

Distinct recovery trajectories of spatiotemporal and trunk kinematic parameters following simultaneous bilateral total hip arthroplasty: a 12-month longitudinal study

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Abstract

Recovery of gait after total hip arthroplasty (THA) has been extensively investigated in unilateral cases; however, the longitudinal recovery process following simultaneous bilateral THA remains unclear. This study aimed to longitudinally evaluate spatiotemporal gait parameters and trunk trajectory for 12 months after simultaneous bilateral THA using wearable inertial measurement unit (IMU) sensors and to compare outcomes at 12 months with healthy controls (HCs).

Twenty-six patients were assessed preoperatively and at 3, 6, and 12 months postoperatively. Twenty-six age-matched healthy women served as controls. Stride length, maximum foot clearance, stride speed, stride duration, stance and swing duration, and lateral sway of the trunk, lateral sway asymmetry, vertical trunk displacement, and vertical displacement asymmetry were analyzed.

Stride length and stride speed improved progressively up to 12 months. In contrast, stride duration and stance duration improved by 6 months and showed no further significant changes thereafter, with no differences compared with HCs at 12 months. Lateral trunk displacement did not demonstrate significant longitudinal improvement. At 12 months, patients exhibited slower stride speed and greater lateral trunk displacement than HCs. Age was negatively associated with postoperative stride speed, whereas body mass index was positively associated with lateral sway of the trunk.

Temporal and spatial aspects of gait recovery appear to follow distinct recovery trajectories after bilateral THA. Regular monitoring using wearable IMU sensors may help identify patients with persistent gait deviations and support individualized rehabilitation strategies.

1. Introduction

Hip osteoarthritis (OA) is a progressive joint disorder primarily characterized by degeneration of the articular cartilage^{1,2}. Its prevalence has been increasing worldwide in parallel with the aging population³. In Japan, hip OA occurs more frequently in women⁴, and its clinical manifestations—including hip pain, restricted range of motion (ROM), and gait disturbance—substantially limit physical activity and represent major contributors to reduced quality of life (QOL)^{5–7}. For patients with end-stage hip OA, total hip arthroplasty (THA) is widely performed with the primary aims of pain relief and functional restoration.

More than 80% of patients scheduled to undergo unilateral THA present with osteoarthritis in the contralateral hip⁸, indicating that hip OA tends to progress bilaterally. Consequently, patients with bilateral hip OA may undergo either staged unilateral THA or simultaneous bilateral THA. Evidence suggests that simultaneous bilateral THA is associated with fewer complications and greater cost-effectiveness compared with staged procedures⁹. However, because patients undergoing simultaneous bilateral THA do not have an unaffected limb, recovery mechanisms that cannot be inferred from studies of unilateral THA may emerge. Therefore, understanding surgical strategies and postoperative functional

recovery in patients with bilateral hip OA is clinically important. Although THA is an effective treatment that alleviates pain and improves QOL¹⁰⁾, many aspects of postoperative gait recovery remain unclear. While numerous studies have investigated gait function following unilateral THA, walking speed and step length have been shown to remain lower than those of healthy individuals even 12 months after surgery¹¹⁾. In contrast, longitudinal studies examining gait function after bilateral THA are limited. Previous studies have suggested that, compared with unilateral THA, bilateral THA may facilitate earlier normalization of pelvic alignment¹²⁾ and greater improvements in walking speed and step length by 6 months postoperatively¹³⁾. These findings suggest that bilateral THA may follow a recovery pattern distinct from that of unilateral THA and potentially result in more favorable functional outcomes. Nevertheless, some reports indicate that gait function remains impaired compared with healthy controls (HCs) even two years after bilateral THA¹⁴⁾ and the detailed recovery trajectory—particularly within the first postoperative year—has not been fully elucidated. Furthermore, although previous studies have focused on spatiotemporal gait parameters and hip joint ROM, no studies to date have evaluated trunk or pelvic trajectory during walking in patients undergoing bilateral THA.

