



# Unaffected Side Hip-Knee Cyclogram for Assessing Gait and Balance in Ambulatory Hemiplegic Stroke Patients

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**Purpose:** Gait disturbances affect mobility and quality of life in patients with post-stroke hemiplegia. While the affected side is traditionally assessed, the evaluation of the unaffected side has remained relatively underexplored. We investigated the potential of the unaffected side's hip-knee cyclogram parameters for assessing gait and balance function in post-stroke patients.

**Materials and Methods:** This study included 152 ambulatory patients with post-stroke hemiplegia. Participants underwent instrumented gait analysis and Berg Balance Scale (BBS) assessment. Hip-knee cyclogram parameters were derived from sagittal plane joint angles during gait. Correlations with BBS and leg length-normalized gait speed were analyzed. Subgroup analyses focused on stiff-knee gait and severity of spasticity.

**Results:** Swing phase area of the unaffected side showed moderately strong correlations with clinical parameters (BBS:  $\rho=0.66$ , leg length-normalized gait speed:  $\rho=0.81$ ) and also correlated with the single-limb support-phase ratio ( $\rho=0.69$ ) and normalized maximal vertical ground reaction force ( $\rho=0.60$ ) on the affected side. The unaffected hip-knee cyclogram demonstrated greater consistency across multiple gait cycles, as indicated by a smaller standard deviation and lower variability in joint coordination. In subgroups with stiff-knee gait and severe spasticity, the unaffected side's swing phase area and perimeter demonstrated stronger correlations than those of the affected side.

**Conclusion:** The hip-knee cyclogram parameters reflected gait function in patients with post-stroke hemiplegia, with the swing phase area of the unaffected side showing stronger correlations with clinical measures and more consistent results.

**Key Words:** Hemiplegia, stroke, gait, kinematics

## INTRODUCTION

Approximately 80% of post-stroke patients experience gait disturbances due to muscle weakness, spasticity, and impaired

motor coordination.<sup>1,2</sup> Gait asymmetry is particularly common in patients with hemiplegic stroke and increases the risk of falls, aggravating the patient's overall health.<sup>3</sup> Weakness of the anti-gravity muscles on the affected side, such as the knee and hip extensors, alters weight-bearing. This causes a decreased stance phase and prolonged swing phase on the affected side.<sup>4</sup> Similarly, weakness of the plantarflexors and hip flexors of the affected side complicates limb advancement,<sup>5,6</sup> resulting in decreased step length and gait speed and compromising gait balance.<sup>7</sup>

The Berg Balance Scale (BBS) is used to assess balance control ability in post-stroke individuals<sup>8</sup> and instrumented gait analysis can be performed to evaluate abnormal gait patterns and guide appropriate therapeutic interventions, such as orthotic prescriptions or botulinum toxin injections into the spastic affected limb. However, these hospital-based evaluations are limited due to space and time constraints. Furthermore, pa-

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tients tend to show better performance during hospital-based evaluations, which can potentially distort the results. Therefore, hospital-based evaluations may not fully reflect gait function in the real world.<sup>9,10</sup> To overcome these limitations, several studies have investigated digital biomarkers to assess gait function using simple kinematic data during real-world gait.<sup>11</sup>

The cyclogram, first introduced by D.W. Grieve in 1968, is a parametric curve that illustrates the relationship between the angles of two joints during a gait cycle. It offers geometric characteristics, such as the area and perimeter, which may aid in analyzing and quantifying gait features.<sup>12</sup> Cyclogram-based analysis may offer several advantages for evaluating post-stroke gait in real-world settings. It relies solely on kinematic data, which can be obtained in daily life using feasible methods such as wearable sensors or 2D video without the need for hospital visits. A previous study demonstrated significant differences in the hip-knee cyclogram area and perimeter of the affected side according to stroke severity.<sup>13</sup> However, these studies only highlighted statistical differences between groups based on disease severity classification and did not include correlation analyses.

