Effects of Unweighting on Gait Kinematics During Walking on a Lower-Body Positive Pressure Treadmill in Patients with Hip Osteoarthritis

Yoshiaki Kataoka
Hokkaido University
Tomohiro Shimizu (simitom@wg8.so-net.ne.jp)
Hokkaido University https://orcid.org/0000-0001-6760-3066
Ryo Takeda
Hokkaido University
Shigeru Tadano
Hokkaido University
Yuki Saito
Hokkaido University
Satoshi Osuka
Hokkaido University
Tomoya Ishida
Hokkaido University
Mina Samukawa
Hokkaido University
Tohru Irie
Hokkaido University
Daisuke Takahashi
Hokkaido University
Norimasa Iwasaki
Hokkaido University
Harukazu Tohyama
Hokkaido University

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Abstract

Background: Hip osteoarthritis (OA) is a musculoskeletal condition that makes walking difficult due to pain induced by weight-bearing activity. Treadmills that support body weight reduce the load on the lower limbs, and those equipped with a lower-body positive pressure (LBPP) device, developed as a new method for unweighting, significantly reduce pain in patients with knee OA. However, the effects of unweighting on gait kinematics remain unclear in patients with hip OA. Therefore, we investigated the effects of unweighting on kinematics in patients with hip OA during walking on a treadmill equipped with an LBPP device.

Methods: Fifteen women with hip OA and fifteen age-matched female controls wore a three-dimensional motion analysis system and walked at a self-selected speed on the LBPP treadmill. Data regarding hip pain using a numeric rating scale under three different unweighting conditions (100%, 75%, and 50% bodyweight) were collected. Three-dimensional peak joint angles during gait under each condition were calculated and compared.

Results: In the hip OA group, numerical rating scores at the unweighted conditions were significantly decreased compared to the 100% bodyweight condition, and peak hip extension angle decreased compared to the healthy controls. In both groups, unweighting significantly decreased the peak hip and knee flexion angle and increased the peak ankle plantarflexion angle during walking.

Conclusions: Although unweighting by LBPP decreased pain in the hip OA group, gait kinematics did not alter despite less load on the hip joint. Therefore, clinicians should consider the benefits of pain reduction, rather than the alternation of gait kinematics, when considering LBPP treadmill for patients with hip OA.

Background

Walking exercises are widely used in individuals with hip osteoarthritis (OA) for rehabilitation [1, 2]. However, individuals with hip OA often find it difficult to walk due to pain and excessive force induced by weight-bearing activity. Treadmills equipped with a lower-body positive pressure (LBPP) device have been developed to provide precise unweighting during walking [3, 4]. Because LBPP treadmills reduce the stress induced by ground reaction forces on the lower limbs, unweighting by the LBPP treadmill has shown to significantly reduce pain in patients with OA and, therefore, has the potential to maintain or enhance aerobic exercise capacity [5, 6]. In addition, LBPP treadmills reduce the load on cardiopulmonary function [3], thereby reducing the rate of perceived exertion compared to treadmills with a harness system [7].

Investigating gait kinematics on LBPP for hip OA is useful information for clinicians when they apply LBPP exercises. However, as a subject's lower limbs are in a waist-high chamber when using an LBPP treadmill, conventional motion analysis using an optical method might be difficult, especially for the hip joint, limiting what is known about how unweighting affects gait kinematics. Due to advances in technology, a wearable-sensor based three-dimensional (3-D) motion analysis system, which can analyze gait kinematics by seven sensors that consist of tri-axial acceleration and tri-axial gyro sensors, has recently been developed as a tool to analyze gait kinematics [8]. Hence, we thought that we could calculate gait kinematics for hip OA subjects by this system while walking on LBPP treadmill.

The purpose of the present study was to investigate the use of wearable-sensors with an LBPP treadmill and investigate unweighting effects on 3-D kinematics in participants with hip OA. The current study hypothesized that unweighting by the LBPP treadmill would increase the peak angle of each joint during gait, leading to alteration of the gait kinematics by reducing pain during walking.

Methods

Participants

This study was approved by the institutional review board of our university and informed consent was obtained from all subjects. In total, 15 female subjects with hip OA and 15 female healthy controls were recruited. Inclusion criteria of the hip OA group were women who were scheduled to undergo unilateral total hip arthroplasty for treatment of moderate to severe OA and aged < 85 years. The severity of OA was determined on radiography according to the Kellgren and Lawrence (KL) grade [9] in all cases. Exclusion criteria of the hip OA group included a history of (1) immunosuppression or autoimmune deficiency, (2) inflammatory arthritis, (3) local or systemic infections, (4) knee arthritis and/or total knee arthroplasty, or (5) symptomatic spinal cord disease. None of the healthy controls had a history of bone fracture or surgery in the lower limbs, history of neurological, respiratory, or cardiovascular diseases, musculoskeletal disorders within the past 6 months, or previous history of trauma.

