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For Patients with Stroke, Balance Ability Affects the Leg Extension Angle on the Affected Side

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Abstract: In stroke patients, the impact of lower limb physical functions on the leg extension angle remains unclear. We set out to reveal the physical impairments of the affected side in such patients that were associated with leg extension angle during gait. Twenty-six stroke patients walked for 16 m at a spontaneous speed. During walking, the leg extension angle and the increment of velocity during late stance, as an indicator of propulsion, were measured by inertial measurement units. The Berg balance scale (BBS), Fugl-Meyer assessment-lower limb, and motricity index-lower limb (MI-LL) were also evaluated. Stepwise multiple regression analysis was employed to reveal functions associated with the leg extension angle on the affected side. A path analysis was also used to confirm the relationship between the extracted factors, leg extension angle, and gait speed. Multiple regression analysis showed that the BBS was significantly related to the leg extension angle on the affected side ($p < 0.001$). Path analysis revealed that the leg extension angle was also indirectly affected by the MI-LL and that it affected gait speed via propulsion on the affected side. These findings could guide the prescription of effective gait training for improving gait performance during stroke rehabilitation.

Keywords: stroke; leg extension angle; balance; inertial measurement units; gait analysis

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1. Introduction

Walking is fundamental to daily life activities and it is associated with the quality of life for post-stroke patients [1,2]. Since many post-stroke patients have impaired gait performance, represented by decreased walking speed and asymmetrical patterns of spatiotemporal parameters and kinematics [3], recovery of the ability to walk is the most important goal in their rehabilitation programs [4]. Propulsion force, the anterior ground reaction force during late stance, is considered a significant indicator in post-stroke gait [5] and affects gait speed [6]. Propulsion deficits during gait negatively impact gait ability and are associated with physical inactivity and a sedentary lifestyle in stroke patients [7,8]. Propulsion deficits of the affected lower limbs, in particular, are correlated with slower walking speeds and a reduced ability to walk long distances [9,10]. Indeed, stroke patients with limited community ambulation have relatively low levels of paretic propulsion [11]. Therefore, improving the propulsion of the affected lower limb during gait is of paramount importance in stroke rehabilitation.

Leg extension angle indicates the lower extremity inclination angle during late stance and is related to the propulsion force during walking in stroke patients [12–14]. Previous studies have shown that the leg extension angle and propulsion force were decreased on the affected side compared with the non-affected side in the post-stroke gait [5]. An increase in the propulsion force on the affected side after gait training results in an increased gait speed in stroke patients [15]. Furthermore, the leg extension angle is associated with the 6-minute walk distance [16] and knee flexion angle during the swing phase [17]. Therefore, the leg extension angle on the affected side is a beneficial indicator of gait quality and the main target for gait training during stroke rehabilitation. The previous literature reports that the leg extension angle can be altered by gait training using bio-feedback, functional electrical stimulation, and treadmill exercises in post-stroke patients [18–21]. However, it remains unclear whether the physical function of the lower limb influences the leg extension angle.

Previous researchers have identified multiple factors that influence the ability of stroke patients to walk, such as the severity of paralysis, muscle strength, and cognitive impairment [22–24]. Importantly, the strongest predictor of walking ability, such as that required for community ambulation in stroke patients, is their ability to balance [24–29]. The Berg balance scale (BBS) is widely used to measure balancing ability in clinical practice [30]. The BBS is commonly used during inpatient rehabilitation and can predict the duration of hospitalization in stroke patients [31]. Thus, the ability to balance could be considered one of the most important factors in post-stroke gait, and it likely affects the leg extension angle during gait. Balancing ability may contribute to gait speed via its effects on the leg extension angle.

Understanding the relationship between the leg extension angle on the affected side, physical functions, such as balancing ability, and the severity of paralysis is critical for planning effective gait training programs that increase the leg extension angle and improve gait velocity in post-stroke gait. This study set out to clarify the physical impairments associated with the leg extension angle on the affected side during walking. We hypothesized that the balancing ability assessed by the BBS could predict the leg extension angle on the affected side during gait in stroke patients, and that the ability to balance influenced gait speed through its effects on the leg extension angle.

