Gait characteristics of post-stroke hemiparetic patients with different walking speeds

Yiji Wang[a,b,c], Masahiko Mukaino[a], Kei Ohtsuka[d], Yohei Otaka[a], Hiroki Tanikawa[d], Fumihiro Matsuda[d], Kazuhiro Tsuchiyama[d], Junya Yamada[e] and Eiichi Saitoh[a]

Hemiparesis resulting from stroke presents characteristic spatiotemporal gait patterns. This study aimed to clarify the spatiotemporal gait characteristics of hemiparetic patients by comparing them with height-, speed-, and age-matched controls while walking at various speeds. The data on spatiotemporal gait parameters of stroke patients and that of matched controls were extracted from a hospital gait analysis database. In total, 130 pairs of data were selected for analysis. Patients and controls were compared for spatiotemporal gait parameters and the raw value (RSI) and absolute value (ASI) of symmetry index and coefficient of variation (CV) of these parameters. Stroke patients presented with prolonged nonparetic stance (patients vs. controls: 1.01 ± 0.41 vs. 0.83 ± 0.25) and paretic swing time (0.45 ± 0.12 vs. 0.39 ± 0.07), shortened nonparetic swing phase (0.35 ± 0.07 vs. 0.39 ± 0.07), and prolonged paretic and nonparetic double stance phases [0.27 ± 0.13 (paretic)/0.27 ± 0.17 (nonparetic) vs. 0.22 ± 0.10]. These changes are especially seen in low-gait speed groups (<3.4 km/h). High RSIs of stance and swing times were also observed (−9.62 ± 10.32 vs. −0.79 ± 2.93, 24.24 ± 25.75 vs. 1.76 ± 6.43, respectively). High ASIs and CVs were more generally observed, including the groups with gait speed of ≥3.5 km/h. ASI increase of the swing phase (25.79 ± 22.69 vs. 4.83 ± 4.88) and CV of the step length [7.7 ± 4.9 (paretic)/7.6 ± 5.0 (nonparetic) vs. 5.3 ± 3.0] were observed in all gait speed groups. Our data suggest that abnormalities in the spatiotemporal parameters of hemiparetic gait should be interpreted in relation to gait speed. ASIs and CVs could be highly sensitive indices for detecting gait abnormalities. *International Journal of Rehabilitation Research* 43: 69–75 Copyright © 2019 The Author(s). Published by Wolters Kluwer Health, Inc.

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[a]Department of Rehabilitation Medicine I, School of Medicine, Fujita Health University, Toyoake, Aichi, Japan; [b]Department of Spinal Cord Injury Rehabilitation, China Rehabilitation Research Center; [c]School of Rehabilitation Medicine, Capital Medical University, Beijing, China; [d]Faculty of Rehabilitation, School of Health Sciences, Fujita Health University and [e]Department of Rehabilitation, Fujita Health University Hospital, Toyoake, Aichi, Japan

Correspondence to Masahiko Mukaino, MD, PhD, Department of Rehabilitation Medicine I, School of Medicine, Fujita Health University, 1-98 Dengakugakubo, Kutsukake, Toyoake, Aichi 470-1192, Japan
Tel: +81 562 93 2167; fax: +81 562 95 2906; e-mail: mmukaino@fujita-hu.ac.jp

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Introduction

Gait disorder is a common clinical problem for stroke survivors and is among the prevalent physical limitations contributing to stroke-related disability that impacts performance of activities of daily living. Gait disorder is therefore a major target for post-stroke rehabilitation. Many studies have investigated the characteristics and mechanism of gait with various biomechanical evaluation methods, including evaluation of spatiotemporal, kinematic, and kinetic parameters (Nadeau *et al.*, 2013; Balaban and Tok, 2014). Among the aforementioned parameters, spatiotemporal parameters are the simplest to analyze. Spatiotemporal parameter data are easy to obtain using affordable systems such as simplified gait analysis or wearable systems. Thus, deeper understanding of the spatiotemporal patterns of gait disorders could contribute to the improvement of the quality of evaluation and intervention on gait in rehabilitation clinics.

