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Impact of spinal-hip types on gait patterns in patients with end-stage hip disease

Zhuyi Ma[1†], Shengxing Fu[2†], Xiangdong Wu[1], Kaiqi Cao[1], Hao Tang[1,3*] and Yixin Zhou[1,3*]

Abstract

Background Patients with end-stage hip disease are classified into distinct spinal-hip types according to sagittal spinal-hip parameters. Each type employs specific compensatory strategies to maintain balance, but the associated alterations in gait patterns remain unclear. This study characterized the gait differences among patients with different spinal-hip types.

Methods This prospective observational study used EOS imaging to obtain full-length sagittal images and classify patients into spinal-hip types. The study included 10 patients in each type (A, B, and C) and 10 healthy controls. Gait analysis was performed to evaluate the spatiotemporal and kinematic parameters, followed by the gait profile score (GPS) analysis. The Kruskal–Wallis test was used to compare relevant parameters across the four groups, with post-hoc comparisons conducted using the Bonferroni method.

Results Significant differences among the types were observed in stride length ($P=0.003$), stance phase percentage ($P=0.001$), and swing phase percentage ($P<0.001$), with type C showing the shortest stride and type A exhibiting the shortest stance phase. The sagittal range of motion (ROM) of the pelvis and hip varied significantly across the gait cycle (both $P<0.001$), with type A exhibiting the largest pelvic ROM and the smallest hip ROM. Types A and C showed lower sagittal center of mass displacement during the stance phase ($P<0.001$). Type A exhibited the most restricted knee ROM during the swing phase ($P<0.001$). The GPS was highest in type A, followed by type C, while type B and healthy controls had the lowest scores ($P<0.001$).

Conclusions Patients with different spinal-hip types exhibited distinct gait adaptations to compensate for sagittal deformities. Patients with severe sagittal imbalance exhibited compensatory increased pelvic swing and demonstrated diminished functional scores. Preoperative assessment is essential for optimizing total hip arthroplasty outcomes and guiding rehabilitation.

Keywords Spinal-hip types, Gait analysis, Spatiotemporal, Kinematic parameters, Sagittal balance, Gait profile score

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Background

The spinal-hip complex relies on the coordinated action of agonist and antagonist muscles to stabilize posture during standing and walking. Maintaining balance in a forward-tilted trunk posture demands considerable muscular effort [1–3]. In patients with different spinal-hip types, the compensatory mechanisms for dynamic balance vary due to the progressive loss of sagittal balance in end-stage hip diseases. However, the gait variations associated with these compensatory mechanisms have not been reported.

In a previous study, Tang et al. [4] proposed a patient-specific method to predict postoperative standing pelvic tilt (PT). This method classifies patients into three main spinal-hip categories: type A (decompensated), type B (globally balanced), and type C (overcompensated spine). This classification is determined by parameters such as the sagittal vertical axis (SVA), pelvic incidence (PI), lumbar lordosis (LL), and thoracic kyphosis (TK), with five subcategories (Fig. 1).

Patients with an SVA > 50 mm are classified as type A, indicating a global imbalance. For patients with an

