



Article

Comparison of Quantitative Evaluation Methods for Pathological Gait Abnormalities in Stroke Survivors

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Abstract

Background/Objectives: The Gait Variable Score (GVS) and Gait Abnormality Score (GAS) have been proposed as methods for quantitatively evaluating deviations from normal gait patterns. This study aimed to investigate whether the GVS or GAS is more useful for evaluating gait in stroke survivors. **Methods:** We used open-access motion capture datasets from 43 stroke survivors and 82 healthy individuals. Nine kinematics and seven muscle activities were extracted. The GVS was calculated as the root mean square difference between the pathological and healthy gait patterns. The modified GAS (mGAS) newly defined in this study was calculated as the mean value of the absolute differences between the pathological and healthy gait patterns divided by the standard deviation of healthy gait patterns. The amplitudes of kinematics and muscle activities were calculated. **Results:** Both the GVS and mGAS were significantly higher in stroke survivors than in healthy individuals. A significant strong correlation for 16 variables (nine kinematics and seven muscle activities) was observed between the GVS and amplitude ($r = 0.921$), but no significant correlation was found between the mGAS and amplitude ($r = 0.167$). **Conclusions:** As the mGAS is not affected by the amplitude of kinematics and muscle activities, it allows for a comprehensive comparison of abnormalities in both kinematics and muscle activities. The mGAS may be more useful than the GVS for evaluating gait abnormalities in stroke survivors.

Keywords: stroke; gait abnormality; kinematic; muscle activity; rehabilitation



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1. Introduction

Stroke is prevalent worldwide and is a leading cause of mortality and disability [1,2]. Furthermore, stroke impairs many activities of daily living, including walking and climbing stairs [3–5]. Preston et al. [6] reported that 60%, 65%, and 91% of stroke survivors achieved gait independence at 3, 6, and 12 months, respectively, indicating that a significant number of stroke survivors are unable to walk independently early after a stroke. Gianella et al. [7] reported that 89.2% of severe stroke survivors were unable to walk independently at 4 months. Improving gait ability is crucial for improving the quality of life of stroke survivors.

Gait training is essential in rehabilitation to promote gait independence in stroke survivors, and many studies have reported its efficacy [8–10]. Peurala et al. [8] and Mehrholz et al. [10] have reported that treadmill and electrically assisted gait training

improved gait independence and speed. Stroke survivors exhibit different kinematics and muscle activities during gait compared with healthy individuals [11–15]. Improving abnormal kinematics and muscle activities during gait in stroke survivors is crucial for rehabilitation.

Recently, methods for quantitatively evaluating abnormal gait patterns that deviate from normal gait patterns have been proposed and their usefulness demonstrated [16–18]. Baker et al. [17] proposed the Gait Variable Score (GVS), a method for calculating the root mean square difference between the pathological and healthy gait patterns. Bigoni et al. [13] demonstrated that the GVS in stroke survivors correlated with the Functional Independence Measure (FIM) and Functional Ambulation Category (FAC). Furthermore, Langley et al. [18] recently proposed the Gait Abnormality Score (GAS), a standardized measure of the deviation of pathological gait patterns from healthy patterns, and reported the usefulness of the GAS in patients after total hip arthroplasty and with knee osteoarthritis (Table 1). This score was calculated by dividing the difference between the pathological and healthy gait patterns by the standard deviation of the healthy gait patterns. Because the GVS is calculated as the root mean square difference between the pathological and healthy gait patterns, it may be affected by the amplitude of the gait pattern. However, because the GAS is standardized using the standard deviation, it is less likely to be affected by the amplitude of the gait pattern. For example, the amplitude of the knee flexion angle was greater than that of the pelvic tilt angle during gait. If both have the same rate of abnormalities (e.g., 10% error from the reference), the GVS of the knee flexion angle should be larger than the GVS of the pelvic tilt angle. This hinders clinicians from determining whether the pelvic tilt or knee flexion angle is more impaired. This phenomenon should not occur in the GAS because the score is standardized. Therefore, the GAS may be more useful clinically than the GVS because it can comprehensively evaluate gait abnormalities in kinematics and muscle activities. However, the differences between the GVS and GAS in stroke survivors remain unclear. Clarifying the differences between these methods may provide more beneficial feedback during gait training for stroke survivors. The present study aimed to investigate whether the GVS or GAS is more useful for evaluating gait in stroke survivors. We hypothesized that the GAS would be more useful because it is not affected by the amplitude of the gait pattern, unlike the GVS, which is strongly affected.

Table 1. Summary of previous studies.

