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Original Research

Characteristics of Gait Event and Muscle Activation Parameters of the Lower Limb on the Affected Side in Patients With Hemiplegia After Stroke: A Pilot Study

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KEYWORDS
Electromyography;
Hemiplegia;
Logistic model;
Rehabilitation;
Stroke

Abstract *Objectives:* To confirm the characteristics of gait events and muscle activity in the lower limbs of the affected and unaffected sides in patients with hemiplegia.
Design: Cross-sectional study.
Setting: Motion analysis laboratory of the Wonkwang University Gwangju Hospital.
Participants: Outpatients, diagnosed with ischemic stroke more than 3 months and less than 9 months before participating in the study (N=29; 11 men, 18 women).
Interventions: Not applicable.
Main Outcome Measures: The gait event parameters and time- and frequency-domain electromyogram (EMG) parameters of the lower limbs of the affected and unaffected sides was determined using BTS motion capture with the Delsys Trigno Avanti EMG wireless system.
Results: The swing time, stance phase, swing phase, single support phase, and median power frequency of the gastrocnemius muscle showed a significant difference between the affected and

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List of abbreviations: EMG, electromyogram; GM, gastrucnemius medialis; MdPF, median power frequency; MPF, mean power frequency; PSD, power spectral density
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unaffected sides. Using a logistic regression model, the swing phase, single support phase, and median frequency of the gastrocnemius muscle were selected to classify the affected side.
Conclusion: The single support phase of the affected side is shortened to reduce load bearing, which causes a reduction in the stance phase ratio. Unlike gait-event parameters, EMG data of hemiplegic stroke patients are difficult to generalize. Among them, the logistic regression model with some affected side parameters expected to be set as the severity and improvement baseline of the affected side. Additional data collection and generalization of muscle activity is required to improve the classification model.

Walking is a representative dynamic function that the human body can perform and is the most basic function of body movement and behavior. The process of walking starts with the brain's cognitive intention to move: neuroelectric signals are generated to induce muscle contraction and relaxation, muscle activation causes the joints to move, the foot changes position, and a series of gait events—called swing and stance phases—are put into action.[1] Gait can vary in the presence of disease, with type of disease, severity, and duration of motor dysfunction or musculoskeletal disease affecting ambulatory patterns.[2]

In patients with hemiplegia after stroke, the affected muscles are weakened because of brain damage and accompanying sensorimotor impairments, while difficulties in motor control, spasticity, and proprioceptive deficits appear during gait.[3] Circumduction is a gait pattern in patients with hemiplegia where the pelvis is artificially raised, drawing the affected leg in a circle. This pattern arises because of weakness in the gluteus medius.[4] The unaffected side shows a decrease in swing time and step length, resulting from inter-limb asymmetry, that is representative of spatiotemporal characteristics. The asymmetrical gait characteristics of the affected and unaffected sides have been quantitatively identified as biomechanical variables.[5]

None of the muscles on the affected side are able to function normally, and neuromuscular activation is decreased, indicating a motor control disorder. Various studies have been conducted to determine the difference between the affected and unaffected sides of the lower extremities during walking in post-stroke patients.[5,6] One study compared the spatiotemporal parameters of hemiplegic gait by measuring trunk movements on the affected and unaffected sides [5]; another compared the differences between the affected and unaffected sides using the gait deviation index.[6] Several studies have compared the strength characteristics of the affected and unaffected-sides. Den Otter et al confirmed that, compared with the unaffected side, the single support phase of the affected-side and the duration of subphases of the gait cycle of the tibialis anterior were reduced.[7] Souissi et al confirmed the differences between the peak muscle force of the knee flexor, plantar flexor, and tibialis anterior in the braking phase, and the peak and mean muscle force of the quadriceps and plantar flexor in the propulsion phase.[8]

The affected and unaffected sides show clear differences. Moreover, the greater the motor function severity, the greater the difference in movement between the affected and unaffected sides of the lower extremity. Prior to treatment, the main characteristics of the affected and unaffected sides need to be identified[9], confirming the quantitative asymmetrical ratio is important for planning treatment strategies. For example, a treatment strategy must include modified constraint-induced movement therapy, where movement on the unaffected side is restricted and the affected lower extremity is both actively and passively exercised. Checking the type of gait characteristics of the affected side is necessary, even if brain imaging or visual diagnoses have been conducted for motor function severity classification. Additionally, planning of treatment strategies should take into consideration that the decrease in the independent variable of the affected side in a predictive model that combines these characteristics can indicate the degree of improvement when treatment is applied. This can be used to quantitatively confirm the adequacy of treatment and improvement of the patient.

