (m)	0.5 ± 0.1 (0.3–0.7)	0.22	0.17
Peak hip joint angle (deg)			
Flexion	34 ± 6 (21–55)	0.02	0.91
Extension	1 ± 9 (10–23)	0.06	0.68
Adduction	5 ± 3 (−2–11)	0.36	0.02 ^a
Abduction	1 ± 3 (−4–7)	0.31	0.06
Components parameters (%)			
Cup height	1.1 ± 0.3 (0.8–1.2)	0.39	0.64
Cup inclination	1.2 ± 0.2 (0.7–1.2)	0.44	0.38
Cup anteversion	1.1 ± 0.4 (0.7–1.4)	0.52	0.69
Stem anteversion	0.9 ± 0.5 (0–1.7)	0.15	0.33
Global offset	1.0 ± 0.1 (0.9–1.1)	0.33	0.03 ^a

BMI: body mass index; LLD: leg length discrepancy; VAS: visual analogue scale; CT: Computed Tomography.

VAS pain was assessed during gait analysis.

The peak hip joint angle was calculated from the entire gait cycle.

^a indicates statistically significant. *P* value < 0.05.

^b Nominal logistic regression analysis.

transepicondylar axis. Global offset was the sum of femoral and acetabular offsets. These measurements were normalized by calculating the pre- and postoperative ratios (%) from their respective values.

Muscle volume was evaluated by measuring the cross-sectional areas (CSAs) of the gluteus maximus (G-max) and gluteus medius (G-med) muscles.^{32,33} The anterior pelvic plane (APP) was defined by the most anterior points of the bilateral ASIS and pubic tubercles. The G-max CSA was measured perpendicular to the APP through the most proximal point of the greater trochanter, and the G-med CSA was measured perpendicular to the APP through the ASIS. Muscle volume was normalized by body weight (mm²/kg). Muscle and other tissue boundaries were manually traced, and volume and HU were measured using SYNAPSE VINCENT, with values normalized by calculating pre- and postoperative ratios (%) from their respective values.

2.5. Statistical analysis

Correlations between peak hip abduction moment and various factors (age, BMI, follow-up period, hip joint angles, gait parameters, CT imaging parameters and pain) were examined using Pearson’s correlation coefficient. Multiple regression analysis was performed with peak hip abduction moment as the dependent variable and significantly correlated factors as independent variables.

A comparison between Trendelenburg gait-positive and -negative groups was conducted using unpaired *t*-test and chi-square test of patient characteristics (age, gender, BMI, postoperative follow-up period), kinematic factors (hip flexion-extension angle, hip adduction-abduction angle), kinetic factors (hip extension and abduction moment, hip extension, and abduction power), and bone morphology (stem anteversion, global offset). Multiple regression analysis was then performed with the presence of a Trendelenburg gait as the dependent variable and the significantly different factors as independent variables. Hip joint

Table 2
Factors influencing peak hip abduction moment.

Factors	Positive Effect	β	p value
Body mass index		-0.18	0.17
Gait speed	Higher speed	0.44	0.02 ^a
Peak hip adduction angle	Larger angle	0.21	0.01 ^a
Global offset	Longer distance	0.32	0.04 ^a

^a indicates statistically significant. *P* value < 0.05.

moment was excluded from this analysis due to its effect on hip joint power.

All statistical analyses were conducted using JMP Pro 15 (SAS

Institute Inc., Cary, NC, USA). Power analysis assumed 80 % statistical power and a 5 % alpha error to detect a 50 % difference in hip joint power between groups, requiring a sample size of 38. Statistical significance was set at $p < 0.05$.

3. Results

Peak hip abduction moment was significantly positively correlated with BMI, gait speed, peak hip adduction angle, and global offset ($p < 0.05$, Table 1). Multiple regression analysis showed that global offset, gait speed, and peak hip adduction angle significantly affected peak hip abduction moment ($p < 0.05$, Table 2).