Author	Score	Study Population	Device	Results
Baker R (2009) [17]	GVS	Children with conditions such as cerebral palsy, Perthes disease, or spina bifida	Three-dimensional motion capture system	The GVS varied across the different levels of the Gillette Functional Assessment Questionnaire and Gross Motor Function Classification System.
Bigoni M (2021) [13]	GVS	Post-stroke patients	Three-dimensional motion capture system	The GVS correlated with the FAC and FIM.
Langley B (2023) [18]	GAS	Patients after total hip arthroplasty and with knee osteoarthritis	Three-dimensional motion capture system	The Gait Abnormality Index, which represents the average of all GAS, was greater in patients after total hip arthroplasty than in those with knee osteoarthritis.

2. Materials and Methods

2.1. Experimental Data

Open-access motion capture datasets of 50 stroke survivors and 138 healthy individuals, which was developed by Criekinge et al., were utilized in this study [19]. Seven stroke survivors and 56 healthy individuals were excluded from the analysis because kinematic and muscle activity data could not be collected from more than two trials. We ultimately used the kinematics and muscle activities data of 43 stroke survivors and 82 healthy individuals as the experimental data (Table 2). The exclusion criteria for healthy individuals were self-reported visual impairments, antalgic gait patterns, abnormal mobility in the lower limbs, and any neurological or musculoskeletal conditions that could influence motor performance and balance [19]. The inclusion criteria for stroke survivors were diagnosis of hemorrhagic or ischemic stroke based on computed tomography or magnetic resonance imaging, no history of previous stroke, occurrence of stroke within five months, and age 18–85 years [19]. The exclusion criteria for stroke survivors were Trunk Impairments Scale (TIS) ≥ 20 [20,21], FAC < 2 [22], unable to maintain independent sitting for 30 s on a stable surface without support and supervision, other neurological and musculoskeletal conditions that could influence motor performance and balance, and unable to understand instructions [19].

Table 2. Demographic data of healthy individuals and stroke survivors.

	Healthy	Stroke	<i>p</i>
Age, years	52.4 (20.0)	63.8 (14.0)	0.001 *
Height, cm	168.6 (10.0)	169.6 (7.9)	0.568
Weight, kg	73.7 (16.0)	72.2 (13.2)	0.602
Sex (Male/female), <i>n</i>	41/41	29/14	0.062 ^a
Time post-stroke, days		53.9 (28.7)	
TIS		13.7 (3.1)	
FAC, <i>n</i>			
0 (Nonfunctional ambulator)		0	
1 (Ambulator, dependent on physical assistance—level I)		0	
2 (Ambulator, dependent on physical assistance—level II)		15	
3 (Ambulator, dependent on supervision)		17	
4 (Ambulator, independent level surface only)		7	
5 (Ambulator, independent)		4	

* $p < 0.05$; ^a Chi-square test.

2.2. Data Collection

The data collection methods conducted by Criekinge et al. [19] are shown in Figure 1. Kinematic, force plate, and muscle activity data were collected using a three-dimensional motion capture system equipped with eight cameras (T10, Vicon Motion Systems Ltd., Oxford, UK, 100 Hz), four force plates (OR 6–7 and AccuGait, Advanced Mechanical Technology, Inc., Watertown, MA, USA, 1000 Hz), and a surface EMG system (Zerowire, Cometa srl, Barregio, Italy) [19]. The reflective markers were positioned according to the standard Plug-In Gait full body model [23,24]. In accordance with the SENIAM guidelines, fourteen EMG electrodes were attached bilaterally to the erector spinae, rectus femoris, vastus lateralis, biceps femoris, semitendinosus, tibialis anterior, and gastrocnemius [19]. The participants were instructed to walk a 12 m walkway at a self-selected comfortable speed. The task was performed without the use of gait aids or orthoses. To keep stroke survivors as safe as possible, a skilled physical therapist walked along the non-paretic side of the participants [19].

