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

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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 comfortable 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. Sagittal plane lower-limb kinematics under each condition were calculated and compared.

Results: In the hip OA group, numerical rating scores at the unweighted condition were significantly decreased compared to the 100% bodyweight condition, and sagittal kinematics in the hip and knee joints significantly decreased compared to the healthy controls. In both groups, unweighting significantly decreased the peak hip 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 improve despite less load on the hip joint. Therefore, clinicians should consider the benefits of pain reduction, rather than improved gait, 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 is not possible, 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 effects of unweighting on 3-D kinematics in the subjects with hip OA during walking on the LBPP treadmill using the wearable-sensor based 3-D motion analysis system. The current study hypothesized that unweighting by the LBPP treadmill would increase the peak angle of each joint during gait, leading to improved 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. 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. Calibration to determine the correlation of gravity and the internal pressure of the chamber was performed for each participant. Participants walked at a comfortable 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 under 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) 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, 9]. 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, 9].

According to a previous study [9], an initial static phase was acquired in the upright position before each trial. To obtain a reference position, accelerometer measurements were used to obtain information about the initial inclination of each sensor with respect to gravity and then the initial 3-D orientation of the body segment to which the sensor was attached was calculated. 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 [10]. The 3-D angular displacement from the initial upright position was calculated in a quaternion according to a previous study [9]. 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. The average of 10 gait cycle during 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 [11]. 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 [10]. 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. Separately, when this system was used to measure a strait 10 m flat floor walking trial, the error for total distance traveled was limited to approximately 5%. The H-Gait system used had a relatively high accuracy compared to conventional systems.

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 ANOVAs with post hoc Bonferroni tests were performed to assess the effects of BW condition and group 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 severity of OA was determined on radiography according to the Kellgren and Lawrence (KL) grade [12] in all cases. The hip OA group included 3 patients with KL grade 3 and 12 with KL grade 4.

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		
Range of motion			
Flexion, degree	89.7 (22.2)		
Abduction, degree	22.0 (9.6)		
Internal rotation, degree	18.0 (9.8)		
External rotation, degree	16.7 (7.5)		
Harris hip score, point	45.1 (15.3)		
Data are presented as mean (standard deviation). OA: osteoarthritis, KL: Kellgren and Lawrence			

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).

Effects of unweighting

The hip OA group exhibited a significant decrease in step length (P = 0.004) and an increase of cadence (P < 0.001) compared to the control group (Table 2). Neither group showed a significant effect of unweighting on step length ($P = 0.600$) or cadence ($P = 0.732$). There were no significant interactions with step length ($P = 0.995$) or cadence ($P = 0.988$) between the unweighted and groups.

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 shows the peak angles of hip, knee, and ankle joints during the stance phase. During the stance phase, participants in the hip OA group exhibited a significant decrease in peak hip extension angle ($P < 0.001$) and peak knee extension angle ($P = 0.020$) compared to the control group. There was no significant difference in peak ankle dorsiflexion angle between the hip OA and control groups ($P = 0.082$). Neither group showed a significant difference from unweighting on peak hip extension angle ($P = 0.797$), peak knee extension angle ($P = 0.061$), or peak ankle dorsiflexion angle ($P = 0.395$). There were no significant interactions with peak hip extension angle ($P = 0.963$), peak knee extension angle ($P = 0.596$), or peak ankle dorsiflexion angle ($P = 0.264$) between the unweighted and control groups.

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 represents the peak angles of hip, knee and ankle joints during the swing phase. During the swing phase, the hip OA group exhibited a significant decrease of peak hip flexion angle ($P = 0.018$) and peak knee flexion angle ($P = 0.006$) compared to the control group. There was no significant difference in peak ankle plantarflexion angle between the hip OA and control groups ($P = 0.425$). Peak hip flexion angle and peak ankle plantarflexion angle at the 50% BW condition in both groups showed significant differences compared to those at the 100% BW condition ($P = 0.017$ and $P = 0.013$, respectively). Neither group showed significant differences of unweighting on peak knee flexion angle ($P = 0.124$). There were no significant interactions of peak flexion angle ($P = 0.999$), peak knee flexion angle ($P = 0.991$), or peak ankle plantarflexion angle ($P = 0.875$) between the unweighted and control groups.