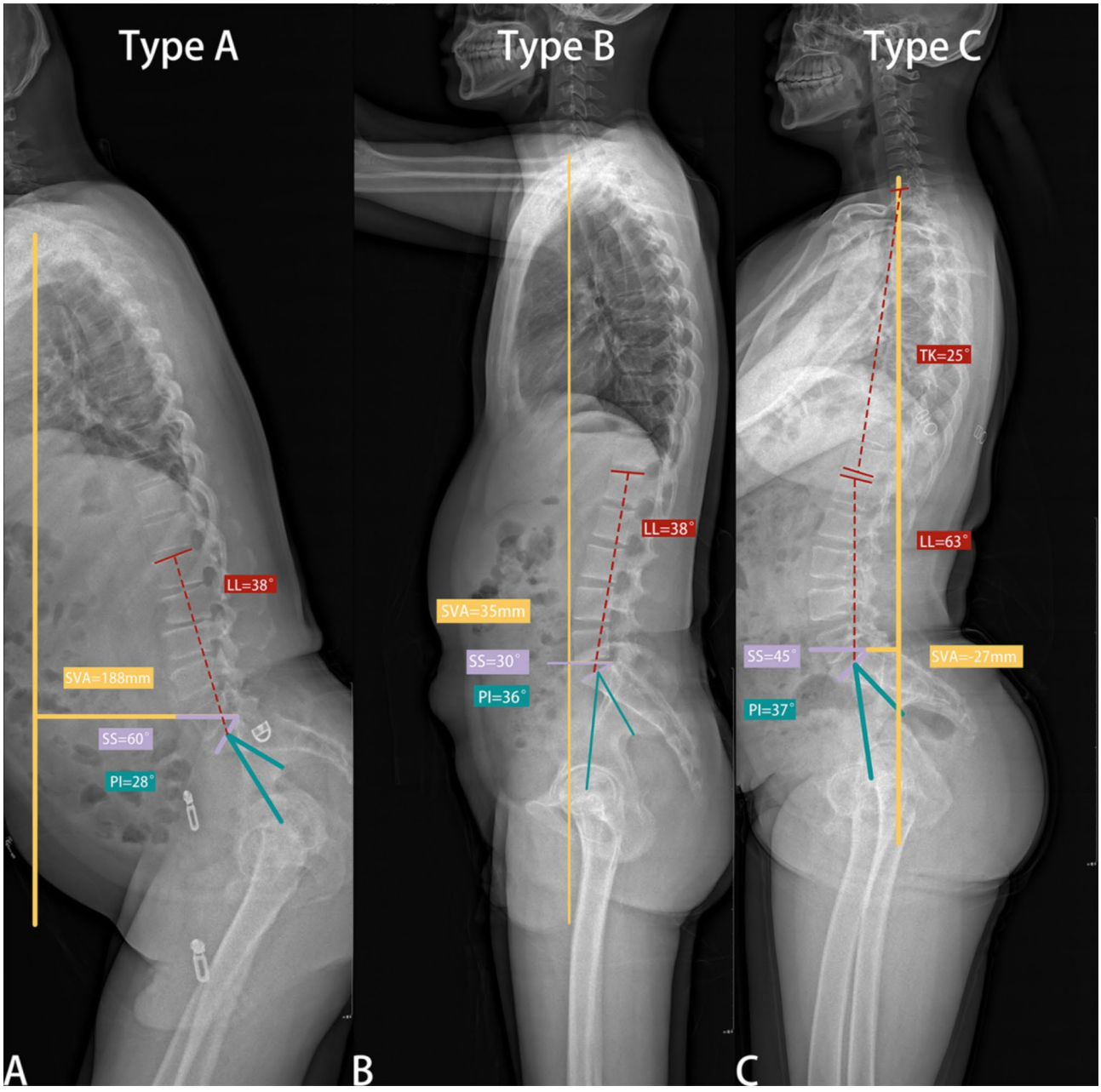

Fig. 1 Lateral views of the three types of patients. **A–C**) The schematic definitions for the classification of patients. LL, lumbar lordosis; PI, pelvic incidence; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis

SVA ≤ 50 mm, further classification depends on the PI-LL angle. A PI-LL between −10° and 10° reflects normal standing balance (type B1), PI-LL > 10° indicates balance maintained by hip extension (type B2), and PI-LL <−10° with LL-TK ≤ 20° represents balance maintained by LL (type B3). If LL-TK > 20°, balance is maintained by global overextension, classified as type C.

Although the aforementioned sagittal parameters can be assessed using EOS imaging (EOS Imaging, Paris, France) [5, 6], these static radiographic measurements fail to capture dynamic postural control mechanisms and their implications during functional tasks in clinical practice [7, 8]. This study therefore characterized gait patterns across the defined spinal-hip types.

Gait analysis (GA) is commonly used to assess the effects of diseases on movement kinematics, evaluating movement trajectories, velocities, linear accelerations, and angular accelerations of various body parts. The photoelectric system employed in GA relies on stereophotogrammetry. During the gait cycle, the unstable phase requires complex postural control. Several kinematic parameters quantify the stance and swing phases, some related to motor performance and others associated with balance, each influenced by distinct factors [8–10]. The center of mass (CoM), identified photoelectrically, represents the central point of mass concentration in an object [11].

Although GA provides a detailed description of the spatiotemporal parameters, joint kinematics, and dynamics throughout the gait cycle, the large and complex data often require extensive expertise for interpretation. To address this issue, researchers have introduced the gait profile score (GPS) as a single indicator that summarizes the overall kinematic characteristics of lower-limb movement and facilitates the assessment of gait quality [12, 13]. The GPS is composed of nine key gait variable scores (GVS) of clinical kinematic variables: pelvic tilt, rotation, and obliquity; hip flexion-extension, adduction-abduction, and rotation; knee flexion-extension; ankle dorsiflexion-plantarflexion; and foot progression. The GPS and GVS have been used to characterize gait quality in individuals undergoing total hip arthroplasty (THA), with higher values indicating poorer gait quality [10, 14].

This study aimed to address the following research question: How do gait patterns differ among patients with end-stage hip disease across different spinal-hip types? To this end, the study investigated the differences in lower-limb movement ability among patients with distinct spinal-hip types at their naturally self-selected walking speed.

