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Title

Uncontrolled manifold analysis of center-of-mass control during gait before and after total hip arthroplasty in patients with hip osteoarthritis

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Abstract

Background: Total hip arthroplasty (THA) is an effective treatment for hip osteoarthritis (HOA), and postoperative gait analysis is important for evaluating recovery and designing rehabilitation strategies. However, conventional gait assessment has focused primarily on the motion of individual joints and may not adequately capture the inter-joint coordination required to control the center of mass (CoM). Uncontrolled manifold (UCM) analysis provides a framework for quantitatively evaluating this coordination. Clarifying how gait coordination changes before and after THA may offer useful insights for rehabilitation. In this study, we used UCM analysis to examine changes in CoM control (V_{UCM}, V_{ORT}, ΔVz) during gait before and after THA in patients with HOA.

Methods: Using a publicly available gait dataset, we analyzed the gait of 53 patients with HOA before and after THA. From motion-capture data, segment angles were defined as the elemental variables and the CoM as the performance variable. V_{UCM}, V_{ORT}, and ΔVz were computed using UCM analysis and compared between the preoperative and postoperative time points.

Results: After surgery, V_{UCM} decreased significantly in all phases, and V_{ORT} decreased significantly in mid-stance and terminal stance ($p < 0.05$). In contrast, ΔVz showed no significant change in any phase ($p > 0.05$). The mean mediolateral CoM position and its trial-to-trial variability did not change between the preoperative and postoperative time points.

Conclusions: These results suggest that, even when hip function changes, the body can flexibly exploit the available degrees of freedom to stabilize the CoM. Given that CoM control is distributed across multiple segments rather than a single segment, postoperative rehabilitation may benefit from considering the coordination of the whole movement system in addition to the affected joint.

Trial registration ClinicalTrials.gov, NCT01907503. Registered 17 July 2013. Retrospectively registered.

Keywords: hip osteoarthritis; total hip arthroplasty; gait; center of mass; uncontrolled manifold.

1. Background

Hip osteoarthritis (HOA) is a common musculoskeletal disorder characterized by pain, restricted range of motion, and muscle weakness, and it substantially impairs activities of daily living and quality of life. Total hip arthroplasty (THA) is an established treatment for HOA, with reported reductions in pain, increases in joint range of motion, and improvements in hip function [1, 2]. However, improvement at the level of impairment does not necessarily mean that function at the level of the motor task is fully normalized. Indeed, spatiotemporal parameters such as gait speed and step length improve after THA [3]. Concurrently, joint kinematics, trunk motion, and left–right symmetry have been reported to remain different from those of healthy individuals for a long period after surgery [4–6]. Understanding these features and linking them to postoperative rehabilitation strategies requires a framework that captures gait from a perspective beyond the level of individual joints.

Conventional gait assessment after THA has focused mainly on the kinematic and kinetic measures of individual joints [3, 7]. Although these measures are useful for quantifying function at the level of a specific joint [8], they provide limited information about the relationships among the multiple joints that make up gait. Gait is a motor task performed by multiple joints that interact with one another [9, 10], and even when the function of individual joints is preserved, changes in the relationships among joints can alter the overall characteristics of gait. Some of the aspects that

remain different from healthy individuals after THA are thought to arise at the level of inter-joint relationships; however, measures focused on individual joints make these difficult to capture directly. Indeed, Longworth et al. noted that gait findings have not changed substantially despite advances in surgical techniques and instrumentation, and that such assessments may not adequately capture the information needed to improve gait and clinical outcomes [6]. Therefore, a comprehensive understanding of postoperative gait calls for a perspective that captures inter-joint coordination, complementing the assessment of individual joints.

Functionally quantifying inter-joint coordination requires an understanding of how multiple joints are organized toward achieving a motor task. Inter-joint coordination before and after THA has been evaluated using methods such as cyclograms and continuous relative phase analysis [6, 11]. However, these methods describe the relative timing and amplitude between joints and do not directly reflect how joints work together under the functional demands of a motor task [12]. Uncontrolled manifold (UCM) analysis is a method that addresses this limitation [13, 14]. In UCM analysis, a performance variable representing the task goal and the elemental variables involved in achieving it are defined, and the trial-to-trial variability of the elemental variables under the same condition is decomposed into a component that does not affect the performance variable (V_{UCM}) and a component that does (V_{ORT}). The synergy index derived from these two components quantifies the degree to which multiple joints coordinate toward achieving the task goal. In UCM analysis of gait,

78 it is common to use the center of mass (CoM) as the performance variable and segment angles as the
79 elemental variables [15, 16]. By decomposing the trial-to-trial variability of segment angles into
80 V_{UCM} (variability that does not affect the CoM) and V_{ORT} (variability that affects the CoM), this
81 framework can quantify how joints coordinate to stabilize the CoM and reveals coordination
82 strategies that respond to the functional demands of movement.
83 Evidence from the UCM analysis of gait coordination has accumulated in healthy adults and older
84 adults, showing associations between age-related changes in motor control and fall risk [15, 17].
85 Inter-joint coordination has been reported to change over a 2-year follow-up even in healthy older
86 adults [16]. In the field of musculoskeletal disorders, the characteristics of inter-joint coordination
87 have been reported in patients with knee osteoarthritis (KOA) [18]. For HOA, Ibara et al. reported a
88 cross-sectional UCM analysis using the hip angle as the performance variable [19], and we recently
89 conducted a cross-sectional analysis using the CoM as the performance variable [20]. In that
90 analysis, both V_{UCM} and V_{ORT} were significantly increased in patients with HOA compared with
91 healthy individuals, whereas the synergy index representing inter-joint coordination was preserved to
92 a similar degree in both groups. That is, in patients with HOA, an increase in trial-to-trial variability
93 (increased V_{UCM} and V_{ORT}) coexists with the preservation of inter-joint coordination (a preserved
94 synergy index). This suggests that, even when trial-to-trial variability increases in HOA, the
95 coordinative structure of the joints for CoM control is largely preserved. However, all of these

findings were obtained from cross-sectional inter-group comparisons. Although inter-joint coordination after joint replacement has been examined using methods such as cyclograms and continuous relative phase [6, 8, 11], no studies appear to have applied UCM analysis longitudinally before and after surgery, and longitudinal UCM studies have been limited to healthy aging [16]. Therefore, how the functional decomposition of variability and coordination changes after an intervention that directly alters joint structure remains unknown.

