Biomechanical Analyses of Gait and Balance in Patients with Subacute Stroke

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Article

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Abstract

Objective: Stroke patients may have balance and gait disturbances due to decreased muscle strength and loss of proprioception. Although previous studies have evaluated balance, walking ability, and functional status of stroke patients, studies that quantitatively evaluate these problems and clarify the correlation between each parameter are insufficient. The purpose of this study was to measure the biomechanical gait parameters of subacute stroke patients and investigate their association with balance and function.

Method: A cross-sectional study was conducted on patients admitted with stroke as the main diagnosis between November 2020 and November 2021. Functional evaluation was performed using the Korean version of the Modified Barthel Index (K-MBI) and the Short Physical Performance Battery (SPPB); balance was evaluated using Berg balance scale (BBS), Trunk Control Test (TCT), and Trunk Impairment Scale (TIS). Quantitative gait parameters were measured using the Zebris gait analysis system. Bilateral hand grip strength, and bilateral knee extension and flexion strength were measured using a dynamometer. The correlation between each evaluation item was analyzed using Spearman's correlation analysis.

Results: Analysis confirmed a strong positive correlation between K-MBI and SPPB, indicators of functional status, and BBS, TIS, and TCT, indicators of balance. Grip, knee extension, and knee flexion strength of the hemiplegic side were positively correlated with overall balance and functional status. The hemiplegic side showed a shorter stance phase and a longer swing phase, and these values showed a significant correlation with functional status. Step length, step time, and gait line length were significantly correlated with balance.

Conclusion: It may be helpful to focus on measuring and correcting the center of pressure and stance phase of the hemiplegic side during gait for balance and functional status improvements. Quantitative biomechanical gait analysis may be helpful in assessing balance and functional status in patients with subacute stroke.

1. Introduction

Stroke is the leading cause of death and disability in adults worldwide [1]. Stroke patients may have balance and gait disturbances due to decreased muscle strength and loss of proprioception in the lower extremities [2]. A balance problem is one of the major issues that reduces the quality of life after stroke [3]. It has been reported that approximately 83% of patients suffer from balance problems after a stroke [4], and approximately 63% of acute and subacute stroke patients experience gait disturbance [5]. Impairment of gait and balance after stroke often results in falls and fall-related injuries [6]. Therefore, restoring independent mobility with a stable gait pattern is one of the main goals of stroke rehabilitation [7, 8].

Gait analysis is used in stroke patients to identify gait disorders, determine the appropriate treatment, and evaluate the effectiveness of treatment [9]. Stroke patients may have asymmetry in stride length and speed when walking [10]. Asymmetrical gait may cause secondary damage by increasing weight bearing on the uninvolved lower extremity [11]. An asymmetric gait pattern after stroke is related to minimizing the single-support time of the involved limb in order to maintain a more stable double-support phase [12]. Some studies evaluated balance in patients with hemiplegia by analyzing center of pressure (COP) fluctuations while standing, and confirmed that the COP of stroke patients was biased to the unaffected extremities, and the fluctuation of the COP was larger than normal [13, 14].

Although previous studies have evaluated the balance, walking ability, and functional status of stroke patients [15–17], studies that quantitatively evaluate these problems and clarify the correlation between each parameter are insufficient. The purpose of this study was to measure the biomechanical gait parameters of subacute stroke patients and investigate their association with balance and function.

2. Methods

Subjects

A cross-sectional study was conducted on patients admitted with stroke as the main diagnosis to the Department of Rehabilitation Medicine, Kyung Hee University Hospital, Gangdong, between November 2020 and November 2021. Inclusion criteria were: (1) adults ≥ 18 years, (2) patients with hemiplegia and within 6 months of stroke onset, (3) those who scored above level 2 out of 5 in a manual muscle test, (4) those with cognitive function sufficient to understand the study, and (5) those who could be evaluated for gait analysis and balance. Exclusion criteria were: (1) age < 18 years, (2) patients with cerebral palsy, traumatic brain injury, and cranial nerve diseases, and (3) patients with severe functional deterioration that would make analyzing gait and evaluating balance difficult.

Clinical assessment

Functional status was assessed using the Korean version of the Modified Barthel Index (K-MBI) and Short Physical Performance Battery (SPPB).

The K-MBI evaluates a patient's degree of dependence when performing activities of daily living in five categories: fully independent, minimal help required, moderate help required, substantial help required, and inability to perform tasks. The evaluation consists of 10 areas: personal hygiene, bathing, feeding, toileting, stair climbing, dressing, bowel control, bladder control, ambulation, wheelchair or chair/bed transfer; complete dependence is scored as 0 points, and complete independence is scored as 100 points.

The SPPB measures balance, walking speed, and rising from a chair to objectively evaluate the physical function of the elderly. The sense of balance is determined by whether tandem, semi-tandem, and side-by-side stances can be maintained for more than 10 s. Walking speed is determined by the seconds that it takes to walk 4 m, and rising from a chair is assessed by the time it takes to repeat standing and sitting five times. Each evaluation is scored 4 points per item, with a maximum of 12 points.