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)

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 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 [13, 14]. 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 improve 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 improvement 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]. Although the current study did not investigate cardiovascular response during the gait trials, a previous study showed lower heart rates during walking in LBPP ambulation than in ambient pressure [3], suggesting that LBPP could be a safe rehabilitation tool in terms of cardiovascular load. Additionally, another study showed that unweighting by the LBPP treadmill reduced the rated perceived exertion and was significantly more comfortable than the harness system [7]. 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 conditions 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 [15, 16]. The findings of less peak extension angles during the stance phase and flexion angles during the swing phase on the hip and knee joints in the hip OA group compared to the control are also consistent with those of previous studies [17, 18]. These findings suggest that the wearable sensor-based 3-D motion analysis system successfully analyzed the kinematics during walking on the LBPP treadmill. Therefore, this system might potentially address the kinematics of other musculoskeletal disorders or longitudinal postoperative course in the future.

There were several limitations to this study. First, only the effects of unweighing 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, only sagittal plane kinematics were considered. Because LBPP might influence the frontal and transverse planes, future studies were needed to evaluate gait kinematics in the frontal and transverse planes.

Conclusions

The present study first showed that unweighting significantly decreased the peak hip flexion angle and increased the peak ankle plantarflexion angle during walking on the LBPP treadmill in participants with hip OA and age-matched healthy controls. Unweighting decreased pain in the hip OA group, but gait kinematics was not improved. 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.

List Of Abbreviations

3-D, three-dimensional

BW, Bodyweight

KL, Kellgren and Lawrence

LBPP, lower-body positive pressure

NRS, numeric rating scale

OA, Osteoarthritis

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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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.

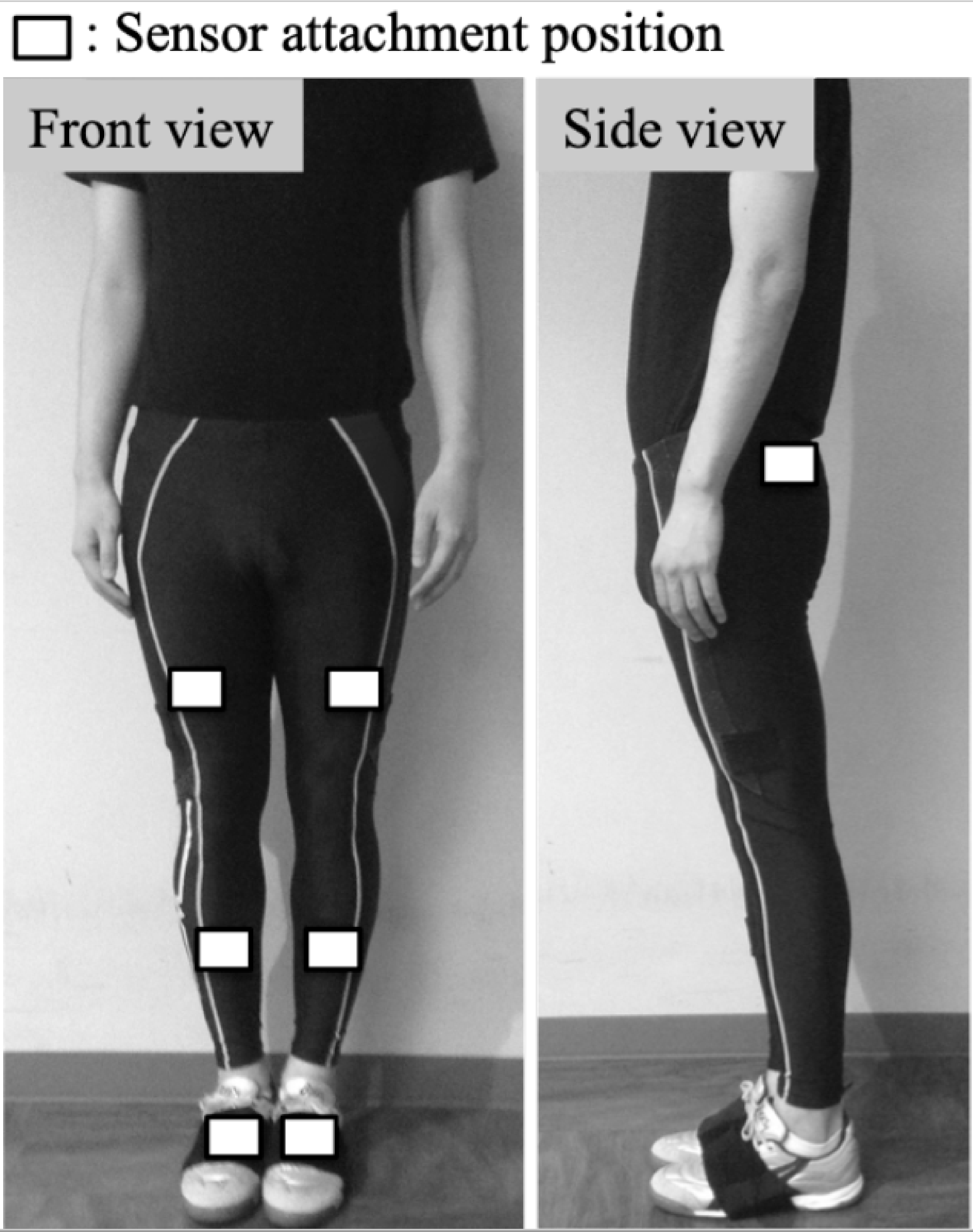

Figure 2

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.