2. Materials and Methods

2.1. Participants

The participants of this cross-sectional study were 26 stroke patients (18 male; 14 left hemiparetic; age: 59.4 ± 14.6 years; time since stroke onset: 20.0 ± 23.1 months; Table 1). All participants except two used a cane and five used an ankle-foot orthosis. Participants were inpatients or outpatients receiving rehabilitation programs of physical therapy, occupational therapy, or speech therapy at the Fujimoto General Hospital, Miyazaki, Japan. Inclusion criteria: (1) a first unilateral stroke occurring ≥3 months before this study, (2) the capacity to walk independently without physical assistance for at least 16 m, and (3) otherwise medically stable. Exclusion criteria: (1) difficulty in understanding the experimental tasks due to cognitive impairment, and (2) a history of neurological disease or orthopedic conditions that could impair gait. All patients gave written informed consent prior to participation. The Ethics Committee of the Fujimoto General Hospital approved this study (approval number 177).

Table 1. Clinical characteristics of study participants.

Variable	Patients (n = 26)
Age (years)	59.4 ± 14.6
Sex (n): male/female	18/8
Height (cm)	163.2 ± 7.0
Weight (kg)	64.5 ± 9.8
Disease (n): hemorrhage/infarction	15/11
Time post-stroke (months)	20.0 ± 23.1
Affected side (n): right/left	12/14

Table 1. *Cont.*

Variable	Patients (n = 26)
T-cane (n)	24
Ankle foot orthosis (n)	21 (DF free and PF limitation: 16, DF free and PF braking: 5)
BRS (n)	III: 10, IV: 7, V: 6, VI: 3
FMA-LL (0–34)	23.3 ± 6.4
MI-LL (0–100)	54.2 ± 12.3
MAS knee flexion muscles (n)	0: 14, 1: 7, 1+: 4, 2: 1
MAS knee extension muscles (n)	0: 11, 1: 9, 1+: 5, 2: 1
MAS ankle PF muscles (n)	0: 3, 1: 4, 1+: 10, 2: 7, 3: 2
FIM walk (n)	5: 4, 6: 20, 7: 2
BBS (0–56)	45.0 ± 5.5
Gait speed (m/s)	0.48 ± 0.19

BRS: Brunnstrom recovery stage; FMA-LL: Fugl-Meyer assessment-lower limb; MI-LL: motricity index-lower limb; MAS: modified Ashworth scale; DF: dorsiflexion; PF: plantarflexion; FIM: functional independence measurement; BBS: Berg balance scale.

2.2. Clinical Assessment

Patients' ability to balance was evaluated using the BBS, a 14-functional balance test [30]. The BBS scores each item on a scale of 0–4 with a total of 56 points, with higher scores representing superior balance. The BBS is a reliable measure of balance in post-stroke patients with high repeatability and sensitivity [31].

The Fugl-Meyer assessment-lower limb (FMA-LL) was used to evaluate lower limb motor dysfunction of the affected limb [32]. The maximum score on the FMA-LL is 34 points. The evaluation consisted of assessments of voluntary movement, coordination, velocity, and reflex action. In addition, the Brunnstrom recovery stage (BRS) was used to assess the degree of motor dysfunction [33]. The BRS grades the degree of motor dysfunction in stages ranging from I to VI.

The muscle strength of the affected lower extremity was assessed with the motricity index-lower limb (MI-LL) [34]. The MI-LL is a feasible, simple, and brief measure of general motor function in the lower limbs that can predict post-stroke mobility outcomes. The spasticity of the muscles in the lower limb of the affected side was assessed with the modified Ashworth scale (MAS) [35]. Performance during the gait of daily living was assessed by functional independence measurement (FIM) [36]. A clinical assessment of gait measurements was performed within seven days by an independent physical therapist to avoid any possible bias.