In addition, as a quantitative strength test, the hand grip strength, and the strength of the extensor and flexor muscles of the knee joint of the hemiplegic and non-hemiplegic sides were measured using a dynamometer. To evaluate flexibility, the sit and reach test was performed, which measures the maximum length that the arm can be extended forward when sitting on the floor with the legs extended.

Balance

Balance was assessed using the Berg balance scale (BBS), Trunk Control Test (TCT), and Trunk Impairment Scale (TIS).

BBS is a tool for objectively evaluating static and dynamic balance in various postures. Fourteen items are applied to daily life, such as sitting, standing, and changing posture, with a score of 0 to 4 for each item, and a total score of 0 to 56. The higher the score, the higher the level of balance, and independent walking is expected.

The TCT is a tool used to evaluate the trunk control of stroke patients. It consists of four items: rolling to the weak side, rolling to the strong side, balance in a sitting position, and sitting up from lying down. Each item is scored from 0 to 25, with a higher score indicating better trunk control. The maximum score possible is 100 points.

The TIS includes three subscales: static sitting balance (3 items), dynamic sitting balance (10 items), and coordination (4 items), with a maximum score of 7, 10, and 6, respectively. The total TIS score ranges from 0 to 23, and the higher the score, the better the trunk control.

Gait analysis

The quantitative gait parameters of the patients were measured using the Zebris FDM-T Treadmill (Zebris Medical GmbH, Germany). The machine has 5370 miniature pressure sensors under the treadmill belt, allowing it to analyze the pressure distribution under the feet while standing or walking. The participants were instructed to keep their gaze facing the front. After a 1 min warm-up, participants walked on the treadmill at a speed of 1 km/h for 30 seconds (Fig. 1).

The description of each parameter used in the gait analysis is as follows.

Foot rotation [°]: Describes the angle between the longitudinal axis of the foot and the running direction. (Negative value = inward rotation, positive value = outward rotation)

Step width [cm]: Describes the distance between the right and left feet.

Step length [cm]: Describes the distance between the heel contact of one side of the body and heel contact of the contralateral side.

Step time [s]: Describes the phase within a gait cycle between the heel contact of one side of the body and the heel contact of the contralateral side.

Stance phase [%]: Describes the phase of a gait cycle in which the foot is in contact with the ground.

Loading response phase [%]: Describes the phase between the initial ground contact and the contralateral toe off.

Mid-stance phase [%]: Describes the contralateral toe-off phase and transfer of the body's center of gravity over the weight-bearing foot.

Pre-swing phase [%]: Describes the phase during a gait cycle that begins at the contralateral initial contact (when the heel of the contralateral side touches the ground) and ends at toe off of the viewed side of the body.

Swing phase [%]: Describes the phase of a gait cycle during which the foot has no contact with the ground.

A butterfly diagram analyzed the course of the center of pressure (COP) during the selected step cycles. When considering the double-stance phase and load transfer, a typical butterfly diagram of the force application points was produced (Fig. 2).

Gait line length: This parameter is characterized by the position of the center of pressure (COP). Only the ground contacts of one side of the body were considered. The parameter covered the progression of the COP of all the steps recorded of one side of the body.

Single support line: This parameter is the length of the movement of the COP during single-leg support.

Anterior/posterior position: This parameter describes the shift forward or backward of the COP intersection point in chronological sequence, taking all the steps into consideration. The initial or zero position is the rearmost place where the heel contacts the ground.

Lateral symmetry: This parameter describes the left/right shift of the COP intersection point in chronological sequence, considering all the steps. A negative value indicates a shift to the left, and a positive value indicates a shift to the right. The initial or zero position is shown as the central point of the illustration.

Statistical analysis

Statistical analysis was performed using SPSS 25.0 version for Windows. Because of the high multicollinearity between independent variables, there was a limitation in implementing multivariate linear regression, and the correlation between each evaluation item was analyzed using Spearman correlation analysis. A p-value < 0.05 was considered statistically significant, $r = 0.1–0.3$ was interpreted as a weak linear relationship, r = 0.3–0.7 as a moderate linear relationship, and r = 0.7 or higher as a strong linear relationship.

3. Results

Characteristics of participants

A total of 43 patients with subacute stroke were included in the study, and the mean age was 63.77 years. Functional status and balance were evaluated using the K-MBI, SPPB, BBS, TCT, and TIS; hand grip strength, and strength of the extensor and flexor muscles of the knee joint were measured on the hemiplegic and non-hemiplegic sides. A total of 29 patients ((average age 64.10 years) completed biomechanical gait analysis using Zebris. Fourteen patients who had difficulty with gait on the treadmill were excluded from biomechanical gait evaluation and were classified as a limited-gait group. (Fig. 3) (Table 1).