Gait protocol

Participants wore specifically designed shorts with sensors while using the LBPP treadmill. The height of the chamber was fixed to accommodate the participant, and sensors from the shorts were attached to the LBPP treadmill. The height of the chamber was set equal to that of the greater trochanter of the participant femur (Fig. 1). Calibration to determine the correlation of gravity and the internal pressure of the chamber was performed for each participant, as previously described [10]. Participants walked at a self-selected speed under 100% bodyweight (BW) conditions on the LBPP treadmill (Anti-Gravity Treadmill M320, Alter G, Inc., Fremont, California, USA). The walking speed under 75% and 50% BW conditions were consistent with the 100% BW condition. Participants walked 30 s under three conditions selected randomly (100% BW, 75% BW, and 50% BW) for the testing procedure. Before recording the walking trials, participants were asked to familiarize themselves with walking on the LBPP treadmill for three minutes and were given 90 s to adapt to each unweighting condition (Fig. 1). Participants in the hip OA group were asked to assess their hip pain using a numeric rating scale (NRS) in which 0 represented no anxiety and 10 represented the highest level of anxiety [11] during walking under 100%, 75%, and 50% BW conditions.

Data collection using the motion analysis system

All data collections were performed on the OA side in the OA group and on the dominant leg in the control group. The dominant side in the control group was defined according to which leg participants used for kicking. Data were collected using a motion analysis system (H-Gait system, Laboratory of Biomechanical Design, Hokkaido University, Sapporo, Japan) where wearable sensors analyzed 3-D gait kinematics [8, 12]. Briefly, seven wearable sensor units (TSDN121, ATR-Promotions, Inc., Kyoto, Japan), which consisted of tri-axial acceleration sensors and tri-axial gyrosensors, were placed on seven lower-limb body segments (pelvis, right and left thigh, right and left shank, and right and left feet) as shown in Fig. 2. Acceleration and angular velocity data were collected simultaneously during gait via wireless connection (Bluetooth) in real-time. Sensor specifications were the same as those mentioned in the previous studies [8, 12].

According to a previous study [12], a calibration test for each participant was performed to measure the acceleration data of the sensors in the upright and inclined positions to calculate the initial inclination of each sensor with respect to the gravity. Before each trial, an initial static phase was acquired in the upright position. When participants started walking, subsequent 3-D orientations from the initial one were estimated by integrating the angular velocity with the drift removal using MATLAB (Mathworks, Natick, MA, USA) software [13]. The 3-D angular displacement from the initial upright position was calculated in a quaternion according to a previous study [12]. From these data, spatiotemporal gait parameters and flexion-extension angles of the hip, knee, and ankle joints during walking under each unweighting condition were evaluated for each participant. This H-Gait system divides a 30 s walking into gait cycles and calculates the joint angles of each joint for each gait cycle. A median of a gait cycle during the 30s walking under each unweighting condition was used for analyses. For the gait cycle, one gait cycle from heel contact to the next heel contact was normalized to 100%. The heel contact was defined on the peak angular velocity of the shank in a forward direction [14]. In regards to the validity and reliability of the gait analysis system, Tadano et al. analyzed the kinematics of lower limbs in walking using the H-Gait system and compared them with that of a camera-based motion analysis system [12]. The correlation coefficient was 0.98 for the hip flexion angle, 0.97 for knee flexion angle, and 0.78 for the ankle dorsiflexion angle, respectively.

Statistical analysis

Comparisons of demographic characteristics and walking speed between the groups were performed using independent Student's t-tests. One-way ANOVAs with post hoc Bonferroni tests were used to investigate differences in NRS scores during walking under 100%, 75%, and 50% BW conditions for the hip OA group. Two-way repeated ANOVAs (3 BW conditions × 2 groups) were performed to assess the main effect of BW condition (100% BW, 75% BW, 50% BW) and group (control, OA) on spatiotemporal gait parameters and peak angles of each joint. When interactions were non-significant, main effects were assessed. If the main effect of the BW condition was statistically significant, post-hoc Bonferroni tests were performed to evaluate significant differences among BW conditions on spatiotemporal gait parameters and peak angles of each joint. The significance level was set at 0.05. Statistical analyses were performed using IBM SPSS version 17 software (SPSS Inc., Chicago, IL, USA).

Results

Demographic characteristics, walking speed, and pain

Table 1 summarizes the demographic characteristics of participants and clinical information in this study. There were no significant differences in age, height, weight, or walking speed between the hip OA and control groups. The hip OA group included 3 patients with KL grade 3 and 12 with KL grade 4.

Among the hip OA group, NRS was significantly lesser at the 50% BW condition that at the 100% (P=0.002) and 75% (P=0.018) BW conditions. NRS pain score was significantly lesser at the 75% BW condition than at the 100% BW condition (P=0.026) (Fig. 3).

Spatiotemporal gait parameters

For the step length, two-way ANOVA showed a statistical difference in the group (P=0.027), but not between body weight conditions (100%, 75%, and 50%) (P=0.536). No interaction was detected between group and bodyweight condition (P=0.147) (Fig.4). Post-hoc Bonferroni tests showed that the hip OA group decreased the step length in all bodyweight conditions compared to the control group (P < 0.001). For the cadence, two-way ANOVA did not show a significant difference in groups (P=0.167) and body weight conditions (100%, 75%, and 50% BW) (P=0.219). No interaction was detected between group and bodyweight condition (P=0.052).