Hemiparetic gait is characterized by specific spatiotemporal patterns, including decreased cadence, prolonged swing duration on the paretic side, prolonged stance duration on the nonparetic side, and step length asymmetry, compared with the gait parameters of healthy subjects (Roth *et al.*, 1997; Chen *et al.*, 2005b; Patterson *et al.*, 2010). However, as the gait speed of healthy subjects is usually higher than that of stroke patients, the differences in spatiotemporal patterns between stroke patients and healthy subjects could be influenced by gait speed (Chen *et al.*, 2005b; Wonsetler and Bowden, 2017). Thus, the speed-matched comparison of gait patterns should be meaningful to understand the features of hemiparetic gait, eliminating the effect of gait speed. Several studies examined speed-matched comparisons between stroke patients and healthy controls and found differences in spatiotemporal patterns of gait, although sample sizes

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were small (Titianova and Tarkka, 1995; Chen *et al.*, 2005b; Rinaldi and Monaco, 2013). However, inconsistencies were noted among the studies. One study found that the swing time on the affected side was prolonged (Titianova and Tarkka, 1995), whereas other studies presented no significant differences between patients and controls (Chen *et al.*, 2005b; Rinaldi and Monaco, 2013). These inconsistencies may be related to differences in gait speed. For example, the asymmetry in step length and swing time is a strong feature of hemiparetic gait (Chen *et al.*, 2005b), but this may only be seen in patients with lower gait speed (Titianova *et al.*, 2008).

To further understand the feature of spatiotemporal characteristics of hemiparetic gait in patients with high- and low-gait speeds, gait speed-based stratified comparison of gait parameters between hemiparetic patients and healthy controls would be meaningful. Thus, this study aimed to retrospectively investigate the characteristics of the spatiotemporal gait parameters of stroke patients by performing a stratified gait speed matching comparison using the database on three-dimensional gait analysis of stroke patients and healthy subjects.

Methods

Participants

Spatiotemporal data during treadmill gait of 136 individuals with cerebrovascular event and resultant hemiparesis and who underwent three-dimensional gait analysis measurement from January 2015 to September 2017 were extracted from the clinical gait analysis database of the Fujita Health University Hospital.

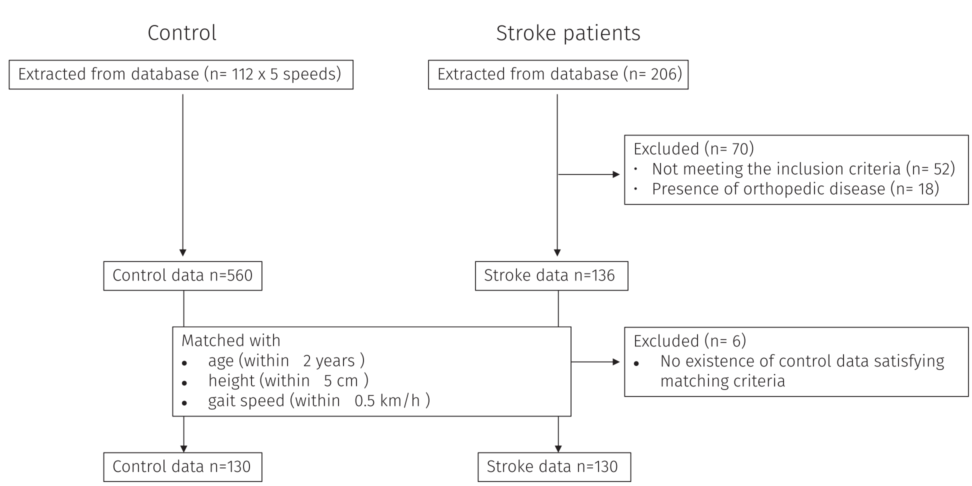
Hemiparetic subjects who normally walked with a cane or ankle-foot orthosis (AFO) during daily living were allowed to use a handrail and/or AFO while walking on the treadmill. Inclusion criteria were those aged 20–69 years and with unilateral hemiparesis due to stroke. The exclusion criteria were presence of orthopedic disease, severe cardiopulmonary disease limiting gait ability, and unstable medical condition. Each subject's walking ability and lower extremity functional motor level were quantified using Brunnstrom's Motor Recovery Stage and Stroke Impairment Assessment Set, which scores lower limb motor function from 0 to 15 (Chino *et al.*, 1994).