Additionally, most previous studies on post-stroke gait have focused on the affected side. Post-stroke gait is influenced by the weakness and spasticity of the affected side, as well as the function of the unaffected side. Few studies have investigated the role of the unaffected lower extremity in post-stroke gait. A study revealed that the unaffected side usually demonstrates compensatory movements for the weakness and spasticity of the affected side and that mutual influence and coordination are crucial in hemiplegic post-stroke gait.<sup>14</sup> Asymmetry between the affected and unaffected sides has been reported to influence gait function in post-stroke patients.<sup>15,16</sup>

In individuals with hemiplegia, gait function and balance control are not solely determined by impairments in the affected limb. Rather, they result from the complex interaction between the degree of disability in the affected limb and the compensatory strategies adopted by the unaffected limb.<sup>17-19</sup> While the affected side may present with similar levels of motor impairment across patients, functional outcomes can vary considerably depending on how effectively the unaffected limb contributes to gait coordination and postural stability. This highlights the importance of examining the movement patterns of the unaffected limb, as its adaptive responses may play a critical role in overall locomotor performance.<sup>20</sup> Therefore, analyzing the gait characteristics of the unaffected limb can provide valuable insights into compensatory mechanisms and help in developing more tailored rehabilitation strategies.<sup>21</sup> Moreover, focusing on the unaffected side in the assessment of gait and balance offers several clinical and biomechanical advantages. In cases where the affected limb exhibits severe spasticity, significant weakness, or joint contractures, its functional movement may remain highly limited, making it difficult to accurately evaluate the effects of rehabilitation and the

severity of gait impairment. In such scenarios, relying solely on the affected side may not provide a comprehensive understanding of gait function. Notably, since the single-limb support (SLS) phase of the affected limb temporally corresponds to the swing phase of the unaffected limb, the latter may indirectly reflect the weight-bearing capacity of the affected side—a critical component for maintaining balance and functional ambulation.<sup>22</sup> Therefore, observing the unaffected limb not only reveals important compensatory strategies but also provides indirect information about the functional integrity and load-bearing ability of the affected limb, offering a more comprehensive view of the patient's gait and balance capabilities.

We hypothesized that the hip-knee cyclogram parameters of the unaffected side could be useful digital biomarkers for assessing gait and balance function, including the weight-bearing ability of the affected side, in post-stroke patients.

## MATERIALS AND METHODS

### Participants

This retrospective study included ambulatory individuals with post-stroke hemiplegia who visited a university-affiliated rehabilitation hospital between 2010 and 2023 and underwent instrumented gait analysis as part of standard clinical protocols, walking independently without assistive devices such as canes. Only patients who demonstrated more than three complete gait cycles and clearly contacted the force plate with the affected limb during the SLS phase were included. Patients with comorbid conditions that could affect gait—such as severe musculoskeletal disorders, neuromuscular diseases, or cardiopulmonary diseases—were excluded. This study was approved by the Institutional Review Board of Yonsei University (IRB approval number: 4-2024-0044).

### Study design

Clinical data at the time of gait analysis were collected through a review of electronic medical records. Stroke etiology, chronicity, Functional Ambulation Category, Modified Ashworth Scale (MAS), and BBS scores were retrospectively obtained. Cyclogram parameters were derived from kinematic data obtained through instrumented gait analysis, and correlation coefficients were calculated between these parameters and clinical measures such as the BBS and leg length-normalized gait speed. In the subgroup analysis, we focused on participants with stiff-knee gait and those with severe spasticity. Stiff-knee gait was defined as a maximum knee flexion angle of  $\leq 45^\circ$  during the swing phase.<sup>23,24</sup> Severe spasticity of the lower extremity was defined as a MAS score  $\geq 2$  in at least one of the hip or knee flexor/extensor muscles on the affected side.