THA is an intervention that directly replaces the affected joint structure itself. By comparing the same patients before and after surgery, it is possible to test whether the features of motor control observed in HOA are reversible with the recovery of joint structure, without being confounded by inter-subject differences. Unlike cross-sectional inter-group comparisons [19, 20], the present study makes it possible to distinguish which components of the UCM indices depend on the state of the joint structure and which reflect more fundamental control principles that are independent of structure. Specifically, if the increases in V_{UCM} and V_{ORT} observed in HOA depend on the joint structure, they would be expected to decrease with the structural improvement provided by THA. In contrast, if the synergy index representing inter-joint coordination is a more fundamental index independent of the state of the joint structure, it would be expected to be maintained before and after surgery. Conversely, if the synergy index also changes, THA would be positioned as an intervention that reorganizes coordination itself. Beyond clarifying the effect of the surgical intervention itself,

114 this distinction may also inform postoperative rehabilitation, by indicating whether it should focus
115 mainly on the function of individual joints or also incorporate a perspective aimed at inter-joint
116 coordination.

117 Accordingly, in the present study, we aimed to evaluate gait before and after THA in patients with
118 HOA using UCM analysis with the CoM as the performance variable, and to quantitatively clarify
119 how the UCM indices (V_{UCM}, V_{ORT}, and the synergy index) change after surgery. The hypotheses of
120 this study are based on: (i) the previous cross-sectional finding that, in patients with HOA, increases
121 in V_{UCM} and V_{ORT} coexist with preservation of the synergy index [20]; and (ii) the theoretical
122 framework that humans can achieve CoM control by flexibly exploiting the available degrees of
123 freedom regardless of the state of the joint structure [21]. Specifically, we hypothesized that V_{UCM}
124 and V_{ORT} would decrease after THA, whereas the synergy index representing inter-joint coordination
125 would be maintained before and after surgery. Testing this hypothesis is expected to clarify which
126 aspects of motor control THA changes and which it preserves in patients with HOA, and, on that
127 basis, to inform postoperative rehabilitation strategies.

128 **2. Materials and methods**

129 2.1 Participants

130 This study is a secondary analysis of a publicly available dataset [22] that includes pre- and post-
131 THA gait data from patients with unilateral HOA. The original dataset, collected at Dijon University

Hospital (France) between 2011 and 2016, comprised 80 asymptomatic healthy volunteers and 106 patients with end-stage unilateral HOA; for the patients with HOA, gait was recorded preoperatively and approximately 6 months postoperatively. In the present study, only the data from the patients with HOA were analyzed.

In the original dataset, the patients with HOA were aged 45–85 years and had been diagnosed with HOA, including imaging assessment, according to the criteria of the American College of Rheumatology [23]. The exclusion criteria included: acute exacerbation of osteoarthritis; painful disorders of the ankle, knee, or foot; acute or chronic low back pain; Parkinson's disease; neuromuscular disease; poorly controlled diabetes; cardiac or respiratory failure; and any other major factor that would preclude standard gait analysis [22].

In the present study, we additionally excluded participants who: (i) were 80 years of age or older, to limit the influence of aging [19, 20]; (ii) lacked Kellgren–Lawrence grade data; (iii) had fewer than 10 preoperative gait trials; (iv) lacked postoperative follow-up gait data; or (v) could not provide the 20 stance phases required to estimate the UCM indices. After applying these criteria, 53 participants (25 men and 28 women) were included in the analysis (Fig. 1). Each participant was assessed at both the preoperative (Pre-THA) and postoperative (Post-THA) time points, and all comparisons were made within subjects. The protocol was conducted in accordance with the Declaration of Helsinki and Good Clinical Practice, and was approved by the Comité de Protection des Personnes (CPP) Est

I — an independent research ethics committee established under the French Public Health Code (the French equivalent of an Institutional Review Board / Research Ethics Committee). The original data were collected at Dijon University Hospital, France, and all participants provided written informed consent before inclusion. The original prospective data collection was registered at ClinicalTrials.gov (NCT01907503) [22].

2.2 Data collection

Participant characteristics, including the Kellgren–Lawrence grade, were obtained through interview and imaging assessment [22]. For gait analysis, kinematic data were recorded at 100 Hz using an eight-camera optical motion-capture system (Vicon MXT40, Vicon, UK), while ground reaction forces were simultaneously acquired at 1000 Hz using two force plates (OR6-5, AMTI, USA). Body segments were tracked using 35 reflective markers attached according to the standard Plug-in-Gait protocol. After a static calibration trial, each participant walked along a 6-m walkway at their own comfortable speed for at least 10 trials per session, and was instructed to look straight ahead and maintain a natural gait pattern. Data were collected over two sessions using the same measurement system. Preoperative data were recorded within 30 days before surgery, and postoperative data were recorded 6–7 months after surgery. Each session was conducted by the same two experienced examiners and took approximately 2 h.

2.3 Data processing

Marker trajectories were labeled in Vicon Nexus (version 2.10, Vicon, UK), interpolated using the Woltring spline method [24], and smoothed with a fourth-order low-pass Butterworth filter (cutoff frequency 10 Hz). Heel-strike and toe-off events were identified using a kinematic algorithm based on the sign change in the anteroposterior velocity of the heel and toe markers [22]. The hip, knee, and ankle joint centers were calculated according to the methods described in the dataset paper [22]. From the resulting data, we extracted the coordinates of the: left and right frontal head markers; C7; T10; the left and right anterior superior iliac spines; and the left and right hip, knee, and ankle centers. Following the same framework as a previous study [15] and our previous study [20], we constructed a 16-degrees-of-freedom geometric model comprising eight segments: the bilateral shanks, bilateral thighs, pelvis, lower trunk, upper trunk, and head. The analysis targeted the stance phase of the affected side, and the same affected side was used in both the preoperative and postoperative conditions. The interval from heel strike to toe-off was extracted and time-normalized to 0–100% [15]. Because each participant performed at least 10 trials per session and two stance phases were obtained per trial, at least 20 steps were secured for analysis per participant. The number of steps used was based on the work of Rosenblatt and Hurt [25]. They reported that, whereas a stable approximation of the synergy index is obtained with approximately 16 steps, accurately estimating V_{UCM} and V_{ORT} individually requires approximately 49 steps. However, the difference between 15–20 steps and 50 steps is small, and at the group level a sufficiently stable

estimate can be obtained with 20 steps. Based on this finding and on our previous study using the same method [20], we also used 20 steps in the present study. Step length and step width were calculated from the coordinates of the left and right ankle centers, and gait speed was calculated by dividing the anteroposterior CoM displacement during the stance phase by the stance time [19]. The CoM was estimated as the position integrating the mass centers of the eight segments described above [15, 26]. For each participant, the mean and standard deviation of the CoM across the 20 secured steps were obtained, and the UCM indices were calculated [15, 20].