Data of healthy controls were drawn from the Fujita Health University Hospital database, which was developed for a previous study on developing gait analysis methodology (Itoh *et al.*, 2012; Tanikawa *et al.*, 2016; Hishikawa *et al.*, 2018; Mukaino *et al.*, 2018). The database included gait analysis data of 560 trials of 112 individuals aged 20–69 years who volunteered to be measured at walking speeds of 1, 2, 3, 4, and 5 km/h as control speeds. Data of 136 stroke patients were matched with those of healthy controls by age (within ±2 years) and height (within ±5 cm). If there were no control data matching either or both of age and height, these data were excluded from the analysis. After matching, 130 pairs of data in total were analyzed (Fig. 1). The stroke patients and controls were then grouped into the following five categories according to their walking speed: 0.5–1.4, 1.5–2.4, 2.5–3.4, 3.5–4.4, and 4.5–5.5 km/h.

Procedure

Data were extracted from the database as follows. The details of the measurement method are described elsewhere (Mukaino *et al.*, 2016; Mukaino *et al.*, 2018). In brief, a three-dimensional motion capture system with force plate measurement (KinemaTracer, Kissei Comtec Co., Ltd., Matsumoto, Japan) was utilized. A simplified set including 12 markers was placed on both sides of

Fig. 1



Flow diagram for data extraction and matching.

the shoulder, pelvis, hip, knee, ankle, and 5th metatarsal head (Mukaino *et al.*, 2016; Mukaino *et al.*, 2018). The participants' subjectively comfortable gait speed was determined based on a 10-m walk test.

Before measurement, the patients walked on the treadmill to get accustomed to treadmill gait for 2 min. After achieving a steady state, data were collected for 20 s and data for at least five complete gait cycles were collected from each subject. Videos were recorded at a sampling frequency of 60 Hz and measurement time of 20 s. Heel-strike and toe-off events were determined automatically by the system, and two experienced physical therapists checked the accuracy of the timing and adjusted if there was an error. The step length, stance, swing, and double stance time were recorded from these events. The double stance of the paretic side was defined as the double stance before paretic swing, whereas double stance of the nonparetic side was defined as that after the paretic swing.

Outcome measures and statistics

The step length, stance, swing, and double stance time were compared between the patients and controls. The values of controls were the averages for both the left and right sides. Asymmetries in spatial and temporal parameters were quantified using the raw and absolute values of symmetry index (SI) (Robinson *et al.*, 1987), which was calculated as follows: raw value of SI (RSI) = (Vparetic − Vnonparetic)/0.5 (Vparetic + Vnonparetic) × 100%, where Vparetic is the value of a gait parameter recorded for the paretic leg of the patient or the left leg of the control, and Vnonparetic is the corresponding value for the nonparetic leg of the patient or right leg of the control. Absolute values of SI (ASI) were employed to evaluate amplitude of the asymmetry, which could vary in direction (Roerdink and Beek, 2011). To evaluate gait parameter variability, coefficient of variation (CV: SD/average) was used.

All statistical analyses were performed using SPSS version 18.0 for Windows (SPSS Inc., Chicago, Illinois, USA). The quantitative variables were tested using the single sample Kolmogorov–Smirnov test if the variables were normally distributed. Student's paired *t*-test as the parametric test and the Wilcoxon signed-rank test as the nonparametric test were used for the comparison. Statistical significance was set at $P < 0.05$.

Ethics

This study was approved by the Research Ethics Board of Fujita Health University. All participants provided written informed consent.

Results

Demographic variables

Participants' characteristics are presented in Table 1. The final study sample included 130 patients and 130 controls. No significant differences were found between the demographic characteristics (e.g. age, height, and velocity) of the stroke and control groups, except for sex, which presented significant differences between the 0.5 and 1.4 and 1.5–2.4 km/h groups.

