International Journal of Gerontology 13 (2019) 144–148
https://doi.org/10.6890/IJGE.201906_13(2).0009

International Journal of Gerontology

journal homepage: http://www.sgecm.org.tw/ijge/

Original Article

Gait and Trunk Movement Characteristics of Chronic Ischemic Stroke Patients

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ARTICLE INFO

Accepted 28 September 2018

Keywords:
accelerometer,
fall,
gait,
stroke,
trunk movement

SUMMARY

Background: Recovery of walking after stroke requires an understanding of how motor control deficits lead to gait impairment. We compared gait patterns and trunk movements of chronic ischemic stroke patients and sex-matched controls.
Methods: Ten patients with chronic ischemic stroke and ten healthy controls were enrolled. An automated trunk three-axial accelerometer-based gait analysis system was used to investigate spatiotemporal gait parameters, including walking speed, step length, and cadence. Trunk movement intensity was measured as the acceleration root mean square. Trunk movement symmetry and regularity were analyzed using the autocorrelation method. Correlations between gait parameters and future falls were studied.
Results: The median time until evaluation following stroke was 30 months. Walking speed, step length, cadence, and trunk movement intensity ($p < 0.001$, $p < 0.001$, and $p = 0.001$, respectively) were significantly lower for the stroke group. Trunk movement symmetry ($p = 0.005$) and regularity ($p = 0.029$) in the vertical axis differed between groups. Future falls were positively associated with trunk movement symmetry and regularity in the anteroposterior axis and root mean square ratio in the medio-lateral axis; however, they were negatively associated with walking speed and trunk movement intensity in the anteroposterior direction.
Conclusions: Patients with chronic stroke develop trunk movement asymmetry and irregularity in a vertical direction, which can contribute to muscular imbalances and potential injury. The trunk accelerometer may have a potential role in evaluating rehabilitation outcomes for stroke patients to regain better mobility, trunk control and stable gait.

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1. Introduction

Stroke is the leading cause of disability wordwide[1] and in Taiwan.[2] According to the Copenhagen Stroke Study, which showed a mortality rate of 21%, 18% could not walk at all, 11% walked when assisted, and the remaining 50% walked independently after rehabilitation.[3] Rehabilitation is an important factor of care in stroke patients.[4] Because there is a high risk of falling for these patients who can independently walk, rehabilitation should focus on improving safe walking[5] and trunk control.[6] Therefore, objectively monitoring post-stroke gait is important to gain a deeper understanding of mobility during rehabilitation.

Conventional gait analysis can provide a large quantity of data that are usually focused on hip, knee, and ankle angular kinematics and kinetics. However, not all clinicians have access to a gait laboratory. Recently, wearable systems such as inertial measurement units or accelerometers have been used.[7] These are light, portable, non-invasive, less expensive, and more accessible for measuring the gait of Parkinson's disease[8] and stroke[9] patients at medical clinics. Gait characteristics derived from trunk acceleration, such as stride regularity, variability, and smoothness, are more sensitive to the risk of falling than typical gait characteristics such as gait speed and cadence.[9] Furthermore, the autocorrelation (AC) coefficient calculated from trunk acceleration were closely associated with trunk motor impairment after stroke.[9] These characteristics can provide clinicians with information regarding underlying gait performance and guide the direction of rehabilitation.[10]

In the current literature, several studies have used an accelerometer attached to the lumbar region for analyzing post-stroke gait quality.[11–16] Two of them examined left-right symmetry of trunk movement in stroke patients.[15,16] In chronic stroke patient, smaller vertical trunk movement, larger mediolateral trunk movement, and lower trunk movement regularity or symmetry have been reported.[13,14] In subacute stroke patients, reduced trunk movement intensity, lower trunk movement regularity and symmetry have also been found.[11,12] Although these studies demonstrated the sequelae of gait asymmetry or irregularity after stroke, few studies have investigated trunk movement patterns and its relationship with future falls of chronic stroke patients. We considered that accelerometers could discriminate gait quality objectively and in greater detail than simple visual observation. Such additional information would be beneficial for gait training during stroke rehabilitation. Our primary

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hypothesis was that the stroke group would have altered temporal and spatial gait parameters and decreased trunk movement symmetry and regularity than the control group. We also want to explore the relationship between gait parameters and future falls.

