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Original Article

Relationship between gait regularity and harmony, and gait speed at discharge in inpatients with subacute stroke

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Abstract. [Purpose] Accelerometry indices are a promising and simple method to quantify gait stability. However, the long-term relationship between gait stability and walking ability in patients with stroke has not been fully investigated. The purpose of this study was to longitudinally examine the relationship between gait regularity and harmony at admission and gait speed at discharge in inpatients with subacute mild stroke. [Participants and Methods] Sixteen patients with subacute stroke (median age, 69.5 years [1st–3rd interquartile range, 58.0–73.8 years]; 13 males) were enrolled in the study. A Spearman's rank correlation coefficient was calculated for step regularity, stride regularity, the harmonic ratio at admission, and the walking speed at discharge. We also calculated the partial rank order correlation, controlling for balance ability. [Results] The vertical step regularity, harmonic ratio, and anterior-posterior harmonic ratio were all positively correlated with the walking speed at discharge. Positive correlations with vertical step regularity and harmonic ratio were found in partial rank order correlations when controlled for balance ability. [Conclusion] Vertical step regularity and gait harmony had predictive validity for discharge gait speed in patients with subacute stroke.

Key words: Abnormal gait, Predictive validity, Gait analysis

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INTRODUCTION

Stroke is the leading cause of long-term disability among adults worldwide[1)]. Approximately 66.7% of patients with their first stroke have been reported to have had a minor stroke[2)]. Decreased walking ability is one of the most serious disabilities that can occur after a stroke. Rehabilitation[3)] and physical therapy (PT)[4)] for patients with stroke focus a lot on improving their walking ability. Walking speed is a common indicator of the state of the abilities of patients with stroke and has been reported to be related to life space[5–7)] and the amount of physical activity[8)]. Therefore, it is important to identify factors related to gait speed in patients with stroke during hospitalization.

There is consensus on the usefulness of balance and gait training as a rehabilitation intervention for fall prevention[9)]. However, the identification of balance and gait impairments in clinical practice typically uses subjective rating scales that depend on the expertise of the examiner[10, 11)] and often suffers from ceiling effects in highly functioning patients[12–14)]. So, it is important to use methods that can measure temporal and spatial parameters with excellent sensitivity to gait disturbances after a stroke.

Three-dimensional motion capture systems, force plates, and small triaxial accelerometers are used for gait analysis as devices capable of recording more detailed temporal and spatial parameters. However, three-dimensional motion capture

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systems and force plates are limited in their use in field research because of the high cost of the equipment and limited measurement space. In contrast, a small triaxial accelerometer is inexpensive, has a simple measurement method, and enables gait analysis without restricting measurement space[15–23]. Furthermore, the index of gait with a small triaxial accelerometer has superior validity for discriminating fall risk in patients with stroke compared to clinical measures such as gait speed and balance index, demonstrating its usefulness in gait assessment[23]. However, to our knowledge, the relationship between gait indices measured with a small triaxial accelerometer in the early onset phase and gait speed at discharge has not been verified in inpatients with a subacute stroke so far. Determining the relationship between gait characteristics early in the onset of stroke and walking speed at discharge from the hospital may contribute to making decisions regarding intervention strategies and goals to improve gait performance.

This study has been aimed at examining the longitudinal association between gait regularity and harmonics, which were measured with a small triaxial accelerometer at admission and walking speed at discharge in inpatients with subacute mild stroke.

PARTICIPANTS AND METHODS

This was a single-center longitudinal observational study. Data were collected from patients with stroke who were admitted consecutively to the general wards of Numata Neurosurgery and Cardiovascular Hospital between October 2020 and June 2022. This study was conducted with the approval of the Ethics Committees at Numata Neurosurgery and Cardiovascular Hospital, Japan (approval no. 027-1), in accordance with the Declaration of Helsinki and the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE)[24]. All patients provided written informed consent before participation.

The study included participants: 1) those who were hospitalized for the first cerebral infarction or cerebral hemorrhage; 2) with motor paralysis in the lower limb on one side; 3) who were able to walk without the use of walking aids (functional ambulation categories ≥3)[25], and 4) age ≥20 years. The study excluded the following participants: 1) who were unable to walk independently before the disease; 2) who had difficulty communicating due to aphasia or cognitive decline; 3) who could not provide consent to participate in the research; 4) those with an interval of fewer than two weeks between measurement days at admission and at discharge.