In this study, the difference in motion and muscle activity characteristics between the affected and unaffected sides in patients with hemiplegia was quantitatively confirmed prior to collecting patient data from a large population at follow-up study. Logistic regression analysis was used to classify the affected and unaffected sides and, in so doing, we confirmed the possibility of developing a severity index for quantifying the characteristics of the affected side based on motion and muscle activity. Patients with hemiplegia after stroke display characteristics of hyperactive stretch, shortening, and lengthening contraction. We aimed to confirm the average characteristics of all participants prior to classification according to muscle activity characteristics so that personalized rehabilitation training could be planned. Through this study, the characteristics of the affected side were confirmed, and the possibility of setting biomechanical evaluation criteria before physical therapy and clinical treatment.

Methods

Selection of participants

The study cohort comprised patients with hemiplegia after stroke who were enrolled as out- or inpatients at the Wonkwang University Gwangju Hospital. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Wonkwang University Medical Center (approval number WKIRB 2021-02, dated February 10, 2021). Written informed consent was obtained from all participants in compliance with the Institutional Review Board requirements. Fifty patients were recruited between October 1, 2021, and January 31, 2022. The inclusion criteria were patients (1) with hemiplegia diagnosed with ischemic stroke more than 3 months and less than 9 months prior to participation in this study, (2) with a functional ambulation category of level 3 or higher (level 3 indicates a patient who can ambulate on a level surface without manual contact with another person but requires a person to stand close for either safety or verbal cueing), (3) with no significant differences between the angles of the affected and unaffected sides when visually inspected in a standing posture, (4) who showed no forms of hyperextension or hyperflexion when simply walking, and (5) had vital signs within normal range. The presence or absence of skin sensitivity was considered as electromyogram (EMG) sensors and reflective markers to the body would be attached to participants. A flowchart of the selection process is shown in figure 1.

Measures

Before conducting the gait experiment, participants received instruction regarding the test protocol; they were given sufficient time to practice the protocol such that they were able to perform their usual gait during the experiment. The standing angle was calculated to quantitatively confirm that the participant's angle of standing posture, checked visually, met the inclusion criteria. The gait experiment was performed 3 times comfortably in a straight line for a distance of 10 m at the participant's usual walking speed.

The standing angle and gait-event parameter data were collected using a 3-dimensional motion capture system consisting of 8 optical infrared cameras. The BTS system[a] was synchronized with an eight-channel EMG.[b] The sampling frequencies of the motion capture system and EMG were 120 and 1112 Hz, respectively, and resampling and synchronization of the EMG data to the motion data were performed. Eighteen reflective markers were attached to each participant according to the Helen Hayes lower limb set in the

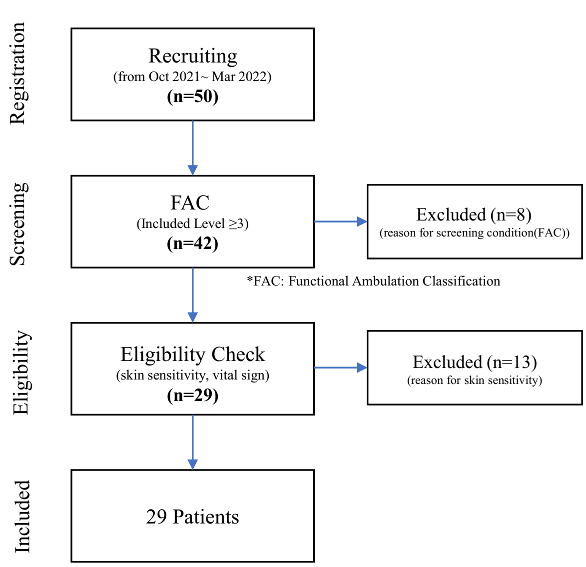

Fig 1 Flowchart of participant selection.