2.4 UCM analysis

Based on the geometric model, the 16 segment angles (θ1–θ8, α1–α8) were used as the elemental variables [15]. The mediolateral position of the CoM was selected as the performance variable. This was because frontal-plane control during gait is inherently demanding [27] and has been reported to become more difficult in HOA [28]; hence, we considered the mediolateral component to be important for capturing CoM control strategies before and after surgery. The CoM is expressed by the following equation [15]:

$$CoM = x_0 + \sum_{i=1}^{8} M_i \, x_i \qquad (1)$$

where

$$x_i = \sum_{j=1}^{i} C_j L_i \cos \alpha_j \sin \theta_j \qquad (2)$$

and

$$C_j = 1 \; for \; j < i \qquad (3)$$

where x0 is the origin of the global coordinate system placed at the ankle center of the stance limb. θ1–θ8 represent the segment angles in the frontal plane, and α1–α8 represent the segment angles in the sagittal and horizontal planes. L1–L8 are the segment lengths, M1–M8 are the segment masses normalized by total body mass, and C1–C8 are the ratios of the mass-center position within each segment; all are based on standard anthropometric values [15, 26].

To map the elemental variables (the 16-degrees-of-freedom segment angles) onto the performance variable (the CoM), we used the Jacobian matrix (J) constructed by taking the partial derivatives of the CoM with respect to each segment angle. Although the musculoskeletal system is nonlinear, the variability that arises during repeated gait is small and occurs in the vicinity of the mean configuration; hence, we judged that it could be treated with a local linear approximation. The null space of J (ε) is the set of segment-angle changes that do not alter the CoM, that is, the UCM, and its dimension is (n − d) (where n = 16 is the dimensionality of the segment configuration and d = 1 is the dimensionality of the CoM). At each time point of the stance phase, the deviation of the segment configuration from its mean was separated into a component lying within the UCM (θ_{UCM}) and a component orthogonal to it (θ_{ORT}).

$$\theta_{UCM} = \sum_{i=1}^{n-d} (\theta - \bar{\theta}) * \varepsilon_i \qquad (4)$$

$$\theta_{ORT} = (\theta - \bar{\theta}) - \theta_{UCM} \qquad (5)$$

222 V_{UCM} was defined as the squared norm of θ_{UCM}, averaged over the 20 steps and normalized by the

223 degrees of freedom of the UCM subspace.

224 $$V_{UCM} = (n-d)^{-1} * N^{-1} * \sum(\theta_{UCM})^2 \quad (6)$$

225 V_{ORT} was defined as the corresponding quantity for θ_{ORT}, normalized by the degrees of freedom of

226 the orthogonal subspace.

227 $$V_{ORT} = d^{-1} * N^{-1} * \sum(\theta_{ORT})^2 \quad (7)$$

228 V_{UCM} represents the variability of segment configurations allowed within the range that does not

229 affect the CoM; a larger value means that redundant degrees of freedom are used to adopt diverse

230 postures while keeping the CoM constant. In contrast, V_{ORT} represents the variability in directions

231 that change the CoM; a larger value indicates that trial-to-trial variation perturbs CoM control to a

232 greater extent. From these two components, the synergy index (ΔV), representing the strength of

233 coordination, was calculated [29].

234 $$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}} \quad (8)$$

235 where

236 $$V_{TOT} = \left(\frac{1}{n}\right)(dV_{ORT} + (n-d)V_{UCM}) \quad (9)$$

237 The synergy index takes a larger value as V_{UCM} exceeds V_{ORT}, and a larger value indicates that

238 multiple segments work cooperatively in the direction that stabilizes the CoM. Because the synergy

239 index does not follow a normal distribution, it was subjected to Fisher's z-transformation and treated

as ΔVz, following previous studies [15, 30]. Because the mechanical demands change over time even within the stance phase, the UCM indices may also differ across phases [15]. Therefore, following a previous study [15], the stance phase (0–100%) was divided equally into three intervals: initial stance (IS, 0–33%), mid-stance (MS, 34–66%), and terminal stance (TS, 67–100%). Representative values of the CoM and each UCM index (V_{UCM}, V_{ORT}, ΔVz) were obtained for each interval, and their transitions across phases throughout the stance phase were evaluated.

2.5 Statistical analysis

All statistical analyses were performed as intra-subject comparisons, independently comparing the preoperative and postoperative time points of the same patients for each of the three phases of the stance phase (IS, MS, TS). The normality of the pre-to-post differences was checked using the Shapiro–Wilk test. V_{UCM} and V_{ORT} were log-transformed, and the synergy index was treated as ΔVz via Fisher's z-transformation [15, 30]. A paired t-test was applied when the differences satisfied normality, and a Wilcoxon signed-rank test otherwise. The type I error associated with multiple comparisons was controlled using a Bonferroni correction applied independently within each variable group.

For the participant characteristics and gait parameters, the preoperative and postoperative time points were compared using paired t-tests or Wilcoxon signed-rank tests, and effect sizes were reported as r.

For the segment angles, both the mean angle and its trial-to-trial standard deviation were compared between the preoperative and postoperative time points in each phase, evaluating changes in trial-to-trial variability in addition to changes in mean posture. For the mean angle and the trial-to-trial standard deviation separately, a Bonferroni correction was applied, treating the 48 comparisons (16 segment angles × 3 phases) as a single variable group. Effect sizes were reported as Cohen's d when a paired t-test was used and as r when a Wilcoxon signed-rank test was used.

For the CoM, the mediolateral position and its trial-to-trial standard deviation were compared between the preoperative and postoperative time points in each phase. Because the CoM is a direct descriptive measure of the center-of-mass position, no covariates were used. A Bonferroni correction was applied to the six comparisons (2 variables × 3 phases). Effect sizes were reported as Cohen's d when a paired t-test was used and as r when a Wilcoxon signed-rank test was used. For comparisons using a paired t-test, the 95% confidence interval (CI) is for the mean difference (post − pre).

For the UCM indices (V_{UCM}, V_{ORT}, ΔVz), because gait speed and body size have been reported to affect the UCM indices [15, 20], preoperative body mass index (BMI) and preoperative gait speed were used as covariates. For each phase, the pre-to-post change (post − pre) was regressed linearly on these covariates, and after adjusting for inter-subject differences due to the covariates, we tested whether the adjusted mean change differed from zero. A Bonferroni correction was applied to the nine comparisons (3 indices × 3 phases). Effect sizes were reported as Cohen's d. The 95% CI is for

276 the covariate-adjusted mean change (post − pre). All statistical analyses were performed in

277 MATLAB (The MathWorks, Natick, MA, USA), and the significance level was set at $p < 0.05$.

278 **3. Results**

279 3.1 Participant characteristics and gait parameters

280 The participant characteristics and gait parameters are shown in Table 1. For the participant

281 characteristics, no significant differences between the preoperative and postoperative time points

282 were found for body height ($p = 0.89$, $r = 0.02$), body mass ($p = 0.28$, $r = 0.15$), or BMI ($p = 0.40$, $r =$

283 0.12). For the gait parameters, gait speed increased significantly from before to after surgery ($p <$

284 0.001, $r = 0.70$). Step length also increased significantly after surgery ($p < 0.001$, $r = 0.64$), and step

285 width decreased significantly ($p < 0.001$, $r = -0.62$).

