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The differences in sagittal plane whole-body angular momentum during gait between patients with hemiparesis and healthy people

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ABSTRACT

Regulation of whole-body angular momentum (WBAM) is essential for maintaining dynamic balance during gait. Patients with hemiparesis frequently fall toward the anterior direction; however, whether this is due to impaired WBAM control in the sagittal plane during gait remains unknown. The present study aimed to investigate the differences in WBAM in the sagittal plane during gait between patients with hemiparesis and healthy individuals. Thirty-three chronic stroke patients with hemiparesis and twenty-two age- and gender-matched healthy controls walked along a 7-m walkway while gait data were recorded using a motion analysis system and force plates. WBAM and joint moment were calculated in the sagittal plane during each gait cycle. The range of WBAM in the sagittal plane in the second half of the paretic gait cycle was significantly larger than that in the first and second halves of the right gait cycle in the controls ($P = 0.015$ and $P = 0.011$). Furthermore, multiple regression analysis revealed the slower walking speed ($P < 0.001$) and larger knee extension moment on the non-paretic side ($P = 0.003$) contributed to the larger range of WBAM in the sagittal plane in the second half of the paretic gait cycle. Our findings suggest that dynamic stability in the sagittal plane is impaired in the second half of the paretic gait cycle. In addition, the large knee extension moment on the non-paretic side might play a role in the dynamic instability in the sagittal plane during gait in patients with hemiparesis.

1. Introduction

Patients with hemiparesis have a high risk of falling, particularly during gait (Ashburn et al., 2008; Jørgensen et al., 2002; Mackintosh et al., 2005). Dynamic stability during gait is assessed based on whole-body angular momentum (WBAM), which represents the rotational momentum around the whole-body center of mass (CoM) resulting from translational and rotational movements of all body segments (Nott et al., 2014). While healthy people maintain a small range of WBAM in all planes during gait (Herr and Popovic, 2008), patients with hemiparesis who have a low clinical balance score exhibit a large range of WBAM in the coronal plane in the paretic single-support phase (Nott et al., 2014). On the other hand, although patients with hemiparesis frequently fall toward not only the paretic side but also the anterior direction (Hyndman et al., 2002; Mackintosh et al., 2005), there was no significant difference in the range of WBAM in the single-support phase between patients with hemiparesis and healthy young adults during various tasks such as gait, obstacle crossing, and step-up in the sagittal plane (Vistamehr et al., 2018). The analysis period in the previous study did not include the double-support phase, when patients with hemiparesis exhibit the deficit of propulsion of paretic leg (Chen et al., 2005). Therefore, it remains unclear whether WBAM control in the sagittal plane throughout the gait cycle is impaired during gait in these patients.

WBAM is regulated by muscle force generation in the lower extremity during gait (Neptune and McGowan, 2011). Neptune and McGowan (2011) reported that hip and knee extensors, hamstrings, and ankle dorsiflexors generated backward angular momentum while plantar-flexors generated forward angular momentum in the early stance phase during gait in healthy people. In the late stance phase, the soleus and gastrocnemius generate forward and backward angular momentum, respectively (Neptune and McGowan, 2011). Furthermore, ankle plantar flexor muscles play a role in maintaining WBAM within a small range in the sagittal plane during gait (Pijnappels et al., 2005). Kinetics disturbance in patients with hemiparesis is characterized by decreased ankle plantar flexion moment and power generation in the late stance phase on the paretic side (Kerrigan et al., 2001; Olney et al., 1991; Teixeira-Salmela et al., 2001) coupled with com-

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pensation by increased hip flexor power generation in the late stance phase on the paretic side and hip and knee extensor power generation in the early stance phase on the non-paretic side (Farris et al., 2015). The above abnormal joint kinetics might affect the range of WBAM in the sagittal plane during gait in patients with hemiparesis.