3-dimensional motion analysis system (fig 2). The EMG was acquired by attaching 8 markers each on the left and right sides, referring to the SENIAM recommendation, targeting the rectus femoris, biceps femoris, tibialis anterior, and gastrucnemius medialis (GM), which are typically used before and after each gait phase during gait (fig 2a).[10]

During the 10-m walking test, the average, data from 6 gait cycles for each lower limb were obtained for analysis (fig 2b). The position data of the markers, measured by the motion camera, were processed with a 6 Hz low-pass filter, and the EMG data were passed through a fourth-order zero-lag Butterworth filter using a 15-450 Hz band-pass to remove noise.[11] MATLAB R2022a software[c] was used for data and statistical analyses. The standing angle and gait event parameters were calculated using motion capture data. Motion analysis software was used to perform the calculations.[a]

For the standing angle, the hip joint angle was defined as the thigh marker of the femoral condyle that descends vertically from the horizontal of the ASIS (anterior superior iliac spine) and sacrum markers in the sagittal plane. The knee joint angle was defined as the angle between the shank marker attached to the thigh and lateral malleolus with respect to the sagittal knee marker. The ankle joint was defined as the line between the heel and metatarsal markers relative to the shank markers (in actuality, the line between the markers at the lateral malleolus and lateral condyle of the thigh, markers 13 and 11 on the right side, and 14 and 12 on the left side).

The 10 gait event parameters were calculated (including stride time, stance time, swing time, stance phase, swing phase, single support phase, double support phase, stride length, stride length as a percentage of height, and step length; fig 2d). The gait cycle is presented as a mean value of 6 stride times from 0% to 100% of a gait event from 1 heel strike to the next.

Eight muscle activity parameters were calculated from the post-processing EMG data. The time and frequency domains each have 4 parameters: for time, they are the mean absolute, variance, magnitude, and peak; for frequency, they are the total power, peak power, median, and mean power frequencies. The mean absolute is the activation mean, and variance is the variability of activation over the entire interval in the time domain. Magnitude refers to total activity and peak indicates maximum activity. A fast Fourier transform was performed on the EMG data in the time domain to express the frequency component using power spectral density (PSD). Total power is the total power, which is the sum of the PSDs. Peak power is the maximum power value. The median power frequency (MdPF) represents the midpoint of power distribution in the PSD. The mean power frequency (MPF) is the average frequency. The average value of the 6-stride gait data were used as the muscle activity parameters. Because the objective was not to confirm the absolute value but to confirm the relative difference between the affected and unaffected sides, the measured value of muscle activity was used directly instead of using the % maximal voluntary contraction calculated as the ratio of the maximum voluntary contraction measurement.