286 3.2 Elemental variable: segment angles

287 The mean segment angles and their trial-to-trial standard deviations before and after surgery are shown

288 in Table 2. For each measure, the preoperative and postoperative time points were compared in each of

289 the IS, MS, and TS phases. For the mean angle, significant differences ($p < 0.05$) after Bonferroni

290 correction were found in four segment angles in IS ($\theta 5$, $\theta 8$, $\alpha 2$, $\alpha 5$), three in MS ($\alpha 4$, $\alpha 6$, $\alpha 7$), and six in

291 TS ($\theta 5$, $\alpha 1$, $\alpha 4$, $\alpha 5$, $\alpha 6$, $\alpha 7$). For the trial-to-trial standard deviation, significant postoperative decreases

292 were found in $\theta 8$ in all phases (IS, MS, and TS) and in $\theta 4$ and $\theta 7$ in MS.

Table 1. Comparison of participant characteristics and gait parameters between Pre-THA and Post-THA

		Pre-THA			Post-THA			p-value	Effect Size
Body height (cm)		165.0	±	7.7	165.0	±	7.7	p = 0.89	r = 0.02
Body mass (kg)		78.5	±	16.7	78.9	±	17.2	p = 0.28	r = 0.15
BMI (kg/m^2)		28.7	±	5.2	28.8	±	5.4	p = 0.40	r = 0.12
Gait speed (m/s)	*	0.9	±	0.3	1.1	±	0.3	p < 0.001	r = 0.70
Step length (cm)	*	40.3	±	9.4	46.0	±	8.6	p < 0.001	r = 0.64
Step width (cm)	*	17.8	±	4.7	14.7	±	4.2	p < 0.001	r = -0.62
Kellgren and Lawrence Grade					KL-stage 2: n=11, KL-stage 3: n=24, KL-stage 4: n=18				

Values are presented as means ± standard deviations.

Comparisons between Pre-THA and Post-THA were made using paired t-tests or Wilcoxon signed-rank tests according to the normality of the differences.

Effect size r is shown. * $p < 0.05$. BMI, body mass index; THA, total hip arthroplasty.

3.3 The performance variable: CoM

The mean mediolateral CoM position and its trial-to-trial standard deviation are shown in Fig. 2. When the preoperative and postoperative time points were compared in each phase, no significant difference was found in any comparison. For the mean position, the results were IS ($t(52) = 1.06$, $p = 1.000$, $d = 0.15$, 95% CI [−0.11, 0.35]), MS ($t(52) = -1.92$, $p = 0.361$, $d = -0.26$, 95% CI [−0.83, 0.02]), and TS ($t(52) = -0.50$, $p = 1.000$, $d = -0.07$, 95% CI [−0.64, 0.38]). For the trial-to-trial standard deviation, the results were IS ($Z = -1.96$, $p = 0.299$, $r = 0.27$), MS ($Z = -2.08$, $p = 0.227$, $r = 0.29$), and TS ($t(52) = -1.95$, $p = 0.341$, $d = -0.27$, 95% CI [−0.12, 0.00]).

3.4 UCM indices

The time courses of the UCM indices are shown in Fig. 3, and the phase-by-phase comparisons between the preoperative and postoperative time points are shown in Fig. 4.

V_{UCM} decreased significantly after surgery in all phases (IS, MS, and TS): IS ($t(50) = -3.29$, $p = 0.017$, $d = -0.45$, 95% CI [−0.36, −0.09]), MS ($t(50) = -3.74$, $p = 0.004$, $d = -0.51$, 95% CI [−0.37, −0.11]), and TS ($t(50) = -3.50$, $p = 0.009$, $d = -0.48$, 95% CI [−0.37, −0.10]).

V_{ORT} decreased significantly after surgery in MS ($t(50) = -3.02$, $p = 0.036$, $d = -0.42$, 95% CI [−0.37, −0.08]) and TS ($t(50) = -3.47$, $p = 0.010$, $d = -0.48$, 95% CI [−0.35, −0.09]); however, the change was not significant in IS ($t(50) = -2.75$, $p = 0.074$, $d = -0.38$, 95% CI [−0.42, −0.07]).

310 ΔVz showed no significant difference between the preoperative and postoperative time points in
311 any phase: IS ($t(50) = 0.32$, $p = 1.000$, $d = 0.04$, 95% CI [−0.10, 0.14]), MS ($t(50) = -0.46$, $p =$
312 1.000, $d = -0.06$, 95% CI [−0.09, 0.06]), and TS ($t(50) = -0.38$, $p = 1.000$, $d = -0.05$, 95% CI
313 [−0.09, 0.06]).

314 **4. Discussion**

315 Using UCM analysis with the mediolateral CoM as the performance variable, the present study
316 examined, within subjects and longitudinally, how the UCM indices (V_{UCM}, V_{ORT}, and the synergy
317 index) change after surgery in the gait of patients with HOA before and after THA. After surgery,
318 V_{UCM} and V_{ORT} (the components representing the trial-to-trial variability of the elemental variables)
319 decreased compared with before surgery. In contrast, ΔVz, which represents inter-joint coordination,
320 did not change, and the mean mediolateral CoM position and its trial-to-trial variability (the
321 performance variable) were also preserved before and after surgery. These results indicate that,
322 although the amount of trial-to-trial variability decreased after surgery, the coordination that
323 organizes this variability toward stabilizing the CoM was preserved. This is consistent with our
324 hypothesis that V_{UCM} and V_{ORT} would decrease while the synergy index would be maintained.
325 Reports applying UCM analysis longitudinally before and after an orthopedic intervention are
326 limited, and the present study provides longitudinal insight into which components of the UCM
327 indices change and which are preserved before and after THA.