Alternation of peak angle of hip joint by unweighting during walking

For the peak hip flexion angle during the swing phase, two-way ANOVA showed a significant difference in body weight conditions (P<0.001), but not between group (P=0.163). No interaction was detected between group and bodyweight condition (P=0.910) (Fig.5A). Post-hoc Bonferroni tests showed that peak hip flexion angle at 50% BW in both groups decreased statistically significantly compared to those at 100% BW (Hip OA; P=0.011 and control; P=0.049, respectively). For the peak hip adduction and external rotation angle during the stance phase, two-way ANOVA did not show a significant difference in groups and bodyweight conditions. No interaction was detected between group and bodyweight conditions.

For the peak hip extension angle during the stance phase, two-way ANOVA showed a significant difference in groups (P=0.044), but not between bodyweight conditions (P=0.682). No interaction was detected between group and bodyweight condition (P=0.950) (Fig.5B). Post-hoc Bonferroni tests showed that the hip OA group decreased the peak hip extension angle in all bodyweight conditions compared to the control group (P<0.001). For the peak hip abduction and internal rotation angle during the swing phase, two-way ANOVA showed significant differences in body weight conditions (P<0.001 and P=0.002, respectively), but not between groups. No interaction was detected between group and bodyweight conditions. Post-hoc Bonferroni tests showed that peak hip adduction angle at 50% BW in the control group decreased statistically significantly compared to that at 100% BW (P=0.012). Post-hoc Bonferroni tests showed that peak hip internal rotation angle at 50% BW in the hip OA group decreased statistically significantly compared to that at 100% BW (P<0.001).

Alternation of peak angle of knee and ankle joints by unweighting during walking

For the peak knee flexion and extension angle, two-way ANOVA showed a significant difference in body weight conditions ($P<0.001$), but not between groups. No interaction was detected between group and bodyweight condition (Fig.6A). Post-hoc Bonferroni tests showed that peak knee flexion angle at 50% BW in both groups decreased statistically significantly compared to those at 100% BW (Hip OA; $P=0.002$ and control; $P=0.002$, respectively) and that peak knee extension angle at 75% and 50% BW in the Hip OA group decreased statistically significantly compared to those at 100% BW ($P=0.029$ and $P<0.001$, respectively).

For the peak ankle plantarflexion angle, two-way ANOVA showed a significant difference in body weight conditions ($P<0.001$), but not between groups. No interaction was detected between group and bodyweight condition (Fig.6B). Post-hoc Bonferroni tests showed that peak ankle plantarflexion angle at 50% BW in both groups increased statistically significantly compared to those at 100% BW (Hip OA; $P=0.020$ and control; $P=0.001$, respectively).

Discussion

In the present study, we first investigated the gait kinematics during walking on the LBPP treadmill in the subjects with hip OA. Findings from the present study revealed that contrary to our expectation, unweighting significantly decreased the peak hip and knee flexion angle, and increased the peak ankle plantarflexion angle during walking on the LBPP treadmill in both the hip OA and control groups. The finding that the control group decreased the peak hip flexion angle during the swing phase under the unweighting condition is consistent with that of previous reports using a treadmill with a harness system [15, 16]. These kinematic changes during gait could be explained by the higher center of gravity due to traction force. Therefore, this study suggests that unloading walking training does not drastically alternate the gait kinematics among patients with hip OA, and clinicians should consider these unweighting effects on gait kinematics when they consider the LBPP treadmill for hip OA patients.

This study showed that unweighting by the LBPP treadmill decreased the NRS pain score among the patients with hip OA, suggesting that the LBPP treadmill is desirable for decreasing pain after aerobic exercise rather than the alternation of gait kinematics. This finding is consistent with those of a previous study that used the LBPP treadmill to assess acute knee pain during weight-bearing exercise in an overweight population of patients with knee OA [5]. Because gait impairments due to hip pain lead to decreased endurance and muscle strength in the lower limbs, it is clinically important for these patients to perform gait training under safe and comfortable conditions [3, 7] with less load on the hip joint. Considering that participants with hip OA showed a significant decrease in the NRS pain score without significant kinematic alternation under 75% BW condition, it might be useful for patients with hip OA to utilize the LBPP treadmill under 75% BW condition.

The significant difference in the spatiotemporal gait parameters and kinematics during the stance and swing phases between the hip OA and control groups in the current study might reflect the characteristics of patients with hip OA during walking. More specifically, shorter step length in the hip OA group than in the control group observed in this study was consistent with that observed in previous studies that showed subjects with hip OA walked with 7-10% shorter step length than an age-matched control group [17, 18]. The findings of less peak extension angle during the stance phase in the hip OA group compared to the control are also consistent with those of previous studies [19, 20]. However, because the H-Gait system uses gravity for its calculations, changes to the gravity should be taken into consideration. On the other hand, because this LBBP treadmill added lift to the body by pressurizing the chamber to which the subject's lower limbs were contained, it could not change the gravity acting on the sensors. The gravitational environmental conditions have not been modified in any way during this current study; therefore, this system might potentially address the kinematics during walking on the LBPP treadmill. On the other hand, because this H-Gait system has not yet been validated for use in an altered gravity environment, the future study should address sensor adjustment to account for different gravity conditions.