Therefore, the primary aim of this study was to longitudinally investigate gait function and, uniquely, trunk trajectory over a 12-month postoperative period in patients undergoing simultaneous bilateral THA using wearable inertial measurement unit (IMU) sensors. The rationale for examining trunk trajectory is to explore compensatory strategies and address existing gaps in knowledge regarding comprehensive gait recovery after simultaneous bilateral THA. The secondary aim was to compare gait parameters and trunk trajectory at 12 months postoperatively with those of HCs in order to identify residual gait impairments following bilateral THA.

2.Method

2.1 Study Design and Participants

This prospective observational cohort study enrolled female patients with end-stage bilateral hip OA who were scheduled to undergo simultaneous bilateral THA via a minimally invasive anterolateral approach (MIS-AL) at the Department of Orthopaedic Surgery, Nissan Tamagawa Hospital, between 2022 and 2023. A total of 40 patients were enrolled in the bilateral THA group. The inclusion criteria were as follows: (1) bilateral end-stage hip OA according to the Japanese Orthopaedic Association (JOA) classification of hip disease, and (2) a minimum joint space (MJS) of less than 1 mm in both hips. An age-matched group of 26 healthy adult women with no history of hip pathology was recruited as the HCs group. The exclusion criteria for both groups were: (1) a history of neurological disorders, cerebrovascular disease, or other musculoskeletal conditions that could affect gait; (2) psychiatric disorders that might influence walking ability; (3) self-reported sensory disturbances in the lower extremities or feet; and (4) inability to walk a short distance (20 m) without assistive devices.

Of the 40 patients enrolled in the bilateral THA group, 26 (65%) completed all assessment time points up to 12 months postoperatively. During the follow-up period, 14 patients (35%) were lost to follow-up. The reasons for dropout were postoperative complications (n = 2), withdrawal of consent (n = 2), transfer to a convalescent rehabilitation hospital (n = 1), and loss to follow-up at 3 months (n = 6), 6 months (n = 2), and 12 months (n = 1). Ultimately, data from 26 patients were included in the longitudinal analyses.

This study was approved by the Institutional Review Board of Nissan Tamagawa Hospital and the Research Ethics Committee of the Institute of Science Tokyo. All participants received oral and written explanations of the study objectives and procedures and provided written informed consent prior to participation. The study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2. Assessments and Procedures

Preoperative physical function assessments were conducted in the bilateral THA group. The hip joint ROM angles were determined by passively moving the patients' legs and measuring the maximum angles via a goniometer. The pelvis was stabilized to prevent rotation or tilting when the passive ROM was measured by an experienced physical therapist¹⁵.

ROM was performed with the patient in the supine position, except for the measurement of the angle of external and internal hip rotation. The external and internal rotation angles were measured in the prone position at 90° knee joint flexion. Knee extension muscle strength was measured while the participants were in a seated position via a handheld dynamometer (μ TAS F-1, Anima Co., Ltd., Tokyo, Japan), with the sensor pad fixed to the distal lower leg. The maximum isometric contraction was measured three times on each side for five seconds, with the highest value recorded as the weight ratio (kgf/kg). Hip abduction muscle strength was measured similarly to that of the patient in the supine position and the sensor pad was fixed to the distal thigh. Spina malleolar distance (SMD) was measured using a common tape measure to measure the distance between the anterior superior iliac spine and the medial malleolus. The minimum joint space (MJS) was measured via plain X-rays by an orthopedic surgeon. Hip function was assessed via the JOA hip score, which includes pain (40 points), ROM (20 points), walking ability (20 points), and activities of daily living (20 points), totaling 100 points. The JOA hip score is designed for the Japanese lifestyle and strongly correlates with the Harris hip score¹⁶. The stage of hip OA was classified by an orthopedic surgeon according to the JOA classification of hip disease. No significant differences were observed in the preoperative physical function assessment items between the left and right sides (Supplementary Table S1).

2.3 Equipment and Gait Measurement

The spatiotemporal gait parameters and trunk trajectory were measured using the WALK-MATE GAIT CHECKER Pro from WALK-MATE LAB Co. Ltd., Tokyo, Japan (Supplementary Figure S1). Two sensors were attached above the lateral malleoli using special bands to measure acceleration and angular velocity and estimate gait parameters. The third IMU sensor was attached above the L3 lumbar vertebra via a band. The acceleration and angular velocity ranges were ± 8 G and ± 1000 dps, respectively, with a

sampling frequency of 100 Hz. The TSND121 sensor measures 37 mm × 46 mm × 12 mm and weighs approximately 22 g.