### Gait analysis and extraction of cyclogram parameters

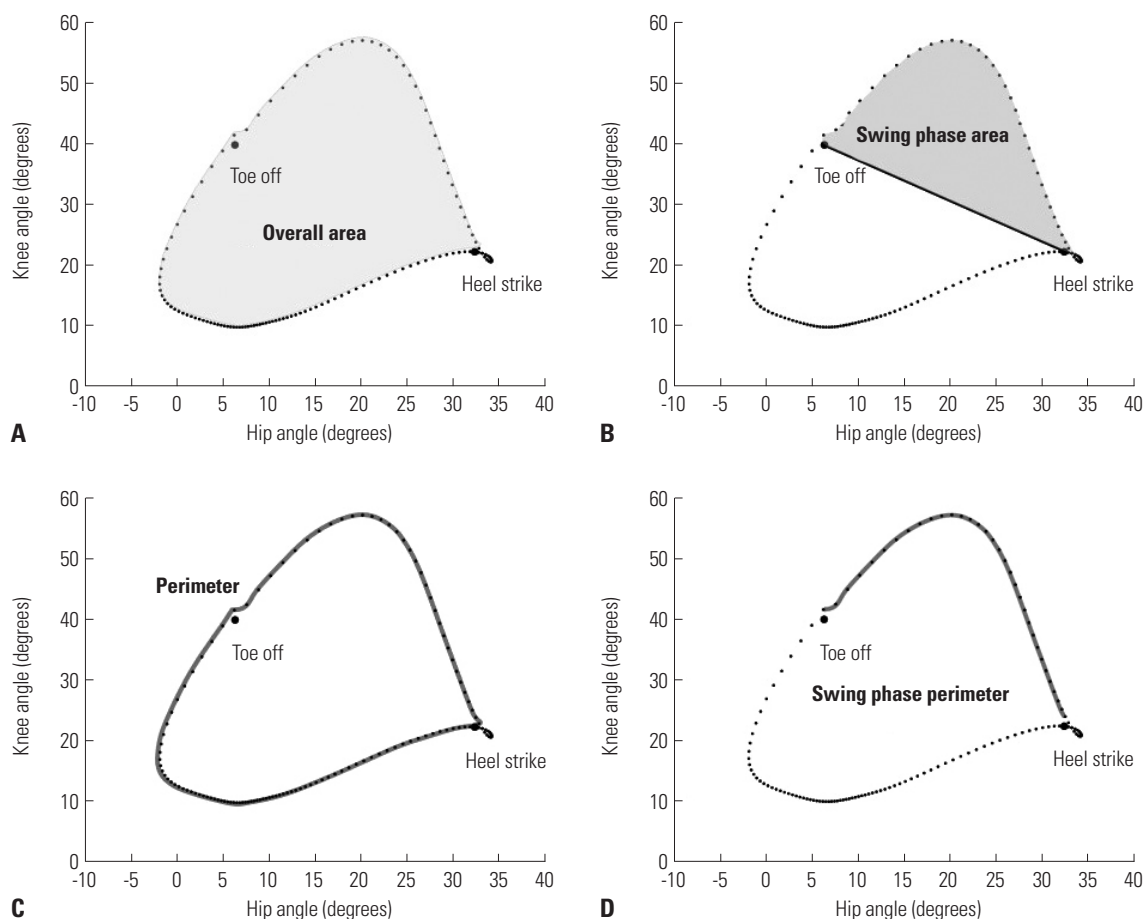
The instrumented gait analysis was performed using a mark-

er-based motion capture system with a VICON camera system (VICON MX-T10; Oxford Metrics Inc., Oxford, UK) and force plates (AMTI Inc., MA, USA). The markers were placed on the participant using a modified Helen Hayes marker set for lower limbs, consisting of 16 reflective markers placed on left and right anterior superior iliac spines, posterior superior iliac spines, lateral midshaft femur, lateral knee joint axis, lateral midshaft shank, lateral malleolus, calcaneus, dorsum of foot between second and third metatarsal heads. Before data collection, patients were instructed to take approximately 20 to 30 steps to ensure stabilization of their gait patterns. They were asked to walk at a self-selected, comfortable pace, which could be an indicator of gait function in neurological disorders.<sup>25</sup> Gait trials were repeated until minimal variability was observed among cycles, ensuring consistency within the trial. A representative gait cycle from the middle of the most consistent trial was selected to extract sagittal plane hip and knee kinematic data using the inverse kinematics method.

Spatiotemporal parameters, such as gait speed, SLS phase ratio, and double-limb support-phase ratio, were calculated. Gait speed was normalized to the average leg length (unit:  $s^{-1}$ ),<sup>26</sup>

which was directly measured prior to the test, as accurate height measurement was limited by patients' difficulty in standing upright. The maximum vertical ground reaction force (GRF) of each limb during the gait cycle was measured using force plates and normalized by dividing it by the body weight.