Methods

Patient selection

All study participants provided informed consent, and the study design was approved by our institution's ethics review board (No. 202201-18-02). This prospective observational study included 30 patients categorized into three groups: A, B, and C, each containing 10 patients. The inclusion criteria were as follows: patients aged between 18 and 75 years; planned to undergo unilateral THA; a minimum interval of 6 months required if the contralateral side had previously undergone THA; and all patients were able to complete the required imaging examinations and gait biomechanical tests. The exclusion criteria were: age below 18 or above 75 years; joint infections; severe developmental dysplasia of the hip (DDH, Crowe type II, III, and IV); or severe osteoarthropathy with a fixed flexion deformity of ≥ 10° in the ipsilateral knee or contralateral hip; incomplete full-length radiographs. The healthy control group consisted of volunteers with no history of lower-limb pain, who understood the experimental procedure, voluntarily agreed to participate, and signed written informed consent forms. No significant differences ($P \geq 0.05$) among the groups were observed in the general patient characteristics, including sex, mean age, body mass index (BMI), and the affected leg, indicating comparability. The patient details are provided in Table 1.

Radiographic measurements

Participants underwent low-dose EOS lateral full-length radiography to measure static bony structural parameters. All parameters were assessed using the Picture Archiving and Communication System (PACS; Carestream Health, Inc, Rochester, NY, Version 11.0). The spinal-hip classification was determined based on pelvic and spinal radiographic parameters, including PI, PT, SS, LL, TK, and SVA (Fig. 1).

Data collection

Each participant completed five walking trials at a self-selected speed, barefoot. Reflective markers were placed bilaterally on anatomical landmarks, including the acromions, anterior and posterior superior iliac spines, femoral condyles, malleoli, metatarsophalangeal joints, toes, and heels. Additional markers were positioned at the L4-L5 intersection and on bilateral thigh and shank clusters (Fig. 2). Three-dimensional (3D) marker trajectories were captured using an eight-camera motion analysis system (Nokov, China) at 200 Hz. Ground reaction forces (GRFs) were recorded with two force plates (Kunwei, China) at 1000 Hz, with kinematic and force data synchronized for analysis.

Table 1 Characteristics of the four groups of participants

Baseline characteristics	Type A (*n* = 10)	Type B (*n* = 10)	Type C (*n* = 10)	Healthy group (*n* = 10)	*p*-value
Sex (M/F)	9/1	6/4	4/6	5/5	0.120
Age (years, mean ± SD)	54.20 ± 11.40	43.40 ± 10.81	51.10 ± 12.56	49.90 ± 7.05	0.161
BMI (kg/m2, mean ± SD)	26.29 ± 4.13	25.26 ± 3.50	24.67 ± 4.41	26.78 ± 3.60	0.621
Affected side (L/R)	6/4	8/2	3/7	—	0.076
Diagnosis					
OA	*n* = 2	*n* = 1	*n* = 3	—	—
AVN	*n* = 5	*n* = 7	*n* = 5		
DDH Crowe I	*n* = 3	*n* = 2	*n* = 2		

SD, standard deviation; BMI, body mass index; OA, osteoarthritis; AVN, avascular necrosis; DDH, developmental dysplasia of the hip