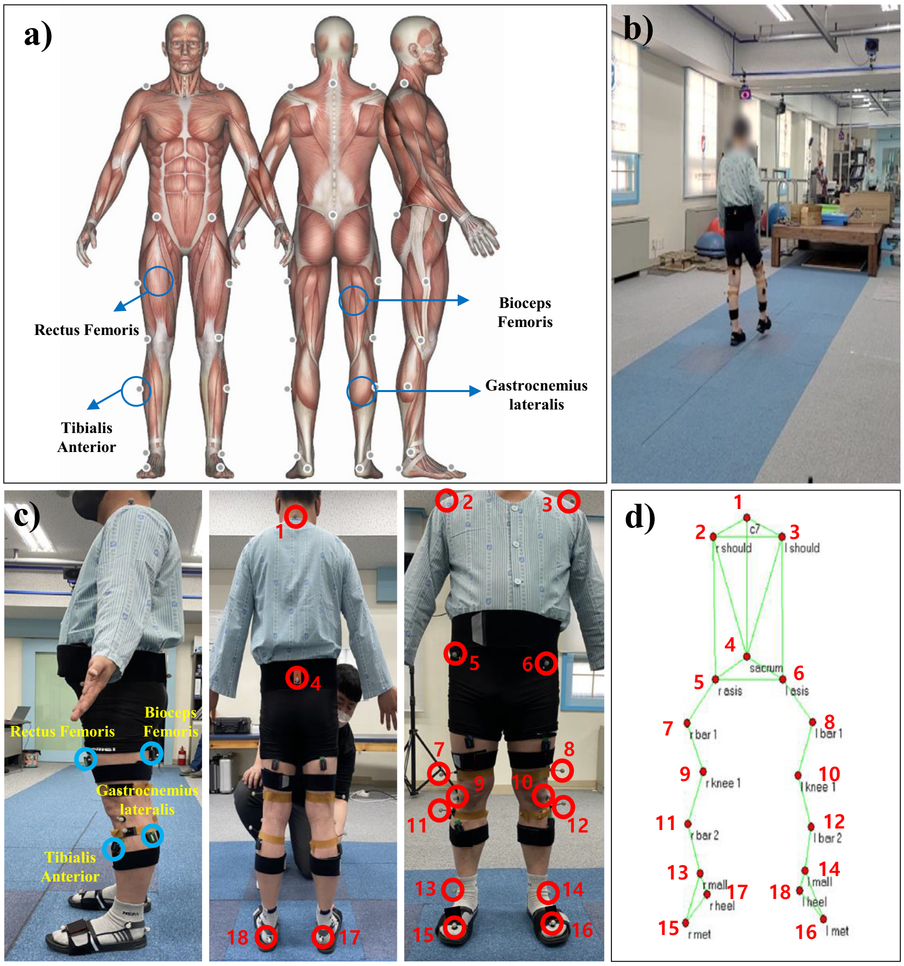

Fig 2 (a) Positions on the muscles to which the EMG sensors were attached. (b) The room in which the gait examinations took place. (c) Positions on the body to which the reflective markers were attached. (d) The simple Helen Hayes protocol (BTS Bioengineering Corp).

Statistical approach

The Wilcoxon rank-sum test was used to compare the gait-event and EMG data of each of the parameters of the affected and unaffected sides.

For classification, the Kruskal-Wallis 1-way analysis of variance score results of the affected and unaffected sides were primarily used to select features. Scores corresponded to $-\log(P \text{ value})$. Four features were selected using a stepwise logistic regression analysis model of gait event parameters: swing time, swing phase, stance phase, and single support phase. Similarly, 4 EMG parameters were selected: MPF of tibialis anterior, MdPF, peak power, and magnitude of GM. All 8 features were used in the classification model based on gait-event and EMG parameters.[12] The affected and unaffected sides were assigned to 2 different classes.

Results

Twenty-nine patients were included; their characteristics are listed in table 1. No statistical differences were noted in the angle of each joint between the affected and unaffected sides, indicating that the static kinematic factor was controlled in the standing position before the gait experiment was performed (table 2).

The 10 gait-event parameters of the affected and unaffected sides of the patients with stroke are shown in table 3. Four parameters showed a significant difference between the affected and unaffected sides: swing time, stance phase, swing phase, and single support phase. The stance

Table 1 Patient characteristics

Variable	Men (Mean ± SD)	Women (Mean ± SD)
No.	11	18
Age (y)	57.60±8.46	64.50±13.53
Height (cm)	166.45±5.42	152.17±7.42
Weight (kg)	73.73±7.09	57.06±8.78
Hemiparetic side (left/right)	5/6	10/8
Time post-stroke (months)	6.00±2.50	6.00±2.10
FAC	4.55±0.71	4.56±0.51
MoCA-Korean	23.00±8.44	23.39±5.68

Abbreviations: FAC, functional ambulation category; MoCA-K, Montreal Cognitive Assessment Korean.

Table 2 Difference between the affected and unaffected side standing angle at static standing posture

Standing Angle	Affected-Side (Mean ± SD)	Unaffected-Side (Mean ± SD)	*P* Value
Hip frontal [deg]	-3.84±6.82	-5.87±5.91	.15
Hip sagittal [deg]	17.29±13.02	16.16±13.35	.65
Hip rotation [deg]	2.42±17.22	-2.17±45.39	.81
Knee sagittal [deg]	3.53±10.80	1.09±8.72	.69
Ankle sagittal [deg]	6.32±7.32	5.36±5.23	.39
Foot progression [deg]	-12.20±10.35	-8.63±7.49	.27

Abbreviations: deg, degree.
Wilcoxon rank sum test: $P \leq .05$.

time on the affected side was approximately 0.1 second shorter than that on the unaffected side, while the swing time was approximately 0.1 second longer, the stance ratio lower, the swing ratio higher, and the single support phase lower.