The cyclogram parameters were calculated based on the hip and knee joint angles in the sagittal plane during a single gait cycle for each leg. The area of the cyclogram was defined as the enclosed area within the entire cyclogram (Fig. 1A). The area of the swing phase was defined as the area enclosed by the line connecting the toe-off to the heel-strike points and the cyclogram plot of the swing phase (Fig. 1B). The perimeter of the cyclogram during the gait cycle was defined as the total length of the plot boundary (Fig. 1C). The perimeter of the swing phase was defined as the length of the cyclogram plot of the swing phase (Fig. 1D). Both positive hip angle and positive knee angle indicate flexion. The perimeter was calculated as the sum of the distances between the hip and knee joint points at each time point. The area was determined by calculating the enclosed area within the perimeter. The cyclogram parameters from both legs were averaged and used for comparison with



**Fig. 1.** Illustrative example of hip-knee cyclogram with key parameters. (A) Overall area: the region enclosed by the full cyclogram trajectory generated from hip and knee joint angles during a single gait cycle. (B) Swing phase area: the portion of the cyclogram area corresponding to the swing phase, defined between toe-off and heel-strike points. (C) Perimeter: the total boundary length of the entire cyclogram. (D) Swing phase perimeter: the boundary length of the cyclogram corresponding only to the swing phase.

clinical parameters.

To evaluate the consistency of the results, the mean trajectory and standard deviation were computed for both the affected and unaffected sides. This analysis was based on a subset of 19 patients, from whom a minimum of five gait cycles per leg were successfully measured. Additionally, the distance from the mean trajectory was compared between the affected and unaffected sides, and the coupling angle variability (CAV) was also computed and compared. The CAV of the hip-knee joint quantifies the temporal variability in inter-joint coordination across the gait cycle.<sup>27</sup> Specifically, it reflects the fluctuation in the coupling angle between the hip and knee joints over time. A lower CAV indicates more consistent and repeatable gait patterns across cycles, whereas a higher CAV suggests greater variability in coordination from one gait cycle to another. It was computed as the standard deviation of the coupling angle time series, as defined in Equation (1). All calculations were performed using MATLAB (MathWorks, Natick, MA, USA).

$$CAV = \sqrt{\frac{1}{N} \sum_{t=1}^N (\phi(t) - \bar{\phi})^2}$$
 Equation (1)

where  $\phi(t)$  = coupling angle at time  $t$  (degree)  
 $\bar{\phi}$  = mean coupling angle across the gait cycle  
 $N$  = number of samples

### Statistical analysis

We performed the Shapiro-Wilk test to assess data normality. As the normality assumption was not met, we used the Spearman rank correlation coefficient to evaluate the correlation between the cyclogram and clinical parameters (the BBS score and gait speed) of the affected and unaffected sides. Correlation coefficients were calculated separately for each side and compared across subgroups. Additionally, we analyzed the relationship between the swing phase of the unaffected side and the maximum vertical GRF of the affected side during its SLS phase, measured using a force plate, and compared these values with the swing-phase area of the unaffected side.

In the subgroup analysis, we compared the correlation coefficients between the cyclogram and clinical parameters of the unaffected and affected sides using Steiger's Z test ( $\alpha$  level, 0.05; confidence level, 0.95). All analyses were conducted using SPSS statistical software (version 27.0, IBM Corp., Armonk, NY, USA), with significance set at  $p < 0.05$ .

## RESULTS

A total of 152 patients with post-stroke hemiplegia were included in the study. The demographic and clinical characteristics of the participants are summarized in Table 1. Cyclogram parameters—including overall area, swing phase area, perimeter, and swing phase perimeter—of both the affected and unaffected limbs showed significant correlations with BBS and

leg length-normalized gait speed. Among these parameters, the swing phase area demonstrated the strongest correlation with the clinical measures. Steiger's Z-test revealed no statistically significant differences between the correlations of the affected and unaffected sides, except for the correlation between perimeter and gait speed (Table 2).

We further analyzed the relationships between the swing phase parameters of the unaffected limb and the stance phase parameters of the affected limb. Notably, the swing phase area of the unaffected side showed a significant positive correlation with the SLS phase ratio ( $\rho = 0.69, p < 0.05$ ) and the normalized maximal vertical GRF ( $\rho = 0.60, p < 0.05$ ) of the affected side (Fig. 2).