All participants received rehabilitation interventions for two to three hours per day. The content was mainly PT, occupational therapy (OT), and speech and language therapy (SLT) when necessary. The duration and content of rehabilitation were individually determined for each participant by a medical team that included a physician. The International Classification of Functioning, Disability, and Health was used to assess what PT, OT, and SLT interventions were required, and the treating physician chose them based on treatment goals. PT includes muscle strengthening exercises, balance exercises, gait exercises, electrical stimulation therapy, and ergometer exercises. OT included upper limb function and activities of daily living (ADL) exercises. The SLT includes cognitive function and swallowing exercises. The intervention was not controlled in this study.

Accelerometry variables were measured within 10 days of admission and walking speed within one week before discharge. Clinical characteristics, including age, gender, height, weight, body mass index (BMI), length of hospital stay, and type of stroke (cerebral infarction or cerebral hemorrhage), were collected from medical records. Other variables collected were Brunnstrom recovery stage (BRS)-lower extremity as a measure of the severity of motor paralysis[26], Mini-Balance Evaluation Systems Test (Mini-BESTest) as a measure of balance ability[27], and functional independence measure (FIM)[28] as a measure of ADL ability. These were collected on the same day as the measurement of accelerometry variables.

Accelerometry variables were measured once when walking at a comfortable speed along a 10-meter-walking path with 3 meter-auxiliary paths at each end, for a total of 16 meter-straight paths[29]. Measurements were obtained while wearing shoes with flat soles that were appropriate for the size of the patients. An electrostatic-capacity type 8-channel compact wireless motion recorder, MVP-RF8-GC-500 (MicroStone Corp., Nagano, Japan), was used to measure the accelerometry variables. The external dimensions of the device were 45 × 45 × 18 mm, and it weighed approximately 60 grams. A band was attached to the trunk at the height of the L3 spinous process to protect the device from moving[30]. The sampling frequency was 200 Hz and corrected for gravitational acceleration. The acceleration signals were analyzed using dedicated software, MVP-RF8-S version 1.6.1.0 (MicroStone Corp., Nagano, Japan). Acceleration signals were transmitted in real-time *via* Bluetooth to a notebook PC equipped with dedicated software and recorded as Excel data after digital conversion. The accelerometric variables were managed using Microsoft Excel for Mac version 16.31 (Microsoft Corp., Redmond, WA, USA). Because the maximum communication distance with the device was 30 meters, sufficient consideration was given to the laptop location. Accelerometry variables were measured by a physical therapist who fully understood the measurement method. One physical therapist accompanied the patient while the other operated the laptop computer and visually checked for any abnormalities in the operation of the equipment during the measurement.

The numerical analysis software MATLAB (MathWorks Inc., Natick, MA, USA) was used to analyze the accelerometry variables. Each acceleration time series was filtered with a second-order Butterworth bandpass filter with a cutoff frequency of 0.1 to 20 Hz, and the processed transformed values were used for analysis. Initial grounding was identified at the peak of the anteroposterior (AP) axis of the gait cycle, and accelerometry variables for the central five gait cycles were extracted. The accelerometry variables, step regularity and stride regularity[30], with unbiased autocorrelation coefficients (AC) and harmonic ratio (HR)[31] as an index of smoothness and stability of trunk movement during gait, were obtained for the mediolateral (ML), vertical (VT), and AP axes, respectively. AC was calculated by correlating the overlapping portions of the time series with duplicates of the same time series that were phase-shifted by the meantime. Step regularity was calculated using the average step time, and stride regularity was calculated using the average stride time. Both values ranged from −1 to 1 and were close to 1 when step and stride regularity were high. But when it was close to −1, only the ML axis of step regularity was considered to be highly regular.

The HR is a method for examining the symmetry of one gait cycle (two steps). After a fast Fourier transform, the HR was calculated by adding up the first 10 components of the even harmonic (EH) and odd harmonic (OH) acceleration signals. The VT and AP acceleration components had one peak per step, and the ML acceleration had one peak per two steps. Therefore, VT and AP were obtained by the sum of EH and the sum of OH, and ML was obtained by the sum of OH and the sum of EH for each HR. A higher HR value indicates a smoother gait. Accelerometry variables have been tested for their reliability and validity in gait assessment after a subacute stroke[19–21, 23].