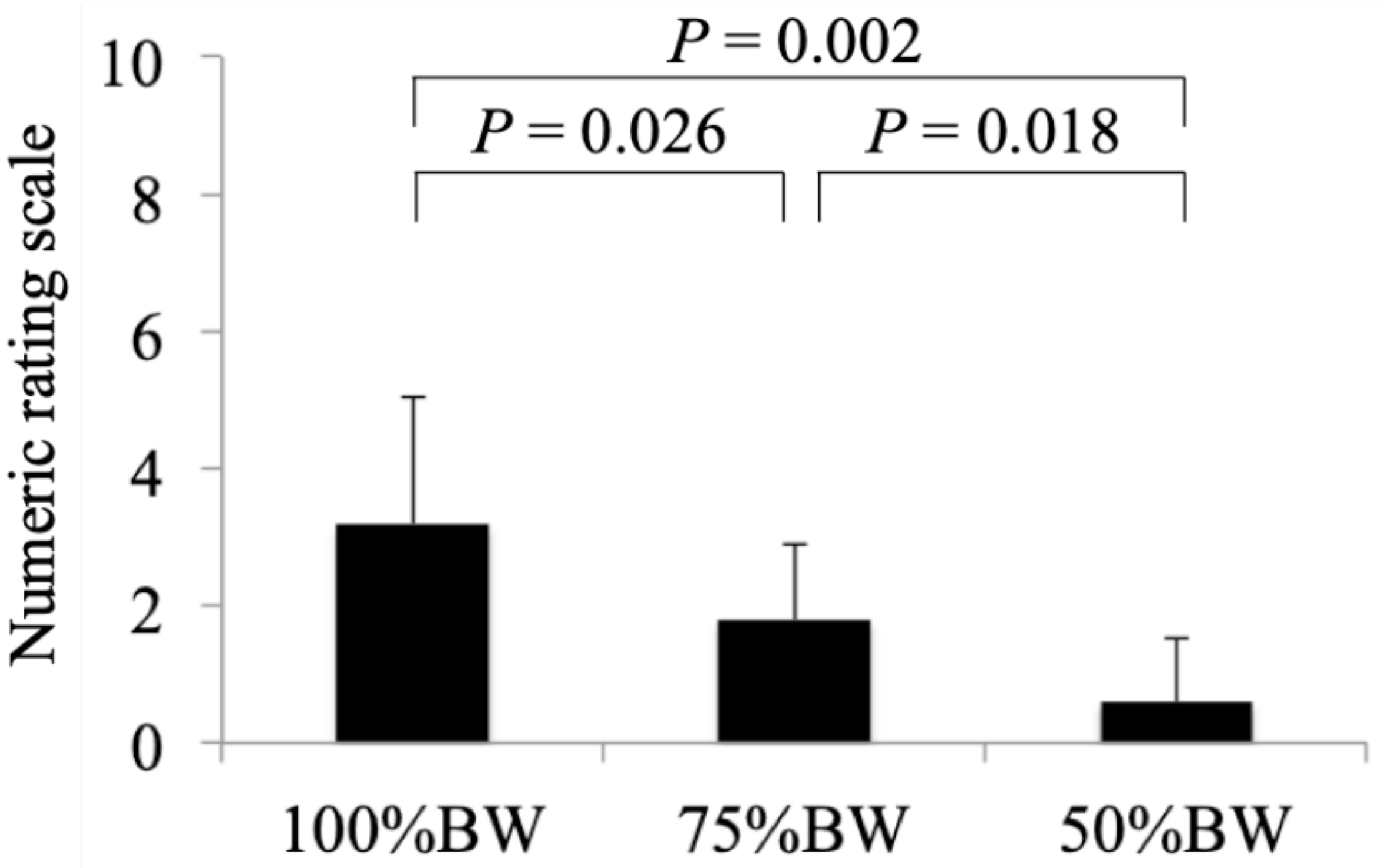

Figure 3

Numeric rating scale pain score during walking under 100%, 75% and 50% bodyweight conditions among the hip osteoarthritis group