2.3. Gait Measurement

Participants walked along a 16-m straight test track at a spontaneous speed with their normal walking aids. Gait speed in the middle of 10 m was measured using a stopwatch. Gait kinematics and segment acceleration were measured using the five inertial measurement units (IMUs; MTw Awinda, Xsens, Enschede, The Netherlands) attached using elastic belts to the sacrum, bilateral anterior thigh, and shank (Figure 1). IMUs were comprised of a 3D gyroscope, an accelerometer, and a magnetometer and could calculate the 3-axis acceleration and Euler angles in a laboratory coordinate system with a sampling frequency of 100 Hz. IMUs are widely used tools in healthcare [17,37–39], with high reliability [40], and are fixed along the frontal plane where possible. Software (MT manager 4.7.2, Xsens, Enschede, The Netherlands) was used to adjust the vertical axis of the IMU to align with gravity during static stance. Prior to gait measurement, the inclination angles and the length of the thigh and shank during static standing were measured to adjust for the alignment reset.

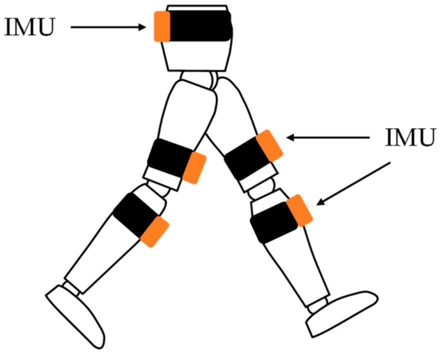

Figure 1. Position of inertial measurement units (IMUs). IMUs were fixed to the sacrum, the bilateral anterior thigh, and shank.

2.4. Data Analysis

The middle 10 walking strides were analyzed. The angle and acceleration data obtained from IMUs were filtered using the Butterworth low-pass filter with a 10 Hz and 20 Hz cutoff frequency, respectively. Leg extension was calculated from the inclination angles obtained from IMUs during late stance on bilateral lower limbs. The definition of the leg extension angle was: the angle of the laboratory's vertical axis and a line linking the lateral malleolus and the greater trochanter in the sagittal plane [41]. The leg extension angle was estimated based on the position of the ankle joint relative to the hip joint in the sagittal plane from the inclination angle obtained from the IMU and the vector of the thigh and shank segments coordinated by the segment lengths, as previously reported [37]. The peak leg extension angle during late stance was used for further analysis. Meanwhile, the increment in the velocity of the trunk during late stance was estimated from anterior acceleration obtained from the IMU to indicate propulsion force. Incremental velocity of the trunk is associated with the anterior ground reaction force during late stance [37]. The data were processed with MATLAB R2018b (MathWorks Inc., Natick, MA, USA).

2.5. Statistical Analysis

The average results from 10 strides were analyzed. Prior to analysis, the Shapiro–Wilk test was used to assess the normality of the data distribution. First, differences in the leg extension angle and the increment of velocity between the affected and non-affected sides were compared with the paired t-test. Consecutively, the relationships between the leg extension angle on the affected side and BBS, FMA-LL, MI-LL, velocity increments on the affected side, and gait velocity were investigated with Pearson's or Spearman's rank correlation coefficient. In addition, a multiple linear regression was performed to determine factors related to the leg extension angle on the affected side. A stepwise procedure was utilized, with variables included in the model at a significance level of $p < 0.05$ and excluded from the model at $p > 0.10$. To avoid multi-collinearity, one of the two factors with a high correlation (>0.8) or a high variance inflation factor (>3.33) was excluded from the later analysis [42]. In addition, a path analysis based on the exploratory regression analysis was used to confirm the relationship among the extracted factors, leg extension angle, and gait speed. The exploratory regression analysis was conducted sequentially to identify the factors related to gait speed according to the methods described above. The leg extension angle and the increment of velocity on the unaffected lower limb were also included in the exploratory analysis. In path analysis, the model fit adequacy was determined using the chi-square test (a non-significant chi-square value indicates a good fit); comparative fit index (CFI, >0.95 indicates a good fit); goodness-of-fit index (GFI, >0.90 indicates a good fit); and root mean square error of approximation (RMSEA, <0.05 indicates a good fit) [43].

Statistical Software R 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria) and AMOS 28.0 for Windows (IBM Japan, Tokyo, Japan) were utilized for all statistical analyses. Statistical significance was set at $p < 0.05$, and values are expressed as average ± standard deviation.