Table 1
Characteristics of the subjects

Characteristics	Total patients (n = 43)	Gait group (n = 29)	Limited-gait group (n = 14)	p value
Demographics				
Age (years)	63.77 ± 11.70	64.10 ± 12.64	63.07 ± 9.85	0.790
Sex (male : female)	30 : 13	19 : 10	11 : 3	
Height (cm)	164.81 ± 7.55	164.31 ± 7.82	165.79 ± 7.18	0.560
Weight (kg)	65.96 ± 12.66	66.12 ± 13.08	65.66 ± 12.27	0.915
Stroke characteristics				
Hemiplegic side (Rt : Lt)	14 : 29	9 : 20	5 : 9	
NIHSS	7.55 ± 4.85	6.94 ± 4.52	8.55 ± 5.43	0.398
Motor function				
Hand grip strength (kg)				
Hemiplegic side	15.72 ± 12.90	18.87 ± 11.61	9.20 ± 13.42	0.019*
Non-hemiplegic side	25.05 ± 10.73	25.21 ± 9.24	24.72 ± 13.72	0.905
Knee extension strength (kg)				
Hemiplegic side	189.31 ± 107.06	221.34 ± 99.03	132.11 ± 99.53	0.011*
Non-hemiplegic side	245.78 ± 104.51	257.70 ± 102.18	224.49 ± 109.05	0.348
Knee flexion strength (kg)				
Hemiplegic side	52.49 ± 45.58	62.91 ± 44.74	34.73 ± 42.78	0.063
Non-hemiplegic side	80.95 ± 46.96	89.37 ± 47.21	65.90 ± 44.19	0.136
Sit and Reach (cm)	-2.54 ± 8.73	-2.72 ± 8.44	-2.19 ± 9.59	0.855
Cognition				
MMSE-K	25.28 ± 4.62	25.14 ± 5.22	25.57 ± 3.18	0.433

Abbreviations: NIHSS; National Institutes of Health Stroke Scale; MMSE-K; Korean version of the Mini Mental Status Evaluation; K-MBI, Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale. *p < 0.05, **p < 0.001.

Characteristics	Total patients (n = 43)	Gait group (n = 29)	Limited-gait group (n = 14)	p value
Functional Ability				
K-MBI	59.76 ± 20.99	69.86 ± 15.62	39.57 ± 14.97	< 0.001**
SPPB	5.56 ± 3.89	7.66 ± 2.70	1.21 ± 1.72	< 0.001**
BBS	30.88 ± 17.94	40.34 ± 11.42	11.29 ± 12.07	< 0.001**
TCT	69.33 ± 28.72	83.48 ± 17.52	40.00 ± 25.11	< 0.001**
TIS	14.44 ± 5.90	17.31 ± 4.44	8.50 ± 3.70	< 0.001**

Abbreviations: NIHSS; National Institutes of Health Stroke Scale; MMSE-K; Korean version of the Mini Mental Status Evaluation; K-MBI, Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale. *p < 0.05, **p < 0.001.

Biomechanical gait analysis

We compared the gait parameter values of the hemiplegic and non-hemiplegic sides of patients who completed the gait evaluation (Table 2). The hemiplegic side had a shorter stance phase, a shorter mid-stance phase, and a longer swing phase than the non-hemiplegic side. In addition, foot rotation was small, step length was long, gait line length of COP was short, and single support line of COP was short. However, according to the paired t-test, these differences were not statistically significant.

Table 2
Results of gait analysis using Zebris®

Variables	Hemiplegic side	Non-hemiplegic side	p value
Foot rotation(°)"	9.562	11.555	0.165
Step length(cm)"	23.069	21.793	0.370
Step time(s)	0.769	0.745	0.388
Phase Stance(%)	72.227	74.117	0.097
Phase Load response(%)	23.372	23.241	0.819
Phase Mid-stance(%)	25.841	27.517	0.150
Phase Pre-swing(%)	23.303	23.324	0.973
Phase Swing(%)	27.772	25.882	0.097
COP Gait line length(mm)	199.555	207.420	0.174
COP Single support line(mm)	55.637	63.400	0.094
COP Anterior/Posterior position(mm)	177.441		
COP Lateral symmetry(mm)	-1.179		
Abbreviation: COP, center of pressure. *p < 0.05, **p < 0.001.			

Association between functional status and balance

The correlation between patients' functional status and balance was analyzed (Table 3). A strong positive correlation ($p < 0.001$) was confirmed between K-MBI and SPPB, indicators of functional status, and BBS, TIS, and TCT, indicators of balance. As a result of subgroup analysis divided into the gait group that performed gait analysis on the treadmill and the limited gait group that did not perform gait analysis, no statistically significant values were found.

Table 3
Correlation between functional status and balance

Variables	BBS	TCT	TIS
K-MBI	r = 0.672 p = < 0.001**	r = 0.584 p = < 0.001**	r = 0.570 p = < 0.001**
SPPB	r = 0.773 p = < 0.001**	r = 0.581 p = < 0.001**	r = 0.635 p = < 0.001**

Abbreviations: K-MBI; Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale. *p < 0.05, **p < 0.001.