The primary aim of this study was to assess gait and trunk movement differences between stroke patients and able-bodied participants using a trunk accelerometer-based gait analysis system in the hospital. The secondary aim was to assess the association between gait parameters and future falls.

2. Materials and methods

2.1. Participants

This was a prospective observational study performed between March 2015 and March 2016 at the rehabilitation department of a teaching hospital. Eligible patients with chronic stroke who were medically stable and underwent outpatient rehabilitation were recruited. Inclusion criteria were an interval of more than three months after stroke, first-ever ischemic stroke with unilateral hemiplegia, and able to walk 10 m unaided. Exclusion criteria were previous lower limb orthopedic surgeries, prosthetics, or ankle-foot orthotics; severe cardiopulmonary disease; and unable to understand the instructions because of communication or cognitive problems. We included ten healthy individuals who were sex-matched to the stroke group as the control group. Inclusion criteria of the control group were age $\geq$ 20 years, the ability to accept and follow verbal instructions, and the ability to walk independently without walking aids. Exclusion criteria were any systemic disease; prior spine or lower extremities surgery; any neurologic disease or comorbid condition that may affect gait. All participants agreed to participate in the study and signed an informed consent form prior to examination. The study was approved by the medical ethics committee of the hospital.

2.2. Procedures

Demographic and clinical characteristics were obtained from medical records. All measurements were performed by a physiatrist. All participants were asked to stand while the accelerometer was secured using a strap on the midline of the low back between the palpated L3 and L4 vertebrae (Fig. 1). Participants were asked to walk for a total of 8 m, with 1.5 m each (3 m total) allocated for gait initiation and termination. The following parameters were collected during two trials for each participant: walking speed; step length; cadence; trunk movement (between-step) symmetry and (between-stride) regularity; acceleration root mean square (RMS) in the anteroposterior (AP), mediolateral (ML), and vertical (VT) directions; and acceleration RMS ratio in the ML direction ($RMSR_{ML}$).

2.3. Trunk accelerometry gait analysis

An automated, infrared-assisted, trunk accelerometer-based gait analysis system was used to detect spatiotemporal gait parameters (walking speed, step length, cadence) and trunk movement symmetry and regularity, which had been proved excellent reliability.[17] In short, linear acceleration of the lower trunk was recorded along the AP, ML, and VT axes using a wireless accelerometer (ADXL345; Analog Devices, Norwood, MA, USA) embedded in a wireless sensor unit measuring 69.5 × 45.5 × 14.5 mm (length × width × height). Acceleration data were digitized and sampled at a rate of 100 Hz and stored on a personal computer via a Bluetooth wireless link. Reliability and validity studies of the accelerometer-based gait analysis system to quantify gait characteristics of control and stroke groups have been reported.[17–19]

2.4. Gait parameters

Walking speed was calculated by dividing the 5-m walking distance by the walking time. Cadence was calculated by dividing the total step count by the walking time.