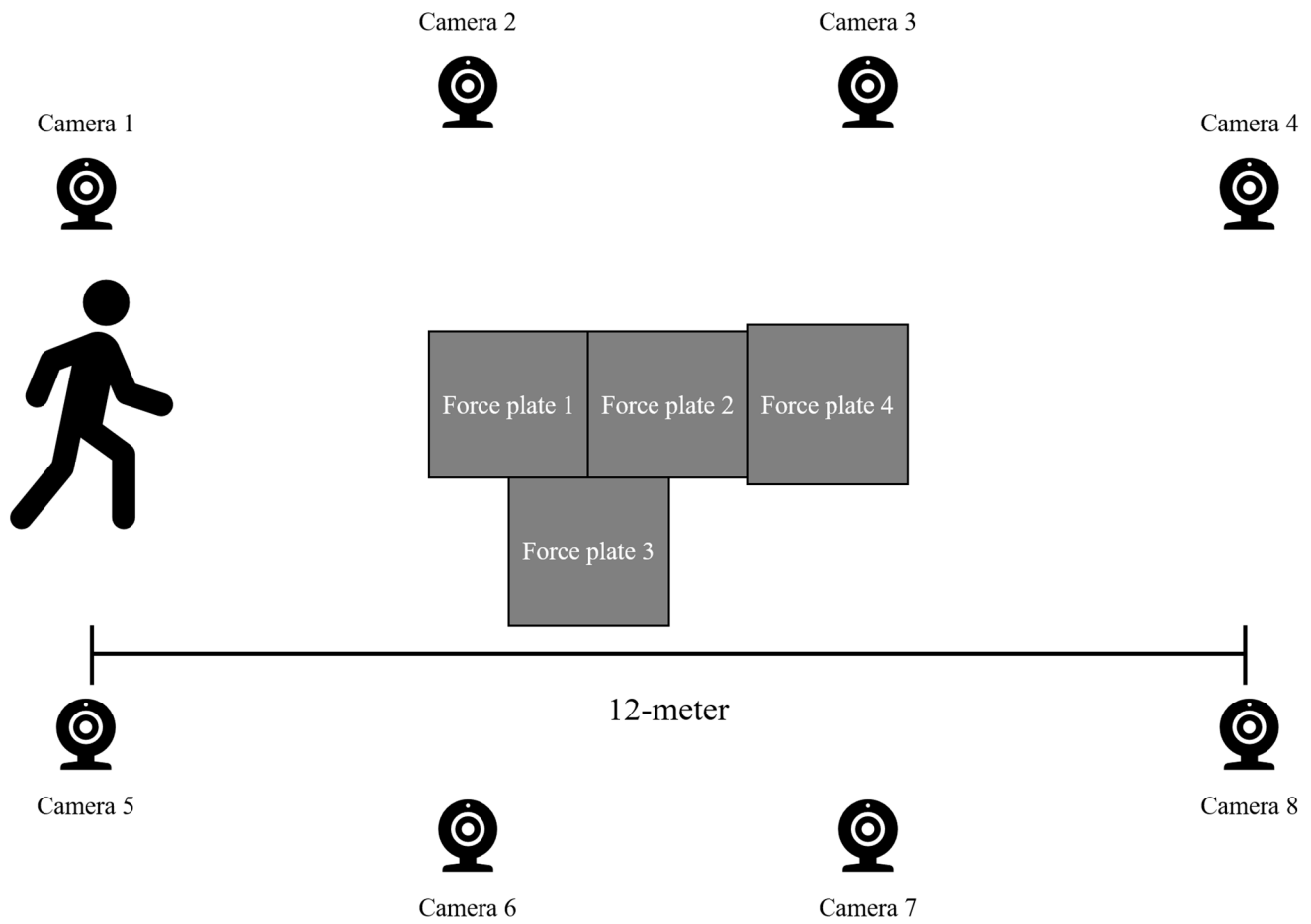


Figure 1. Data collection methods conducted by Crieckinge et al. [19].

2.3. Data Processing

Pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip adduction, hip internal rotation, knee flexion, ankle dorsiflexion, and foot progression angles were extracted from kinematic data calculated using the Vicon Nexus (versions 1.8.5 to 2.10.1) [17,19]. The kinematic data were low-pass filtered at a cutoff frequency of 10 Hz using a 4th-order reversed Butterworth filter. Rectified EMG data were bandpass filtered with a frequency range of 10–300 Hz, smoothed using a 50 ms moving average filter, and a linear envelope was generated [19,25]. The EMG data were normalized to the maximum value for each muscle throughout the stride of each participant [19]. All relevant data, including demographic data, kinematics, and muscle activities, were obtained from a MATLAB structure (MAT files) (R2021a, MathWorks Inc., Natick, MA, USA). Kinematics and muscle activities were analyzed on the paretic side in stroke survivors and on both sides in healthy individuals.

2.4. Abnormalities in Kinematics and Muscle Activities

To quantitatively evaluate the pathological gait abnormalities in stroke survivors, we adopted two methods: GVS and GAS [17,18]. GVS was calculated based on previous studies [17], as follows:

$$GVS = \sqrt{\frac{1}{N} \sum_{i=1}^N (P_i - \bar{H})^2} \quad (1)$$

where N is the total number of data points, i is each data point, P is each patient's data point, and $\bar{H}$ is the mean value for healthy individuals.

The original GAS is calculated as follows [18]:

$$d_i = \sqrt{(P_i - \bar{H}_i)^2} \quad (2)$$

$$\text{original GAS} = \frac{1}{N} \sum_{i=1}^N \left| \frac{d_i - \bar{dH}_i}{\sigma_i} \right| \quad (3)$$

where d is the Euclidean distance and σ is the standard deviation of healthy individuals.