The purpose of this study was to investigate the differences in WBAM in the sagittal plane during gait between patients with hemiparesis and healthy individuals. We hypothesized that the range of WBAM in the sagittal plane during gait in patients with hemiparesis would be larger than that in healthy individuals, and would be related to the insufficient ankle plantar flexion moment on the paretic side during gait.

2. Methods

2.1. Participants

The present study included 33 patients with hemiparesis due to either brain hemorrhage or infarction, confirmed using computed tomography or magnetic resonance imaging and medical records of neurologic symptoms, and 22 age- and gender-matched healthy controls. The inclusion criteria for patients with hemiparesis were as follows: (1) a first-time unilateral stroke occurring at least 6 months before this study, (2) the ability to walk at least 7-m without assistive devices, and (3) the ability to follow verbal commands. The exclusion criteria for both groups were as follows: (1) abnormal circulatory and respiratory status, (2) a history of orthopedic problems interfering with gait, (3) brainstem or cerebellar lesions, (4) abnormal mental status, and (5) higher brain dysfunction, which skewed measurements. The study was approved by the Institutional Ethics Committee. All participants provided written informed consent before participating in the experiment.

2.2. Data collection

The patients with hemiparesis and the control subjects were instructed to walk at a comfortable and matched speed along a 7-m walkway for 3 to 10 trials. The control subjects were instructed to walk at a speed ranging from 0.1 to 0.8 m/s, which coincides with the walking speed range for patients with hemiparesis reported in a previous study (Perry et al., 1995). Control subjects who walked faster or slower than 0.1 m/s to 0.8 m/s were asked to increase or reduce their walking speed accordingly. Thirty-one reflective markers were attached to 12 segments composed of the torso, upper arms, forearms, pelvis, thighs, shanks, and feet based on the anthropometric data reported by Dumas et al. (2007). Three-dimensional coordinates for 31 reflective markers attached to various body segments were recorded during overground walking using an 8-camera motion analysis system (MAC 3D; Motion Analysis Corporation, Santa Rosa, CA, USA) operating at 120 Hz. Furthermore, ground reaction force (GRF) data were collected using four 90 cm × 60 cm force plates (Anima Corporation, Choufu, Tokyo, Japan) synchronized with the 8-camera system and operated at 1200 Hz.

2.3. Data analysis

The three-dimensional coordinates and GRF data were smoothed using a bidirectional fourth-order Butterworth low-pass filter with a cutoff frequency of 6 and 20 Hz. The 12-segment model comprised the feet, shanks, thighs, pelvis, thorax, upper arms, and forearms. In addition, segment masses, CoM positions, and tensors of inertia were calculated using the scaling factors described in a previous report (Dumas et al., 2007). The whole-body CoM position was computed based on participant-specific properties and the three-dimensional coordinates of anatomical landmarks. Spatio-temporal parameters were calculated using the standard method (Rose and Gamble, 2006). The double-support time on the paretic and non-paretic sides was defined as the time of the double-support phase and included the push-off point for the paretic and non-paretic legs, respectively.

In the present study, WBAM about the whole-body CoM was calculated as follows:

$$WBAM = \sum_{i=1}^{n} \left[\left(\vec{r}_i^{\,CoM} - \vec{r}^{\,CoM} \right) \times m_i (\vec{v}_i^{\,CoM} - \vec{v}^{\,CoM}) + \overleftrightarrow{I}_i \vec{\omega}_i \right]$$