Step length was calculated by dividing the 5-m distance by the total number of steps taken.[17]

Acceleration RMS values in the AP, ML, and VT directions were utilized to represent trunk movement intensity,[20] which is the mean magnitude of acceleration along each three-dimensional axis. Acceleration $RMSR_{ML}$ represented the ratio between acceleration RMS in the ML direction and the acceleration RMS vector magnitude.[21] RMSR could be useful as a normalized RMS because RMS is highly sensitive to walking speed.[22] $RMSR_{ML}$ is a more effective measurement for detecting gait differences than measurements in the AP and VT directions because $RMSR_{ML}$ was not correlated with the preferred walking speed and was found to be a potential indicator of gait abnormality.[21]

Symmetry and regularity of trunk movements in the AP and VT directions were estimated using the AC method proposed by Moe-Nilssen.[23] The AC coefficient is an estimate of the similarity of time points within a series during a given time shift. The first (Ad1) and second (Ad2) dominant periods represent phase shifts equal to one step and one stride, respectively. Trunk movement (between-step) symmetry is the value of the AC coefficient corresponding to the Ad1 dominant period. Trunk movement (between-stride) regularity is the value of the AC coefficient corresponding to the Ad2 dominant period, which expressed similarity between strides over time. An AC

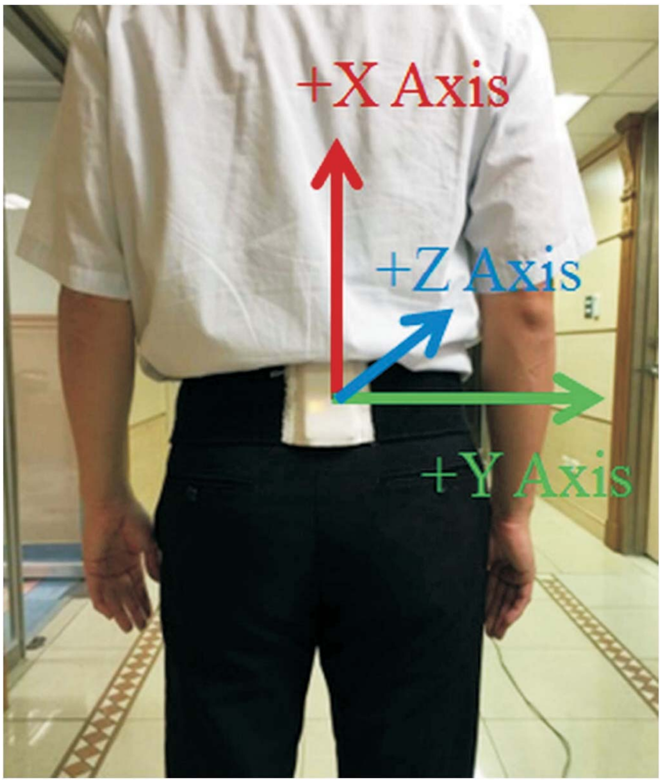

Fig. 1. The accelerometer was fixed to a belt at the level of the L3–L4 spinous process (x-axis: vertical; y-axis: medial–lateral; and z-axis: antero-posterior).

coefficient approaching 1.0 reflects high symmetry or regularity.[24] The ML signal was not used for regularity or symmetry assessments because of its small conspicuous waveforms and significant variation.[25]

2.5. Fall assessment

Patients who completed the gait analysis were contacted by telephone 24 months after the gait analysis and were asked the following question: Did you fall during the 24 months after the gait analysis? A fall was defined as the patient unintentionally coming to rest on the floor or a lower level that was not because of a major intrinsic event.

2.6. Statistical analysis

Nonparametric statistics were used because of the small sample size. Data are expressed as median and interquartile range. Spearman's group differences for age, body height, body weight, and sex were assessed using Fisher's exact test or the Mann-Whitney U test. Differences between the control and stroke groups for gait characteristics were analyzed using the Mann-Whitney U test. Spearman's rank correlation coefficient was used to identify associations between future falls and gait parameters. Correlation coefficients were interpreted as follows: 0–0.25, little if any correlation; 0.26–0.49, low correlation; 0.5–0.69, moderate correlation; 0.7–0.89, high correlation; and 0.9–1.0, very high correlation.[9] Data were analyzed using SPSS software version 21.0 (IBM Corp., Armonk, NY, USA). The significance level was set at $p < 0.05$ for all tests.