This calculation method is complex and deviates from the concept of the z-score [26]. Therefore, we modified the GAS from previous studies to fit the concept of the z-score and termed the new score modified GAS (mGAS) [18]. The formula is as follows:

$$\text{mGAS} = \frac{1}{N} \sum_{i=1}^N \left| \frac{P_i - \bar{H}_i}{\sigma_i} \right| \quad (4)$$

We also evaluated the amplitudes of kinematics and muscle activities during gait in both healthy individuals and stroke survivors. The formula is as follows:

$$\text{Amplitude} = \text{max value} - \text{minimum value} \quad (5)$$

2.5. Statistical Analysis

Differences in demographic data, GVS, mGAS, amplitude of kinematics and muscle activities during gait between the healthy individuals and stroke survivors were analyzed using an unpaired t test. Among the demographic data, sex distribution was evaluated using the Chi-square test. The association of the GVS and mGAS with the FAC in stroke survivors was examined using Spearman's rank correlation coefficients. Furthermore, the association of the amplitudes of kinematics and muscle activities with the GVS and mGAS in stroke survivors was examined using Pearson's correlation coefficient for 16 variables, including nine kinematics and seven muscle activities. The calculation formulas for Spearman's rank correlation coefficient and Pearson's correlation coefficient are as follows [27]:

$$r_p = \frac{\sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{(\sum_{i=1}^N (X_i - \bar{X})^2)(\sum_{i=1}^N (Y_i - \bar{Y})^2)}} \quad (6)$$

$$r_s = 1 - \frac{6 \sum_{i=1}^N (X'_i - Y'_i)^2}{N(N^2 - 1)} \quad (7)$$

where r_p is Pearson's correlation coefficient, X and Y are the values on the X-axis and Y-axis, $\bar{X}$ and $\bar{Y}$ are the mean values of X and Y , r_s is Spearman's rank correlation coefficient, and X' and Y' are the ranks of X and Y . The threshold for statistical significance was set at $p < 0.05$.

3. Results

Stroke survivors were significantly older than the healthy individuals. No statistically significant differences were observed between stroke survivors and healthy individuals regarding height, weight, or sex (Table 2). The post-stroke time, TIS, and FAC scores of stroke survivors are presented in Table 2.

The mean waveforms of the kinematics and muscle activities during gait in stroke survivors and healthy individuals are shown in Figure 2. The GVS, except for the pelvic tilt angle, and the mGAS, except for the pelvic tilt and foot progression angles, were significantly higher in stroke survivors than in healthy individuals (Table 3). While the amplitude of the pelvic tilt angle was significantly higher in stroke survivors than in

healthy individuals, the amplitudes of the pelvic obliquity, hip flexion, hip adduction, knee flexion, ankle dorsiflexion, and foot progression angles, and erector spinae, biceps femoris, tibialis anterior, and gastrocnemius muscle activities were significantly lower in stroke survivors than in healthy individuals. There were no significant differences in the amplitudes of pelvic rotation and hip internal rotation angles, and rectus femoris, vastus lateralis, and semitendinosus muscle activities between stroke survivors and healthy individuals (Table 3).