328 After surgery, gait speed and step length increased significantly and step width decreased
329 significantly compared with before surgery (Table 1). Moreover, significant changes in segment
330 angles were found in several phases (Table 2). These suggest that the gait parameters improved after
331 THA, consistent with a previous study [3]. In contrast, the mean mediolateral CoM position and its
332 trial-to-trial variability (the performance variable) did not change before or after surgery in any
333 phase (Fig. 2a, b). That is, even though the motion of each segment changed after surgery,
334 mediolateral control of the CoM was maintained. The CoM is a quantity that integrates the
335 segmental motion of the whole body, and its stabilization (particularly control in the frontal plane) is
336 known to be shared by multiple joints centered on the hip, rather than by a single joint [31–33]. In
337 the present study as well, the motion and trial-to-trial variability of several segments changed after
338 surgery, and θ8, which had large variability before surgery, decreased significantly in all phases
339 (Table 2). The preservation of CoM stability despite such changes in the motion of some segments
340 suggests that the coordinative function that integrates the motion of each segment to stabilize the
341 CoM was maintained before and after surgery. Although reduced gluteus medius function in HOA
342 can affect CoM stability [31], the actions of the ankle [34] and trunk [35] can also contribute to
343 mediolateral stabilization. The extent to which each segment contributed to CoM stabilization cannot
344 be individually identified from the data of the present study. However, the fact that CoM control is
345 distributed across multiple segments rather than concentrated in a single segment is considered to

346 leave room for the relative contributions to be reorganized among segments even when the action of
347 a given segment changes. The preservation of CoM stability after surgery, despite the change in the
348 state of the hip due to THA, is consistent with such control distributed across multiple segments.
349 In the present study, V_{UCM} and V_{ORT} (the components representing the trial-to-trial variability of
350 the elemental variables) decreased after surgery compared with before surgery. V_{UCM} decreased
351 significantly in all phases, and V_{ORT} decreased significantly in MS and TS but not in IS (Fig. 4a, b).
352 V_{UCM} represents the variability component that does not affect the performance variable, and V_{ORT}
353 represents the component that does [13]. The decrease in both components indicates that both the
354 variability that affects and the variability that does not affect the performance variable decreased
355 after surgery. In a cross-sectional study, we reported that both V_{UCM} and V_{ORT} were higher in
356 patients with HOA than in healthy older adults [20]. Whereas that study examined the difference
357 between HOA and healthy individuals, the present study compared the same patients before and
358 after surgery to examine how that difference changes after the structural intervention of THA. The
359 decrease in V_{UCM} and V_{ORT} after surgery indicates that the elevated trial-to-trial variability
360 characteristic of the HOA state was reduced following the structural intervention of THA. In this
361 respect, the findings of the two studies are complementary. Indeed, many segment angles differed
362 significantly between before and after surgery (Table 2), suggesting that movement patterns changed
363 according to the state of hip function. The reduction after surgery of the movement patterns

364 associated with the limitation of hip function seen before surgery may be related to the decrease in
365 trial-to-trial variability [3, 34–37]. Such changes in variability can be understood from the concept of
366 motor redundancy. The body has more degrees of freedom than the minimum required to control the
367 CoM. By exploiting these surplus degrees of freedom, it stabilizes the CoM while allowing
368 variability within a range that does not affect task achievement (V_{UCM}). The amount of this
369 variability that does not affect task achievement is not fixed but is known to be adjusted according to
370 the situation [21]. Furthermore, V_{UCM} and the synergy index have been reported to be higher in
371 patients with KOA than in healthy individuals [18]. The decrease in V_{UCM} and V_{ORT} after surgery in
372 the present study can also be interpreted within this framework. That is, the use of the surplus
373 degrees of freedom may have changed in response to the altered joint structure, such that more
374 variability was exploited before surgery, when the affected joint constrained movement, and less was
375 required after the structural intervention.
376 While V_{UCM} and V_{ORT} decreased after surgery, we examined whether inter-joint coordination
377 changed before and after surgery using ΔVz. ΔVz showed no significant change between before and
378 after surgery in any phase (Fig. 4c). The effect sizes were all very small (d = −0.06 to 0.04), and the
379 95% CIs were within a narrow range that included zero. These results suggest that a substantial
380 change in inter-joint coordination before and after surgery is unlikely and that coordination was
381 largely maintained. From the UCM perspective, the elemental variables are considered to have

coordinated to stabilize the CoM (the performance variable) throughout the pre- and postoperative period [16]. The lack of a large change in ΔVz corresponds to V_{UCM} and V_{ORT} decreasing by approximately the same magnitude. The amounts of change in the two components were approximately equal on a logarithmic scale, and their 95% CIs overlapped substantially. Because ΔVz is an index that reflects the relative magnitudes of V_{UCM} and V_{ORT}, its value was preserved as a result of both decreasing by approximately the same proportion. That is, although the absolute amount of trial-to-trial variability decreased, the coordinative structure represented by the balance between V_{UCM} and V_{ORT} was maintained. This finding is consistent with our cross-sectional study, in which ΔVz did not differ between patients with HOA and healthy older adults [20], and with the present study, in which the trial-to-trial variability of the CoM did not change before or after surgery. These support the view that, within the scope of the present study, coordination toward CoM stabilization does not change substantially even when the state of the hip changes. In light of the motor-redundancy framework, the body has more degrees of freedom than the minimum required to control the CoM and can adjust the amount of variability according to the situation while maintaining their distribution [21]. The change in variability observed in the present study (more before surgery and less after surgery) is consistent with the interpretation that the amount was adjusted while the coordinative framework was preserved. However, the present study evaluated a single time point, 6 months after surgery. Whether the absence of a large change in coordination

400 reflects robust preservation of the coordinative structure or that neuromuscular coordination has not
401 yet been reorganized at 6 months after surgery cannot be distinguished from the present study.
402 Future longitudinal evaluation at multiple time points is needed to examine how coordination
403 changes over time.
404 The results of the present study suggest that CoM control can be achieved by flexibly using the
405 available degrees of freedom even when the state of hip function changes. Gait coordination after
406 joint replacement has been evaluated mainly using descriptive methods such as cyclograms and
407 continuous relative phase, and changes in coordination patterns have been reported [6, 8, 11]. The
408 present study complements these by showing that functional coordination toward CoM stabilization
409 is preserved even when the motion of individual segments changes. This perspective has important
410 implications for rehabilitation. Conventional approaches often focus on the affected joint, but a
411 holistic approach that considers the interactions among segments across the whole movement system
412 may yield more effective outcomes. A previous study showed that balance training for patients
413 undergoing THA improves both balance and mobility [38], and Chiu et al. noted the need for clinical
414 efforts aimed at improving inter-joint coordination [11]. The present findings support this view. That
415 is, rather than targeting only the affected joint or relying on repetitive single-task exercises,
416 rehabilitation should incorporate diverse tasks and graded difficulty to make use of inter-joint
417 coordination. Specifically, tasks that simultaneously recruit the trunk, hip, and ankle for frontal-