In this study, participants were instructed to walk a distance of 10 meters at a comfortable self-selected speed. A 3-meter auxiliary path was provided at both ends of the 10-meter measurement section to allow for acceleration at the beginning and deceleration at the end of the walk[29]. Walking time of 10 meters was measured using a digital stopwatch, and walking speed was calculated. Comfortable walking speed is a reliable and valid indicator of walking ability after a stroke[29].

All statistical analyses were conducted using IBM SPSS Statistics for Windows, version 25 (IBM Corp., Armonk, NY, USA). The level of significance was set at $p<0.05$.

Descriptive statistics of clinical characteristics are presented as median (1st–3rd interquartile range) or rate and frequency distributions. Accelerometry variables at admission were reported, including mean and standard deviation, and minimum and maximum values, in addition to the median.

A Spearman's rank correlation coefficient (ρ) was calculated for the association between step regularity, stride regularity, and HR on all three axes (ML, VT, and AP) at admission and walking speed at discharge. Furthermore, because balance ability may influence motor characteristics during walking after stroke[32], partial rank order correlations were calculated with the Mini-BESTest as the adjustment variable. The strength of the coefficient was determined as follows: 0.00–0.25, minimum correlation (if any); 0.26–0.49, weak correlation; 0.50–0.69, moderate correlation; 0.70–0.89, strong correlation; 0.90–1.00, very strong correlation[33].

RESULTS

The clinical characteristics of the participants are presented in Table 1. There were 16 patients, most of whom were male and diagnosed with cerebral infarction. The BRS lower extremity had a score of 75% (score 6), and motor paralysis was mild in most cases. The median (1st–3rd interquartile range) age was 69.5 (58.0–73.8) years.

Table1. Clinical characteristics of patients

Age (years)	69.5 (58.0–73.8)
Males, n (%)	13 (81.3)
Height (m)	1.64 (1.55–1.67)
Weight (kg)	68.5 (60.4–73.1)
Body Mass Index (kg/m^2)	25.0 (23.0–27.9)
Length of stay (days)	24.0 (25.0–32.8)
Type of stroke, n (%)	
Cerebral infarction	12 (75.0)
Intra-cerebral hemorrhage	4 (25.0)
Affected side, n (%)	
Right	9 (56.3)
Left	7 (43.7)
BRS-lower extremity, n (%)	
Score 4	1 (6.2)
Score 5	3 (18.8)
Score 6	12 (75.0)
Mini-BESTest (points)	17.0 (12.3–21.8)
FIM (points)	88.5 (68.0–107.0)
Gait speed at discharge (m/sec)	1.2 (1.0–1.3)

Values are median (1st–3rd interquartile range) or n (%). BRS: Brunnstrom Recovery Stage; Mini-BESTest: Mini-Balance Evaluation Systems Test; FIM: Functonal Independence Measure.

The distribution of the accelerometry variables at admission is shown in Table 2. The median values for each of the accelerometry variables were, in order of ML, VT, and AP, 0.058, 0.669, and 0.681 for step regularity; 0.440, 0.512, and 0.523 for stride regularity; 1.683, 1.561, and 1.511 for HR, respectively.

Bivariate correlations between accelerometry variables at admission and gait speed at discharge are shown in Table 3. Gait speed at discharge showed a significantly weak positive correlation with the VT axis of step regularity ($p<0.05$). Gait speed at discharge showed a significant weak positive correlation with the VT and AP axes of the HR ($p<0.05$). There was no significant correlation between gait speed at discharge and stride regularity at admission.

Table 4 shows the results of partial rank order correlations between accelerometry variables at admission and gait speed at discharge controlled for balance ability. Gait speed at discharge showed a significantly weak positive correlation with the VT axis of step regularity and HR ($p<0.05$).

DISCUSSION

To the best of our knowledge, this is the first study to examine the association between quantitative gait indices measured using a small triaxial accelerometer at admission and gait speed at discharge in inpatients with subacute mild stroke. The primary finding of this study was that the vertical step regularity and gait harmonic measured at admission were associated with walking speed at discharge in inpatients with subacute mild stroke. The results of this study are expected to help clinicians in making decisions about rehabilitation interventions and setting goals to improve walking ability in inpatients with subacute stroke.