Supplementary Fig. 1 (only online) presents the mean  $\pm$  standard deviation trajectories of the hip-knee cyclogram across six gait cycles from 19 patients who had more than five gait cycles per leg. In 17 of the 19 patients, the mean Euclidean distance from the average trajectory was greater on the affected side, indicating a larger deviation from the mean path than on the unaffected side. Supplementary Fig. 1 (only online) further demonstrates that the affected side exhibited higher CAV than the unaffected side. Additionally, Table 3 reveals that the average coefficient of variation for the cyclogram parameters was lower on the unaffected side, suggesting more consistent joint co-

**Table 1.** Demographic and Clinical Characteristics (n=152)

Demographic variable	Value
Sex	
Male	108 (71.2)
Female	44 (28.8)
Age (yr)	61.7 $\pm$ 15.1
Hemiplegic side	
Right	87 (57.5)
Left	65 (42.5)
Stroke etiology	
Hemorrhagic	48 (31.6)
Ischemic	104 (68.4)
Stroke chronicity	
Acute and subacute (<6 months)	130 (85.5)
Chronic ( $\geq$ 6 months)	22 (14.5)
FAC	
4	64 (42.5)
5	88 (57.5)
Gait pattern	
Stiff-knee group	69 (45.4)
Non-stiff-knee group	83 (54.6)
Spasticity	
Severe spasticity	63 (41.4)
No/mild spasticity	89 (58.5)
BBS score, median (IQR)	30.0 (25.0–41.0)

FAC, Functional Ambulation Category; BBS, Berg Balance Scale; IQR, interquartile range.

Data are presented as mean  $\pm$  standard deviation or n (%).

ordination and reduced variability.

In the subgroup analysis of the stiff-knee gait group, the correlation coefficients between BBS scores and leg length-normalized gait speed were significantly higher on the unaffected side than on the affected side (BBS:  $Z=-2.00$ ,  $p<0.05$ ; leg length-normalized gait speed:  $Z=-2.47$ ,  $p<0.05$ ). In the non-stiff-knee gait group, only the correlation with gait speed showed a significant difference between the unaffected and affected sides (Table 4A). In the severe spasticity group, the swing phase area of the unaffected side also showed significantly higher correlation coefficients with both the BBS score and leg length-normalized gait speed compared to the affected side (BBS:  $Z=-1.96$ ,  $p<0.05$ ; leg length-normalized gait speed:  $Z=-2.35$ ,  $p<0.05$ ). In the mild or no spasticity group, a significant difference between the unaffected and affected sides was observed only in the correlation with gait speed (Table 4B). The median, first quartile, and third quartile values of swing phase in the sub-

group analysis are presented in Supplementary Table 1 (only online).

## DISCUSSION

We identified a correlation of cyclogram parameters on both the affected and unaffected sides with the clinical parameters (BBS score and leg length-normalized gait speed). Among the cyclogram parameters of both sides, the swing phase of the unaffected side—which correlated with the SLS and maximal GRF of the affected side—demonstrated a stronger association with the BBS score and leg length-normalized gait speed, particularly in the subgroup analysis of the stiff-knee gait and severe spasticity groups.

Weakness of the affected lower extremity causes decreased range of motion (ROM), slowed leg length-normalized gait speed, and shortened SLS phase during gait. These impairments are particularly due to reduced hip extension during the stance phase and diminished peak torque in the hip flexors, knee extensors, and ankle plantarflexors.<sup>16,28</sup> Because of these factors, the cyclogram parameters of the affected side, which possibly indicate hip and knee joint ROM during gait, could show a correlation with the BBS score and leg length-normalized gait speed. This also supports previous studies that showed differences in the cyclogram parameters between patients with severe and mild stroke.<sup>13</sup>

Among the cyclogram parameters, the swing phase area exhibited the strongest correlation with the clinical measures. A