3. Results

3.1. General characteristics of the stroke and control groups

Ten patients with chronic ischemic stroke and ten sex-matched healthy controls were enrolled. Characteristics of the stroke and control groups are shown in Table 1. No significant differences in sex, body height, and body weight were seen between groups. The median time of evaluation following stroke was 30.0 months. During the 24 months after the gait analysis, fall episodes were reported by two patients.

3.2. Differences of gait parameters between stroke and control groups

Table 2 shows the differences in trunk accelerometric profiles between stroke and control groups. Walking speed, step length, and cadence ($p < 0.001$, $p < 0.001$, and $p = 0.001$, respectively) were significantly lower for the stroke group than for those in the control group. Trunk acceleration RMS in the AP, ML, and VT axes ($p = 0.001$, $p = 0.019$, and $p = 0.019$, respectively) were significantly lower for the stroke group than for the control group. VT trunk movement symmetry (Fig. 2) and regularity (Fig. 3) were significantly lower for the stroke group than the control group ($p = 0.005$ and $p = 0.029$, respectively). Trunk acceleration $RMSR_{ML}$ ($p = 0.143$) was not significantly different between groups.

3.3. Correlations between future falls and gait parameters

Table 3 presents the correlation between future falls and gait parameters. There was a moderate rank correlation between trunk movement symmetry and regularity in the AP axis and $RMSR_{ML}$ and

Table 1
Characteristics of stroke patients and healthy control participants.

Variable	Stroke (N = 10), median (IQR)	Controls (N = 10), median (IQR)	p-value*
Age, years	66.0 (17.3)	34.5 (21.0)	0.009
Sex, men/women	8/2	8/2	1.000
Body height, cm	168.5 (14.5)	171.0 (10.8)	0.218
Body weight, kg	63.5 (18.3)	63.5 (28.5)	0.971
Time from stroke, months	30.0 (36.0)	NA	NA
Hemiparetic side, right/left, n	5/5	NA	NA
Diabetes mellitus, n	2	0	0.474
Hypertension, n	5	0	0.033
Hyperlipidemia, n	2	0	0.474
Heart disease, n	1	0	1.000
Stroke subtype, n			NA
Large vessel	3	NA	NA
Cardioembolism	3	NA	NA
Small vessel	2	NA	NA
Other/undetermined	2	NA	NA

* Differences in sex, diabetes mellitus, hypertension, hyperlipidemia, and heart disease between group were analyzed with Fisher's exact test. Differences in age, body height, and body weight were analyzed with the Mann-Whitney U test.
IQR, interquartile range; NA, not applicable.

Table 2
Comparison of gait parameters between stroke patients and healthy controls derived from trunk acceleration signals.

	Stroke median (IQR) (N = 10)	Control, median (IQR) (N = 10)	Absolute difference, median (95% CI)*	p-value†
Walking speed, m/s	0.68 (0.37)	1.22 (0.23)	-0.61 (-0.67 to -0.48)	< 0.001
Step length, cm	36.7 (17.9)	57.2 (9.6)	-18.9 (-23.4 to -12.9)	< 0.001
Cadence, step/min	105.6 (23.5)	132.0 (18.9)	-28.9 (-40.7 to -14.5)	0.001
AP acceleration RMS, g	0.07 (0.04)	0.14 (0.04)	-0.06 (-0.09 to -0.04)	0.001
Step symmetry	0.69 (0.18)	0.68 (0.15)	-0.01 (-0.11 to 0.10)	0.796
Stride regularity	0.63 (0.19)	0.57 (0.14)	0.02 (-0.07 to 0.19)	0.190
ML acceleration RMS, g	0.08 (0.03)	0.15 (0.07)	-0.06 (-0.09 to 0.01)	0.019
Acceleration RMSR	0.58 (0.11)	0.53 (0.20)	0.03 (-0.05 to 0.16)	0.143
VT acceleration RMS, g	0.10 (0.09)	0.19 (0.07)	-0.07 (-0.11 to -0.02)	0.019
Step symmetry	0.53 (0.10)	0.65 (0.11)	-0.08 (-0.22 to -0.02)	0.005
Stride regularity	0.45 (0.16)	0.59 (0.11)	-0.12 (-0.22 to -0.01)	0.029