Note: — represents disease-free data for healthy group participants

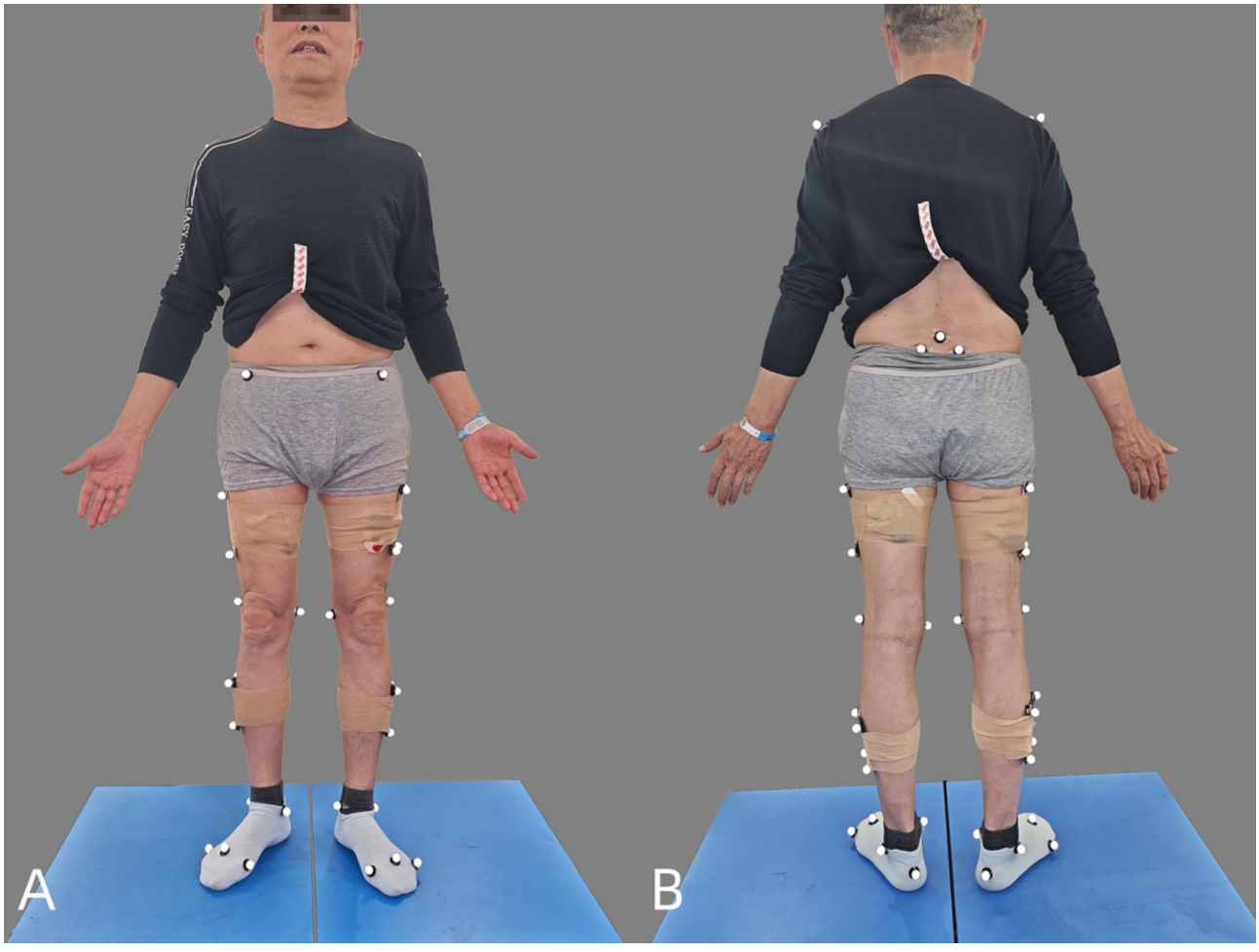

Fig. 2 Participant after placing the fluorescent markers. **A**) The front of the participant. **B**) The back of the participant

Data extraction

All data were processed using Visual3D software (v2024, HAS-Motion Inc., Canada). The raw 3D trajectories of the reflective markers were filtered through a Butterworth recursive low-pass digital filter with an estimated optimal cut-off frequency of 13.3 Hz [15]. Pelvic angles were calculated with reference to the laboratory coordinate system. Lower extremity joint angles were

determined as the distal segment relative to the proximal segment using a Cardan rotation sequence of flexion/extension, adduction/abduction, and internal/external rotation. The CoM was calculated as the weighted average of all body segments. Heel strike and toe-off events were defined using a threshold of 20 N for non-normalized vertical ground reaction force [16].

Spatiotemporal parameters were calculated, including gait speed, cadence, stride length, and step width. The peak angles of the pelvis, hip, knee, and ankle during the stance and swing phases were analyzed for each leg. Additionally, the displacement of the CoM in the sagittal plane was quantified. The duration of each gait cycle phase was normalized to 100%, and continuous time-series data of the pelvis and lower extremity joint angles throughout the entire gait cycle were exported for GPS assessment.

Calculation of the GPS

The GPS was calculated following the methods proposed by Baker et al. [13] as the mean of the root mean square (RMS) differences of 15 key clinical kinematic variables, referred to as the GVS. The RMS differences among types A, B, and C were obtained by comparing them with the mean values of the healthy control group, while those in healthy control group were compared relative to their mean values. The GPS was then derived by summing the RMS of the 15 GVS. Subsequently, the GPS and GVS were compared across the groups.

Data analysis

Statistical analysis was performed using the SPSS software (version 26.0; IBM Corp., Armonk, NY, USA). The normality of the data was tested using the Kolmogorov–Smirnov test. Continuous variables are presented as means and standard deviations (mean ± SD) while categorical data as frequencies (N). Owing to the non-normal distribution of the data, comparisons among the four subgroups were made using the Kruskal–Wallis test. Pairwise comparisons were conducted using the Bonferroni method. Categorical parameters were compared using Pearson's chi-square test. Statistical significance was defined as $P < 0.05$.

Results

Comparisons of Spatiotemporal parameters

Stride length varied significantly among groups ($P = 0.003$). Patients with types A and C exhibited shorter strides than healthy controls ($P = 0.011$ and $P = 0.005$, respectively), whereas type B exhibited values comparable to those of the control group. Significant differences were observed in the stance phase percentage ($P = 0.001$) and swing phase percentage ($P < 0.001$). Type A patients exhibited a shorter stance phase than controls ($P < 0.001$), while type B and type C patients were intermediate. The swing phase percentage exhibited an inverse relationship, with type A patients exhibiting a significantly longer swing phase compared to controls ($P < 0.001$), while type B and type C patients maintained values closer to controls (Table 2).

Comparisons of kinematic parameters

Pelvic ROM progressively decreased from type A to healthy controls, while hip ROM exhibited an inverse trend ($P < 0.001$ for both comparisons). Type A patients exhibited the greatest pelvic ROM throughout the gait cycle, accompanied by the most restricted hip ROM compared to the healthy control group (both $P < 0.001$). During the swing phase, knee sagittal ROM was the most constrained in type A patients ($P < 0.001$). Additionally, sagittal displacement of the CoM during the stance phase was lower in types A and C than in type B and healthy controls ($P < 0.001$) (Table 3). The sagittal tilting curves of the pelvis and the sagittal ROM curves of the hip, knee, and ankle throughout the gait cycle are shown in Fig. 3.