The spatiotemporal gait parameters included stride length, maximum foot clearance, stride speed, stride duration, stance duration, and swing duration for the left and right lower limbs^{17,18}. Trunk trajectory variables were calculated from IMU data collected at the level of the third lumbar vertebra (L3). Measures included lateral sway of the trunk, lateral sway asymmetry, vertical trunk displacement, and vertical displacement asymmetry during gait^{19,20}.

Participants walked along a 16 m straight corridor at a self-selected comfortable speed, with a 10 m central measurement zone flanked by 3 m approach and deceleration zones at either end. All participants were measured without any walking aids.

2.4. Statistical Analysis

A priori sample size estimation was performed for the primary longitudinal analysis of postoperative changes. Assuming a medium effect size ($f = 0.25$), a significance level of $\alpha = 0.05$, and statistical power of $1 - \beta = 0.80$, a required sample size of 24 participants was calculated for a two-way repeated-measures analysis of variance (ANOVA). To account for potential attrition, 40 patients were enrolled. All statistical analyses were conducted using R software (version 4.3.3), and statistical significance was set at $p < 0.05$.

Longitudinal analysis of postoperative changes

To evaluate longitudinal changes in the bilateral THA group (preoperatively and at 3, 6, and 12 months postoperatively), a two-way repeated-measures ANOVA (4 time points × 2 sides) was applied for parameters that included left and right limb data. For parameters without side-specific values, a one-way repeated-measures ANOVA (4 time points) was performed.

The assumption of sphericity was assessed using Mendoza's test. When the assumption was violated, the Greenhouse–Geisser correction was applied. If a significant main effect of time was observed, post hoc multiple comparisons were performed using Shaffer's modified sequentially rejective Bonferroni procedure. When a significant interaction was detected, simple main effects were examined.

Between-group comparisons and associations with preoperative factors

To compare outcomes at 12 months postoperatively between the bilateral THA group and HC group, a mixed-design ANOVA was used for parameters that included side-specific data. For parameters without side-specific values, normality was assessed using the Shapiro–Wilk test, and either an independent-samples t-test or the Mann–Whitney U test was applied accordingly.

To control for multiplicity across the 10 primary outcome measures in the between-group comparisons, p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. Adjusted p-

values (q-values) less than 0.05 were considered statistically significant.

Furthermore, for outcome variables that showed significant between-group differences at 12 months postoperatively, associations with preoperative factors (demographic characteristics, ROM, and muscle strength) were examined within the bilateral THA group. Depending on data distribution, Pearson's or Spearman's correlation coefficients were calculated. As this analysis was exploratory and hypothesis-generating, no adjustment for multiple comparisons was applied.

3.Results

Representative examples of three-dimensional foot trajectories and trunk trajectories during gait for the bilateral THA group (preoperatively and at 3, 6, and 12 months postoperatively) and the HC group are shown in Fig. 1.

3.1 Participant characteristics

Baseline characteristics of the participants are presented in Table 1. There were no significant differences between the bilateral THA and HC groups in age, height, body weight, or BMI.

3.2 Longitudinal postoperative changes

The results of the repeated-measures ANOVA for gait parameters and trunk trajectory variables in the bilateral THA group across the four time points (preoperatively and at 3, 6, and 12 months postoperatively) are shown in Tables 2 (gait parameters) and 3 (trunk trajectory). A significant main effect of time was observed for stride length, stride speed, stride duration, stance duration, and vertical trunk displacement. Stride length and stride speed were found to increase significantly over time up to 12 months postoperatively. In contrast, stride duration and stance duration significantly decreased up to 6 months postoperatively, with no significant changes observed between 6 and 12 months (Fig. 2). For maximum foot clearance, a significant interaction between time and side was detected. Right-side clearance was found to decrease significantly toward 12 months postoperatively, whereas no significant changes were observed on the left side. For vertical trunk displacement, both the main effects of time and side were significant (Table 3), with consistently greater displacement on the left side compared with the right throughout the study period. No significant longitudinal changes were observed for swing duration or the other trunk trajectory variables.