where n is the number of segments; $\vec{r}^{\,CoM}$ and $\vec{v}^{\,CoM}$ are the whole-body CoM position and velocity, respectively; $\vec{r}_i^{\,CoM}$ and $\vec{v}_i^{\,CoM}$ are the ith segment CoM position and velocity, respectively; m_i is the ith segment mass; and $\overleftrightarrow{I}_i$ and $\vec{\omega}_i$ are the tensor of inertia and angular velocity of the ith segment about the segment CoM, respectively. Positive and negative values indicated the backward and forward WBAM, respectively. WBAM was normalized by the body mass (kg), height (m), and walking speed (m/sec), as these parameters affect the range of WBAM (Bennett et al., 2010; Silverman and Neptune, 2011). In patients with hemiparesis, the range of WBAM in the sagittal plane was calculated as the peak-to-peak value in the first and second halves of the paretic gait cycle, respectively. On the other hand, in the healthy controls, the range of WBAM in the sagittal plane was calculated as the peak-to-peak value in the first and second halves of the right gait cycle, respectively. The paretic and non-paretic gait cycles were determined as the period from the foot contacts of the paretic and non-paretic leg to the second foot contact of the ipsilateral leg, respectively. The first half of the paretic gait cycle was composed of the double-support phase on the non-paretic side and the single-support phase on the paretic side. The second half of the paretic gait cycle was also composed of the double-support phase on the paretic side and the single-support phase on the non-paretic side. Similar to the patients with hemiparesis, the right and left gait cycles were also determined in the healthy controls.

Ankle, knee, and hip joint moment were calculated based on inverse dynamics at each joint, and these value were normalized by the body weight (Selbie et al., 2013). The representative parameters for joint moment were defined as follows: peak ankle plantar flexion moment in the late stance phase, peak knee extension moment in the early stance phase, peak hip flexion moment in the late stance phase, and peak hip extension moment in the early stance phase. We determined the peak joint moments on the paretic and non-paretic sides in each phase of the paretic and non-paretic gait cycles, respectively. In the healthy controls, the peak joint moments on the right and left sides were determined in each phase of the right and left gait cycles, respectively. The early and late stance phases were determined as the first and second halves of the stance phases, respectively. These parameters for joint moment are important for supporting body weight, initiating swing, and producing propulsion during gait (Eng and Winter, 1995). All parameters were calculated using custom software in MATLAB (The Math Works Incorporated, Natick, MA, USA).

2.4. Statistical analysis

Differences in the physical characteristics (age, height, and weight) were analyzed with an unpaired t-test. In addition, gender differences were confirmed using a chi-square test. The mean values of five gait cycles for each participant were used for statistical analysis. Walking speed, step width, cadence, and stride length were analyzed with an unpaired *t*-test. Step length, double-support time, single-support time, and joint moment were analyzed using two-way analysis of variance (ANOVA) with side (2 levels: paretic and non-paretic sides for patients with hemiparesis; right and left sides for healthy controls) as a within-subject factor and group (2 levels: patients with hemiparesis and healthy controls) as an independent factor. WBAM was also examined using two-way ANOVA with phase (2 levels: first and second halves of the gait cycle) as a within-subject factor and group as an independent factor. When a significant difference was observed, a Bonferroni post-hoc test was conducted. Furthermore, when the range of WBAM in the first and/or second half of the gait cycle in patients with hemiparesis significantly differed from that in the control group, a stepwise multiple linear regression was used to determine which joint moment was the most explanatory variable for the range of WBAM. Walking speed was included as an independent variable in the stepwise regression because it is significantly related to the normalized range of WBAM (Bennett et al., 2010; Olney et al., 1991). We used both forward and backward selection methods. In each forward step, the independent variable was included if the probability of F not in the regression equation was smallest and ≤ 0.05. In each backward step, the independent variable in the regression equation was removed if the probability of F was ≥ 0.10. If none of the variables satisfied the criteria for inclusion or exclusion, stepwise regression analysis was ended. The statistical significance level was set at a P value of 0.05 for all analyzes. Statistical analyzes were performed using a statistical software package (SPSS Ver.24, IBM-SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Subject characteristics

Physical characteristics were not significantly different between the groups (Table 1).