Table 2 The Spatiotemporal parameters of the lower limb on the affected side in the three patient groups and on the dominant side (right leg) in the healthy control group (mean ± standard deviation)

Parameter	Type A ($n = 10$)	Type B ($n = 10$)	Type C ($n = 10$)	Healthy group ($n = 10$)	*p*-value	Post-hoc analysis
Speed (m/s)	0.82 ± 0.18	0.85 ± 0.12	0.78 ± 0.18	0.92 ± 0.09	0.172	-
Cycle time (s)	1.26 ± 0.27	1.23 ± 0.18	1.34 ± 0.42	1.15 ± 0.12	0.618	-
Stride length (m)	0.99 ± 0.04	1.02 ± 0.03	0.97 ± 0.07	1.05 ± 0.02	**0.003**	A-D **0.011**
						C-D **0.005**
Stride width (m)	0.09 ± 0.03	0.12 ± 0.03	0.1 ± 0.05	0.12 ± 0.03	0.149	-
Affected side						
Stride length (m)	0.99 ± 0.05	1.02 ± 0.03	0.98 ± 0.07	1.04 ± 0.02	**0.009**	A-D **0.044**
						C-D **0.011**
Stance percent (%)	0.58 ± 0.03	0.62 ± 0.03	0.62 ± 0.05	0.64 ± 0.02	**0.001**	A-D **< 0.001**
Swing percent (%)	0.41 ± 0.03	0.38 ± 0.03	0.38 ± 0.05	0.37 ± 0.02	**< 0.001**	A-B **0.025**
						A-D **< 0.001**

Table 3 The sagittal kinematics parameters of the lower limb on the affected side in three patient groups and on the dominant side (right leg) in the healthy control group (mean ± standard deviation)

Parameter	Type A ($n=10$)	Type B ($n=10$)	Type C ($n=10$)	Healthy group ($n=10$)	*p*-value	Post-hoc analysis
Stance phase						
Pelvic ROM (°)	11.62 ± 3.4	8.47 ± 3.7	7.78 ± 3.76	2.65 ± 0.44	**< 0.001**	A-D **< 0.001**
						B-D **0.004**
						C-D **0.010**
Hip ROM (°)	11.56 ± 4.8	18.37 ± 5.94	24.28 ± 7.62	31.16 ± 2.85	**< 0.001**	A-C **0.017**
						A-D **< 0.001**
						B-D **0.008**
Knee ROM (°)	37.24 ± 6.96	42.04 ± 5.86	38.93 ± 10.56	44.58 ± 6.31	0.160	-
Ankle ROM (°)	24.62 ± 3.88	25.54 ± 5.45	26.74 ± 6.29	25.20 ± 4.13	0.784	-
CoM_distance (m)	0.59 ± 0.03	0.64 ± 0.02	0.62 ± 0.03	0.68 ± 0.02	**< 0.001**	A-B **0.019**
						A-D **< 0.001**
						C-D **0.007**
Swing phase						
Pelvic ROM (°)	8.52 ± 3.26	5.22 ± 3.37	4.47 ± 2.21	1.85 ± 0.49	**< 0.001**	A-D **< 0.001**
						B-D **0.017**
Hip ROM (°)	9.86 ± 3.74	16.43 ± 5.4	21.44 ± 6.51	24.43 ± 3.24	**< 0.001**	A-C **0.005**
						A-D **< 0.001**
Knee ROM (°)	47.45 ± 7.96	57.81 ± 6.9	55.43 ± 7.86	62.91 ± 3.85	**< 0.001**	A-D **< 0.001**
Ankle ROM (°)	17.84 ± 5.71	18.27 ± 6.69	22.63 ± 5.05	18.60 ± 4.40	0.233	-
CoM_distance (m)	0.40 ± 0.03	0.37 ± 0.02	0.35 ± 0.05	0.37 ± 0.02	0.085	-

ROM, range of motion; CoM, center of mass

Comparisons of GPS parameters

Gait profile score and GVS parameters were compared across the four groups (Table 4). The GPS was significantly higher in type A patients, followed by type C patients, indicating poorer gait quality than healthy controls ($P<0.001$ and $P=0.003$, respectively). Type B patients exhibited no significant difference in GPS values compared to healthy controls, indicating similar gait quality.

Significant differences were found in GVS, including PT and pelvic obliquity (both $P<0.001$). Type A patients had a higher GVS for PT and pelvic obliquity compared to type B and healthy controls, with type C showing values in between. Furthermore, higher GVS was observed in patients with more severe sagittal deformity types, particularly in hip flexion-extension on both sides ($P<0.001$ for the affected side; $P=0.028$ for the contralateral side), hip adduction-abduction on the affected side ($P=0.007$), knee flexion-extension on the affected side ($P<0.001$), and ankle dorsiflexion-plantarflexion on the contralateral side ($P=0.002$) (Table 4).