3.3 Between-group comparisons at 12 months and associations with preoperative factors

Comparisons of gait parameters and trunk trajectory variables between the bilateral THA group and the HC group at 12 months postoperatively are presented in Table 4. The results of the mixed-design ANOVA are shown in Supplementary Table S2. After adjustment for multiple comparisons using the false

discovery rate (FDR) procedure, significant between-group differences were identified in two parameters. Compared with the HC group, the bilateral THA group demonstrated significantly slower stride speed (bilaterally) and significantly greater lateral sway of the trunk (Fig. 4). Although stride length, stride duration, and swing duration showed significant postoperative changes within the bilateral THA group, no significant differences between groups were observed for these parameters after FDR correction. The correlations between stride speed and lateral sway of the trunk at 12 months postoperatively and preoperative factors are presented in Supplementary Table S3.

Age was significantly negatively correlated with stride speed at 12 months postoperatively for both the left ($R = -0.57$, $p = 0.003$, 95% CI $[-0.783, -0.230]$) and right ($R = -0.63$, $p < 0.001$, 95% CI $[-0.815, -0.314]$) sides (Fig. 5). Height was significantly positively correlated with stride speed for both the left ($R = 0.43$, $p = 0.027$, 95% CI $[0.056, 0.703]$) and right ($R = 0.41$, $p = 0.038$, 95% CI $[0.026, 0.688]$) sides. Preoperative BMI showed a significant positive correlation with the lateral sway of the trunk at 12 months ($\rho = 0.56$, $p = 0.003$) (Fig. 5). A similar correlation was observed for preoperative body weight ($\rho = 0.56$, $p = 0.003$). No significant correlations were found between preoperative range of motion or muscle strength and stride speed or lateral sway of the trunk at 12 months postoperatively.

4. Discussion

To our knowledge, this is the first study to longitudinally quantify trunk kinematics using wearable IMU sensors in patients undergoing simultaneous bilateral THA. The present study aimed to clarify the longitudinal recovery of spatiotemporal gait parameters and trunk trajectory from preoperatively to 12 months after simultaneous bilateral THA, and to compare gait characteristics at 12 months with those of HCs. The principal findings were as follows: (1) gait function markedly improved over 12 months after THA, although recovery patterns differed among parameters, and lateral waist sway did not significantly improve; and (2) even at 12 months postoperatively, patients with bilateral THA exhibited slower stride speed and greater lateral waist sway compared with HCs.

Regarding the postoperative recovery process, stride length and stride speed showed progressive and significant improvements up to 12 months. In contrast, stride duration and stance duration improved significantly until 6 months, with no further significant change between 6 and 12 months. Moreover, at 12 months, no significant differences in these temporal parameters were observed compared with HCs. These findings suggest that temporal components of the gait cycle may largely recover by 6 months after bilateral THA. This pattern partially aligns with longitudinal studies of unilateral hip arthroplasty²¹⁾, but in unilateral hip arthroplasty, single-leg stance time continues to improve up to 12 months postoperatively¹¹⁾, indicating a tendency for recovery over a longer timeframe.

Bilateral THA patients tend to exhibit greater preoperative symmetry than unilateral THA patients²²⁾, potentially requiring fewer compensatory strategies. Because temporal parameters such as stance and stride duration are closely linked to walking rhythm and speed²³⁾, the relatively symmetrical

reconstruction of the gait cycle after bilateral THA may allow earlier normalization of these time-related variables. In contrast, improvements in stride length and stride speed—spatial parameters associated with hip joint range of motion and joint moments related to propulsion²⁴⁾—may require longer recovery periods. Previous studies have shown that hip joint kinetics continue to improve up to 12 months postoperatively¹¹⁾, which may explain the gradual recovery of spatial parameters observed in the present study.

With respect to trunk trajectory, the vertical trunk displacement increased until 6 months postoperatively, whereas lateral sway of the trunk did not significantly improve. The persistence of lateral sway of the trunk despite improvements in other parameters may reflect compensatory motor strategies established preoperatively due to chronic pain²⁵⁾. Such strategies may remain as maladaptive motor patterns even after restoration of joint function. These findings suggest that targeted motor relearning interventions aimed at restoring appropriate frontal-plane trunk control may be important following bilateral THA.