There were several limitations to this study. First, only the effects of unweighting on the kinematics of lower limbs were investigated, rather than including the effects of unweighting on the kinematics of the trunk and upper limbs. Second, this system might have a larger measurement error compared to a camera-based system such as a VICON system. However, we believed that wearable sensors are an excellent application for this investigation as the treadmill design makes it difficult to acquire motion analysis data using traditional skin marker motion analysis technologies. Third, this current study investigated the moderate or severe cases to receive THA; therefore, the results of this current study could be limited to observe the training effect of LBPP. Future studies should investigate the training effect of LBPP among patients with early-stage hip OA.

Conclusions

Unweighting decreased pain in the hip OA group but did not alter gait kinematics drastically compared to the control. Therefore, clinicians should consider the benefits of pain reduction during unweighting, rather than the potential for gait improvement, when recommending LBPP treadmill in patients with hip OA.

Declarations

Ethics approval and consent to participate: This study was approved by the Hokkaido University Institutional Review Board (#015-0096), and informed consent for participation in the study was obtained from all participants.

Consent for publication: Not applicable.

Availability of data and materials: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: YK, YS and SO collected the data. YK, TS, TI, MS and HT designed the study and drafted the manuscript. YK, RT and ST performed data processing. YK, TS, TI, DT, NI and HT participated in designing the study. All authors read and approved the final manuscript.

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Author details:

[1]Faculty of Health Sciences, Hokkaido University, Kita 12, Nishi 5, Kita-ku, Sapporo 060-0812, Japan. [2]Department of Rehabilitation, Health Sciences University of Hokkaido Hospital, 2-5 Ainosato, Kita-ku, Sapporo 002-8072, Japan. [3]Department of Orthopaedic Surgery, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, Kita 15, Nishi 7, Kita-ku, Sapporo 060-8638, Japan [4]Faculty of Engineering, Hokkaido University, Kita 12, Nishi 8, Kita-ku, Sapporo 060-8628, Japan.

Abbreviations

3-D, three-dimensional

BW, Bodyweight

KL, Kellgren and Lawrence

LBPP, lower-body positive pressure

NRS, numeric rating scale

OA, Osteoarthritis

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Tables

Table 1. Demography and walking speed

	Hip OA (n=15)	Control (n=15)	*P*-value
Age, years	60.4 (9.6)	61.2 (6.3)	0.780
Height, cm	152.8 (2.9)	155.8 (3.7)	0.174
Weight, kg	57.1 (11.4)	53.5 (7.3)	0.329
Walking speed, km/h	1.2 (0.3)	1.3 (0.4)	0.636
OA KL grade 3 (moderate)	3 cases		
OA KL grade 4 (severe)	12 cases		
Harris hip score, point	45.1 (15.3)		

Data are presented as mean (standard deviation). OA: osteoarthritis, KL: Kellgren and Lawrence

Table 2
Spatiotemporal gait parameters

	Hip OA (n = 15)			Control (n = 15)			P-value	
	Body weight			Body weight			OA vs Control	Effect of unweighting
	100%	75%	50%	100%	75%	50%		
Step length (cm)	35.5 (16.5)	37.7 (19.3)	40.9 (21.5)	48.0 (19.7)	51.3 (23.4)	53.8 (25.0)	0.004	0.600
Cadence (step/min)	137.3 (55.7)	133.1 (57.6)	126.7 (58.6)	94.4 (26.3)	91.3 (22.2)	87.1 (23.2)	< 0.001	0.732

Data are presented as mean (standard deviation). OA: osteoarthritis

Table 3

The peak angles of hip, knee and ankle joints during stance phase

	Hip OA (n = 15)			**Control (n = 15)**			**P-value**	
	Body weight			Body weight			OA vs Control	Effect of unweighting
	100%	75%	50%	100%	75%	50%		
Hip EXT, degree	0.2 (6.0)	-0.8 (5.8)	-0.7 (5.3)	4.0 (4.2)	3.3 (4.8)	3.7 (4.6)	< 0.001	0.797
Knee EXT, degree	-8.2 (5.2)	-6.2 (4.0)	-4.4 (3.4)	-4.9 (5.7)	-4.1 (3.4)	-3.3 (3.2)	0.020	0.061
Ankle DF, degree	11.5 (5.5)	11.7 (10.9)	7.0 (5.6)	11.1 (5.1)	7.6 (3.5)	8.1 (4.0)	0.082	0.395

Data are presented as mean (standard deviation). OA: osteoarthritis, EXT: extension, DF: dorsiflexion

Table 4

The peak angles of hip, knee and ankle joints during swing phase

	Hip OA (n = 15)			**Control (n = 15)**			**P-value**	
	Body weight			Body weight			OA vs Control	Effect of unweighting
	100%	75%	50%	100%	75%	50%		
Hip FLX, degree	20.9 (8.7)	19.0 (9.7)	14.7 (7.2)*	25.8 (8.8)	23.8 (8.0)	19.4 (8.8)*	0.010	0.018
Knee FLX, degree	44.8 (13.6)	42.4 (14.8)	36.4 (11.2)	55.9 (20.5)	52.7 (18.9)	46.2 (22.2)	0.006	0.124
Ankle PF, degree	3.8 (7.3)	7.0 (7.4)	10.2 (10.3)*	4.0 (10.5)	9.1 (10.1)	13.0 (12.1)*	0.425	0.022

Data are presented as mean (standard deviation). OA: osteoarthritis, FLX: flexion, PF: plantarflexion, BW: body weight, *P < 0.05 (vs 100%BW condition)

Figures

Figure 1

Lower-body positive pressure (LBPP) treadmill Participants walked on an LBPP treadmill. Positive pressure inflates the chamber to create traction force on the lower limbs.