The pelvis frontal lean angle used to evaluate the Trendelenburg gait

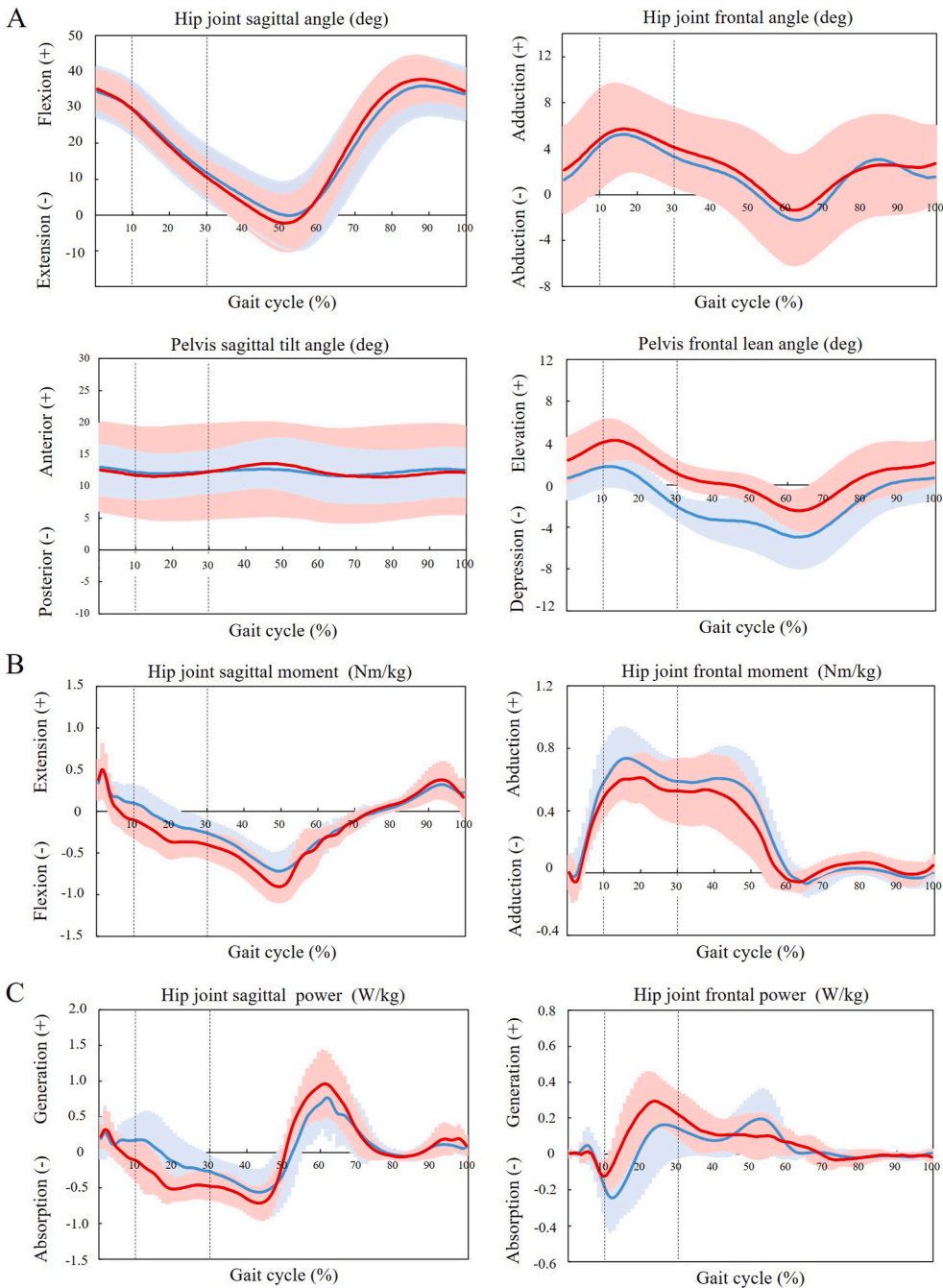


Fig. 4. Gait analysis for the positive Trendelenburg gait group (red line) and the negative group (blue line) more than one year after unilateral THA. Shaded areas indicate the respective standard deviations. The hip joint and pelvis angles (A), hip joint moment (B), and hip joint power (C) are shown in the sagittal and frontal planes.

Table 3
Comparison of Trendelenburg gait positive and negative groups.