At 12 months postoperatively, stride speed remained significantly slower and lateral sway of the trunk significantly greater in the bilateral THA group than in HCs, even after adjustment for multiple comparisons. These findings indicate that although fundamental spatiotemporal parameters approach normal levels within 12 months, deficits in walking speed and frontal-plane trunk control persist. Some reports suggest that bilateral THA may show more pronounced improvements in speed and stride length compared with unilateral THA¹³⁾. The results of this study also may suggest a potentially favorable recovery pattern compared with previous reports on unilateral THA. Nevertheless, differences in preoperative gait ability and surgical invasiveness should be considered when interpreting these comparisons. We further examined associations between preoperative factors and gait outcomes at 12 months. Preoperative hip ROM and muscle strength were not significantly associated with postoperative stride speed or lateral sway of the trunk. This suggests that dynamic postoperative gait performance may not be predicted solely by static preoperative physical function, consistent with previous findings in unilateral THA populations²⁶⁾.

Notably, a significant positive correlation was observed: patients with higher preoperative BMI exhibited greater lateral sway of the trunk at 12 months postoperatively. It is known that in obese individuals, increased trunk mass leads to greater hip abduction moment²⁷⁾, resulting in reduced gait stability²⁸⁾. In patients after THA, residual trunk sway, particularly in the frontal plane, makes control of the hip abductor muscles especially critical²⁹⁾. In patients following bilateral THA, incomplete recovery of hip abductor function may limit the ability to meet these increased mechanical demands, resulting in persistent lateral sway of the trunk. Increased trunk sway may reduce gait efficiency and may also contribute to reduced walking speed as a strategy to enhance stability³⁰⁾.

A significant negative correlation was observed between age and stride speed at 12 months postoperatively, independent of BMI, indicating that older patients tended to exhibit slower walking speed after surgery. This finding is consistent with a previous meta-analysis of unilateral THA¹¹⁾, which

identified age as an important factor associated with postoperative gait speed recovery. Together, these findings suggest that age may be an important determinant of gait speed recovery following THA. This association may reflect age-related declines in neuromuscular function as well as inter-individual differences in tissue healing capacity.

These findings suggest that rehabilitation strategies following simultaneous bilateral THA may benefit from being individualized rather than uniform. For patients with higher BMI, preoperative weight management may be important, and postoperative rehabilitation may need to emphasize trunk stability and the relearning of efficient center-of-mass transfer during gait. In contrast, for older patients, interventions focusing on fall prevention and enhancement of lower-limb strength, which underpins walking speed, may be particularly relevant. Regular monitoring of the recovery process using wearable IMU sensors, as applied in the present study, may facilitate early identification of patients exhibiting atypical recovery patterns and support the implementation of personalized rehabilitation strategies.

Limitations

Several limitations should be acknowledged. First, the sample size was relatively small, and analyses examining associations between BMI, age, and postoperative parameters were exploratory. Larger studies are needed to confirm these findings. Second, although gait parameters and waist trajectory were assessed longitudinally, muscle strength was evaluated only preoperatively. Therefore, the relationship between postoperative muscle recovery and persistent trunk sway could not be directly examined. Third, the HC group was assessed cross-sectionally at a single time point. Longitudinal assessment of controls would have enabled more rigorous comparisons of recovery patterns. Finally, potential confounding factors, including postoperative rehabilitation content, adherence, and daily physical activity levels, were not fully controlled and may have influenced gait recovery.

6. Conclusion

This study longitudinally investigated recovery of spatiotemporal gait parameters and trunk trajectory up to 12 months after simultaneous bilateral THA using wearable IMU sensors and compared outcomes at 12 months with healthy controls. Temporal parameters, including stride duration and stance duration, largely normalized by 6 months postoperatively, whereas spatial parameters, such as stride length and stride speed, continued to improve up to 12 months. At 12 months, patients with bilateral THA still demonstrated significantly slower stride speed and greater lateral waist sway compared with HCs. Postoperative stride speed was associated with age, and lateral sway of the trunk was associated with BMI. Regular monitoring of gait recovery using wearable IMU sensors may help identify patients with persistent deviations in speed or trunk control and support the development of individualized rehabilitation strategies following bilateral THA.