**Table 2.** Correlation Coefficients of the Cyclogram Parameters (n=152)

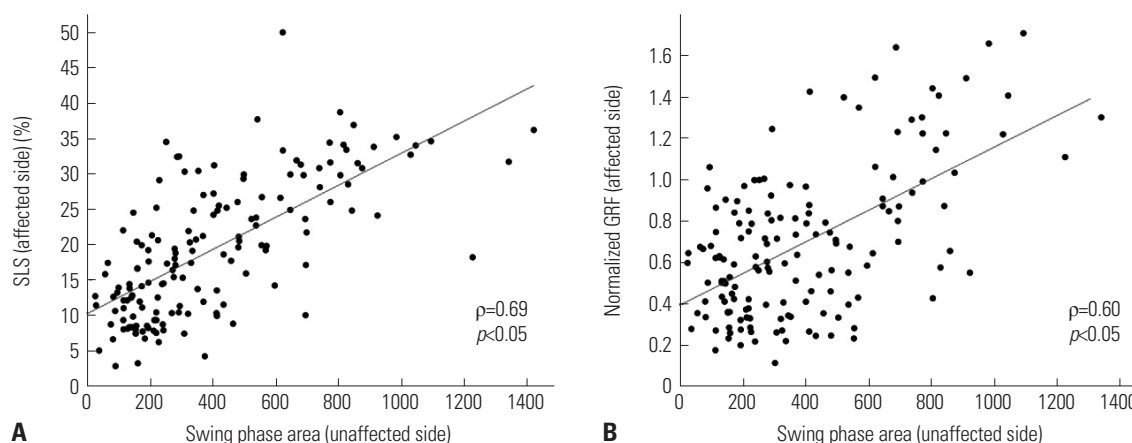
	Affected side	Unaffected side	Z score	p
Overall area				
BBS score	0.61*	0.55*	1.03	0.30
Gait speed (/s <sup>-1</sup> )	0.73*	0.66*	1.44	0.15
Swing phase area				
BBS score	0.61*	0.66*	-1.13	0.25
Gait speed (/s <sup>-1</sup> )	0.75*	0.81*	-1.80	0.07
Perimeter				
BBS score	0.42*	0.34*	1.02	0.30
Gait speed (/s <sup>-1</sup> )	0.56*	0.39*	2.34	0.02 <sup>†</sup>
Swing phase perimeter				
BBS score	0.60*	0.66*	-1.35	0.17
Gait speed (/s <sup>-1</sup> )	0.76*	0.80*	-1.20	0.23

BBS, Berg Balance Scale; Gait speed, normalized by leg length.

\* $p<0.05$  for significantly correlated cyclogram parameters with clinical parameters; <sup>†</sup> $p<0.05$  for differences in correlation between the affected and unaffected sides).

**Table 3.** Average Coefficient of Variation of the Cyclogram Parameters for the Affected and Unaffected Sides in 19 Patients with More Than Five Gait Cycles Per Leg

	Area	Swing phase area	Perimeter	Swing phase perimeter
Affected side	46.23	63.65	14.52	13.29
Unaffected side	26.01	38.09	9.51	7.51



**Fig. 2.** Correlation between the swing phase area of the unaffected side and SLS (A) and normalized GRF (B) of the affected side. SLS, single limb support; GRF, ground reaction force.

**Table 4.** Correlation Coefficient Comparison between the Swing Phase Area of the Affected and Unaffected Sides in Stiff-Knee Gait Group (A) and Severe Spasticity Group (B)

	Affected side	Unaffected side	Z score	p
<b>(A) Stiff-knee gait group</b>				
Participants with stiff-knee gait (n=69)				
BBS score	0.36	0.56	-2.00	0.04*
Leg length-normalized gait speed (/s <sup>-1</sup> )	0.37	0.61	-2.47	0.01*
Participants without stiff-knee gait (n=83)				
BBS score	0.53	0.62	-1.35	0.17
Leg length-normalized gait speed (/s <sup>-1</sup> )	0.71	0.81	-2.04	0.04*
<b>(B) Severe spasticity group</b>				
Participants with severe spasticity (n=63)				
BBS score	0.37	0.57	-1.96	0.04*
Leg length-normalized gait speed (/s <sup>-1</sup> )	0.40	0.63	-2.35	0.01*
Participants with mild or no spasticity (n=89)				
BBS score	0.53	0.62	-1.40	0.16
Leg length-normalized gait speed (/s <sup>-1</sup> )	0.71	0.81	-2.12	0.03*

BBS, Berg Balance Scale; MAS, Modified Ashworth Scale.