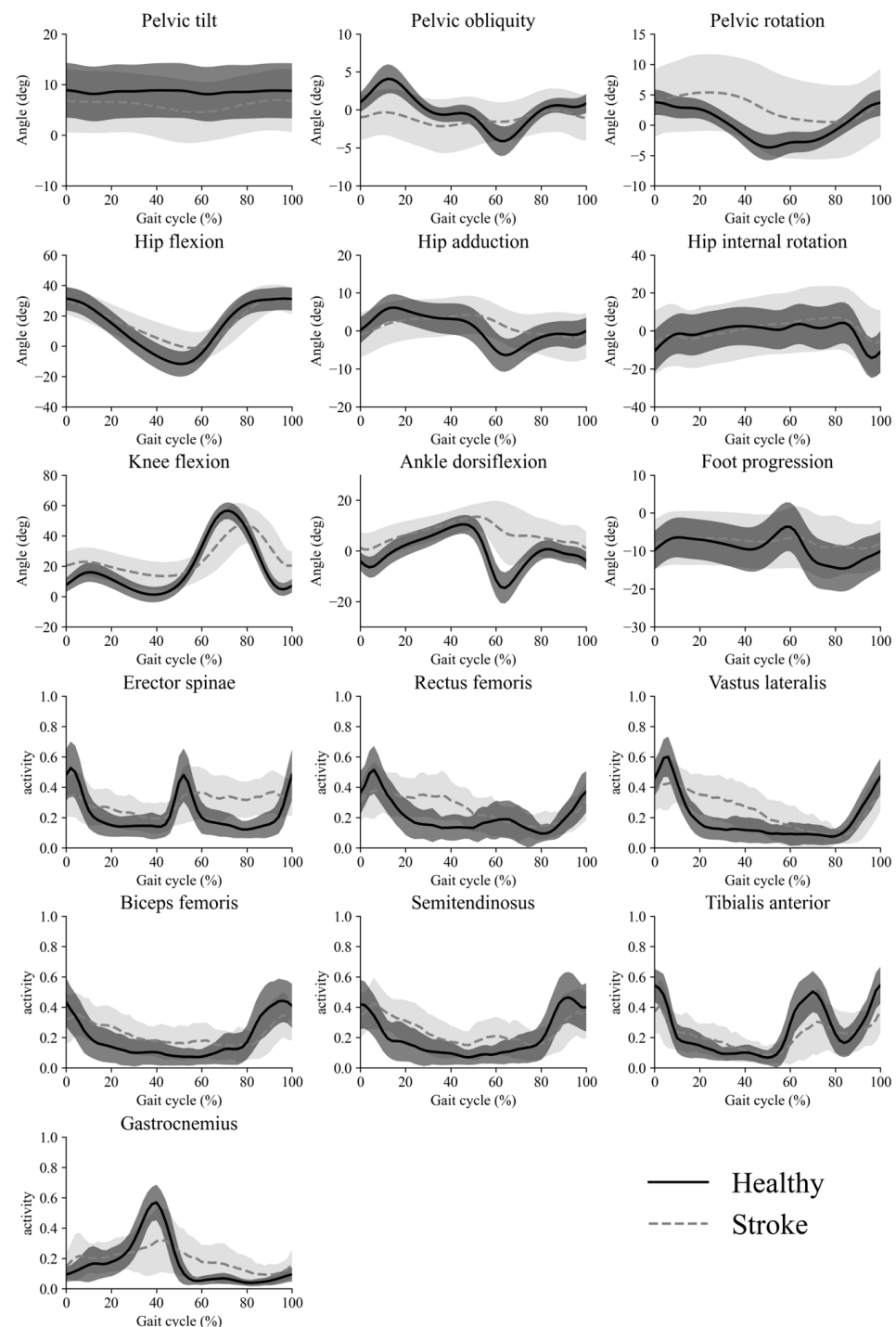


Figure 2. Mean waveforms of kinematics and muscle activities during gait in healthy individuals and stroke survivors. The solid black line represents the mean waveform of healthy individuals, while the dashed gray line represents that of stroke survivors.

Table 3. GVS, mGAS, and amplitude of kinematics and muscle activities during gait in healthy individuals and stroke survivors.

	GVS			mGAS			Amplitude		
	Healthy	Stroke	<i>p</i>	Healthy	Stroke	<i>p</i>	Healthy	Stroke	<i>p</i>
Kinematics									
Pelvic tilt	4.11 (3.42)	5.31 (3.84)	0.077	0.76 (0.64)	0.95 (0.72)	0.136	3.10 (0.81)	5.65 (3.03)	<0.001 *
Pelvic obliquity	1.20 (0.66)	3.35 (1.66)	<0.001 *	0.77 (0.42)	2.25 (1.31)	<0.001 *	8.85 (3.49)	5.29 (2.04)	<0.001 *
Pelvic rotation	1.58 (0.77)	6.07 (3.79)	<0.001 *	0.79 (0.39)	3.15 (2.18)	<0.001 *	9.71 (3.49)	9.61 (4.12)	0.886
Hip flexion	6.24 (4.83)	10.29 (6.10)	<0.001 *	0.73 (0.62)	1.09 (0.70)	0.003 *	44.79 (4.35)	37.15 (7.38)	<0.001 *
Hip adduction	3.31 (1.92)	5.75 (2.48)	<0.001 *	0.78 (0.50)	1.32 (0.65)	<0.001 *	13.78 (3.61)	10.06 (2.94)	<0.001 *
Hip internal rotation	8.51 (6.18)	14.06 (8.76)	<0.001 *	0.75 (0.59)	1.24 (0.86)	<0.001 *	24.53 (4.54)	23.85 (10.21)	0.610
Knee flexion	5.28 (2.07)	15.46 (6.28)	<0.001 *	0.81 (0.36)	2.41 (1.06)	<0.001 *	57.18 (5.64)	47.73 (8.71)	<0.001 *
Ankle dorsiflexion	3.91 (1.92)	10.39 (4.76)	<0.001 *	0.78 (0.47)	1.84 (0.96)	<0.001 *	26.90 (4.96)	21.88 (6.98)	<0.001 *
Foot progression	4.96 (3.01)	6.58 (4.03)	0.013 *	0.79 (0.53)	1.01 (0.72)	0.053	14.64 (3.56)	11.63 (4.41)	<0.001 *
Muscle activities									
Erector spinae	0.10 (0.03)	0.18 (0.05)	<0.001 *	0.79 (0.31)	1.63 (0.64)	<0.001 *	0.70 (0.08)	0.64 (0.11)	0.001 *
Rectus femoris	0.10 (0.04)	0.15 (0.05)	<0.001 *	0.74 (0.33)	1.22 (0.42)	<0.001 *	0.66 (0.10)	0.65 (0.09)	0.459
Vastus lateralis	0.08 (0.03)	0.16 (0.06)	<0.001 *	0.76 (0.29)	1.52 (0.70)	<0.001 *	0.70 (0.09)	0.69 (0.10)	0.378
Biceps femoris	0.10 (0.04)	0.15 (0.04)	<0.001 *	0.75 (0.32)	1.21 (0.54)	<0.001 *	0.71 (0.08)	0.66 (0.10)	0.003 *
Semitendinosus	0.11 (0.03)	0.16 (0.04)	<0.001 *	0.77 (0.25)	1.25 (0.48)	<0.001 *	0.72 (0.09)	0.69 (0.11)	0.122
Tibialis anterior	0.10 (0.03)	0.16 (0.05)	<0.001 *	0.77 (0.23)	1.25 (0.52)	<0.001 *	0.75 (0.08)	0.69 (0.10)	<0.001 *
Gastrocnemius	0.08 (0.03)	0.16 (0.05)	<0.001 *	0.76 (0.30)	2.12 (1.08)	<0.001 *	0.70 (0.09)	0.64 (0.14)	0.002 *