3. Results

The BBS, FMA-LL, and MI-LL in the study participants were assessed to be 45.0 ± 5.5 points, 23.3 ± 6.4 points, and 54.2 ± 12.3 points, respectively, and gait speed was 0.48 ± 0.19 m/s (Table 1). Addressing the affected side, the leg extension angle (10.0 ± 7.1°, $p = 0.009$) and the velocity increment at the late stance (0.18 ± 0.09 m/s, $p < 0.001$) were significantly lower than those on the non-affected side (leg extension angle, 14.1 ± 4.8°; velocity increment, 0.32 ± 0.11 m/s).

The correlation between the leg extension angle, BBS, FMA-LL, MI-LL, velocity increment of the affected side, and gait speed are given in Table 2. The leg extension angle showed a significant positive correlation with BBS ($r = 0.757$, $p < 0.001$), FMA-LL ($r = 0.393$, $p = 0.047$), MI-LL ($r = 0.532$, $p = 0.005$), velocity increment ($r = 0.863$, $p < 0.001$), and gait speed ($r = 0.732$, $p < 0.001$) (Table 2).

Table 2. Correlations among leg extension angle, physical impairments, and gait parameters on the affected side.

Variable	1	2	3	4	5	6
1. Leg extension angle	-	0.757 **	0.393 *	0.532 **	0.863 **	0.732 **
2. BBS		-	0.487 **	0.594 **	0.597 **	0.709 **
3. FMA-LL			-	0.793 **	0.109	0.605 **
4. MI-LL				-	0.399 *	0.619 **
5. Increment of velocity					-	0.622 **
6. Gait speed						-

* $p < 0.05$, ** $p < 0.01$. BBS: Berg balance scale; FMA-LL: Fugl-Meyer assessment-lower limb; MI-LL: motricity index-lower limb.

BBS, FMA-LL, and MI-LL were included in the multiple regression analysis to identify the factors determining the leg extension angle on the affected side (Table 3); BBS was the only factor that showed a significant association ($\beta = 0.757$, $p < 0.001$).

Table 3. Clinical factors associated with the leg extension angle on the affected side in stepwise multiple regression analysis.

Independent Variable	B	β	*t* Value	*p* Value	95% CI	VIF
BBS	0.984	0.757	5.675	<0.001	0.626–1.342	1.000

$R^2 = 0.555$ (F = 32.209, $p < 0.001$). B: unstandardized coefficient; β: standardized coefficient; CI: confidence interval; VIF: variance inflation factor; R^2: adjusted coefficient of determination; BBS: Berg balance scale.

The results of the path analysis based on an exploratory regression analysis (Appendix A, Tables A1–A4) were used to derive the model shown in Figure 2. The model fitted well (chi-square test: $\chi2 = 4.219$, df = 8, $p = 0.837$; CFI: 1.000; GFI: 0.949; RMSEA: < 0.001). The leg extension angle on the affected side was directly associated with BBS ($\beta = 0.757$, $p < 0.001$) and indirectly affected by MI-LL via BBS ($\beta = 0.668$, $p < 0.001$). The leg extension angle on the affected side modulated gait speed via the increment of velocity on the affected side ($\beta = 0.863$, $p < 0.001$). The BBS also directly affected the gait speed ($\beta = 0.356$, $p = 0.027$).

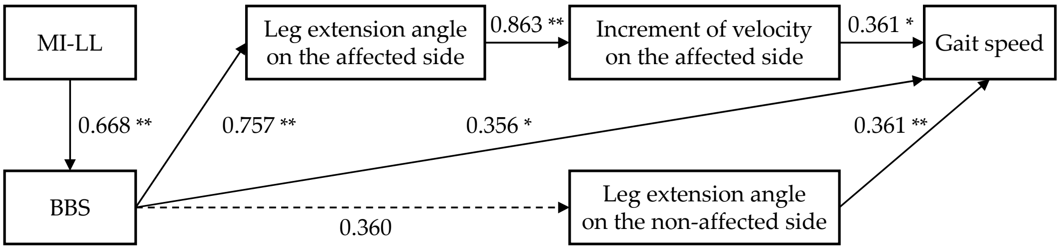

Figure 2. Path analysis for the effect of the Berg balance scale (BBS) and leg extension angle on gait speed. Numbers represent standardized coefficient values (β). Continuous arrows represent the statistically significant paths ($p < 0.05$), and dashed arrows represent non-significant paths. * $p < 0.05$, ** $p < 0.01$.