The results of the electromyogram parameters of the affected and unaffected sides of the participants are shown in table 4. Among the 32 parameters, a significant difference between the affected and unaffected sides was only found in the MdPF of GM. In the comparison of the time-domain parameters, no significant difference was found in the variables. Of the frequency-domain parameters, the affected side frequency of the MdPF of GM was approximately 17 Hz lower than unaffected sides.

The results of the logistic regression analysis for classification of affected and unaffected sides are shown in table 5. The swing phase, single support phase, and median frequency of GM were finally selected in the logistic regression model for classifying the affected side.

Discussion

In this study, gait-event and EMG parameters were calculated and compared with quantitatively confirm the differences between the affected and unaffected lower extremities in patients with hemiplegia after stroke. The gait event parameters of swing time, stance phase, swing phase, and single support phase were confirmed to be different between the affected and unaffected sides.

An increase in swing time on the affected side is a typical gait characteristic of patients with hemiplegia,[2] as confirmed by the results in the current study. The increased swing time is characteristic of temporal asymmetry and is shown by the difference in the stance and swing phase ratios. Patients with hemiplegia exhibit changes in the ratios of stance and swing phases relative to what may be considered normal. However, this is not what changes stride length. Stride length is changed by the amplitudes of movements in the hip and knee joints. As a rule, the lengths of stance phases increase significantly on both sides. However, many more occur on the unaffected side and, judging by the duration of stance phases, the main function of the unaffected side thus becomes 1 of support, with transfer to the affected side to swing. In this case, the swing phase is not an independent quantity. This is what remains in the gait cycle after the stance phase.

Stride length on the affected side increases in patients with hemiplegia because the propulsion of the unaffected side increases. Moreover, as the severity increases, so does the stride length.[13] In the stance phase, the hip extensors generate propulsion power and in the swing phase, the hip flexors play a role in pulling the leg up.[4] The negative influence of the hip abductor muscles on the affected side causes hip circumduction, and the swing time increases because it differs from the general pelvic movement. This also affects the knee flexion and extension. Circumduction on the affected side decreases knee flexion during the swing phase,

Table 3 Difference between the affected and unaffected side gait event parameters

Gait Event Parameters	Affected-Side (Mean ± SD)	Unaffected-Side (Mean ± SD)	*P* Value
Stride time [s]	1.33±0.37	1.33±0.33	.85
Stance time [s]	0.83±0.21	0.91±0.36	.31
Swing time [s]	0.50± 0.16*	0.42±0.04*	.02
Stance phase [%]	62.46±3.56*	67.00±7.37*	.02
Swing phase [%]	37.40±2.89*	33.16±6.21*	.01
Single support phase [%]	33.28±6.48*	37.39±3.39*	.02
Double support phase [%]	15.36±5.44	14.79±3.66	.85
Stride length [m]	0.97±0.25	0.97±0.25	.97
Stride length [%height]	61.78±14.98	61.19±14.24	.91
Step length [m]	0.48±0.13	0.49±0.13	.97

* Wilcoxon rank sum test: $P \leq .05$.

Table 4 Difference between the affected and unaffected side of stroke patients' EMG parameters

EMG Parameters		Affected-Side (Mean ± SD)	Unaffected-Side (Mean ± SD)	*P* Value
Time domain				
Mean absolute [mV]	RF	0.12±0.31	3.32±1.18	.23
	BF	0.10±1.02	0.26±0.91	.46
	TA	0.31±0.67	0.30±0.73	.57
	GM	0.36±0.95	0.16±0.18	.20
Variance ($\times 10^{-7}$) [mV]	RF	2.14±9.63	21.65±0.01	.18
	BF	0.32±0.71	11.00±0.58	.44
	TA	10.43±46.77	8.25±0.40	.60
	GM	18.58±68.53	0.99±2.32	.27
Magnitude ($\times 10^{4}$) [mV]	RF	2.49±5.93	6.06±2.09	.43
	BF	1.95±1.88	4.83±1.59	.67
	TA	6.93±1.72	4.94±1.03	.56
	GM	7.27±1.89	3.50±0.51	.21
Peak [mV]	RF	5.05±15.79	9.25±29.44	.10
	BF	3.14±3.58	6.20±18.47	.54
	TA	11.06±29.70	7.56±16.60	.58
	GM	12.97±35.48	5.22±7.45	.34
Frequency domain				
Total power [V^2/Hz]	RF	20.35±50.74	53.53±188.60	.32
	BF	16.22±13.91	31.94±83.39	.41
	TA	52.03±102.51	39.25±57.20	.69
	GM	49.55±106.77	27.72±29.25	.58
Peak power [V^2/Hz]	RF	0.42±1.34	1.23±4.22	.26
	BF	0.30±0.45	0.92±3.39	.49
	TA	0.80±1.76	0.97±2.76	.68
	GM	1.29±3.82	0.52±0.66	.15
Median power frequency [Hz]	RF	31.41±23.92	52.03±53.59	.40
	BF	37.72±38.89	34.51±41.19	.91
	TA	24.98±32.81	31.98±39.08	.88
	GM	22.90±21.59*	39.69±41.19*	.04
Mean power frequency [Hz]	RF	77.16±14.16	74.64±15.66	.66
	BF	74.86±15.06	76.24±12.75	.76
	TA	74.83±14.97	78.89±13.21	.33
	GM	71.39±15.98	71.38±13.47	.67