* Absolute differences are provided for median values of all gait parameters.
† Differences in walking speed, step length, cadence, and acceleration RMS, step symmetry, stride regularity, and RMSR were analyzed with the Mann-Whitney U test.
IQR, interquartile range; CI, confidence interval; RMS, root mean square; RMSR, root mean square ratio; AP, anteroposterior; g, gravity; ML, medial-lateral; VT, vertical.

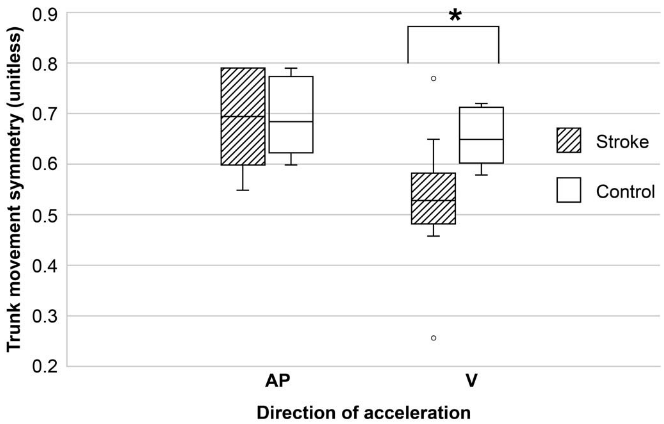

Fig. 2. Box and whisker plot for trunk movement symmetry. The stroke and control groups are illustrated in the anteroposterior (AP) and vertical (V) directions. The plot was derived from trunk acceleration data using the autocorrelation method.

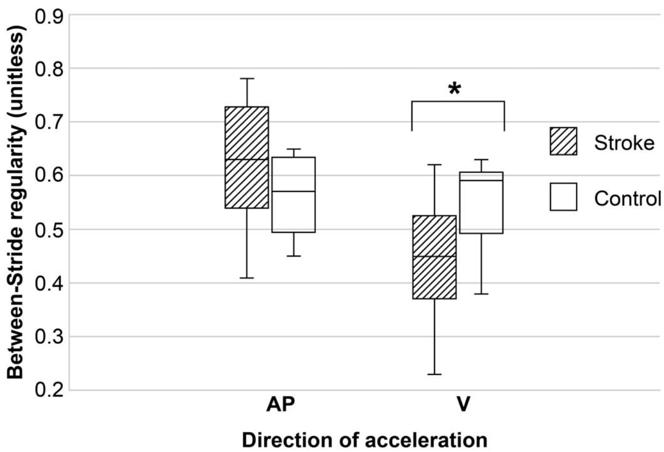

Fig. 3. Box and whisker plot for trunk movement regularity. The stroke and control groups are illustrated in the anteroposterior (AP) and vertical (V) directions. The plot was derived from trunk acceleration data using the autocorrelation method.

future falls (r = 0.70, r = 0.70, and r = 0.70, respectively). An inversely moderate rank correlation was found between walking speed and trunk movement intensity in the AP direction and future falls (r = -0.70 and r = -0.70, respectively).

4. Discussion

Our results demonstrated that walking speed, step length, cadence, and trunk movement intensity were significantly lower for the stroke group than the control group. Trunk movement symmetry and regularity in the VT direction decreased significantly. Furthermore, trunk movement intensity, symmetry, and regularity in the AP axis, $RMSR_{ML}$, and walking speed were moderately associated with future falls.