3.2. Gait-related parameters

Comparisons of gait-related parameters for the patients with hemiparesis and the control group are shown (Table 2). The walking speed of the patients with hemiparesis was not significantly different from that of the controls ($P = 0.431$). While the step width and cadence were not significantly different between groups ($P = 0.114$ and $P = 0.149$), the stride length of the patients with hemiparesis was significantly shorter than that of the controls ($P = 0.001$). A significant main effect of the group was observed on step length ($F_{1,51} = 13.150$; $P = 0.001$). The step length of the patients with hemiparesis was significantly shorter than that of the controls ($P = 0.001$). Furthermore, there were significant main effects of the group ($F_{1,51} = 33.736$; $P < 0.001$) and side ($F_{1,51} = 42.564$; $P < 0.001$) as well as interactions between the group and side ($F_{1,51} = 45.938$; $P < 0.001$) in single-support time. The post-hoc test indicated that the single-support time on the paretic side was shorter than that on the non-paretic side in patients with hemiparesis ($P < 0.001$) and was also shorter than the single-support time on both sides in the controls ($P < 0.001$ and $P < 0.001$). In contrast, no significant main effect and interaction were observed for the double-support time.

The time series data for joint moment are shown during one gait cycle in patients with hemiparesis and controls (Fig. 1). A significant main effect of the group ($F_{1,51} = 9.627$; $P = 0.003$) and side ($F_{1,51} = 26.423$; $P < 0.001$) as well as interactions between the group and side ($F_{1,51} = 15.314$; $P < 0.001$) were observed in the plantar flexion moment in the late stance phase (Table 2). The paretic plantar flexion moment in the late stance phase of the paretic gait cycle was significantly lower than that on the non-paretic side ($P = 0.002$) and that on left ($P < 0.001$) and right ($P < 0.001$) sides in the controls. A significant main effect of the group ($F_{1,51} = 6.474$; $P = 0.014$) and interactions between the group and side ($F_{1,51} = 13.688$; $P = 0.001$) were observed in knee extension moment in the early stance phase (Table 2). The non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle was significantly higher than that on the paretic side ($P = 0.043$) as well as that on the left side in the controls ($P < 0.001$). A significant main effect of the side ($F_{1,51} = 23.557$; $P < 0.001$) and interactions between the group and side ($F_{1,51} = 18.115$; $P < 0.001$) were observed in the hip extension moment in the early stance phase (Table 2). The non-paretic hip extension moment in the early stance phase of the non-paretic gait cycle was significantly higher than that on the paretic side ($P < 0.001$) and that on the right side in the controls ($P = 0.033$).

3.3. Whole-body angular momentum (WBAM) in the sagittal plane

The average WBAM curves are shown in the sagittal plane during one gait cycle in patients with hemiparesis and healthy controls (Fig. 2A). The time series data for WBAM in the sagittal plane showed a bimodal peak during one gait cycle in both groups. As shown in Fig. 2B, a significant main effect of the group ($F_{1,51} = 5.077$; $P = 0.029$) and side ($F_{1,51} = 27.721$; $P < 0.001$) and interactions between the group and phase ($F_{1,51} = 33.313$; $P < 0.001$) were observed in the range of WBAM in the sagittal plane. The range of WBAM in the second half of the paretic gait cycle was significantly larger than that in the first and second halves of the right gait cycle in the controls ($P = 0.015$ and $P = 0.011$).

The results obtained with multiple regression analysis of the range of WBAM in the sagittal plane for patients with hemiparesis and healthy controls are shown (Table 3). For the former, the non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle and walking speed were identified as contributors to the range of WBAM in the second half of the paretic gait cycle. The extent of the variance inflation factor (VIF) was 1.028. In contrast, only walking speed was identified as a contributor to the range of WBAM in the second half of the right gait cycle for healthy controls.

Table 1
Characteristics of patients with hemiparesis and healthy controls.