Discussion

The spinal-hip complex is closely associated with variations in gait patterns during walking. The trunk-flexed postures necessitate compensatory adjustments in lower-limb kinematics to maintain stability [17]. Moreover, the discrepancy between standing and walking spinal balancing is associated with PI-LL mismatch [1]. However, no previous study has explored gait differences among patients with end-stage hip disease across different spinal-hip sagittal types. This study addressed this gap by investigating the impact of these spinal-hip classifications on lower-limb mobility during level walking at a self-paced speed.

The analysis of spatiotemporal parameters revealed that, compared to the healthy control group, the disease group exhibited significant reductions in stride length, particularly in types A and C. Additionally, type A patients showed a marked reduction in the stance phase. In type A patients, the loss of spinal compensatory capacity caused the thoracic and lumbar spine to function as a rigid unit. Combined with hip flexion deformity, this led to a forward shift of the CoM in a static position [18], contributing to a gait pattern characterized by reduced stride length and pain-avoidance behaviors [19, 20]. In contrast, type B patients maintained a more balanced global alignment, leading to gait patterns closely resembling those of healthy controls. Type C patients typically exhibited severe pelvic anteversion but maintained balance through spinal overextension, resulting in mobility levels that were intermediate between types A and B. Mourad et al. [8] studied 35 healthy male volunteers who wore a kyphotic thoracolumbar corset to induce reversible anterior sagittal imbalance (ASI). Their analysis found that ASI led to significant alterations in spatiotemporal parameters, which aligns with the findings of our study.