Stride length, step length, and cadence

The stride length, cadence, and step length on the paretic and nonparetic sides of stroke patients are presented in Table 2. Overall, there was no significant difference between stroke patients and controls in stride length, cadence, and step lengths (effect size: 0.09, 0.34, and 0.07, respectively). The stratified comparison with gait speed revealed a significant difference between stroke patients and controls at 0.5–2.4 km/h; stride length and step length were significantly longer (0.5–1.4 km/h) and the cadence was significantly lower in the hemiparetic group than in controls (0.5–2.4 km/h). Although there was no significant difference observed between stroke patients and controls in RSI of step length (effect size: 0.34), ASI of step length was significantly higher and the effect size was high (0.98). The significantly high ASI was also observed in the stratified comparison, except

Table 1 **Demographic and clinical measures of stroke patients and healthy controls**

	0.5–1.4 km/h		1.5–2.4 km/h		2.5–3.4 km/h		3.5–4.4 km/h		4.5–5.5 km/h	
	Patients; N = 38	Controls; N = 38	Patients; N = 33	Controls; N = 33	Patients; N = 29	Controls; N = 29	Patients; N = 18	Controls; N = 18	Patients; N = 12	Controls; N = 12
Age (years)	56.4 ± 8.8	56.7 ± 8.2	54.7 ± 11.5	54.8 ± 11.5	53.0 ± 12.5	52.0 ± 12.4	50.7 ± 12.5	50.4 ± 12.5	48.8 ± 13.1	48.3 ± 13.1
Percentage of female	29**	3	30*	6	31	17	6	6	8	17
Stroke type	CI 25; CH 13		CI 20; CH 13		CI 16; CH 13		CI 15; CH 3		CI 10; CH 2	
Time post-stroke (months)	11.9 ± 24.8		13.4 ± 25.9		11.1 ± 19.8		5.2 ± 11.8		2.3 ± 2.1	
Height (cm)	165.3 ± 6.9	166.1 ± 6.5	165.2 ± 7.6	165.8 ± 6.6	166.0 ± 7.1	165.8 ± 7.0	169.6 ± 6.23	170.6 ± 6.5	168.4 ± 8.6	166.6 ± 8.3
Affected side	55		48		41		33		58	
BMRS	3.7 ± 1.1		4.3 ± 1.1		5.1 ± 1.0		5.6 ± 0.8		5.8 ± 0.4	
SIAS	7.4 ± 3.1		8.8 ± 2.7		10.6 ± 2.8		12.7 ± 2.3		13.3 ± 1.4	
Percentage of handrail use	79		64		14		11		0	
Percentage of orthosis use	76		61		24		11		0	
Velocity	0.99 ± 0.25	1.00	1.95 ± 0.25	2.00	2.92 ± 0.27	3.00	3.93 ± 0.20	4.00	4.89 ± 0.23	5.00

Data are presented as mean ± SD.

BMRS, Brunnstrom's Motor Recovery Stage; CI, cerebral ischemia; CH, cerebral hemorrhage; SIAS, Stroke Impairment Assessment Set.

*$P < 0.05$, **$P < 0.01$.

Table 2 Step length, stride length, and cadence of stroke patients and healthy controls

		Patient group				Control group		
		Paretic	Nonparetic	RSI	ASI	Average	RSI	ASI
Step length	All	40.00 ± 14.43	40.34 ± 14.94	−0.70 ± 24.23	17.32 ± 16.89**	38.90 ± 15.95	−0.95 ± 7.08	5.19 ± 4.89
	0.5–1.4 km/h	24.64 ± 7.32*	24.33 ± 7.89*	1.11 ± 36.94	29.27 ± 22.04**	20.90 ± 5.53	0.32 ± 10.08	7.99 ± 6.02
	1.5–2.4 km/h	35.72 ± 7.50	36.54 ± 6.65	−3.02 ± 21.58	17.38 ± 12.79**	33.69 ± 5.41	−0.28 ± 6.18	4.55 ± 4.10
	2.5–3.4 km/h	45.57 ± 7.32	46.08 ± 7.70	−0.57 ± 16.87	13.41 ± 10.40**	45.65 ± 4.94	−2.33 ± 4.71	4.08 ± 3.25
	3.5–4.4 km/h	56.00 ± 5.38	55.37 ± 5.76	1.21 ± 9.17	6.56 ± 7.03	57.95 ± 5.00	−2.38 ± 4.95	3.06 ± 4.52
	4.5–5.4 km/h	62.93 ± 4.58	65.05 ± 5.24	−3.27 ± 6.74	6.21 ± 3.87*	65.33 ± 4.58	−1.69 ± 4.18	3.49 ± 2.71
Stride length	All	80.27 ± 28.89				77.68 ± 31.88		
	0.5–1.4 km/h	48.28 ± 13.48*				41.74 ± 11.0		
	1.5–2.4 km/h	72.40 ± 12.12				67.27 ± 10.79		
	2.5–3.4 km/h	91.83 ± 11.3				91.33 ± 9.92		
	3.5–4.4 km/h	111.63 ± 9.92				115.05 ± 9.51		
	4.5–5.4 km/h	128.26 ± 8.78				131.18 ± 9.95		
Cadence	All	95.80 ± 23.67**				103.34 ± 20.78		
	0.5–1.4 km/h	72.72 ± 22.84*				85.00 ± 20.43		
	1.5–2.4 km/h	91.71 ± 13.73*				101.62 ± 16.02		
	2.5–3.4 km/h	105.56 ± 10.35				110.92 ± 12.69		
	3.5–4.4 km/h	116.49 ± 8.23				116.68 ± 10.35		
	4.5–5.4 km/h	125.51 ± 9.23				127.67 ± 9.72		