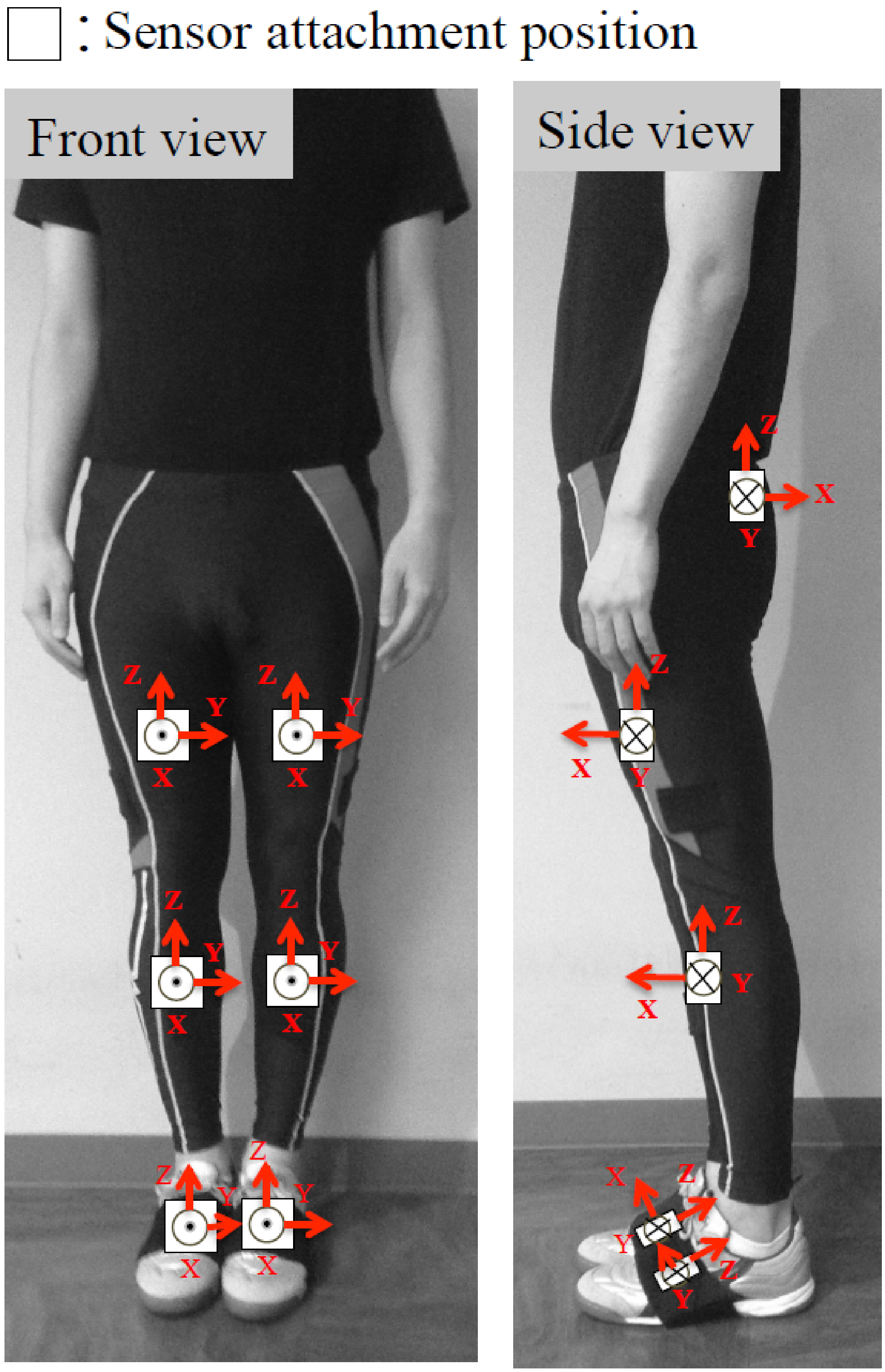

Figure 2

Sensor attachment position on lower limbs Seven wearable sensor units were placed on the pelvis, both thighs, both shanks, and both feet of the participants.