The difference in correlation coefficients was analyzed using Steiger’s Z test, and the significance is reported with Z-scores and p-values.

\*p<0.05. Severe spasticity was defined as MAS score of ≥2 in at least one of the hip flexor/extensor or knee flexor/extensor muscles of the affected side.

previous study reported that insufficient hip and knee flexion is a characteristic feature during the swing phase.<sup>28</sup> Additionally, the ROM of the hip and knee joints during the swing phase is driven principally by the individual’s muscular strength and spasticity, whereas during the stance phase, joint motion is more significantly affected by the magnitude and direction of the GRF. For instance, spasticity of the ankle plantarflexors during the stance phase can shift the GRF vector anterior to the knee joint,<sup>29,30</sup> contributing to abnormal knee kinematics such as genu recurvatum. Therefore, the swing phase component of the hip–knee cyclogram, which reflects voluntary movement with minimal influence from GRF-related external forces, may demonstrate a stronger association with clinical parameters.

The cyclogram parameters of both the affected and unaffected sides were associated with clinical parameters. In the affected side, reduced ROM of the hip and knee joints may be a direct cause of decreased swing phase area. However, the reduced swing phase area of the unaffected side was unlikely due to weakness or spasticity of the unaffected side. The reduced weight-bearing on the affected side likely shortened its SLS phase, which might decrease the swing phase duration and joint ROM on the unaffected side. This was supported by the finding that the swing phase area of the unaffected side demonstrated a moderately strong correlation with the SLS phase ratio and the weight-bearing ability on the affected side measured as GRF using the force plate. In patients with post-stroke hemiplegia, the weight-bearing capacity of the affected side is essential for maintaining proper locomotion and balance.<sup>31,32</sup> Reduced weight-bearing ability on the affected side leads to decreased SLS and compensatory increased weight-bearing on the unaffected side.<sup>33,34</sup> Previous studies recommended that rehabilitation strategies should emphasize reducing the SLS

time on the unaffected side while encouraging weight bearing on the affected side.<sup>35</sup> However, the direct assessment of the GRF during gait is significantly challenging. While using a force plate remains the gold standard method for measuring weight bearing, it has notable limitations related to time and space constraints. The swing phase of the unaffected side, which indirectly reflects the weight-bearing capacity of the affected side, may serve as a practical monitoring tool for evaluating changes in the weight-bearing function of the affected side.

In addition to its role in assessing the weight-bearing capacity of the affected side, the cyclogram of the unaffected side offers further advantages. It exhibited more consistent results compared to the affected side. Specifically, the mean Euclidean distance from the average trajectory was shorter on the unaffected side, indicating more stable and repeatable movement patterns. Furthermore, the CAV was lower on the unaffected side, suggesting lower variability in joint coordination. As a quantitative measure, CAV reflects the variability in coordination between two joint segments during movement and is calculated as the standard deviation of the coupling angle, which represents the orientation of the vector formed by two joint angles (e.g., hip and knee) over time.<sup>27</sup> Therefore, the lower CAV observed on the unaffected side indicates more consistent and coordinated joint motion compared to the affected side. Owing to synergistic movements and reduced selective motor control, the kinematics of the affected side showed significant variability across gait cycles. In contrast, the kinematics of the unaffected side were more consistent even in hemiplegic gait caused by stroke. Due to these factors, the coefficient of variation of the cyclogram parameters on the unaffected side was found to be smaller than that on the affected side (Table 4). Therefore, observing the unaffected side may help yield more

consistent results in evaluating balance control and gait functions. However, as the analysis was limited to 19 patients with more than five gait cycles, further studies are warranted to validate these findings.