418 plane stabilization (such as mediolateral weight shifting, single-leg standing, and responding to
419 perturbations during gait) may serve as means to exploit the preserved coordination. Furthermore,
420 variable practice that gradually changes gait speed, direction of progression, support-surface
421 stability, and dual-task conditions may help elicit the same coordination under a variety of situations.
422 However, these are directions derived from the findings of the present study, and their effectiveness
423 needs to be verified in future intervention studies.
424 The present study has several limitations. First, the postoperative assessment was at a single time
425 point only, 6 months after THA. Because hip function often recovers around 6 months after surgery
426 [39], we set this as the assessment point, considering that it would provide an opportunity to observe
427 motor control during an important period of recovery. However, assessment at multiple time points
428 (e.g., 1 month, 3 months, and 1 year after surgery) could clarify changes in motor control across the
429 entire recovery period. Second, the present study is a secondary analysis of an existing publicly
430 available dataset and does not include clinical measures such as pain, range of motion, or hip
431 function. Therefore, the relationships between the observed changes in motor control and these
432 factors could not be examined. Third, because the UCM indices are relative values, further data are
433 needed to establish clinical reference values. Fourth, differences in HOA severity were not
434 considered. The present study treated patients with HOA as a single group and did not examine how
435 the UCM indices change according to disease severity. Future studies should analyze the UCM

436 indices by disease stage and examine their relationships with clinical measures (e.g., degree of pain
437 and degree of functional impairment). Such examinations would further clarify the usefulness of the
438 UCM indices in the disease management of HOA and in rehabilitation assessment using gait data.
439 Despite these limitations, to the best of our knowledge, the present study is the first to quantitatively
440 demonstrate changes in motor control before and after THA using UCM analysis. The present study
441 revealed aspects of gait that are not adequately captured by conventional parameters. In particular,
442 the present findings suggest that the body can flexibly exploit the available degrees of freedom in
443 response to changes in hip function. This assessment method can also be extended to other
444 musculoskeletal disorders and used to track individual adaptation during the recovery process after
445 THA. This may contribute to more targeted rehabilitation strategies according to disease stage and,
446 ultimately, to the optimization of functional recovery and patient satisfaction.

447 **5. Conclusion**

448 In the present study, we used UCM analysis with the mediolateral CoM as the performance variable
449 to compare CoM control during gait before and after THA in patients with HOA. After surgery,
450 V_{UCM} and V_{ORT} decreased significantly compared with before surgery, whereas ΔVz did not change
451 significantly, and the mean mediolateral CoM position and its trial-to-trial variability were also
452 preserved. These results suggest that, even when hip function changes, the body can flexibly exploit
453 the available degrees of freedom to stabilize the CoM. Given that CoM control is distributed across

multiple segments rather than a single segment, postoperative rehabilitation may benefit from considering the coordination of the whole movement system in addition to the affected joint.

List of abbreviations

BMI, body mass index

CI, confidence interval

CoM, center of mass

HOA, hip osteoarthritis

KOA, knee osteoarthritis

IS, initial stance

MS, mid-stance

THA, total hip arthroplasty

TS, terminal stance

UCM, uncontrolled manifold

V_{ORT}, variance orthogonal to the uncontrolled manifold

V_{UCM}, variance within the uncontrolled manifold

ΔVz, Fisher z-transformed synergy index

Declarations

Ethics approval and consent to participate

This study is a secondary analysis of a publicly available, fully anonymized gait dataset [22]. The original study protocol was approved by the Comité de Protection des Personnes (CPP) Est I — an independent research ethics committee established under the French Public Health Code (the French equivalent of an Institutional Review Board / Research Ethics Committee) — and written informed consent was obtained from all participants prior to inclusion; the original data were collected at Dijon University Hospital, France. The original prospective data collection was registered at ClinicalTrials.gov (NCT01907503). The registration date of the clinical trial is 17 July 2013. Accordingly, no additional ethics approval or consent was required for the present secondary analysis.

Consent for publication

Not applicable.

Availability of data and materials

The original dataset analyzed during the current study is publicly available as described by Bertaux et al. [22].

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

RY contributed to conceptualization, methodology, software, formal analysis, data curation, visualization, writing the original draft, and writing (review and editing). YS contributed to conceptualization, methodology, and writing (review and editing). SO contributed to conceptualization, methodology, and writing (review and editing). NS contributed to conceptualization, methodology, supervision, funding acquisition, project administration, and writing (review and editing). All authors read and approved the final manuscript.