	Patients with hemiparesis	Controls	*P*-value[c]
Number[a]	33	22	
Gender (Male/Female)[a]	28/5	14/8	0.070
Age (years)[b]	56.8 (SD 10.3)	58.7 (SD 16.2)	0.588
Height (m)[b]	1.66 (SD 0.08)	1.66 (SD 0.08)	0.997
Weight (kg)[b]	69.3 (SD 10.2)	61.5 (SD 10.6)	0.401
Diagnosis (Hemorrhage/Infarction)[a]	20/13		
Paretic side (Right/Left)[a]	22/11		
Times since neurologic event (month)[b]	54.8 (SD 44.8)		
Brunnstrom recovery stage (III/IV/V/VI)[a]	16/8/8/1		
Stroke Impairment Assessment Set motor function (0/1/2/3/4/5)[a]			
Ankle joint	6/7/3/8/5/4		
Knee joint	0/1/2/15/11/4		
Hip joint	0/1/2/9/17/4		

[a] Number of participants.
[b] Mean (standard deviation).
[c] Gender was compared with the chi-square test; Age, Height, and Weight were compared with the unpaired *t*-test.

Table 2
Mean (and SD) values of spatio-temporal parameters and peak joint moment in the lower extremity of patients with hemiparesis and healthy controls.

	Patients with hemiparesis		Controls	
	Paretic side	Non-paretic side	Right side	Left side
Spatio-temporal parameters				
Walking speed (m/s)	0.40 (0.25)		0.45 (0.16)	
Step width (m)	0.16 (0.05)		0.14 (0.03)	
Cadence (step/min)	74.7 (21.0)		66.7 (17.5)	
Stride length (m)[*]	0.64 (0.27)		0.86 (0.15)	
Step length (m)[a]	0.33 (0.13)	0.30 (0.15)	0.41 (0.07)	0.42 (0.08)
Double-support time (s)	0.34 (0.21)	0.41 (0.34)	0.35 (0.18)	0.35 (0.19)
Single-support time (s)[a,b,c]	0.38 (0.15)	0.58 (0.10)	0.60 (0.11)	0.60 (0.12)
Peak joint moment (Nm/kg)[†,‡]				
PF in the late stance phase[a,b,c]	0.66 (0.28)	0.88 (0.25)	0.94 (0.17)	0.97 (0.17)
KE in the early stance phase[a,c]	0.27 (0.21)	0.42 (0.26)	0.26 (0.18)	0.17 (0.12)
HE in the early stance phase[b,c]	0.22 (0.18)	0.43 (0.20)	0.30 (0.10)	0.31 (0.14)
HF in the late stance phase	−0.74 (0.30)	−0.63 (0.26)	−0.62 (0.13)	−0.59 (0.14)

PF, ankle plantar flexion moment; KE, knee extension moment; HE, hip extension moment; HF, hip flexion moment.
† The peak joint moments on the paretic and non-paretic sides were determined in each phase of the paretic and non-paretic gait cycles in patients with hemiparesis, respectively.
‡ The peak joint moments on the right and left sides were determined in each phase of the right and left gait cycles in healthy controls, respectively.
* Significant difference between patients with hemiparesis and healthy controls with $P < 0.05$.
a Significant main effect of group with $P < 0.05$.
b Significant main effect of side with $P < 0.05$.
c Significant interaction between group and side with $P < 0.05$.