Abbreviations: BF, biceps femoris; Hz, Hertz; mV, millivolt; RF, rectus femoris; TA, tibialis anterior.
* Wilcoxon rank sum test: $P \le .05$.

making the paretic limb relatively longer. Therefore, the limb can be moved forward only by moving along an arc across the side. In general, knee movement in post-stroke patients is characterized by increased knee flexion during the stance phase at initial contact, hyperextension in the late stance phase, and excessive knee hyperextension during the stance phase of the subsequent contact. However, the joint angles were only measured in a standing posture in this study: therefore, it is only possible to estimate the result with general knee movement characteristics. From the perspective of the gait event, the shorter stance phase on the affected side is a result of a number of events that occur relative to the unaffected side. The affected side has less load bearing capacity, causing the unaffected side to work harder during the stance phase and the affected side to work harder during the swing phase.

Table 5 The results of the classification performance of logistic regression model

Accuracy (%)	Sensitivity	Specificity	Precision	Nagelkerke R^2
74.14%	0.69	0.79	0.76	0.42
Parameter Predictors	**B**	**Standard Error**	**95% Confidence Interval**	***P* Value**
(Constant)	-1.25	4.39		.77
Swing phase	0.23	0.09	1.04-1.52	.01
Single support phase	-0.17	0.08	0.70-0.99	.04
Median power frequency of GM	-2.42	1.27	0.01-1.08	.05

The electromyography analysis examined the total data of repeated gait events measured during walking. Repeated gait event measurements were used to enable a comparison between the affected and unaffected sides as deviations in individual strides make it difficult to generalize the values of several participants if time-domain data are obtained from only 1 stride. Time- and frequency-domain parameters were calculated for each trial data point. The only parameter that showed a significant difference between the affected and unaffected sides was the MdPF of GM, which is known to be a variable indicative of the characteristics of hemiplegia. In general, the mean and median frequencies are used as indices to check for muscle fatigue; in particular, MPF is used as a fatigue index for concentric contraction of muscles.[14] Muscle fatigue is generally defined as a muscle's activity-induced loss of ability to produce force.[15] The GM is activated at all stages of the stance phase and it is related to movement of the hip joint and hyperextension of the knee extensors. Thus, an increase in fatigue owing to excessive contraction is expected in this muscle.[16]

The EMG results were difficult to generalize and quantify. EMG parameters represent the muscle activity in the motion characteristics of stroke patients, with the EMG characteristics of hemiplegic patients being classified into 4 types.[17] A type 1 disorder is a hyperactive stretch reflex, type 2 a lack of activation during both shortening and lengthening contraction, type 3 a stereotyped coactivation of several muscle groups, and type 4 a combination of the other 3 types. Individual differences that generate abnormal patterns and types may have influenced the results. The greater motor function the severity, the greater the difference in movement between the affected and unaffected sides of the lower extremity in patients with hemiplegia after stroke.

The swing phase, single support phase, and MdPF of GM were finally selected in the logistic regression model to classify the affected side. The accuracy of the classification model was 74.14%, and the R-square was 0.42. The location of the hyperplane of the decision boundary can be set as the severity baseline of the affected side in the model.