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596

597

Figure

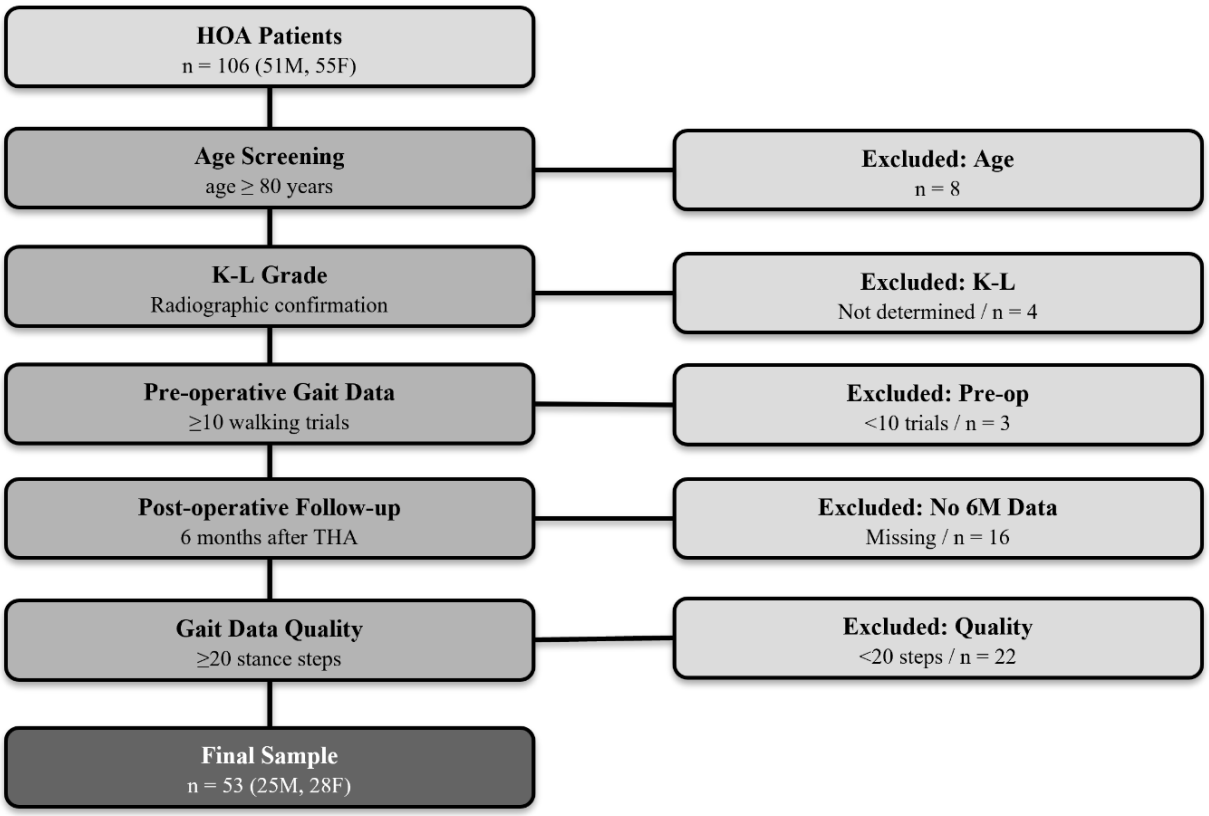
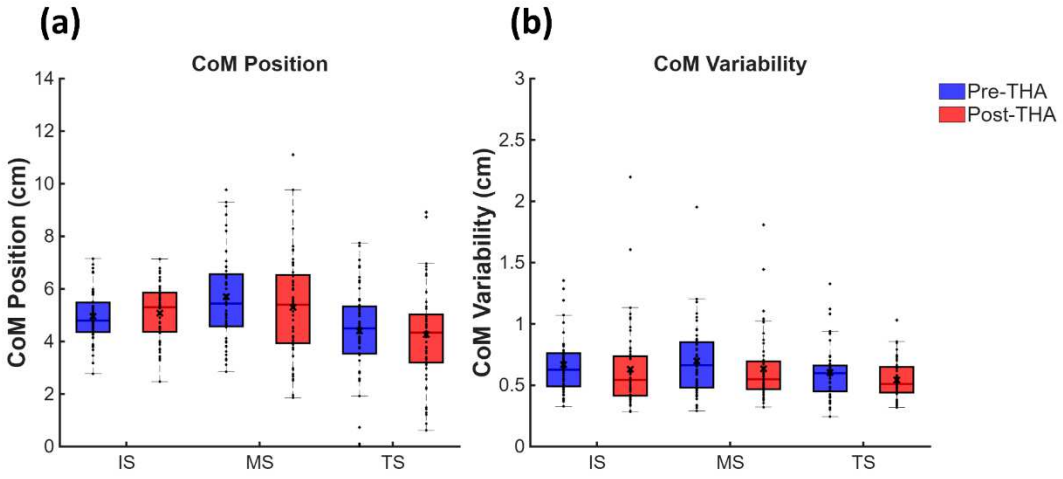


Fig. 1 Flow diagram of participant selection

Beginning with 106 patients with hip osteoarthritis (HOA; 51 men, 55 women), patients were sequentially excluded for: age 80 years or older (n = 8); undetermined Kellgren–Lawrence (K-L) grade (n = 4); fewer than 10 pre-operative walking trials (n = 3); missing 6-month post-operative follow-up data (n = 16); and insufficient gait-data quality, defined as fewer than 20 stance steps (n = 22). The final analyzed sample comprised 53 patients (25 men, 28 women) with complete pre-operative and 6-month post-operative gait data following total hip arthroplasty (THA). M, male; F, female. Data were obtained from the publicly available dataset of Bertaux et al. [22].



609

610 **Fig. 2 CoM position and variability**

611 Box-and-whisker plots of the CoM position and its trial-to-trial variability for the Pre-THA and Post-
612 THA states across the normalized stance phase. (a) CoM position and (b) CoM variability for the
613 Pre-THA (blue) and Post-THA (red) states. The normalized stance phase (0–100%) was divided into
614 IS (0–33%), MS (34–66%), and TS (67–100%). Dots represent individual participant data points; the
615 horizontal line within each box denotes the median, the cross the mean, and the box edges the first
616 and third quartiles. No significant differences between the Pre-THA and Post-THA states were found
617 in any phase. CoM, center of mass; IS, initial stance; MS, mid-stance; THA, total hip arthroplasty;
618 TS, terminal stance.

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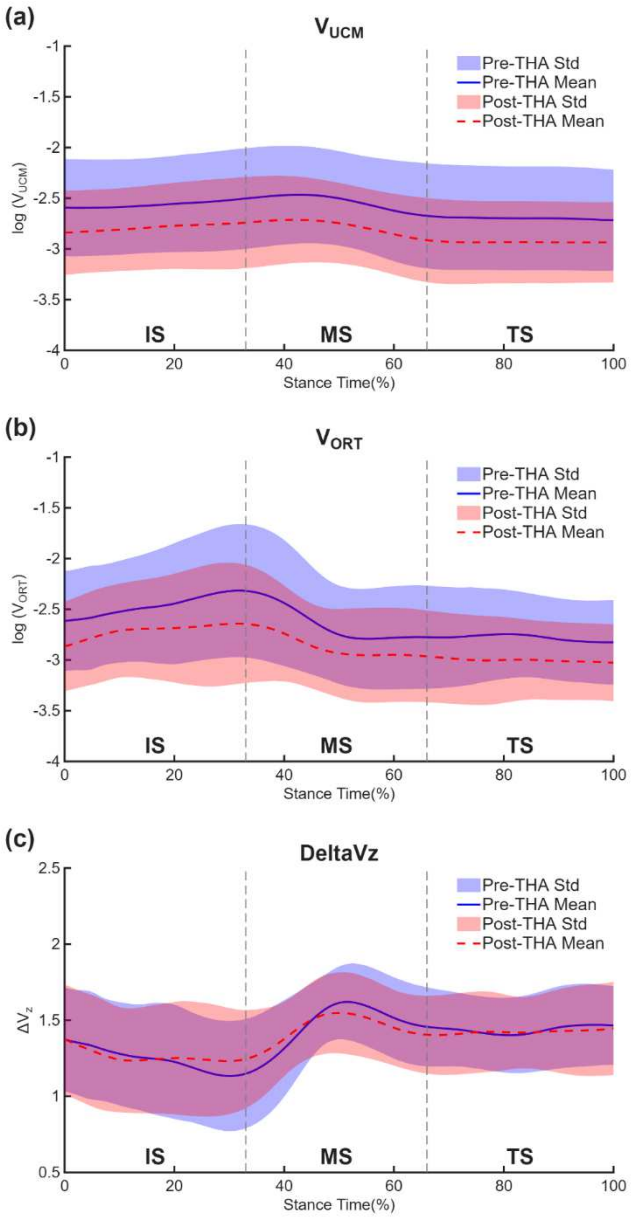
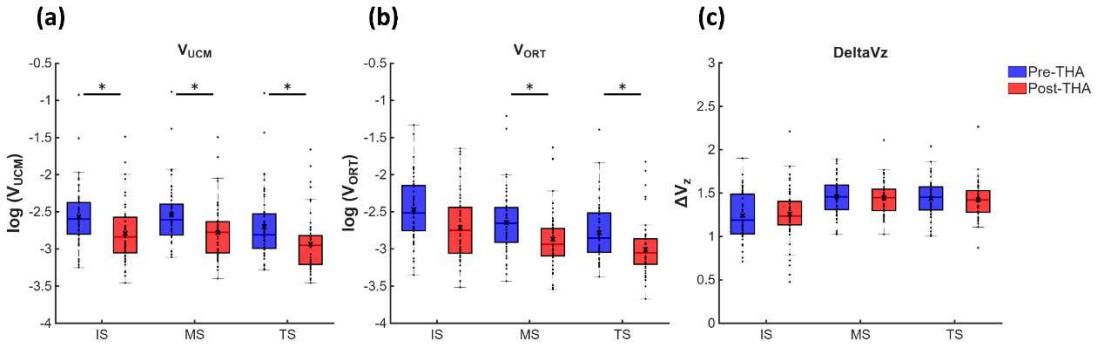