Date availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Author Contribution

Y.K. and H.U. designed this study. Y.K. conducted the experiment and analyzed the data. Y.K., H.U., M.M. and Y.M. discussed and interpreted the results. Y.K. and H.U. drafted the manuscript, and all authors reviewed the manuscript and approve the final version of the paper for publication.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

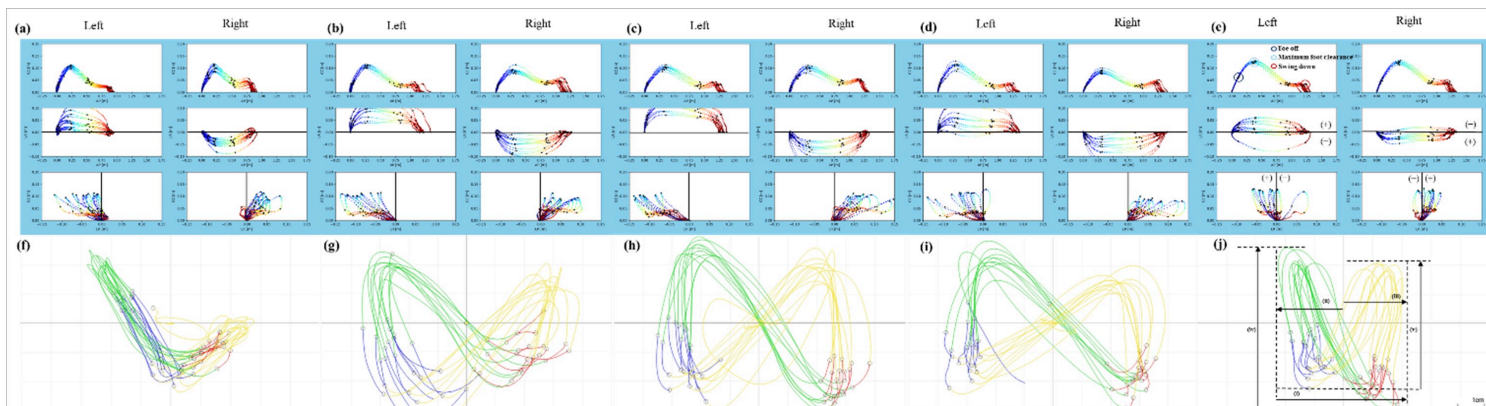
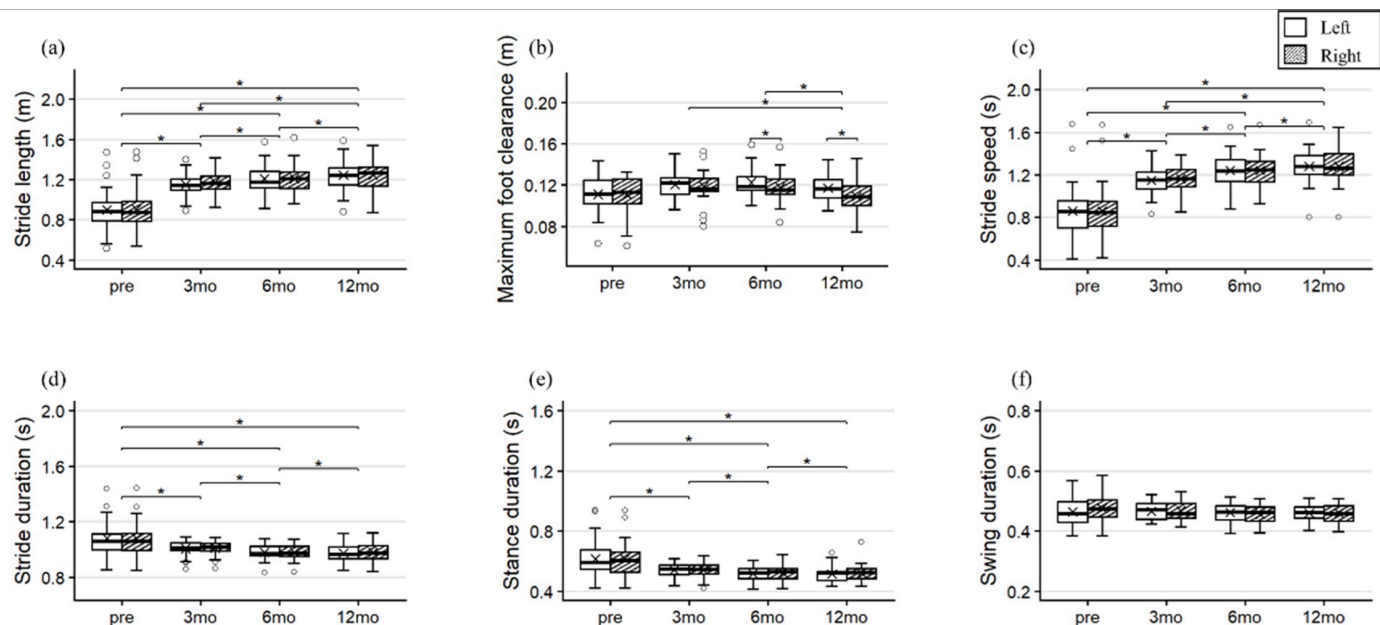