	Positive group n = 24 (27 %)	Negative group n = 65 (73 %)	p value
Patient characteristics			
Age (years)	67.1 ± 3.2 (56–73)	66.3 ± 10.7 (43–79)	0.77
Gender (male/ female) ^a	8/16	20/45	0.21
BMI (kg/m ²)	26.3 ± 4.8 (21.9–34.7)	23.1 ± 3.4 (15.8–32.8)	0.02 ^b
FU duration (years)	1.1 ± 0.2 (1.1–1.4)	1.4 ± 0.5 (1.1–2.6)	0.37
LLD (mm)	10.6 ± 4.1 (2.1–17.6)	12.1 ± 6.6 (4.4–18.2)	0.24
VAS Pain (mm)	3.7 ± 1.9 (0–14)	2.9 ± 4.2 (0–30)	0.40
Gait parameters			
Gait speed (m/ sec)	1.1 ± 0.1 (0.6–1.4)	1.0 ± 0.1 (0.6–1.6)	0.44
Cadence (steps/ min)	110 ± 4 (77–133)	111 ± 5 (84–146)	0.94
Stride time (sec)	1.1 ± 0.0 (0.9–1.5)	1.1 ± 0.1 (0.8–1.4)	0.68
Step time (sec)	0.5 ± 0.1 (0.4–0.8)	0.5 ± 0.0 (0.4–0.7)	0.76
Stride length (m)	1.1 ± 0.2 (0.7–1.3)	1.1 ± 0.1 (0.6–1.4)	0.58
Step length (m)	0.6 ± 0.0 (0.3–0.7)	0.6 ± 0.1 (0.3–0.7)	0.52
Hip joint kinematics			
Peak hip joint angle (deg)			
Flexion	34 ± 5 (24–40)	34 ± 7 (21–55)	0.87
Extension	2 ± 7 (-12–10)	0 ± 9 (-16–9)	0.35
Adduction	5 ± 4 (-1–11)	5 ± 2 (-2–10)	0.74
Abduction	1 ± 4 (-2–7)	2 ± 3 (-3–7)	0.87
Gait cycle 10–30 % angle (deg)			
Flexion	25 ± 5 (20–33)	27 ± 6 (18–37)	0.34
Adduction	5 ± 4 (-1–11)	5 ± 2 (-2–10)	0.75
Hip joint Kinetics			
Peak hip joint moment (Nm/kg)			
Extension	0.52 ± 0.1 (0.21–0.79)	0.49 ± 0.2 (0.28–0.83)	0.73
Abduction	0.62 ± 0.1 (0.39–0.86)	0.79 ± 0.2 (0.35–1.20)	0.04 ^b
Gait cycle 10–30 % hip joint moment (Nm/kg)			
Extension	−0.41 ± 0.2 (−0.85 to −0.22)	−0.25 ± 0.2 (−0.63– 0.12)	0.02 ^b
Abduction	0.62 ± 0.1 (0.39–0.86)	0.79 ± 0.2 (0.35–1.20)	0.04 ^b
Peak hip joint power (W/kg)			
Extension	0.95 ± 0.3 (0.49–1.73)	0.77 ± 0.5 (0.33–1.91)	0.37
Abduction	0.31 ± 0.1 (0.16–0.57)	0.28 ± 0.2 (0.14–0.63)	0.06
Gait cycle 10–30 % hip joint power (W/kg)			
Extension	−0.06 ± 0.3 (−0.51– 0.45)	0.25 ± 0.4 (−0.34– 1.39)	0.02 ^b
Abduction	−0.03 ± 0.1 (−0.20– 0.19)	−0.31 ± 0.3 (−1.07– 0.03)	0.01 ^b
Muscle volume parameters (%)			
Gluteus maximus	1.3 ± 0.2 (0.9–1.4)	1.1 ± 0.4 (0.8–1.3)	0.35
Gluteus medius	1.2 ± 0.4 (0.8–1.5)	1.5 ± 0.3 (0.9–1.6)	0.21
Components parameters (%)			
Cup height	1.1 ± 0.1 (0.8–1.2)	1.0 ± 0.3 (0.9–1.1)	0.58
Cup inclination	1.0 ± 0.3 (0.7–1.1)	1.1 ± 0.2 (0.8–1.2)	0.72
Cup anteversion	1.1 ± 0.1 (0.9–1.4)	1.2 ± 0.1 (0.7–1.3)	0.33
Stem anteversion	0.9 ± 0.4 (0.8–1.1)	0.9 ± 0.5 (0.8–1.2)	0.18
Global offset	0.8 ± 0.1 (0.7–1.2)	1.1 ± 0.1 (0.8–1.2)	0.02 ^b

BMI: body mass index; FU: Follow-up; LLD: leg length discrepancy; VAS: visual analogue scale.

^a chi-square test.

^b indicates statistically significant. *P* value < 0.05.

showed a peak elevation angle of 2.6 ± 2.3° and a peak depression angle of 4.4 ± 3.5°. At 30 % of the gait cycle during the mid-stance phase, the operative pelvis depression angle was 1.8 ± 2.3°. A Trendelenburg gait was observed in 24 patients (27 %), while 65 patients (73 %) did not exhibit this gait. At 30 % of the gait cycle, the operative pelvis frontal lean angle was 2.3 ± 1.6° of elevation in the Trendelenburg-positive group and 3.4 ± 1.1° of depression in the negative group.

The Kinematics and kinetics data for both Trendelenburg gait-positive and -negative groups, along with the comparison results, are presented in Fig. 4 and Table 3. Multiple regression analysis, with BMI, hip extension power, hip abduction power, and global offset at 10–30 % of the gait cycle as explanatory variables, indicated that hip abduction power (*p* = 0.01) and hip extension power (*p* = 0.03) at 10–30 % of the

Table 4
Factors influencing Trendelenburg gait.

Factors	Positive Effect	β	p value
Body mass index		−0.09	0.52
Global offset		11.84	0.36
Gait cycle 10–30 % hip joint power			
extension	Larger concentric contraction	3.81	0.03*
abduction	Larger eccentric contraction	−9.27	0.01*

*indicates statistically significant. *P* value < 0.05.

gait cycle were significant factors influencing the presence of a Trendelenburg gait (Table 4).