Association between functional status, balance, and gait parameters

Analysis of the association between the gait parameters and the evaluation of functional status and balance (Table 4) revealed a negative correlation between K-MBI and the foot rotation angle of the hemiplegic side (r=-0.437, p = 0.020), a negative correlation with the stance phase of the hemiplegic side (r=-0.382, p = 0.045), a negative correlation with the load response phase of the hemiplegic side (r=-0.375, p = 0.049), and a positive correlation with the swing phase of the hemiplegic side (r = 0.382, p = 0.045).

Table 4
Correlation between gait analysis and functional status, balance

Variables	K-MBI	SPPB	BBS	TCT	TIS
Foot rotation (°)					
Hemiplegic side	r=-0.437 p = 0.020*	r=-0.153 p = 0.429	r=-0.337 p = 0.074	r=-0.052 p = 0.787	r=-0.029 p = 0.883
Non-hemiplegic side	r=-0.016 p = 0.934	r=-0.074 p = 0.702	r=-0.251 p = 0.188	r = 0.012 p = 0.952	r=-0.062 p = 0.748
Step length (cm)					
Hemiplegic side	r=-0.104 p = 0.599	r = 0.008 p = 0.968	r = 0.431 p = 0.020*	r = 0.127 p = 0.510	r = 0.345 p = 0.067
Non-hemiplegic side	r = 0.174 p = 0.376	r = 0.129 p = 0.506	r = 0.329 p = 0.081	r = 0.079 p = 0.683	r = 0.292 p = 0.125
Step time (sec)					
Hemiplegic side	r=-0.217 p = 0.266	r=-0.107 p = 0.582	r = 0.374 p = 0.045*	r = 0.213 p = 0.267	r = 0.353 p = 0.060
Non-hemiplegic side	r=-0.124 p = 0.530	r=-0.040 p = 0.839	r = 0.457 p = 0.013*	r = 0.013 p = 0.948	r = 0.185 p = 0.336
Phase Stance(%)					
Hemiplegic side	r=-0.382 p = 0.045*	r=-0.389 p = 0.037*	r=-0.168 p = 0.385	r = 0.093 p = 0.630	r = 0.216 p = 0.261
Non-hemiplegic side	r=-0.349 p = 0.069	r=-0.395 p = 0.034*	r=-0.358 p = 0.056	r = 0.313 p = 0.099	r = 0.280 p = 0.141
Phase Load response(%)					
Hemiplegic side	r=-0.375 p = 0.049*	r=-0.396 p = 0.034*	r=-0.267 p = 0.161	r = 0.268 p = 0.160	r = 0.278 p = 0.145
Non-hemiplegic side	r=-0.345 p = 0.072	r=-0.360 p = 0.055	r=-0.204 p = 0.289	r = 0.147 p = 0.446	r = 0.302 p = 0.111
Phase Mid-stance(%)					
Hemiplegic side	r = 0.322 p = 0.094	r = 0.370 p = 0.048*	r = 0.416 p = 0.025*	r=-0.263 p = 0.168	r=-0.209 p = 0.276
Non-hemiplegic side	r = 0.325 p = 0.092	r = 0.376 p = 0.044*	r = 0.147 p = 0.446	r=-0.063 p = 0.745	r=-0.164 p = 0.395

Abbreviations: K-MBI; Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale; COP, center of pressure. *p < 0.05, **p < 0.001.

Variables	K-MBI	SPPB	BBS	TCT	TIS
Phase Pre-swing(%)					
Hemiplegic side	r=-0.276 p = 0.155	r=-0.306 p = 0.106	r=-0.233 p = 0.223	r = 0.207 p = 0.281	r = 0.260 p = 0.172
Non-hemiplegic side	r=-0.339 p = 0.077	r=-0.371 p = 0.047*	r=-0.256 p = 0.180	r = 0.255 p = 0.181	r = 0.271 p = 0.155
Phase Swing(%)					
Hemiplegic side	r = 0.382 p = 0.045*	r = 0.389 p = 0.037*	r = 0.168 p = 0.358	r=-0.093 p = 0.630	r=-0.216 p = 0.261
Non-hemiplegic side	r = 0.349 p = 0.069	r = 0.395 p = 0.034*	r = 0.358 p = 0.056	r=-0.313 p = 0.099	r=-0.280 p = 0.141
COP Gait line length(mm)					
Hemiplegic side	r=-0.013 p = 0.946	r=-0.044 p = 0.823	r = 0.346 p = 0.066	r = 0.266 p = 0.164	r = 0.386 p = 0.038*
Non-hemiplegic side	r=-0.040 p = 0.841	r = 0.000 p = 0.998	r = 0.475 p = 0.009*	r = 0.261 p = 0.171	r = 0.415 p = 0.025*
COP Single support line(mm)					
Hemiplegic side	r = 0.299 p = 0.122	r = 0.208 p = 0.279	r = 0.428 p = 0.020*	r=-0.033 p = 0.864	r = 0.092 p = 0.635
Non-hemiplegic side	r = 0.158 p = 0.423	r = 0.187 p = 0.331	r = 0.512 p = 0.004*	r=-0.092 p = 0.636	r = 0.027 p = 0.888
COP ant/post position (mm)	r=-0.088 p = 0.656	r=-0.078 p = 0.687	r = 0.350 p = 0.063	r = 0.012 p = 0.952	r = 0.135 p = 0.486
COP lateral symmetry (mm)	r = 0.053 p = 0.790	r = 0.098 p = 0.613	r=-0.209 p = 0.277	r = 0.412 p = 0.027*	r = 0.188 p = 0.329
Abbreviations: K-MBI; Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale; COP, center of pressure. *p < 0.05, **p < 0.001.					