ASI, absolute value of symmetrical index; RSI, raw value of symmetrical index.
*$P < 0.05$.
**$P < 0.01$.

Table 3 Stride length and cadence of stroke patients walking without handrail and healthy controls

(Without handrail)		Patients	Controls
Stride length	All	91.6 ± 27.97	93.49 ± 28.8
	0.5–1.4 km/h	39.88 ± 12.65	42.56 ± 8.7
	1.5–2.4 km/h	69.46 ± 9.04	68.83 ± 13.21
	2.5–3.4 km/h	89.97 ± 10.40	91.17 ± 10.15
	3.5–4.4 km/h	111.35 ± 10.38	115.15 ± 10.12
	4.5–5.4 km/h	128.36 ± 9.20	131.23 ± 10.43
Cadence	All	108.97 ± 16.42	109.96 ± 18.92
	0.5–1.4 km/h	95.19 ± 29.16	81.21 ± 17.65
	1.5–2.4 km/h	97.11 ± 11.09	100.21 ± 18.74
	2.5–3.4 km/h	106.62 ± 9.78	111.64 ± 13.22
	3.5–4.4 km/h	116.58 ± 8.68	116.79 ± 11.04
	4.5–5.4 km/h	126.24 ±9 .31	127.88 ± 10.32

in the 3.5–4.4 km/h group. Given the previous reports showing that handrail use affects stride length (Abe *et al.*, 2009; IJmker *et al.*, 2015), comparison of stride and cadence between patients and matched controls without the handrail was also performed (Table 3) and showed no difference was found in the handrail-free condition.

Temporal gait parameters

The temporal parameters in all patients and matched controls are shown in Table 4. Overall, stance time for the paretic and nonparetic sides of patients were significantly longer (effect size: 0.24 and 0.53, respectively); the stratified comparison revealed significantly longer paretic stance time at 0.5–1.4 km/h and nonparetic stance time at 1.5–3.4 km/h. The difference in RSI and ASI of stance time between stroke patients and controls was significant (effect size: 1.16 and 1.29, respectively) at 0.5–3.4 km/h.

The paretic swing time was significantly longer (effect size: 0.61) and nonparetic swing time was shorter (effect size: 0.57) than those controls. Both RSI and ASI were higher in stroke patients (effect size: 1.20 and 1.28, respectively). In the stratified comparison, paretic swing lengthening was significant at 0.5–3.4 km/h, whereas nonparetic swing time shortening was observed at 0.5–2.4 km/h. RSI was significantly higher in stroke patients at 0.5–3.4 km/h, and ASI was significantly higher in all gait speed groups.

The double stance time of the paretic and nonparetic sides was significantly longer in hemiparetic patients than in controls (effect size: 0.43 and 0.36, respectively). ASI was significantly higher in stroke patients (effect size: 0.69); however, there was no significant difference in RSI (effect size: 0.10). The longer paretic and nonparetic double stance time and higher RSI were observed at 0.5–2.4 km/h. ASI was significantly high in gait speed <3.4 km/h.