Acceleration RMS is an indication of the average acceleration during walking and is closely associated with walking speed.[26] Interestingly, VT trunk acceleration RMS can reflect the amount of center of gravity displacement during walking and has been found to be a significant determinant of basic functional mobility and balance ability for stroke patients; this is measured by the Timed Up and Go (TUG) and Berg Balance Scale (BBS) tests, respectively.[27] On the contrary, trunk acceleration RMS values were not significantly different between the different Brunnstrom stages in any axis.[13] In the present study, no differences in acceleration $RMSR_{ML}$ were found between groups. This supports the finding that stroke survivors are able to maintain some stability in the ML direction, and this is probably accomplished by increasing the step width.[28]

Table 3
Correlations for future falls and gait parameters.

Variable	Fall	
	Correlation	p-value*
Walking speed, m/s	-0.70	0.025
Step length, cm	-0.53	0.119
Cadence, step/min	-0.52	0.120
AP acceleration RMS, g	-0.70	0.024
Symmetry	0.70	0.025
Stride regularity	0.70	0.025
ML acceleration RMS, g	-0.18	0.628
Acceleration RMSR	0.70	0.025
VT acceleration RMS, g	-0.18	0.629
Symmetry	-0.18	0.629
Stride regularity	0	1.000

* Correlations between falls and gait parameters were analyzed with Spearman's rank correlation coefficient.
LEFS, Lower Extremity Functional Scale; AP, anteroposterior; ML, medial-lateral; VT, vertical; RMS, root mean square; RMSR, root mean square ratio.

The AC coefficient was an index of gait pattern similarity. The lower value of AC coefficient may indicate less smooth, inconsistent, and asymmetrical gait patterns compared with those of control subjects. In the present study, trunk movement symmetry and regularity in VT direction were significantly lower for the stroke group compared to the control group, which was in accordance with two previous chronic stroke studies.[11,13] Furthermore, the trunk acceleration AC coefficient were found to be closely associated with trunk motor impairment in patient with stroke.[9] Gait indices calculated from trunk acceleration in the VT direction were relevant to balance ability after stroke.[27] Therefore, accelerometry gait parameters can be considered useful for evaluating the dynamic gait balance, and can guide rehabilitation strategies that target trunk control to regain better mobility and stable gait for patients after stroke.[9]

Falls are common complications after stroke.[29] Trunk movement and balance ability are essential factors for functional independence of post-stroke patients.[30] Trunk coordination has been found to be significantly related to AC coefficients in AP and VT axes.[9] Moreover, the $RMSR_{ML}$ could be useful as an indicator of gait abnormality and a record of recovery from impairment.[21] In a previous study, inter-stride variability of ML trunk acceleration was found to be significantly associated with fall history.[31] The amplitude of trunk accelerations and the trunk movement symmetry or regularity could provide valuable information about subject-specific motor strategies, discriminate between different levels of walking ability, and may be correlated with future falls.

The current study had some limitations. First, the number of included participants was relatively small. Second, the results obtained in our study represent a chronic stage of stroke during outpatient rehabilitation, which may limit its external generalizability to other rehabilitation stages. Third, age was not matched between groups. Age itself is a factor that influences the gait parameters.[32] Finally, we did not explore the underlying causes of gait deficits. However, the current findings support the importance of trunk rehabilitation after stroke. The accelerometry gait parameters can discriminate between stroke patients and the control group. Further investigations are necessary to examine the relationship between gait indices and falls for stroke patients.

In conclusion, patients with chronic stroke develop trunk movement asymmetry and irregularity in a vertical direction, which can contribute to muscular imbalances and potential injury. Gait indices calculated from trunk accelerations reflecting the AP and ML directions maybe relevant to future falls. The trunk accelerometer may have a potential role in helping clinicians evaluate rehabilitation outcomes after stroke to regain better mobility, trunk control and stable gait.

Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics approval and consent to participate

This study was approved by the Ten-Chan General Hospital ethics board (reference number 103-B-12-05). All subjects provided written informed consent prior to their participation in the study.

Acknowledgements

None.

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