4. Discussions

We examined the physical impairments associated with leg extension angle during gait in patients, post-stroke. The present results demonstrated the association of leg extension angle with BBS, FMA-LL, and MI-LL. Consistent with our hypothesis, multiple regression analysis revealed that balancing ability, assessed by BBS, was a significant predictor of leg extension angle during gait in post-stroke patients. Our findings suggest that improving a patient's ability to balance would be useful in increasing the leg extension angle and improving gait speed in clinical practice. This novel study demonstrates the relationship between clinical physical impairment and leg extension angle.

Leg extension angle had a significant positive relationship with the BBS. Previous studies have reported that the ability to balance, as assessed by BBS, is associated with step length and gait speed in post-stroke patients [44–46]. Lopes et al. [47] reported that balancing ability, assessed by the velocity and sway area of the center of pressure in the upright standing position, significantly relates to stride length during gait in chronic stroke patients. Our findings are consistent with the reported evidence pertaining to stride length and indicate that balancing ability is associated with the leg extension angle. The BBS, which includes both static and dynamic tasks, was used to assess balancing ability in this study. Walking with a substantial leg extension angle requires adequate balance control to avoid body fluctuation; therefore, the BBS score is expected to modulate the leg extension angle of the affected side during post-stroke gait.

The leg extension angle also showed a significant positive relationship with the FMA-LL and MI-LL. Path analysis also showed that MI-LL indirectly impacted the leg extension angle on the affected side through balancing ability. There are inconsistent suggestions regarding the relationship between motor impairments of the affected lower limb and walking ability in patients, post-stroke. Previous studies report a significant relationship between walking speed and the muscle strength of an affected lower limb [48–50] and the severity of motor paralysis in stroke patients [51]. In addition, the motor function of the affected lower limb can be correlated with the leg extension angle [17] and spatiotemporal parameters, including cadence, step length, and stride length [52]. In contrast, other studies report that muscle strength is not significantly associated with gait parameters, including step length and gait ability (speed and distance) in stroke patients [53,54]. Mizuta et al. [55] reported that leg extension angles on the affected side were not consistent even with the same level of the FMA-LL, despite the correlation of the FMA-LL with gait speed. These contradictions might be explained by the indirect effect of motor function of the affected lower limb on the leg extension angle and gait speed observed in the model-derived path analysis. The effect of MI-LL on the leg extension angle of the affected lower limb and gait speed is likely elicited via BBS. Thus, although the FMA-LL and MI-LL are important factors in post-stroke gait, their effect on gait performance is limited.

Leg extension angle has an indirect effect on gait speed through the increment of velocity on the affected side. Foot position, relative to the pelvis (i.e., the leg extension angle), influences the forward propulsion of the center of mass (COM). Balasubramanian et al. [56] reported that foot placement relative to the pelvis in the sagittal plane is correlated with the propulsion on the affected side and step length asymmetry, suggesting a link between the leg extension angle and forward propulsion of the body COM during gait. Therefore, training to increase the leg extension angle on the affected side during gait is recommended as an essential component of the rehabilitation strategy targeting the improvement of gait speed in stroke patients.

Our findings examined the effects of motor function and balancing ability on the leg extension angle of the affected side, and could assist in the identification of target parameters during training to improve the leg extension angle in stroke patients. Path analysis revealed that the balancing ability had a direct effect on the leg extension angle and gait speed, while MI-LL indirectly affected the leg extension angle through the ability to balance. This contribution of the balancing ability on gait performance agreed with previous studies. Louie et al. [28] reported that the BBS at rehabilitation admission was a significant predictor of community ambulation speed at discharge. In addition, Liao et al. [29] reported that BBS was thought to be the only significant predictor of the 6-minute walk test at discharge. Therefore, stroke rehabilitation to improve the leg extension angle on the affected side during gait would require an improvement in balancing ability in addition to direct gait intervention and recovery of the affected lower limb function.