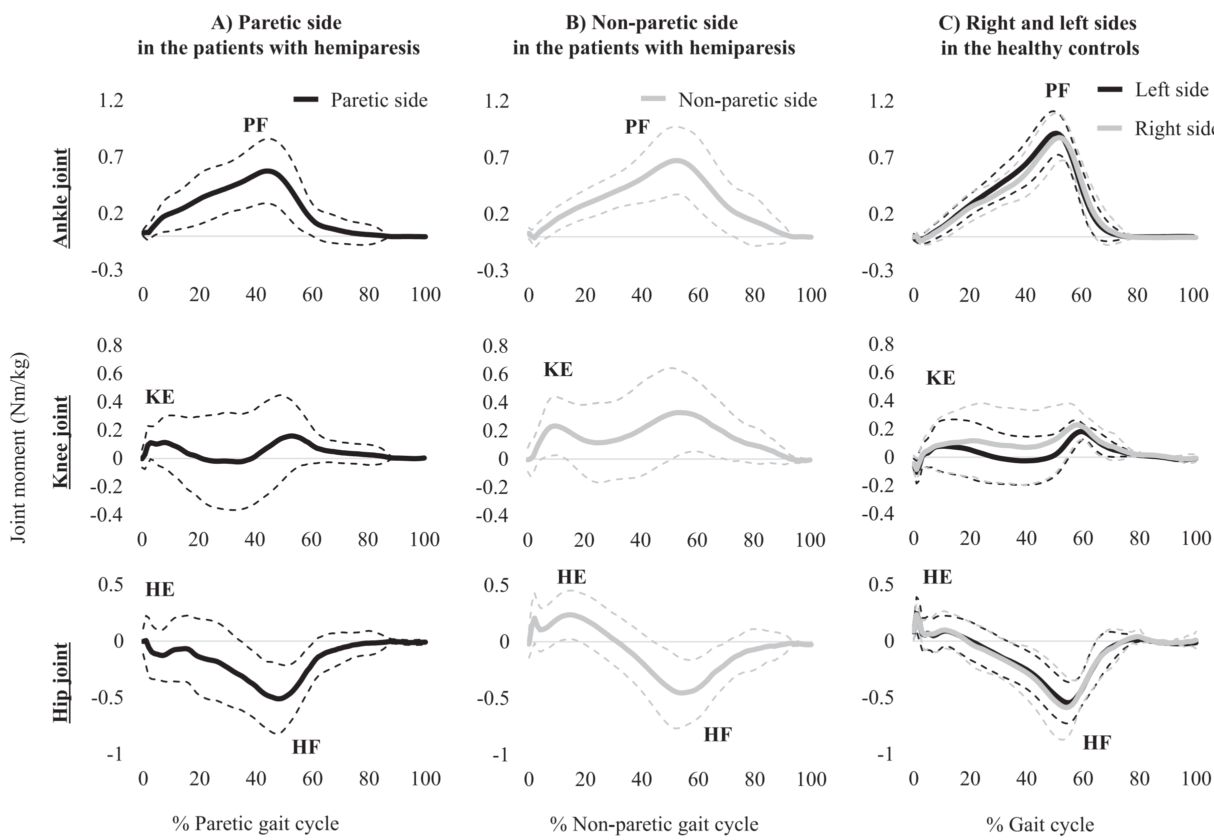

Fig. 1. Average (solid line) and ±1 SD (dashed line) of joint moment in the sagittal plane during paretic gait cycle (A) and non-paretic gait cycle (B) in patients with hemiparesis and right and left gait cycle in healthy controls (C). The paretic (non-paretic) gait cycle was determined as the period from the foot contact of the paretic (non-paretic) leg to the second foot contact of the ipsilateral leg. PF, ankle plantar flexion moment in the late stance phase; KE, knee extension moment in the early stance phase; HE, hip extension moment in the early stance phase; HF, hip flexion moment in the late stance phase.

4. Discussion

The present study demonstrates that the range of WBAM in the sagittal plane in the second half of the paretic gait cycle in patients with hemiparesis is significantly larger than that in the first and second half of the right gait cycle in healthy controls and is also significantly related to the walking speed and the non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle. To the best of our knowledge, this is the first study to find significant differences in the range of WBAM in the sagittal plane