4. Discussion

We conducted an inverse dynamics analysis of gait motion in patients approximately one year after unilateral primary THA to examine factors influencing: 1) peak hip abduction moment during gait and 2) a Trendelenburg gait. The results showed that gait speed, peak hip adduction angle, and global offset length were factors influencing peak hip abduction moment during gait after THA. Hip abduction and extension power during 10–30 % of the gait cycle were found to be factors influencing the occurrence of a Trendelenburg gait. Joint power, indicated by its positive (concentric contraction) or negative (eccentric contraction) polarity, showed reduced eccentric contraction in hip abduction movements and reduced concentric contraction in hip extension movements during the load-response phase to mid-stance, which is indicative of a Trendelenburg gait.

Kurihara et al.³⁴ reported the peak hip abduction moment after THA as 0.6 ± 0.2 Nm/kg at 4 weeks postoperatively, and Miki et al.³⁵ reported it as 0.8 ± 0.2 Nm/kg at 1 year postoperatively. In our study, the peak hip abduction moment was 0.75 ± 0.2 Nm/kg, comparable to previous studies with similar Asian cohorts.^{34,35} Gait speed improves after THA, correlating with increased peak hip abduction moment.³⁵ Our study showed a gait speed of 1.1 ± 0.2 m/s at 1 year postoperatively, surpassing the sarcopenia-related cut-off values of 0.8 m/s³⁶ and 1.0 m/s,³⁷ supporting the relationship between gait speed and peak hip abduction moment.

Global offset length and hip adduction angle also influenced peak hip abduction moment. THA implant placement is adjusted to compensate for dislocation, LLD, and femoral and acetabular offset.^{38,39} Rüdiger et al.⁴⁰ noted that increased stem anteversion decreases femoral offset, and a 20 % decrease in femoral offset decreases hip abduction moment by approximately 15 %. Higher femoral offsets imply a greater hip abductor moment arm, enhancing abductor moment generation.⁴¹ Similarly, as hip adduction angle decreases and the hip becomes more abducted, the hip abduction moment decreases.⁴² Thus, increased global offset and hip adduction angle are crucial for facilitating a greater hip abduction moment.

In the Trendelenburg gait-positive group, hip extension moment was low in the sagittal plane, producing more centrifugal contraction, and hip abduction moment was low with weaker eccentric contraction in the frontal plane compared to the negative group. Since eccentric contraction allows higher muscle torque than concentric contraction,⁴³ the lower eccentric contraction during hip abduction likely contributed to the presence of a Trendelenburg gait. Inefficient hip stabilization in the sagittal plane, due to decreased concentric contraction of hip extensors, may inhibit eccentric contraction of the hip abductors, leading to a Trendelenburg gait.

Our study highlights the importance of hip abduction moment arm and suggests evaluating global offset changes before and after surgery, ensuring a range of hip adduction motions during postoperative gait practice. Exercises focusing on eccentric contraction during hip abduction and concentric contraction during hip extension may be beneficial.

One limitation of this study is its retrospective design, which lacked

preoperative function and hip abductor strength data. Trendelenburg gait observations were inferred from kinematic and kinetic factors. Despite this, our study is one of the few examining muscle contraction patterns, laying a foundation for future research. Although gait analysis was performed at a comfortable speed, not a fixed speed, to reflect daily life gait behavior accurately, this approach introduces potential measurement bias. Finally, results may not generalize to other THA surgical approaches.

5. Conclusion

Gait speed, peak hip adduction angle, and global offset length were significant factors influencing peak hip abduction moment approximately one year after unilateral THA. Additionally, hip joint abduction and extension power during 10–30 % of the gait cycle were linked to the presence of a Trendelenburg gait. Eccentric contraction of hip abduction and reduced concentric contraction power of hip extension are important determinants for hip stabilization during gait after THA.

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CRedit authorship contribution statement

Tsutomu Fujita: Conceptualization, Formal analysis, Investigation, software tracking, Project administration, Writing – original draft. **Satoshi Hamai:** Data curation, writing, Supervision, Funding acquisition, Writing – review & editing. **Daisuke Hara:** Formal analysis, Writing – review & editing. **Shinya Kawahara:** Formal analysis, Writing – review & editing. **Ryosuke Yamaguchi:** Formal analysis, Writing – review & editing. **Satoshi Ikemura:** Formal analysis, Writing – review & editing. **Goro Motomura:** Formal analysis, Writing – review & editing. **Kenichi Kawaguchi:** Writing – review & editing. **Yasuharu Nakashima:** Writing – review & editing. As described above, all authors meet the authorship criteria and have read and approved the final version of the submitted manuscript.

Declaration of competing interest

None.

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