This study had several limitations. First, other factors that may affect overall gait function were not examined. For example, impaired somatosensation of the affected lower extremity and muscle strength of the unaffected side may affect leg extension angle during post-stroke gait. Second, utilization of walking aids, including ankle-foot orthoses or T-canes, could affect the leg extension angle and the ability to balance. A systematic review and meta-analysis showed that an ankle-foot orthosis can affect ankle and knee kinematics in post-stroke gait [57,58]. Third, the effect of balance exercises on leg extension angle was not analyzed in this study, owing to its cross-sectional nature. Finally, a biased ratio of stroke type compared with the common ratio and a large deviation of the time post-stroke were observed owing to the small sample size [59,60]. These might have caused some bias in our results and reduced the statistical power. Therefore, further studies addressing the above limitations are necessary to clarify the relationships between the leg extension angle during post-stroke gait and the balancing ability.

5. Conclusions

This study identified balancing ability, assessed by the BBS, as a significant predictor of leg extension angle on the affected side during post-stroke gait. Our findings indicate that the leg extension angle of the affected side increases with the increasing ability to balance. In clinical settings, training to improve balance, in addition to gait training, may be recommended to increase leg extension angle on the affected side during post-stroke gait. Finally, adequate leg extension angle might lead to increased walking speed and improved function of the affected lower limb. These findings could guide the prescription of effective gait training to achieve a safe and efficient gait during stroke rehabilitation.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of Fujimoto General Hospital (number 177, date of approval: 12 July 2018).

Informed Consent Statement: All participating patients gave written informed consent for the publication of their data.

Data Availability Statement: Data associated with the current study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Exploratory Regression Analysis

Results of the exploratory regression analysis of clinical factors associated with gait speed.

Table A1. Dependent variable: Gait speed. Independent variable: BBS, FMA-LL, MI-LL, leg extension angle, and increment of velocity on affected and non-affected sides.

Independent Variable	B	β	*t* Value	*p* Value	95% CI	VIF
BBS	0.012	0.356	2.361	0.027	0.001 to 0.023	1.672
Leg extension angle on the non-affected side	0.014	0.361	2.881	0.009	0.004 to 0.024	1.152
Increment of velocity on the affected side	0.710	0.361	2.479	0.021	0.116 to 1.304	1.561

$R^2 = 0.660$ (F = 17.177, $p < 0.001$).

Table A2. Dependent variable: Increment of velocity on the affected side. Independent variable: BBS, MI-LL, leg extension angle on the affected and non-affected side.

Independent Variable	B	β	*t* Value	*p* Value	95% CI	VIF
Leg extension angle on the affected side	0.012	0.863	8.386	<0.001	0.009 to 0.014	1.000

$R^2 = 0.735$ (F = 70.329, $p < 0.001$). FMA-LL was excluded due to high VIF (3.54).

Table A3. Dependent variable: Leg extension angle on the non-affected side. Independent variable: BBS, FMA-LL, MI-LL, leg extension angle on the affected side.

Independent Variable	B	β	*t* Value	*p* Value	95% CI	VIF
BBS	0.314	0.360	1.888	0.071	−0.029 to 0.656	1.000

$R^2 = 0.093$ (F = 3.565, $p = 0.071$).

Table A4. Dependent variable: BBS. Independent variable: FMA-LL, MI-LL.

Independent Variable	B	β	*t* Value	*p* Value	95% CI	VIF
MI-LL	0.298	0.668	4.394	<0.001	0.158 to 0.438	1.000

$R^2 = 0.423$ (F = 19.305, $p < 0.001$). Multiple regression analyses using a stepwise method. B: unstandardized coefficient; β: standardized coefficient; CI: confidence interval; VIF: variance inflation factor; R^2: adjusted coefficient of determination; BBS: Berg balance scale; FMA-LL: Fugl-Meyer assessment-lower limb; MI-LL: motricity index-lower limb.

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