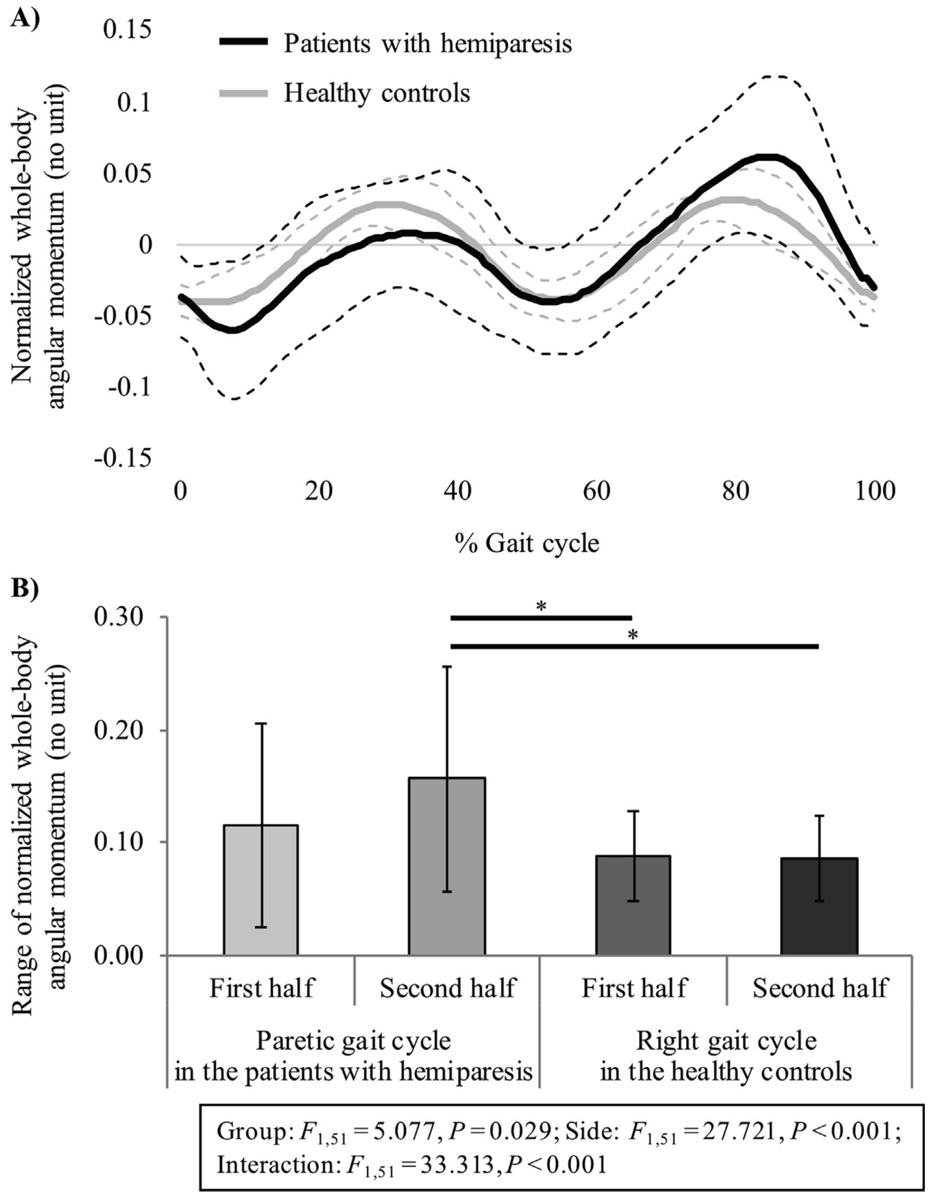

Fig. 2. (A) Average (solid line) and ±1 SD (dashed line) of whole-body angular momentum in the sagittal plane during paretic gait cycle in patients with hemiparesis (black) and right gait cycle in healthy controls (grey). (B) Mean and ±1 SD of the range of whole-body angular momentum in the sagittal plane in the first and second half of the gait cycle in patients with hemiparesis and healthy controls. *: significant difference between the second half of the paretic gait cycle in the patients with hemiparesis and both halves of the right gait cycle in the controls ($P < 0.05$).

Table 3
Multiple regression analysis with the range of whole-body angular momentum in the sagittal plane in patients with hemiparesis and healthy controls.

Variable	Partial regression coefficient	Standardized partial regression coefficient	Variance, R^2	*P*-value	VIF
Second half of paretic gait cycle					
Walking speed	−0.312	−0.787	0.696	<0.001	1.028
Non-paretic KE in the early stance phase of the non-paretic gait cycle	0.109	0.286	0.776	0.003	1.028
Second half of right gait cycle					
Walking speed	−0.186	−0.871	0.758	<0.001	1.000

KE, knee extension moment; VIF, variance inflation factor.

between patients with hemiparesis and healthy elderly adults during gait and to clarify the effect of knee joint moment on the non-paretic side on the range of WBAM in patients with hemiparesis.