Focusing on the unaffected side may offer clinical or analytical advantages, especially in a subgroup of patients with a stiff-knee gait and severe spasticity. In that subgroup, the cyclogram of the unaffected side demonstrated a stronger correlation with the BBS score and leg length-normalized gait speed than that of the affected side. A stiff-knee gait, characterized by limited knee flexion during the swing phase, is common in patients with stroke and is associated with muscle weakness and spasticity. This gait pattern usually reduces gait speed and step length, possibly because of compensatory rectus femoris contraction to counteract hip flexor weakness<sup>1,23</sup> or insufficient ankle push-off on the affected side.<sup>24</sup> Since stiff-knee gait restricts knee ROM, it complicates the differentiation of patients with stroke based on cyclogram analysis, which represents ROM during gait. Similarly, in a subgroup of patients with severe spasticity, the swing phase of the unaffected side showed a stronger correlation with the BBS score and leg length-normalized gait speed than that of the affected side. Although previous studies have shown that spasticity does not directly cause complications in gait and balance function in patients post-stroke,<sup>36</sup> it could lead to spastic synergistic patterns during gait<sup>37</sup> and the abnormal activation of the lower extremity muscles, which increase hip and knee extension during gait.<sup>38</sup> This abnormal muscle activation, which may cause reduced ROM owing to severe spasticity, complicates functional differentiation based on cyclogram analysis. In patients with reduced ROM, such as those with a stiff knee gait or severe spasticity, analyzing the cyclogram of the unaffected side may offer valuable and reliable information instead of focusing only on the affected side.

The recent rapid advancements in technologies, such as wearable sensors and markerless motion capture from 2D videos, along with a growing interest in real-world activity monitoring and digital healthcare, have underscored the critical significance of developing digital biomarkers for activity and gait function monitoring in out-of-hospital settings.<sup>10,39</sup> Traditional hospital-based assessments are valuable; however, they usually fail to capture the complete range of an individual's functional abilities in the natural environment. Digital biomarkers derived from simple kinematic data provide valuable information to address this gap, enabling the continuous real-world monitoring of gross motor and gait functions.

This retrospective study has some limitations. First, it did not account for the participants' demographic characteristics, such as sex, age, or brain lesion location, which could influence gait and balance outcomes. Second, although we identified correlations between the cyclogram parameters of the affected and unaffected sides with the BBS score and leg length-normalized gait speed, we did not develop a predictive model to estimate gait and balance function based on these parameters. Third, we

did not evaluate changes in cyclogram parameters before and after rehabilitation or treatment, limiting our ability to assess the impact of interventions on gait and balance. Additionally, while we propose cyclogram parameters as potential digital biomarker candidates that can be obtained using kinematic data from IMUs or 2D video markerless motion capture algorithms, we used kinematic data acquired retrospectively through a marker-based motion capture system. Although this approach provided high-quality data, it limits the immediate applicability of our findings to more accessible and scalable assessment methods.

Future studies should explore the feasibility of deriving cyclogram parameters using more affordable and accessible motion capture technologies, such as wearable sensors or markerless systems, to enhance the clinical utility of these digital biomarkers.

This study proposes a novel approach for assessing gross motor, gait, and balance function in post-stroke patients using only hip and knee kinematic data during gait, which can be easily obtained from IMUs or 2D videos in out-of-hospital settings. This study highlighted the function of the unaffected side, which is usually overlooked in traditional assessments of hemiplegic gait. Especially for patients exhibiting a stiff-knee gait or severe spasticity, focusing on the swing phase of the unaffected side offers valuable insights into the assessment of gait and balance function, indirectly reflecting the weight-bearing ability of the affected side.

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## AUTHOR CONTRIBUTIONS

**Conceptualization:** Jehyun Yoo and Dong-wook Rha. **Data curation:** Jehyun Yoo. **Formal analysis:** Jehyun Yoo and Dong-wook Rha. **Funding acquisition:** Dong-wook Rha. **Investigation:** Jehyun Yoo and Dong-wook Rha. **Methodology:** Jehyun Yoo and Dong-wook Rha. **Project administration:** Jehyun Yoo. **Resources:** Juntaek Hong, Yebin Cho, and Jeehee Lee. **Software:** Jeehee Lee and Jehyun Yoo. **Supervision:** Dong-wook Rha, Deog Young Kim, and Juntaek Hong. **Validation:** Jehyun Yoo and Dong-wook Rha. **Visualization:** Jehyun Yoo. **Writing—original draft:** Jehyun Yoo. **Writing—review & editing:** Dong-wook Rha and Deog Young Kim. **Approval of final manuscript:** all authors.

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