* $p < 0.05$.

The GVS of the pelvic rotation, knee flexion, ankle dorsiflexion, and foot progression angles, and tibialis anterior and gastrocnemius muscle activities, and the mGAS of the pelvic rotation, hip flexion, ankle dorsiflexion, and foot progression angles, and vastus lateralis, biceps femoris, and gastrocnemius muscle activities in stroke survivors were significantly correlated with the FAC (Table 4).

Table 4. Correlation coefficients between FAC and two scores, GVS and mGAS. GVS and mGAS show similar correlation coefficients, indicating that both reflect the FAC.

FAC		
	Correlation Coefficient (ρ)	p
GVS		
Kinematics		
Pelvic tilt	0.031	0.845
Pelvic obliquity	−0.185	0.236
Pelvic rotation	−0.407	0.007 *
Hip flexion	−0.297	0.053
Hip adduction	−0.213	0.170
Hip internal rotation	−0.089	0.570
Knee flexion	−0.331	0.030 *
Ankle dorsiflexion	−0.397	0.008 *
Foot progression	−0.378	0.012 *
Muscle activities		
Erector spinae	−0.150	0.337
Rectus femoris	−0.162	0.299
Vastus lateralis	−0.275	0.074
Biceps femoris	−0.196	0.207
Semitendinosus	−0.188	0.228
Tibialis anterior	−0.346	0.023 *
Gastrocnemius	−0.333	0.029 *
mGAS		
Kinematics		
Pelvic tilt	0.042	0.789
Pelvic obliquity	−0.215	0.167
Pelvic rotation	−0.357	0.019 *
Hip flexion	−0.313	0.041 *
Hip adduction	−0.255	0.099
Hip internal rotation	−0.084	0.593
Knee flexion	−0.287	0.062
Ankle dorsiflexion	−0.323	0.035 *
Foot progression	−0.368	0.015 *
Muscle activities		
Erector spinae	−0.158	0.312
Rectus femoris	−0.168	0.282
Vastus lateralis	−0.322	0.036 *
Biceps femoris	−0.305	0.047 *
Semitendinosus	−0.235	0.130
Tibialis anterior	−0.234	0.131
Gastrocnemius	−0.544	<0.001 *

* $p < 0.05$.

A significant correlation for a total of 16 variables, including nine kinematics and seven muscle activities, was observed between the GVS and the amplitude of all kinematics and muscle activities, but no significant correlation was found between the mGAS and the amplitude (Figure 3).