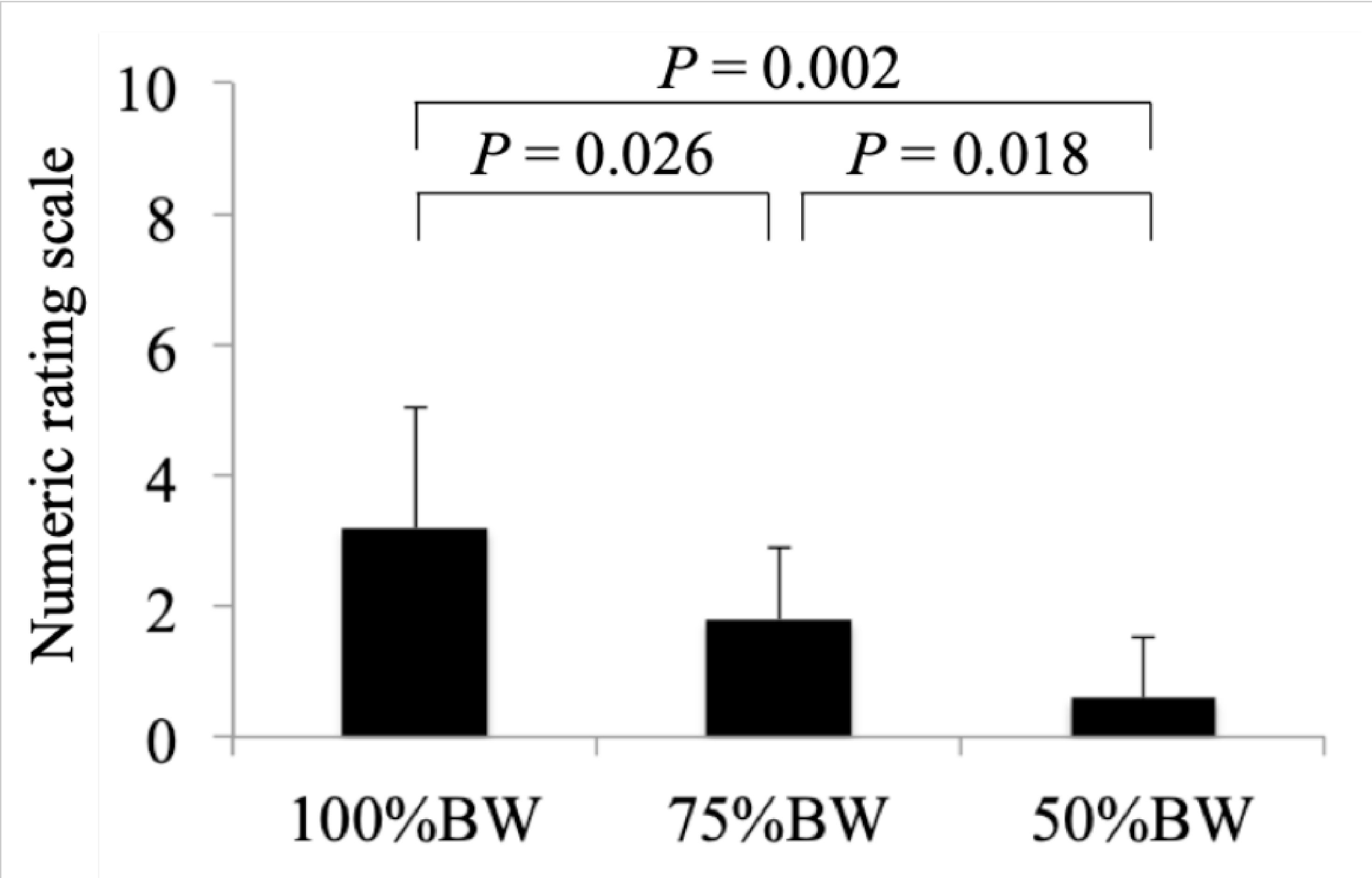

Figure 3

Numeric rating scale pain score during walking under 100%, 75% and 50% bodyweight conditions among the hip osteoarthritis group. 0 represented no anxiety and 10 represented the highest level of anxiety.