The HR is an indicator of the smoothness and stability of trunk movement during walking and is associated with trunk function in inpatients with subacute stroke[20]. The HRs in patients with stroke were significantly lower in the AP and VT axes than in age-matched healthy adults and healthy young adults, allowing us to characterize specific changes in gait after a stroke[19]. In this study, univariate analysis showed a positive correlation between the HR on the VT and AP axes and walking speed at discharge. Since the anterior component of the floor reaction force and ankle plantar flexion moment are reduced

Table 2. Distribution of accelerometry variables at admission

		Mean	SD	Minimum value	Maximum value	Median	IQR 1st	IQR 3rd
Step regularity	ML	0.061	0.404	−0.479	0.634	0.058	−0.282	0.484
	VT	0.619	0.212	0.101	0.819	0.669	0.568	0.757
	AP	0.664	0.121	0.310	0.779	0.681	0.608	0.763
Stride regularity	ML	0.425	0.200	−0.237	0.669	0.440	0.388	0.516
	VT	0.524	0.147	0.146	0.767	0.512	0.453	0.626
	AP	0.550	0.095	0.370	0.769	0.523	0.488	0.621
HR	ML	1.728	0.384	1.126	2.332	1.683	1.451	2.087
	VT	1.795	0.830	0.760	3.128	1.561	1.048	2.693
	AP	1.773	0.926	0.825	3.746	1.511	1.021	2.215

Descriptive statistics of accelerometry variables are shown. SD: standard deviation; IQR: interquartile range; ML: mediolateral; VT: vertical; AP: anteroposterior; HR: harmonic ratio.

Table 3. Bivariate correlations between accelerometry variables at admission and gait speed at discharge

	Step regularity			Stride regularity			HR		
	ML	VT	AP	ML	VT	AP	ML	VT	AP
Gait speed at discharge	−0.226	0.568*	0.329	−0.082	0.344	0.412	0.165	0.618*	0.512*

Spearman's rank correlation (ρ). ML: mediolateral; VT: vertical; AP: anteroposterior; HR: harmonic ratio. *p<0.05.

Table 4. Partial rank order correlation between accelerometry variables at admission and gait speed at discharge

	Step regularity			Stride regularity			HR		
	ML	VT	AP	ML	VT	AP	ML	VT	AP
Gait speed at discharge	−0.433	0.517*	0.270	−0.292	0.326	0.394	0.154	0.539*	0.509

Partial rank order correlation. ML: mediolateral; VT: vertical; AP: anteroposterior; HR: harmonic ratio. *p<0.05.

due to gait disturbance after stroke[34], we believe that this affected the smoothness and stability of the VT and AP axes of the trunk during walking in this study as well.

It has been reported that the duration of stance support[21], step length[21], and arm swing during gait[35] are related to the vertical component of sway during gait in patients with stroke. The present study showed that the stability of the vertical component of trunk movement during walking was associated with walking speed in patients with stroke independent of balance ability. In rehabilitation interventions focusing on walking speed in patients with stroke, the study suggested the usefulness of focusing on the smoothness and stability of trunk movement in the vertical direction during walking at an early stage.

Walking speed at discharge was found to be significantly correlated with vertical step regularity. Walking is a highly automated movement, repeated at regular intervals[36]. However, after stroke, motor paralysis and spasticity can lead to an asymmetric gait with a high energy cost[37]. Vertical step regularity is an important indicator for proper control of the body's center of gravity during walking after stroke, and it is more related to walking speed than other directions.

No significant correlation was found between walking speed at discharge and stride regularity at admission. The patients with stroke in this study had superior stride regularity compared with those in previous studies[21]. It was suggested that stride regularity may have less effect on walking speed than step regularity.

This study has several limitations. First, because of the small sample size and a high degree of walking independence, the generalization of the findings was limited to the population with mild motor paralysis. In the future, external validity should be checked by using the results of studies involving a wider range of populations. Second, it was unclear whether walking speed at discharge was associated with physical activity or falls after discharge. In the future, it will be desirable to investigate the outcomes over a longer period and examine their relationship with post-discharge outcomes.

In this study, we determined the association between gait regularity and harmonics measured with a small triaxial accelerometer at admission and gait speed at discharge in patients with mild stroke admitted to the subacute phase. The findings of this study may help in making decisions about intervention strategies and goals for developing rehabilitation to improve gait performance.

Funding and Conflict of interest

None.

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