SPPB was negatively correlated with the stance phase of the hemiplegic side and the non-hemiplegic side (r=-0.389, p = 0.037; r=-0.395, p = 0.034, respectively) Furthermore, there was a negative correlation between SPPB and the load response phase of the hemiplegic side (r=-0.396, p = 0.034), a positive correlation with the mid-stance phase of the hemiplegic side and non-hemiplegic side (r = 0.370, p = 0.048; r = 0.376, p = 0.044, respectively), a negative correlation with the pre-swing phase of the non-hemiplegic side (r=-0.371, p = 0.047), and a positive correlation with the swing phase of the hemiplegic side and non-hemiplegic side (r = 0.389, p = 0.037; r = 0.395, p = 0.034, respectively).

BBS was positively correlated with the step length of the hemiplegic side (r = 0.431, p = 0.020), with the mid-stance phase of the hemiplegic side (r = 0.416, p = 0.025), with step time of the hemiplegic side and non-hemiplegic side (r = 0.374, p = 0.045; r = 0.457, p = 0.013, respectively), with gait line length of the non-hemiplegic side (r = 0.475, p = 0.009), and with a single support line on the hemiplegic and non-hemiplegic sides (r = 0.428, p = 0.020; r = 0.512, p = 0.004, respectively).

TIS was positively correlated with the gait line length of the hemiplegic and non-hemiplegic sides (r = 0.386, p = 0.038; r = 0.415, p = 0.025, respectively). The TCT did not show a statistically significant correlation with the gait parameters.

Association between strength and balance

The correlation between hand grip strength, knee extensor and flexor muscle strength, functional status, and balance was analyzed (Table 5). Grip strength, and knee flexion and extension strength of the hemiplegic side in patients with subacute stroke showed a positive correlation with K-MBI, SPPB, BBS, TCT, and TIS. On the non-hemiplegic side, the only confirmed statistically significant correlation was that knee flexion strength showed a positive correlation with BBS. Flexibility on the non-hemiplegic side as evaluated by the sit and reach test did not show any correlation with functional status and balance.

Table 5
Correlation between motor strength and functional status, balance

Variables	K-MBI	SPPB	BBS	TCT	TIS
Hand grip strength					
Hemiplegic side	r = 0.345 p = 0.025*	r = 0.396 p = 0.009*	r = 0.301 p = 0.050*	r = 0.329 p = 0.031*	r = 0.361 p = 0.017*
Non-hemiplegic side	r = -0.060 p = 0.707	r = 0.108 p = 0.490	r = 0.093 p = 0.553	r = 0.129 p = 0.411	r = 0.094 p = 0.550
Knee extension strength					
Hemiplegic side	r = 0.438 p = 0.006*	r = 0.442 p = 0.005*	r = 0.369 p = 0.021*	r = 0.415 p = 0.009*	r = 0.403 p = 0.011*
Non-hemiplegic side	r = 0.225 p = 0.174	r = 0.212 p = 0.195	r = 0.249 p = 0.126	r = 0.260 p = 0.110	r = 0.140 p = 0.396
Knee flexion strength					
Hemiplegic side	r = 0.488 p = 0.002*	r = 0.380 p = 0.017*	r = 0.325 p = 0.044*	r = 0.333 p = 0.038*	r = 0.332 p = 0.039*
Non-hemiplegic side	r = 0.282 p = 0.086	r = 0.283 p = 0.081	r = 0.327 p = 0.042*	r = 0.288 p = 0.076	r = 0.261 p = 0.108
Sit and reach	r = -0.056 p = 0.726	r = -0.064 p = 0.692	r = -0.171 p = 0.284	r = 0.088 p = 0.583	r = 0.069 p = 0.666

Abbreviations: K-MBI; Korean version of the Modified Barthel Index; SPPB, Short Physical Performance Battery; BBS, Berg balance scale; TCT, Trunk Control Test; TIS, Trunk Impairment Scale. *p < 0.05, **p < 0.001.

4. Discussion

In this study, hand grip strength, knee flexion and extension strength on the hemiplegic side were positively correlated with functional status and balance. Hand grip strength, along with Skeletal Muscle Index (SMI), is a major indicator of sarcopenia. According to Park et al., decreased hand grip strength in patients with subacute stroke had a negative effect on recovery of functional status, including the 6-minute walk test (6MWT), Timed Up and Go test (TUG), and K-MBI. In previous studies, the main muscles contributing to forward gait in healthy populations were identified as ankle dorsiflexors, hip flexors, and hip extensors [18]. Mentiplay et al. conducted a systematic review of the relationship between lower extremity muscle strength and walking speed in stroke patients. Their results revealed that ankle dorsiflexors contributing to forward walking showed a strong correlation with walking speed, but knee extensors showed a relatively poor correlation [19]. However, as it is known that the knee extensor plays a key role in maintaining postural stability and functional activities such as sit to stand [20], it can be inferred that the improvement of knee extension strength can have a positive effect on the improvement of function and balance. According to Cruz et al., lower extremity strength on the hemiplegic side in stroke patients was highly correlated with compensatory movement patterns during gait, and was associated with gait speed and compensatory pelvic movement [21].