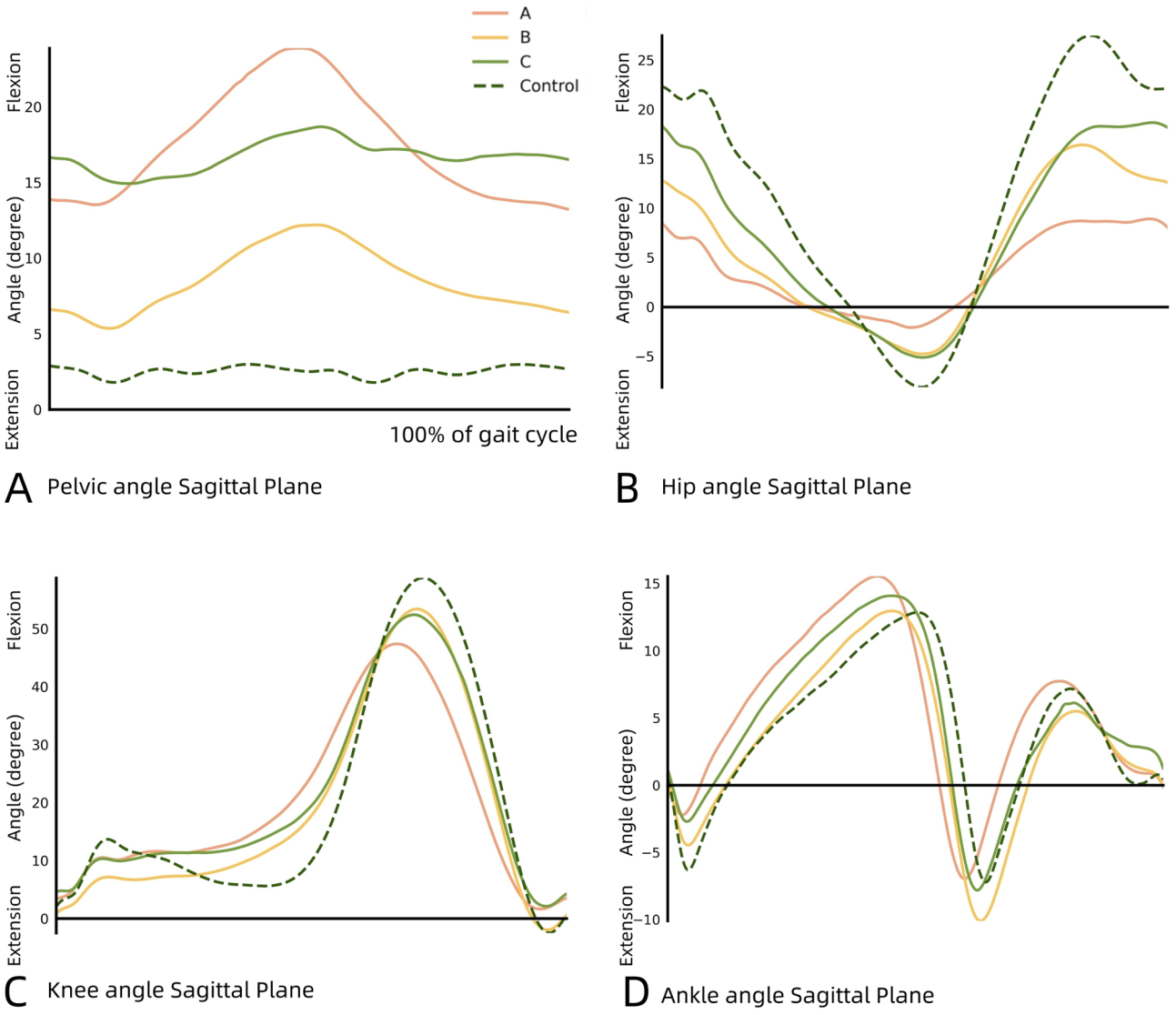

Fig. 3 Full-cycle sagittal range of motion curves for the pelvis, hip, knee, and ankle in the four groups of participants. **A–D**) Range of motion curves for the pelvis, hip, knee, and ankle, respectively

Previous studies have demonstrated that alterations in gait patterns significantly impact the hip, knee, ankle, and pelvis [9, 21, 22]. This study specifically analyzed the sagittal ROM of the pelvis, hip, knee, and ankle in the affected limb, as well as the sagittal displacement of the CoM. Type A patients exhibited the largest pelvic ROM during walking, suggesting that increased pelvic movement serves as a compensatory strategy for sagittal imbalance in the spinal-hip complex. However, compared to type B, type C patients exhibited a more restricted pelvic ROM, likely owing to excessive spinal compensation, which led to a more posterior SVA and reduced pelvic flexibility. Gait curves analysis revealed that type A and type B patients exhibited increased pelvic swing amplitude, whereas type C patients maintained a more stable motion pattern, with swing amplitude closer to that of healthy controls, confirming the restricted pelvic mobility in type C patients.

Both hip and knee ROMs in type A patients were markedly reduced, indicating a decline in lower-limb mobility [23, 24]. In contrast, the ankle dorsiflexion angle in type A patients closely resembled that of healthy controls, potentially functioning as a shock-absorbing mechanism to mitigate loading during walking [25]. During the stance phase, type A and type C patients exhibited limited sagittal CoM displacement, further indicating restricted lower-limb mobility, which may contribute to inefficient gait patterns. These findings are consistent with previous studies [26, 27]. However, prior research did not differentiate patients based on spinal-hip classifications, potentially masking distinct movement patterns

Table 4 Results of the gait variable scores and gait profile score in four groups of participants (°, mean ± standard deviation)

Parameter	Type A	Type B	Type C	Healthy group	*p*-value	Post-hoc analysis
Pelvic tilt	15.53 ± 4.01	7.75 ± 4.54	14.44 ± 7.08	4.75 ± 3.01	**< 0.001**	A-B **0.033**
						A-D **< 0.001**
						C-D **0.006**
Pelvic obliquity	4.61 ± 2.38	3.08 ± 1.78	4.27 ± 2.79	1.67 ± 0.63	**< 0.001**	A-D **< 0.001**
						C-D **0.011**
Pelvic rotation	5.35 ± 1.82	7.04 ± 3.52	6.62 ± 3.17	3.62 ± 1.65	0.062	-
Affected side						
Hip flexion-extension	11.26 ± 2.64	8.06 ± 2.57	7.08 ± 3.78	4.63 ± 2.57	**< 0.001**	A-D **< 0.001**
Hip adduction-abduction	3.86 ± 1.04	4.47 ± 1.82	4.04 ± 1.74	2.38 ± 0.71	**0.007**	A-D **0.035**
						B-D **0.009**
Hip rotation	4.52 ± 2.17	4.7 ± 1.27	4.64 ± 2.28	4.33 ± 1.97	0.886	-
Knee flexion-extension	12.76 ± 2.94	7.6 ± 1.8	11.11 ± 4.58	6.12 ± 2.93	**< 0.001**	A-B **0.011**
						A-D **< 0.001**
						C-D **0.042**
Ankle dorsi-plantarflexion	6.95 ± 5.51	4.35 ± 1.83	6.16 ± 2.57	3.89 ± 2.15	0.074	-
Foot progression	5.61 ± 2.14	7.88 ± 3.09	7.94 ± 3.25	5.82 ± 3.46	0.159	-
Contralateral side						
Hip flexion-extension	10.62 ± 5.19	5.67 ± 3.22	6.51 ± 3.89	5.06 ± 2.7	**0.028**	A-B **0.037**
Hip adduction-abduction	5.1 ± 2.64	4.49 ± 2.87	3.93 ± 1.39	2.98 ± 1.66	0.152	-
Hip rotation	5.92 ± 3	5.88 ± 2.01	4.45 ± 1.25	4 ± 1.72	0.138	-
Knee flexion-extension	13.21 ± 5.49	8.13 ± 5.35	10.39 ± 7.71	6.8 ± 3.17	0.057	-
Ankle dorsi-plantarflexion	7 ± 2.48	5.04 ± 2.62	6.56 ± 8.28	3.04 ± 0.87	**0.002**	A-D < **0.001**
Foot progression	7.52 ± 4.79	5.44 ± 3.53	6.83 ± 4.03	5.38 ± 2.58	0.588	-
GPS	9.2 ± 1.84	6.69 ± 1.27	8.27 ± 2.64	4.94 ± 0.91	**< 0.001**	A-D **< 0.001**
						C-D **0.003**

GPS, gait profile score

by averaging ROM values across heterogeneous groups [9].