Variability

CVs of step length and temporal parameters are presented in Table 5. CVs of step length, stance time, and swing time of the paretic and nonparetic sides were larger in stroke patients [effect size (paretic/nonparetic): step length 0.59/0.56, stance time 0.72/0.63, swing time 0.72/0.79]. CVs of stance time were larger in patients in the paretic side at gait speeds <3.4 km/h. CVs of swing time for both sides at speeds <3.4 km/h were larger in patients than in controls. CVs of swing time of the paretic side at 3.5–4.4 km/h were larger in patients than in controls. There was no significant difference in CVs of paretic double support time between controls and stroke patients.

Discussion

Our study revealed differences in the spatiotemporal parameters between stroke patients and speed-, age-, and height-matched controls with its gradation in different

Table 4 Temporal parameters of stroke patients and healthy controls

		Stroke patients				Control		
		Paretic	Nonparetic	RSI	ASI	Average	RSI	ASI
Stance time (s)	All	0.90 ± 0.34**	1.01 ± 0.41**	−9.62 ± 10.32**	10.64 ± 8.86**	0.83 ± 0.25	−0.79 ± 2.93	2.33 ± 1.98
	0.5–1.4 km/h	1.27 ± 0.40*	1.46 ± 0.45**	−13.99 ± 9.06**	14.14 ± 8.78**	1.07 ± 0.31	−0.93 ± 3.44	2.51 ± 2.08
	1.5–2.4 km/h	0.87 ± 0.14	0.99 ± 0.17**	−11.73 ± 9.34**	12.55 ± 8.26**	0.82 ± 0.14	−1.05 ± 2.64	2.28 ± 2.05
	2.5–3.4 km/h	0.73 ± 0.10	0.80 ± 0.09**	−8.94 ± 11.22**	10.44 ± 10.11**	0.73 ± 0.08	−1.09 ± 3.26	2.35 ± 2.15
	3.5–4.4 km/h	0.67 ± 0.07	0.69 ± 0.05	−3.17 ± 9.77	4.30 ± 4.45	0.67 ± 0.05	−0.2 ± 1.74	1.93 ± 1.73
	4.5–5.4 km/h	0.61 ± 0.06	0.62 ± 0.05	−1.34 ± 5.3	4.35 ± 3.13	0.60 ± 0.04	0.29 ± 2.35	2.43 ± 1.59
Swing time (s)	All	0.45 ± 0.12**	0.35 ± 0.07**	24.24 ± 25.75**	25.79 ± 22.69**	0.39 ± 0.07	1.76 ± 6.43	4.83 ± 4.88
	0.5–1.4 km/h	0.53 ± 0.16**	0.34 ± 0.10**	43.52 ± 25.59**	43.94 ± 24.83**	0.43 ± 0.10	2.51 ± 8.58	6.96 ± 6.19
	1.5–2.4 km/h	0.47 ± 0.10**	0.35 ± 0.07*	26.35 ± 21.7**	29.09 ± 18.67**	0.40 ± 0.06	2.12 ± 5.35	4.39 ± 4.19
	2.5–3.4 km/h	0.42 ± 0.07**	0.35 ± 0.06	17.25 ± 20.93**	20.21 ± 18.65**	0.37 ± 0.05	2.11 ± 6.38	5.33 ± 4.34
	3.5–4.4 km/h	0.37 ± 0.04	0.35 ± 0.05	5.79 ± 17.58	9.81 ± 15.67*	0.37 ± 0.04	0.38 ± 3.05	2.28 ± 2.73
	4.5–5.4 km/h	0.35 ± 0.03	0.34 ± 0.03	1.99 ± 9.29	7.92 ± 5.10**	0.35 ± 0.04	−0.57 ± 4.2	1.91 ± 1.80
Double support (s)	All	0.27 ± 0.13**	0.27 ± 0.17**	3.84 ± 25.78	19.31 ± 17.89**	0.22 ± 0.10	1.89 ± 12.67	9.79 ± 7.91
	0.5–1.4 km/h	0.43 ± 0.11**	0.46 ± 0.19**	−1.33 ± 37.18	27.52 ± 25.38**	0.32 ± 0.12	5.22 ± 11.16	9.78 ± 7.24
	1.5–2.4 km/h	0.27 ± 0.06**	0.25 ± 0.06**	8.18 ± 19.67	16.95 ± 13.03*	0.21 ± 0.05	3.68 ± 12.90	9.80 ± 8.79
	2.5–3.4 km/h	0.20 ± 0.04	0.18 ± 0.04	8.93 ± 20.26*	17.69 ± 13.33**	0.18 ± 0.02	−1.17 ± 11.46	8.93 ± 6.93
	3.5–4.4 km/h	0.16 ± 0.03	0.16 ± 0.03	0.36 ± 17.06	13.46 ± 11.10	0.15 ± 0.02	−7.15±10.14	10.99 ± 10.65
	4.5–5.4 km/h	0.13 ± 0.02	0.13 ± 0.03	1.15 ± 16.84	13.40 ± 10.11	0.12 ± 0.02	5.83±16.29	10.74 ± 5.57