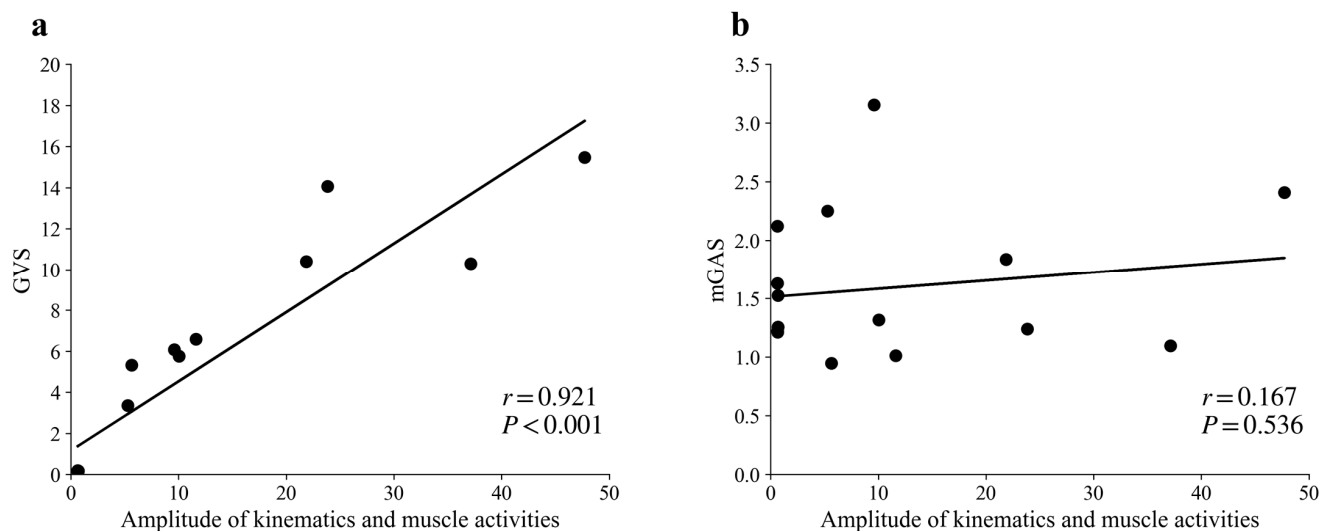


Figure 3. Correlations between two scores, the GVS and mGAS, and amplitudes of kinematics and muscle activities in stroke survivors. Scatter plots show that GVS (a) is significantly correlated with amplitude of kinematics and muscle activities, whereas mGAS (b) is not correlated with amplitude. Each sample in a scatter plot represents 16 variables that include nine kinematics and seven muscle activities.

4. Discussion

The primary objective of this study was to determine whether the GVS or GAS is more useful for evaluating gait in stroke survivors. Our results showed that both the GVS and mGAS were higher in stroke survivors than in healthy individuals. The GVS and mGAS were similarly correlated with gait independence in stroke survivors. Furthermore, we demonstrated that the GVS showed a strong correlation with the amplitude of kinematics and muscle activities, whereas the mGAS showed no significant correlation with the amplitude of kinematics and muscle activities. The mGAS is a standardized measure that can comprehensively evaluate gait abnormalities across all kinematics and muscle activities because it is not affected by the amplitude of kinematics and muscle activities. Therefore, the mGAS is believed to be more useful than the GVS for evaluating gait abnormalities in stroke survivors.

The altered kinematics and muscle activities observed in stroke survivors are factors that affect gait ability. Bigoni et al. [13] quantitatively evaluated the abnormality of kinematics in stroke survivors using the GVS and reported that stroke survivors had a larger GVS of lower-limb kinematics than healthy individuals. They also showed that the GVS in stroke survivors was significantly correlated with the FAC and FIM [13]. Supporting these results, our findings also demonstrated that the mGAS and GVS are useful for detecting abnormalities in kinematics and muscle activities in stroke survivors.

Our results show that the GVS is strongly affected by the amplitude of kinematics and muscle activities, whereas the mGAS is not affected by the amplitude of kinematics and muscle activities. The mGAS is a standardized measure that allows for a comprehensive comparison of abnormalities across all kinematics and muscle activities. Even if data exhibit substantial differences in the amplitude, the mGAS can rank abnormalities across all kinematics and muscle activities. Additionally, if data with high inter-subject variability are included, the GVS, which evaluates the root mean square difference between the pathological and healthy gait patterns, may fail to detect high-priority clinical abnormalities. In contrast, the mGAS, a standardized measure, is expected to accurately detect such abnormalities, even if highly variable data are included. Therefore, the mGAS is clinically useful because it enables interventions focused on kinematics and muscle activities with a

higher priority in gait training for stroke survivors. As an example of mGAS utilization, Figure 4 shows representative waveforms of kinematics and muscle activities during gait in two stroke survivors who were dependent on supervision (FAC, 3) (Figure 4). The mGAS can be calculated using only a single-frame data point, which indicates the frame with a larger abnormality. The single-frame mGAS and mGAS for the entire gait cycle in the two stroke survivors are shown in Figure 4. Areas where the single-frame mGAS is 3 or more are colored. Despite having the same gait ability (FAC, 3), the two stroke survivors showed different abnormalities in kinematics and muscle activities. These differences are observed not only in the magnitude of the mGAS for each kinematic and muscle activity but also in the timing when the mGAS exceeds 3. The mGAS is considered to be a more useful indicator in rehabilitation because it can identify the type and timing of kinematics and muscle activities that should be prioritized for intervention. Although various feedback methods have been used for gait training in stroke survivors [28–30], the type and timing of kinematics and muscle activities that should be prioritized for intervention have not been quantitatively investigated. In addition to these feedback methods, utilizing the mGAS may contribute to the provision of more beneficial feedback.