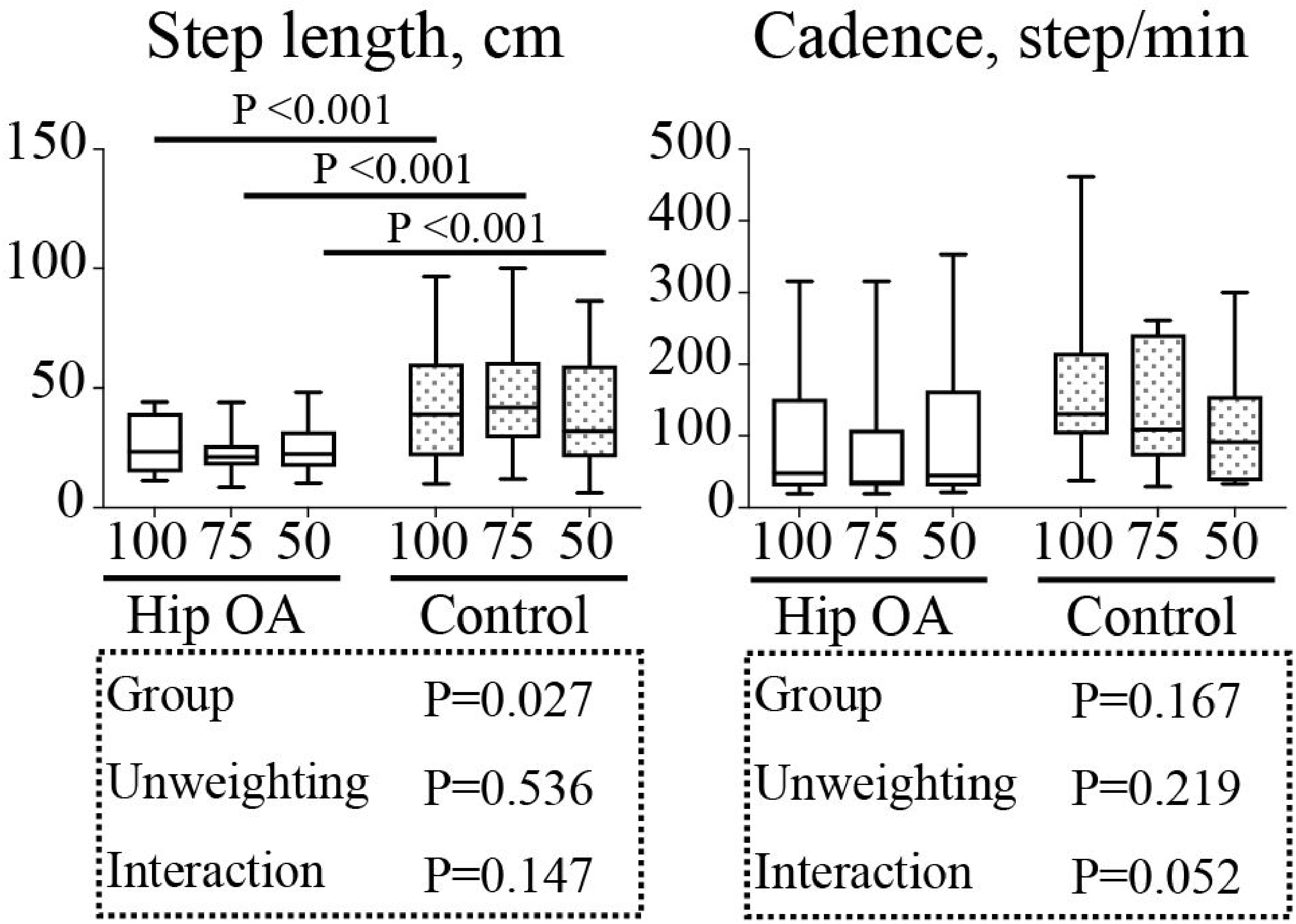

Figure 4

Step length and cadence during walking under 100%, 75% and 50% bodyweight conditions among the hip osteoarthritis and control groups.