Figure 1. Representative examples of three-dimensional ankle and trunk trajectories during gait in a patient with bilateral total hip arthroplasty (THA) and a healthy control participant.
 (a–e) Three-dimensional ankle trajectories during gait. (a) Preoperative condition, (b) 3 months postoperatively, (c) 6 months postoperatively, (d) 12 months postoperatively, and (e) an age-matched healthy control. Black dots indicate the positions of toe-off, maximum foot clearance, and swing-down during the swing phase. In the horizontal and frontal planes, the midline was defined as 0, and the lateral distance (LD) from the midline was calculated, with the swing-leg side defined as positive (+) and the stance-leg side as negative (–). From left to right and top to bottom, the panels show the sagittal, horizontal, and frontal planes. AP, anterior–posterior; CC, cranio–caudal; LR, left–right.
 (f–j) Trunk trajectories measured at the level of the third lumbar vertebra (L3). (f) Preoperative condition, (g) 3 months postoperatively, (h) 6 months postoperatively, (i) 12 months postoperatively, and (j) an age-matched healthy control. Trunk trajectories are shown according to gait phases: double-support phase (red), right single-leg support phase (yellow), double-support phase (blue), and left single-leg support phase (green). The trunk trajectory variables include total lateral trunk sway, lateral trunk sway toward the left and right sides, and vertical trunk displacement during trunk lifting on the left and right sides.

Figure 1

See image above for figure legend.



* $p < 0.05$

Figure 2. Changes in gait parameters from preoperative to postoperative follow-up in patients undergoing bilateral THA.

Box plots show the distribution of gait parameters measured preoperatively and at 3, 6, and 12 months postoperatively. Solid boxes represent the left limb and hatched boxes represent the right limb. The central line indicates the median, the box represents the interquartile range, and whiskers indicate the range. Cross marks indicate the mean values. Asterisks indicate statistically significant differences (* $p < 0.05$). The panels show (a) stride length, (b) maximum foot clearance, (c) speed, (d) stride duration, (e) stance duration, and (f) swing duration.

Figure 2

See image above for figure legend.