Study limitations

This study had some limitations. The number of participants for whom parameters were extracted was relatively small: for 29 patients, 58 training data points for each feature of the affected and unaffected sides were gathered. Therefore, overfitting the test-set of the model used for classification may have occurred. Future research that adds data through additional experiments is expected to help overcome this limitation and further increase the accuracy of the model and reduce overfitting. The test set did not check the accuracy of the logistic model because the number of participants was small; we intend to perform verification with additional data in a follow-up study.

Conclusions

This study examined the characteristics of the affected and unaffected sides in patients with hemiplegia after stroke. Four gait event variables showed differences, namely, swing time, stance phase, swing phase, and single support phase. The only EMG variable which showed a difference was the MdPF of GM. In patients with hemiplegia, the single support phase on the affected side was shortened, reduce the load bearing on the affected limb, which then caused a reduction in the stage phase ratio. This study confirmed that the EMG characteristics are influenced by the individual muscle characteristics of each patient and, unlike kinematic characteristics, they are difficult to generalize. The classification model developed using the characteristic variables showed an accuracy of 74.14% and this is expected to be further improved with additional data.

Suppliers

a. BTS SMART DX Motion Capture Camera System, BTS Bioengineering Corp.
b. Delsys Trigno Avanti EMG Wireless System, Delsys Corp.
c. Matlab software version 2022a, Mathworks Corp.

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References

1. Baker R, Esquenazi A, Benedetti MG, Desloovere K. Gait analysis: clinical facts. Eur J Phys Rehabil Med 2016;52:560–74.
2. Doi T, Nakakubo S, Tsutsumimoto K, Kurita S, Ishii H, Shimada H. Spatiotemporal gait characteristics and risk of mortality in community-dwelling older adults. Maturitas 2021;151:31–5.
3. Balaban B, Tok F. Gait disturbances in patients with stroke. PM R 2014;6:635–42.
4. Stanhope VA, Knarr BA, Reisman DS, Higginson JS. Frontal plane compensatory strategies associated with self-selected walking speed in individuals post-stroke. Clin Biomech 2014;29:518–22.
5. Seo JW, Kim SG, Kim JI, et al. Principal characteristics of affected and unffaected side trunk movement and gait event parameters during hemiplegic stroke gait with IMU Sensor. Sensors (Basel) 2020;20:7338.
6. Guzik A, Drużbicki M. Application of the Gait Deviation Index in the analysis of post-stroke hemiparetic gait. J Biomech 2020;99:109575.
7. Den Otter AR, Geurts ACH, Mulder Th, Duysens J. Abnormalities in the temporal patterning of lower extremity muscle activity in hemiparetic gait. Gait Posture 2007;25:342–52.
8. Souissi H, Zory R, Boudarham J, Pradon D, Roche N, Gerus P. Muscle force strategies for poststroke hemiparetic patients during gait. Top Stroke Rehabil 2019;26:58–65.
9. Zhu Y, Zhou C, Liu Y, et al. Effects of modified constraint-induced movement therapy on the lower extremities in patients with stroke: a pilot study. Disabil Rehabil 2016;38:1893–9.

10. Recommendations for sensor locations on individual muscles. Available at: http://seniam.org/. Accessed September 29, 2023.
11. Hussain I, Park SJ. Prediction of myoelectric biomarkers in post-stroke gait. Sensors (Basel) 2021;21:5334.
12. Loh WY, He X, Man M. A regression tree approach to identifying subgroups with differential treatment effects. Stat Med 2015;34: 1818–33.
13. Oken O, Yavuzer G. Spatio-temporal and kinematic asymmetry ratio in subgroups of patients with stroke. Eur J Phys Rehabil Med 2008;44:127–32.
14. Bonato P, Roy SH, Knaflitz M, De Luca CJ. Time-frequency parameters of the surface myoelectric signal for assessing muscle fatigue during cyclic dynamic contractions. IEEE Trans Biomed Eng 2001;48:745-53.
15. Naik GR. Computational intelligence in electromyography analysis: a perspective on current applications and future challenges. 1st ed. Rijeka, Croatia: InTech; 2012:196-220.
16. Beyaert C, Vasa R, Frykberg GE. Gait post-stroke: pathophysiology and rehabilitation strategies. Neurophysiol Clin 2015;45:335–55.
17. Olney SJ, Richards C. Hemiparetic gait following stroke. Part I: characteristics. Gait Posture 1996;4:136–48.