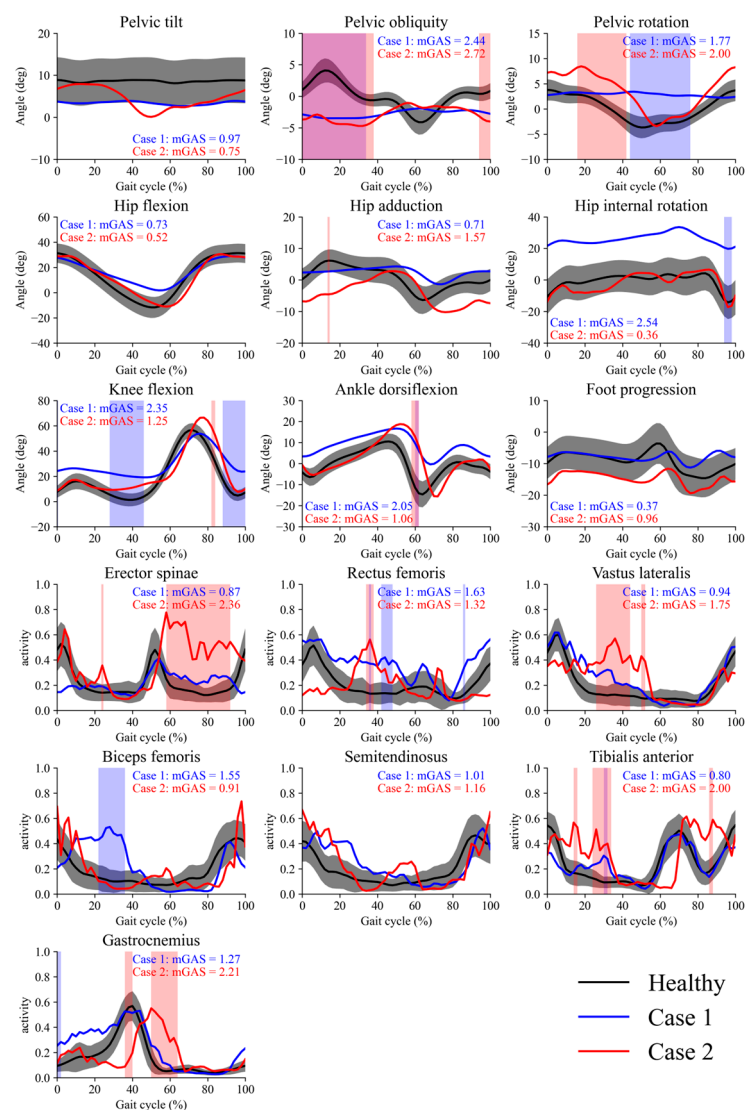


Figure 4. Utilization of single-frame mGAS for two representative stroke survivors. The highlighted frames show that single-frame mGAS is 3 or higher. These areas indicate which frames of kinematics and muscle activities are with abnormalities. The mGAS for entire gait cycle is shown in legend of each plot.

This study has several limitations. First, although data from 82 healthy individuals were used as the normal gait data, it is possible that they did not include gait data from the entire population of healthy individuals. Second, it was not possible to evaluate the differences in waveform patterns because gait abnormalities in this study were evaluated only by deviation from the waveform data of healthy individuals. Finally, the muscle activities were normalized by the maximum value throughout the entire stride of each subject instead of the maximum voluntary contraction (MVC). This approach is considered one of the best methods currently available because it is often difficult for stroke survivors with paralysis to measure their true MVC [31,32].

5. Conclusions

Our findings suggest that both the GVS and mGAS can detect gait abnormalities in kinematics and muscle activities in stroke survivors and are significantly associated with gait ability. While the GVS is strongly affected by the amplitude of kinematics and muscle activities, the mGAS is not affected by the amplitude of kinematics and muscle activities. Because the mGAS allows for a comprehensive comparison of abnormalities in both kinematics and muscle activity, it may be more useful than the GVS for evaluating gait in stroke survivors.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are openly available in Figshare at <https://doi.org/10.6084/m9.figshare.c.6503791> [19].

Conflicts of Interest: Kento Sabashi works for ORGO Inc. as an independent contractor. Ryo Ueno is a director of ORGO Inc.

Abbreviations

The following abbreviations are used in this manuscript:

GVS	Gait Variable Score
GAS	Gait Abnormality Score
FAC	Functional Ambulation Category
FIM	Functional Independence Measure
TIS	Trunk Impairments Scale
MVC	Maximum Voluntary Contraction

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