ASI, absolute value of symmetrical index; RSI, raw value of symmetrical index.
$^{*}P<0.05$.
$^{**}P<0.01$.

Table 5 Variability of spatiotemporal parameters of stroke patients and matched controls

		Stroke patients		Controls
		Paretic	Nonparetic	Average
Step length CV (%)	All	7.7 ± 4.9**	7.6 ± 5.0**	5.3 ± 3.0
	0.5–1.4 km/h	11.4 ± 6.9*	12.0 ± 6.4*	8.9 ± 2.6
	1.5–2.4 km/h	7.3 ± 3.3**	6.5 ± 3.5*	4.8 ± 2.0
	2.5–3.4 km/h	6.0 ± 2.1**	6.4 ± 2.1**	3.4 ± 0.9
	3.5–4.4 km/h	5.2 ± 1.7**	4.8 ± 1.8**	3.2 ± 1.1
	4.5–5.4 km/h	4.5 ± 0.8**	4.0 ± 1.1*	2.8 ± 0.9
Stance time CV	All	4.7 ± 2.7**	4.2 ± 1.9**	3.2 ± 1.2
	0.5–1.4 km/h	6.1 ± 3.1**	5.6 ± 2.3**	4.1 ± 1.4
	1.5–2.4 km/h	4.8 ± 2.9*	3.8 ± 1.3	3.2 ± 1.0
	2.5–3.4 km/h	4.3 ± 1.9**	3.8 ± 1.5	3.0 ± 0.7
	3.5–4.4 km/h	3.1 ± 1.0	3.5 ± 1.1*	2.4 ± 0.9
	4.5–5.4 km/h	3.3 ± 1.2	2.6 ± 0.8	2.5 ± 0.6
Swing time CV	All	8.1 ± 4.7**	7.7 ± 3.6**	5.5 ± 2.0
	0.5–1.4 km/h	11.1 ± 6.6**	9.7 ± 3.8**	6.7 ± 2.3
	1.5–2.4 km/h	7.8 ± 3.6**	8.0 ± 3.5**	5.2 ± 1.6
	2.5–3.4 km/h	6.9 ± 2.7*	7.3 ± 3.1**	5.2 ± 1.9
	3.5–4.4 km/h	6.6 ± 1.9**	5.5 ± 2.1	4.5 ± 1.3
	4.5–5.4 km/h	5.0 ± 1.6	4.4 ± 1.5	4.0 ± 0.8
Double support CV	All	9.7 ± 4.5	10.5 ± 4.5	9.1 ± 3.0
	0.5–1.4 km/h	11.5 ± 5.2	11.8 ± 4.9	10.4 ± 3.2
	1.5–2.4 km/h	8.9 ± 5.0	10.0 ± 4.9	9.3 ± 3.0
	2.5–3.4 km/h	9.7 ± 3.5	10.2 ± 4.4	8.3 ± 2.8
	3.5–4.4 km/h	7.8 ± 2.3	9.9 ± 3.1	8.4 ± 2.5
	4.5–5.4 km/h	8.7 ± 4.0	10.1 ± 3.9	7.6 ± 1.9

CV, coefficient of variation.
$^{*}P<0.05$.
$^{**}P<0.01$.

gait speed groups. The longer stride length and step length, and lower cadence were evident in individuals with a very low-gait speed (<1.4 km/h or <2.4 km/h). This might relate to the high rate of handrail use in patients. In the previous studies, handrail use was shown to lengthen the stride length (Abe *et al.*, 2009; IJmker *et al.*, 2015). In this study, a large number of the patients in the low-gait speed group (<2.4 km/h) used a handrail. Consistently, no significant differences between controls and patients walking without a handrail were observed (Table 2).