Fig. 3 Time-series of the UCM indices across stance phases

The mean (lines) and standard deviation (shaded bands) of the UCM indices (V_{UCM}, V_{ORT}, and ΔVz) across the normalized stance phase for the Pre-THA and Post-THA states. (a) log(V_{UCM}), (b) log(V_{ORT}), and (c) ΔVz for the Pre-THA (blue solid line, mean; blue band, standard deviation) and Post-THA (red dashed line, mean; red band, standard deviation) states. The normalized stance phase (0–100%) was divided into IS (0–33%), MS (34–66%), and TS (67–100%), separated by the vertical dashed lines. IS, initial stance; MS, mid-stance; THA, total hip arthroplasty; TS, terminal stance; UCM, uncontrolled manifold; V_{ORT}, variance orthogonal to the uncontrolled manifold; V_{UCM}, variance within the uncontrolled manifold; ΔVz, Fisher z-transformed synergy index.



631

632 **Fig. 4 UCM indices before and after THA across stance phases**

633 Box-and-whisker plots of the UCM indices (V_{UCM}, V_{ORT}, and ΔVz) for the Pre-THA and Post-THA
634 states across the normalized stance phase. (a) log(V_{UCM}), (b) log(V_{ORT}), and (c) ΔVz for the Pre-
635 THA (blue boxes) and Post-THA (red boxes) states. The normalized stance phase (0–100%) was
636 divided into IS (0–33%), MS (34–66%), and TS (67–100%). Dots represent individual participant
637 data points; the horizontal line within each box denotes the median, the cross the mean, and the box
638 edges the first and third quartiles. * indicates a significant difference between the Pre-THA and Post-
639 THA states after covariate adjustment (Bonferroni-corrected $p < 0.05$). IS, initial stance; MS, mid-
640 stance; THA, total hip arthroplasty; TS, terminal stance; UCM, uncontrolled manifold; V_{ORT},
641 variance orthogonal to the uncontrolled manifold; V_{UCM}, variance within the uncontrolled manifold;
642 ΔVz, Fisher z-transformed synergy index.

643

644 **Table 2. Mean segment angles and their trial-to-trial standard deviations before and after surgery.**

	Pre-THA						Post-THA					
Variables	IS		MS		TS		IS		MS		TS	
Angle (degree)	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
θ1	-5.0	0.9	-6.6	0.9	-6.8	1.2	-5.9	0.9	-7.4	0.9	-8.1	1.3
θ2	-1.1	0.8	0.8	0.7	-0.9	0.8	-0.1	0.7	1.8	0.7	0.3	0.8
θ3	2.2	0.6	2.9	0.6	2.5	0.5	2.6	0.6	2.6	0.5	2.3	0.5
θ4	2.4	0.8	3.9	0.8	2.0	0.6	2.0	0.7	3.1	0.7 †	1.5	0.6
θ5	7.0	1.4	5.2	1.1	4.8	0.8	8.6 *	1.4	5.9	1.0	5.6 *	0.8

θ6	4.3	1.6	4.7	1.6	3.9	1.5	3.9		1.5		4.4		1.4		3.7		1.4		
θ7	-5.0	2.9	-5.1	2.9	-4.3	2.7	-3.3		1.3		-3.1		1.3	†	-2.9		1.2		
θ8	-13.6	6.8	-13.3	7.4	-13.7	7.4	-10.4	*	4.8	†	-10.0		4.9	†	-10.3		4.7	†	
α1	-5.6	1.3	-11.3	2.2	-30.8	1.9	-6.3		1.2		-11.7		1.7		-33.0	*	1.6		
α2	-0.7	2.4	-11.6	1.4	-15.4	1.2	1.4	*	1.9		-12.1		1.3		-17.4		1.2		
α3	1.2	0.6	3.8	1.5	6.1	2.0	1.3		0.5		4.2		1.4		6.7		1.8		
α4	14.7	3.7	-2.5	1.2	-1.3	1.0	14.8		2.9		-4.9	*	1.3		-3.5	*	1.0		
α5	32.6	4.6	13.7	6.0	-5.0	1.7	36.5	*	3.4		13.8		4.7		-7.1	*	1.6		
α6	-42.6	1.1	-40.5	1.1	-40.3	1.0	-44.8		1.0		-43.8	*	1.0		-44.0	*	0.9		
α7	21.3	2.2	22.8	2.2	22.7	2.2	19.2		1.6		20.0	*	1.5		19.6	*	1.5		

α8	63.5	5.3	64.1	5.2	63.9	5.3	60.1	4.4	60.7	4.4	60.3	4.4

Mean segment angles and their trial-to-trial standard deviations are shown for each phase. The stance phase (0–100%) was divided into three periods: initial stance (IS, 0–33%), mid-stance (MS, 34–66%), and terminal stance (TS, 67–100%). Comparisons between Pre-THA and Post-THA were made using paired *t*-tests or Wilcoxon signed-rank tests according to the normality of the differences.

* indicates a significant difference in the mean angle and † a significant difference in the trial-to-trial standard deviation between Pre-THA and Post-THA (both significant after Bonferroni correction, corrected $p < 0.05$). Std, standard deviation; THA, total hip arthroplasty.