According to Lopes et al., generally, in most patients the non-hemiplegic side leg has a longer total standing time than the hemiplegic side leg, and the hemiplegic side has a longer step length and a shorter stride length [22]. As a result of the biomechanical gait analysis conducted in the current study, we found that the non-hemiplegic side supported the body weight longer in the stance phase and for less time in the swing phase. This pattern is considered as a way to minimize single-support of the hemiplegic side limb and to provide more stable double support [12].

The main findings of this study were that the gait parameters measured using the Zebris FDM-T Treadmill were correlated with functional indicators such as K-MBI and SPPB, and balance indicators such as the BBS. The Zebris FDM-T Treadmill has been shown to be a valid and reliable measurement tool for gait and balance in previous studies [23]. Chang et al. confirmed that MBI and BBS scores were significantly correlated with gait speed and stance phase time of non-hemiplegic limbs in patients with hemiplegic stroke [24]. In the current study, it was confirmed that a shorter stance phase and a longer swing phase of the hemiplegic limb were associated with the MBI score. If single-support on the hemiplegic side is reduced, more stable gait is possible, and improvement in functional indicators such as MBI can be expected.

The center of pressure (COP) is defined as the center of all external forces acting on the sole surface, and is used to control balance, evaluate foot function, and evaluate the effectiveness of treatment [25]. When there was little fluctuation in the COP back and forth or left and right during walking, the symmetry was well maintained, so it was thought that good results would be obtained in the balance evaluation. However, a clear correlation was not found in this study. The gait line length of the COP is a value indicating the movement distance of the COP and is known to correspond to 83% of the total foot contact length [26], and the single support line is a value indicating the movement distance of the COP during single-leg support. These two values were positively correlated with BBS in both the hemiplegic and non-hemiplegic sides, and it was shown that patients who could walk while maintaining a larger COP trajectory scored higher in the balance assessment. In addition, step length and step time were also positively correlated with BBS, and it was found that if one step could be continued larger and longer at the same walking speed, a higher score was obtained in the balance evaluation.

In a previous study, the balance of stroke patients evaluated by BBS showed a good correlation with functional status evaluated by MBI, and TIS evaluation became a meaningful alternative for patients who had difficulty performing the BBS [27]. In this study, functional status was evaluated using the K-MBI and SPPB, and balance was evaluated by BBS, TIS, and TCT; a strong positive correlation was confirmed between these measures. This shows that balance assessment can be a good alternative to support functional assessment, and suggests that gait assessment and training to improve balance can also help improve function.

Our results imply that checking the quantitative biomechanical gait analysis for subacute stroke patients who can walk can be helpful in evaluating functional status and balance. In addition, it is necessary to recognize that strength training to improve hand grip strength, and knee flexion and extension strength of the hemiplegic side is essential. Finally, training to shorten the stance phase of the hemiplegic side may be helpful in improving functional status.

This study had several limitations. First, patients with severe motor and balance disorders were excluded because of the inability to perform gait evaluation on the treadmill. Second, the number of patients satisfying the inclusion criteria among the patients in our hospital was limited; therefore, there was a limit to evaluating a sufficient number of patients for statistical power. Third, for ease of measurement, walking on the treadmill was uniformly limited to a relatively slow speed of 1 km/h. This affected the evaluation of natural walking because the preferred walking speed for each patient could be different. Fourth, multivariate linear regression was limited due to the high multicollinearity between the independent variables. In addition, the correlation coefficient of the indicators showing a significant correlation was a moderate correlation of $r = 0.3–0.7$, not a strong correlation. While the gait parameter of the hemiplegic side was expected to affect the balance, additional research may be needed on the result that the parameter of the non-hemiplegic side is related to the balance. To overcome these limitations, further studies using a larger patient population and diverse biometric data are needed.

5. Conclusion

The results of this study imply that to improve balance and functional status in pa-tients with subacute stroke, rehabilitation should focus on increasing hand grip strength and knee flexion/extension strength. It may also be helpful to focus on measuring and correcting the COP and stance phase of the hemiplegic side during gait. Among the bal-ance evaluations, BBS is found to support functional status evaluation better than TCT and TIS. Quantitative biomechanical gait analysis may be helpful in assessing balance and functional status in patients with subacute stroke.

Declarations

Funding:

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Institutional Review Board Statement:

The study protocol was approved by the Institutional Review Board (IRB) of Kyung Hee University Hospital at Gangdong, Korea (IRB approval number: 2020-09-037).

Statement in the Methods:

All methods were performed in accordance with the relevant guidelines and regulations.