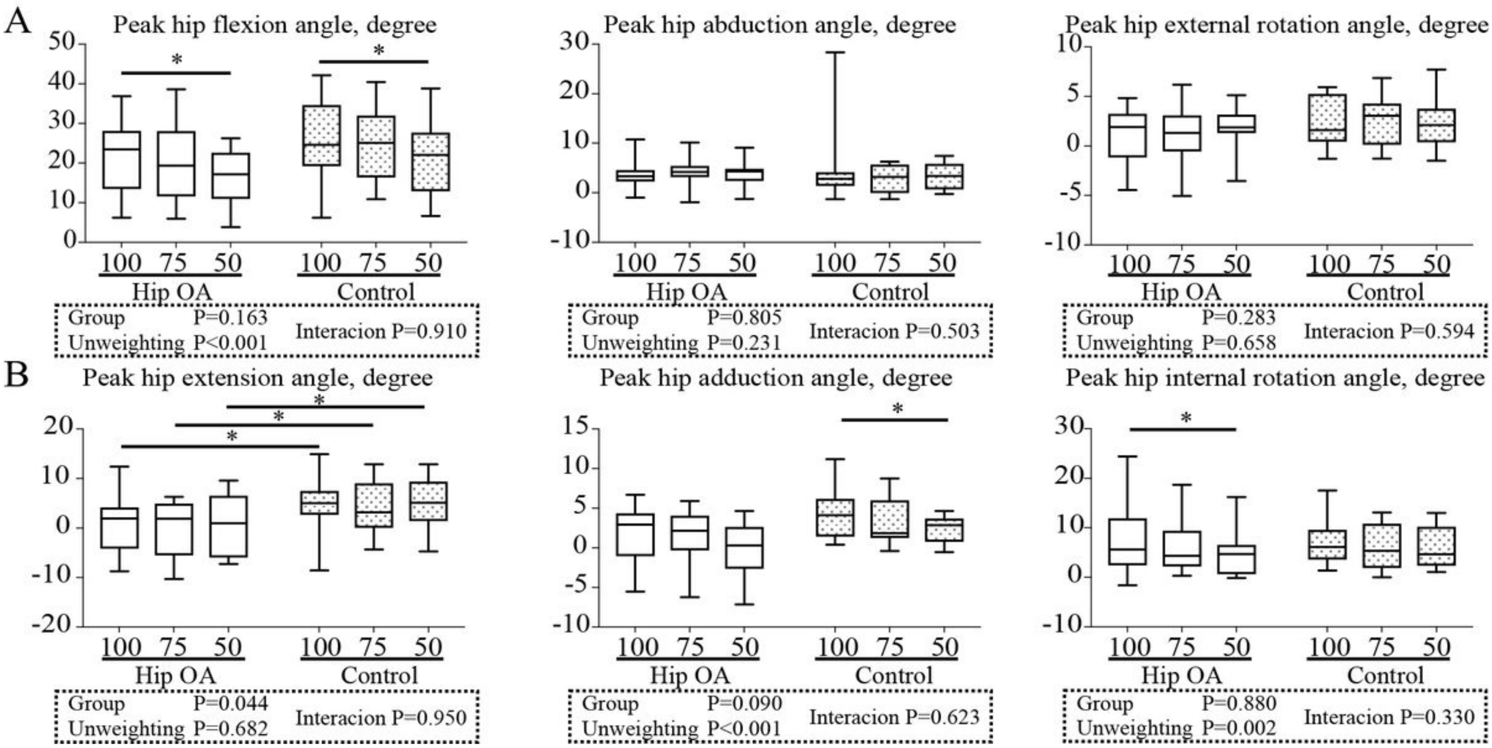

Figure 5

Kinematics of hip joint during walking under 100%, 75% and 50% bodyweight conditions among the hip osteoarthritis and control groups. (A) swing phase (B) stance phase. *: P < 0.05 with post hoc Bonferroni tests. OA: osteoarthritis.

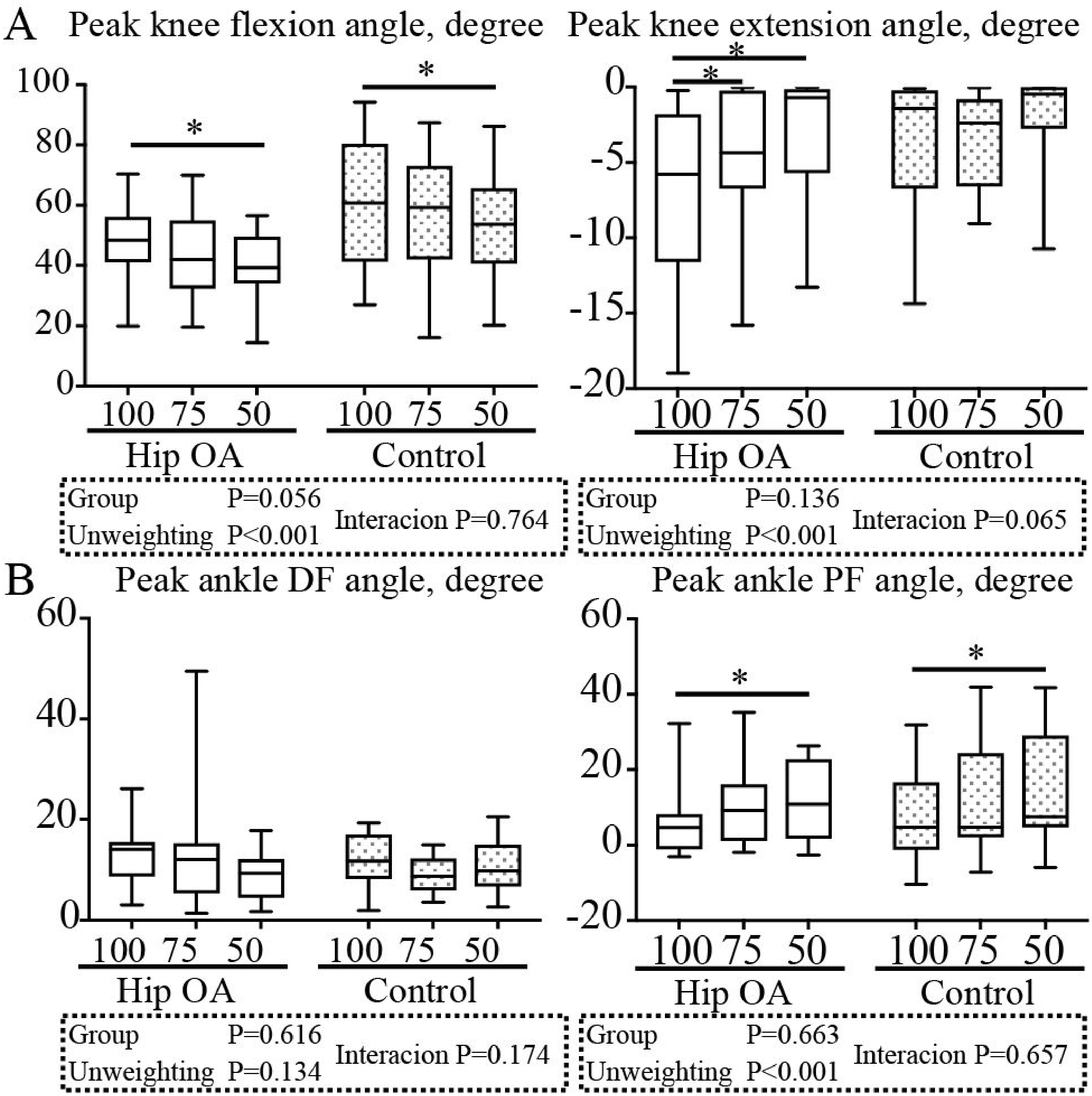

Figure 6

Kinematics of (A) knee joint and (B) ankle joint during walking under 100%, 75% and 50% bodyweight conditions among the hip osteoarthritis and control groups. *: P < 0.05 with post hoc Bonferroni tests. OA: osteoarthritis. DF: dorsiflexion. PF: plantarflexion.