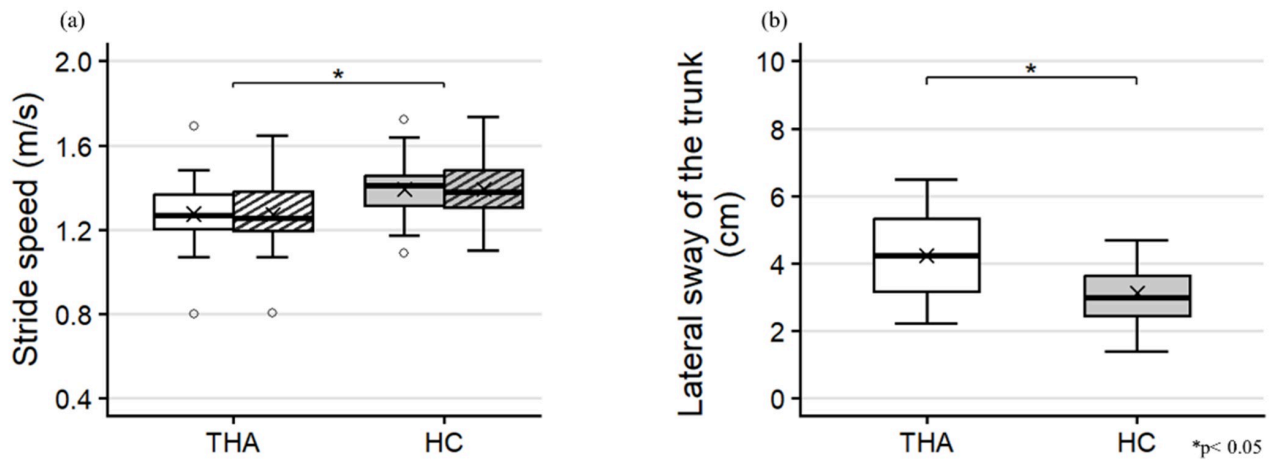


Figure 3. Comparison of stride speed and lateral trunk sway between patients with bilateral total hip arthroplasty (THA) and healthy controls (HC) at 12 months postoperatively. White boxes represent the THA group, and gray boxes represent the HC group. Solid boxes indicate the left limb, and hatched boxes indicate the right limb. The central line represents the median, the boxes indicate the interquartile range, and the whiskers indicate the range. *p < 0.05. The panels show (a) stride speed and (b) lateral sway of the trunk.

Figure 3

See image above for figure legend.

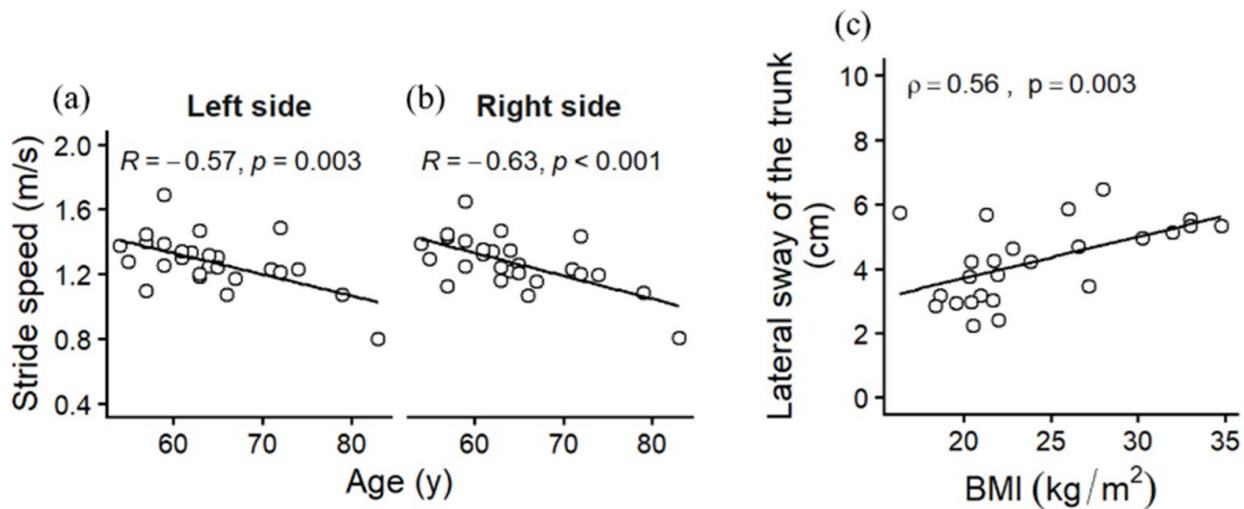


Figure 4. Associations between preoperative factors and gait parameters 12 months after bilateral total hip arthroplasty (THA). (a, b) Relationships between age and stride speed (left and right). (c) Relationship between body mass index (BMI) and lateral trunk sway. Each dot represents an individual participant, and solid lines indicate linear regression fits. Correlations were evaluated using Pearson correlation for normally distributed variables and Spearman's rank correlation for non-normally distributed variables.

Figure 4

See image above for figure legend.

Image not available with this version

Figure 5

Legend not included with this version.

Supplementary Files

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- [supplemental.docx](#)
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