Informed Consent Statement:

Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest:

The authors declare no conflict of interest.

Data availability:

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author's Contributions:

Choi MK wrote the main manuscript text. Yoo SD supervised setting up the research plan. Kim MG and Kim JM prepared figures 1-3 and Chung SJ and Park EJ prepared tables 1-5. All authors read and approved the final manuscript.

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Figures

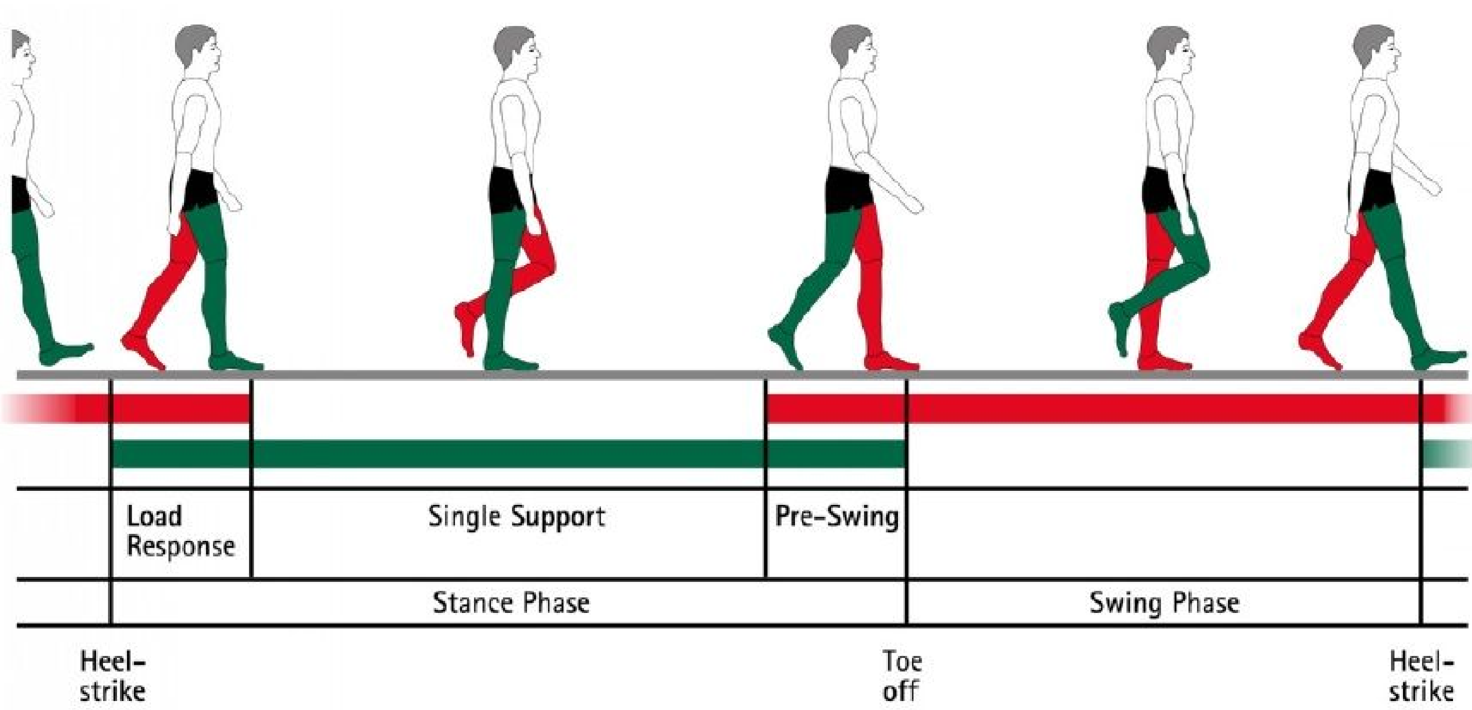

Figure 1

Gait parameters: Phase of gait cycle

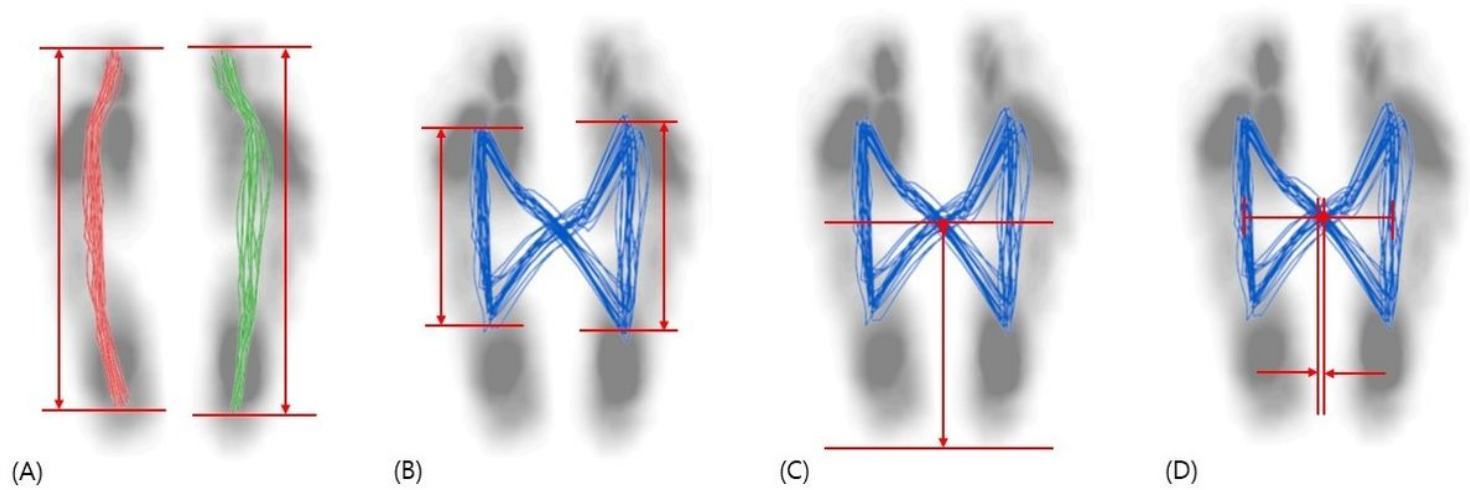

Figure 2

Gait parameters: Center of pressure (COP) parameters. (A) Gait line length (B) Single support line (C) Anterior/posterior position (D) Lateral symmetry

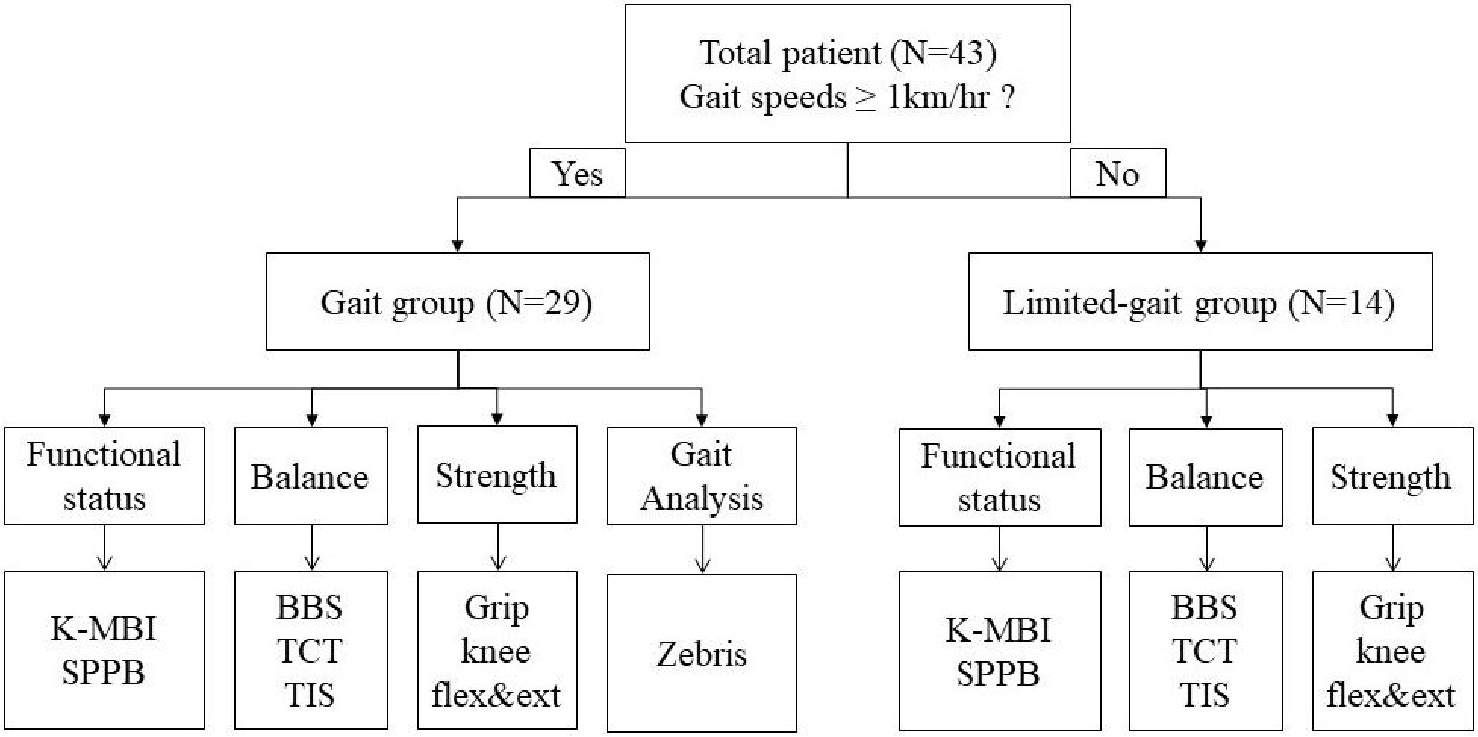

Figure 3

Flow chart for study subject selection