Although the averaged step length and RSI of stroke patients were similar to the control groups, ASI of step length was significantly high in the stroke patients, indicating that the direction of the step length asymmetry varied in all gait speed groups. Previous studies have indicated that the step length asymmetry would be determined by the ability for propulsive force generation(Balasubramanian *et al.*, 2007) and balance with swing capacity or compensatory strategy (Roerdink and Beek, 2011; Allen *et al.*, 2011). Thus, the present results may reflect the variety in gait ability and compensatory strategy among the stroke patients.

Moreover, the changes in temporal parameters were observed in low-gait speed groups, which may reflect the compensatory response of patients when walking: instability on the paretic limb could cause compensatory shortening of paretic stance time, as this is considered to reflect balance ability (Patterson *et al.*, 2008); leg stiffness due to the impaired paretic limb causes compensatory prolonged swing time (Nadeau *et al.*, 1999).

This typical temporal pattern of gait abnormality in hemiparetic patients with prolonged paretic swing time and shortened nonparetic swing reflects paretic limb function impairment (Brandstater *et al.*, 1983). Thus, swing time symmetry that strongly correlates stance time symmetry (Lauziere *et al.*, 2014) has been used as the representative temporal parameter to describe post-stroke gait. In the present study, both prolonged paretic swing and shortened paretic single stance, and subsequent increase in swing asymmetry was observed. Although the prolonged paretic swing and double stance were less evident in the without handrail condition, the increase in RSI and ASI was still evident.

Interestingly, the abnormal increase in ASI of swing time was also seen in the high-gait speed groups who presented no significant increase in RSI, indicating that the extent of asymmetry was increased similar to that of the low-gait speed groups, but the direction was varied, suggesting patients with asymmetry in nontypical direction were included. Previous studies have shown the strong relationship between the extent of swing time asymmetry and balance ability (Lewek *et al.*, 2014; Hendrickson *et al.*, 2014). The asymmetry in nontypical direction observed in high-gait speed groups may relate more to the balance ability of patients than to hemiparesis.

Variability of gait pattern indices is considered to reflect the instability of gait (Maki, 1997), which is influenced by various impairments. For example, poorer strength, balance, and processing speed are reported to be associated with greater stance time variability (Hausdorff et al., 2001a, 2001b; Brach *et al.*, 2008; Lamoth *et al.*, 2011), poorer strength, and processing speed with greater step length variability (Kang and Dingwell, 2008; Brach *et al.*, 2008). Considering these relationships with various impairments and the fact that the abnormality was seen in all gait speeds in this study, the variability indices should be sensitive indices for gait abnormality.

Additionally, the asymmetry and variability in gait indices were shown to be related to fall risk (Kressig *et al.*, 2008; Verghese *et al.*, 2009; Parker *et al.*, 2013); thus it could also be used concurrently for risk management. As these indices are easily acquired in outpatient clinics using clinical measurement tools, including simple systems such as accelerometer systems or carpet-type walkway systems, it is feasible to measure these indices in daily clinical settings for gait disorder assessment.

There are several limitations in this study. The sample includes patients who used a handrail during the assessments. As discussed previously, the lengthening of stride in low-gait speed patients was due to the high handrail usage rate. Handrail use has also been shown to increase nonparetic swing time and improve swing time asymmetry (Chen *et al.*, 2005a). However, the nonparetic swing time was significantly shorter in low-gait speed groups despite the high handrail use rate. Additionally, the temporal asymmetry and CVs were also significantly high (<0.05) in stroke patients without handrail use (data not shown). Thus, the overall tendency seen in this study seemed to be robust. Another limitation is the significant difference in sex ratio between patients and controls, which might have affected the results. However, the influence is expected to be significantly reduced by the height matching.

In conclusion, our data showed the changes in spatiotemporal pattern of hemiparetic gait with the gradation of different walking speeds, in comparison with the matched control data, which may serve as a reference to evaluate gait abnormality. The asymmetry and variability indices presented as sensitive indicators of gait abnormality, which may also serve as fall risk indicators. Further investigation into the underlying mechanisms and detailed relationships to fall risks may facilitate the utility of spatiotemporal parameters for daily practices.

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Conflicts of interest

There are no conflicts of interest.

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