Our findings demonstrate that the range of WBAM in the second half of the paretic gait cycle in the sagittal plane was significantly larger than that in healthy controls. This is in contrast to the results from a previous study (Vistamehr et al., 2018). The difference in the results between the present and previous studies could be explained by the analysis period. While Vistamehr et al. (2018) focused on the single-support phase, we showed that there was a significant difference in the range of WBAM from the double-support phase with the paretic push-off point to the non-paretic single-support phase (i.e. the second half of the paretic gait cycle). Neptune and McGowan (2011) demonstrated that lower limb muscles mainly generate forward and backward angular momentum in the early and late stance phases, so the double-support phase (i.e. around the early and late stance phases) might be an important period for the regulation of WBAM during gait. Therefore, we suggest that the patients with hemiparesis exhibits dynamic instability in the sagittal plane in the second half of the paretic gait cycle.

As there was a significantly larger range of WBAM in the second half of the paretic gait cycle, we examined the relationship between the range of WBAM in this phase and joint moment in the lower extremities. While we expected that an inadequate paretic plantar flexion moment in the late stance phase of the paretic gait cycle independently affects the range of WBAM in the sagittal plane during gait in patients with hemiparesis, stepwise regression analysis demonstrated that the non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle significantly contributes to the large range of WBAM in the second half of the paretic gait cycle. An increase in the non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle occurred with an increase in the backward WBAM in the second half of the paretic gait cycle (Figs. 1B and 2A), because the second half of the paretic gait cycle consists of the period from the heel contact of the non-paretic limb to the heel contact of the paretic limb. These results support a previous study which showed that knee extensor muscles play a role in generating backward angular momentum in the early stance phase during gait in healthy people (Neptune and McGowan, 2011). Furthermore, our results showed that the paretic ankle plantar flexion moment in the late stance phase of the paretic gait cycle was lower than that in the controls, whereas the non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle was higher. These results are consistent with the findings in a previous study (Farris et al., 2015). Therefore, the compensation of the non-paretic knee extensor muscle for inadequate propulsion, which is related to weakness of the paretic ankle plantar-flexor muscle, might lead to dynamic instability in the sagittal plane during gait in patients with hemiparesis.

This study had several limitations. First, the walking pattern in the healthy controls may have differed from their normal walking pattern at a comfortable speed because they were instructed to walk at a slow speed. However, walking speed influences WBAM in the sagittal plane (Bennett et al., 2010). Therefore, measurement of WBAM at a slow walking speed in healthy controls is necessary for accurate comparison with the WBAM of patients with hemiparesis in the sagittal plane, who walk at decreased speed. Second, we did not include the head segment in the segment-link model used for the calculation of WBAM. However, a previous study demonstrated that the contribution of the head segment to the generation of WBAM in the sagittal plane was extremely small (Herr and Popovic, 2008). Therefore, lack of the head segment likely had a minimal effect on the results for WBAM in the sagittal plane. Finally, the patients with hemiparesis completed the walking trial without assistive devices, such as canes and orthosis. Our findings therefore cannot be applied to the walking pattern for patients with hemiparesis using assistive devices.

In conclusion, the range of WBAM in the sagittal plane in the second half of the paretic gait cycle was larger than that in healthy controls. Furthermore, the larger range of WBAM in the second half of the paretic gait cycle was involved with the slower walking speed and the larger non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle. Our findings suggest that dynamic stability in the sagittal plane is impaired in the second half of the paretic gait cycle. The larger non-paretic knee extension moment in the early stance phase of the non-paretic gait cycle and slower walking speed might play a role in the dynamic instability in the sagittal plane during gait in patients with hemiparesis.

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Conflict of interest statement

We have no financial and personal conflicts of interest associated with this work.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.02.012.

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