Given the complexity of the analyzed parameters, we incorporated GVS and GPS to synthesize the results. Compared to the healthy control group, the disease group exhibited significantly higher GPS values, with type A patients showing the highest scores, followed by type C. In contrast, type B patients and healthy controls demonstrated lower GPS values, indicating better gait quality. These functional differences likely stem from variations in the static bony structures characteristic of each patient type. Additionally, the abnormally elevated GVS on the contralateral side underscores the compensatory role of contralateral limb in supporting motor function [23, 26].

Among the various functional impairments caused by hip diseases, gait alterations have the greatest impact on quality of life. The application of quantitative GA techniques has proven essential in providing precise and objective insights into the kinematic and kinetic aspects of walking in patients with hip diseases [14, 26]. Early clinical intervention targeting gait dysfunction can improve long-term outcomes [28]. A comprehensive understanding of the kinematic factors affecting lower-limb joints is crucial for effective disease management [22, 26, 29], because it deepens our understanding of gait changes associated with spinal-hip classification and compensation mechanisms. Moreover, this information is critical for preoperative planning to optimize THA outcomes, ensure proper prosthesis reconstruction, and develop personalized rehabilitation strategies [30]. Specifically, for Type A patients, rehabilitation should emphasize pelvic stabilization exercises and gait retraining to minimize compensatory pelvic swing. For Type C patients, rehabilitation protocols should prioritize enhancing spinal flexibility and core muscle strength to mitigate compensatory spinal hyperextension. Type B patients may adhere to standard rehabilitation protocols while closely monitoring for subtle deviations in balance during follow-up.

This study has some limitations. First, a detailed subgroup analysis of type B patients was not conducted due to the limited sample size. However, since type B patients belong to the balanced group, this limitation is unlikely to substantially impact the overall findings. Future research should investigate compensatory mechanisms in subgroups such as type B3 and type C patients. Second, this study focused primarily on sagittal plane motion, and future analyses should incorporate coronal and axial plane mobility to provide a more comprehensive understanding of gait compensation. Third, the uneven sex distribution across groups, although statistically

non-significant, may have introduced subtle biases due to anatomical and biomechanical differences between genders. Future studies with larger cohorts should stratify analyses by sex to further elucidate gender-specific compensatory mechanisms. Fourth, while we included 4 patients with contralateral THA (≥6 months post-operation) based on established evidence of functional recovery [31, 32], the potential influence of prosthetic components on gait mechanics cannot be completely ruled out. Future studies with larger sample sizes could benefit from separate analyses of native and prosthetic hip cohorts to further validate our findings.

Conclusions

Gait patterns are closely associated with spinal-hip classification. Increased pelvic swing is a compensatory mechanism for sagittal imbalance in the spinal-hip complex. Type A patients exhibited the most severe sagittal imbalance, resulting in the poorest lower-limb mobility. In contrast, type B patients demonstrated mobility closest to that of healthy controls. Type C patients showed intermediate mobility between types A and B, attributable to excessive spinal compensation. Preoperative assessment of spinal-hip parameters is crucial for optimizing THA outcomes and guiding effective rehabilitation strategies.

Abbreviations

GPS	Gait profile score
ROM	Range of motion
PT	Pelvic tilt
SVA	Sagittal vertical axis
PI	Pelvic incidence
LL	Lumbar lordosis
TK	Thoracic kyphosis
GA	Gait analysis
CoM	Center of mass
GVS	Gait variable scores
THA	Total hip arthroplasty
BMI	Body mass index
3D	Three-dimensional
GRFs	Ground reaction forces
RMS	Root mean square
SD	Standard deviations
ASI	Anterior sagittal imbalance
OA	Osteoarthritis
AVN	Avascular necrosis
DDH	Developmental dysplasia of the hip

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Not applicable.

Author contributions

All authors were involved in the drafting of this article or the critical revising for the important intellectual content, and all authors approved the final version to be published. All authors had full access to all the data in the study and are responsible for the integrity of the data and the accuracy of data analysis.Conceptualization: ZM, HT, and SF; Data curation and Formal analysis: SF and KC; Writing-original draft: ZM; Writing - review & editing: ZM, XW, and YZ; Funding acquisition: YZ and XW.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Implementation of this study was approved by the Institutional Review Board of Beijing Jishuitan Hospital, and all methods were performed in accordance with the Declaration of Helsinki (No. 202201-18-02). Informed consent to participate was obtained from all subjects involved in the study.

Consent for publication

All presentations provided consent for publication.

Competing interests

The authors declare no competing interests.

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