Motor Impairment and Its Influence in Gait Velocity and Asymmetry in Community Ambulating Hemiplegic Individuals

Consuelo B. Gonzalez-Suarez, MD, PhD, Christine Grace V. Ogerio, MD, Angelo R. dela Cruz, PhD, Edison A. Roxas, PhD, Belinda C. Fidel, MD, Ma Roxanne L. Fernandez, MSPT, Christopher Cruz, MSPT

Research Center for Health Science, Faculty of Medicine and Surgery, University of Santo Tomas, Manila, Philippines
Department of Physical Medicine and Rehabilitation, Our Lady of Lourdes Hospital, Manila, Philippines
Research Center for Natural and Applied Sciences, University of Santo Tomas, Manila, Philippines
Electronics Engineering Department, Faculty of Engineering, University of Santo Tomas, Manila, Philippines
Center for Health Research and Movement Science, College of Rehabilitation Sciences, University of Santo Tomas, Manila, Philippines

Abstract

Objectives: To determine the most important motor impairments that are predictors of gait velocity and spatiotemporal symmetrical ratio in patients with stroke.

Design: Cross-sectional, descriptive analysis study.

Setting: Human performance laboratory of the University of Santo Tomas.

Participants: Individuals with chronic stroke (N=55; 34 men, 21 women) who are community dwellers.

Interventions: Not applicable.

Main Outcome Measures: The gait velocity and spatiotemporal symmetrical ratio (step length; step, stance, swing, single-leg support, and double-leg support stance times) was determined using Vicon motion capture. We also calculated motor impairment of the leg and foot using Brunstrom’s stages of motor recovery, evaluated muscle strength using the scoring system described by Collin and Wade, and assessed spasticity using by the modified Ashworth Scale.

Results: Regression analysis showed that plantarflexor strength is a predictor of gait velocity and all temporospatial symmetry ratio. Knee flexor and extensor strength are predictors.

List of abbreviations: BSSR, Brunstrom stages of stroke recovery; DLST, double-leg support time; MAS, modified Ashworth Scale; SLST, single-leg support time; StT, stance time; SwT, swing time.

Supported by the Philippine Council for Health Research and Development.

Disclosures: none.

Cite this article as: Arch Rehabil Res Clin Transl. 2021;3:100093.
Stroke results in a wide array of sensorimotor impairment, including weakness of contralateral extremities, decreased sensation and balance, spasticity, loss of motor control, and the inability to walk. Gait recovery is one of the main goals of rehabilitation because gait impairment affects the quality of life and functional status of stroke patients.

In general, poststroke hemiparetic gait is slow compared with healthy individuals with asymmetry in the spatiotemporal parameters such as step length, swing time (SwT), stance time (StT), single-leg support time (SLST), and double-leg support time (DLST). However, there is a wide-range heterogeneity of gait patterns among stroke patients. Because of the varied gait patterns, gait speed and symmetry ratios have been used to assess gait among stroke patients. However, gait speed may be unable to determine the underlying impairments and compensatory mechanism in this patient group. Improvement may not be the result of motor recovery but could be a result of a compensatory mechanism by the nonaffected leg. The pattern of temporal asymmetry is characterized by a shorter StT and a longer SwT on the affected leg. StT, SwT, StT, SLST, and DLST are temporal parameters used in calculating symmetry. Although the step length ratio is the most frequently used symmetry ratio in research, it has been suggested that the temporal symmetry ratio also be analyzed. With this, gait control in the phases of gait can be better understood and targeted ambulation training could be instituted for better gait recovery.

Analyzing the SLST and DLST is of interest because they have different subtasks, namely supporting the upper body during the stance phase and generating enough mechanical energy for leg propulsion respectively. Furthermore, there is more temporal gait asymmetry compared with spatial asymmetry, as reported by Lauzière et al in their review, in which studies reported that 60% of stroke patients had temporal asymmetry whereas only 33% to 49% had step length asymmetry.

Studies have determined the relationship of motor deficits of muscle strength, spasticity, and motor recovery with spatiotemporal symmetry ratio. The strength of the plantarflexors and dorsiflexors has a negative correlation with SLST symmetry ratio, whereas the strength of plantarflexors and knee extensors have a negative correlation with the step length symmetry ratio. However, a limited number of muscles were assessed. Spasticity of ankle plantarflexors was positively correlated with the symmetry ratio for step length, SwT, and SLST. Spasticity of the knee extensors and ankle invertors was positively correlated with SwT, StT, and SLST symmetry ratio, whereas the spasticity of hip adductors and extensors was positively correlated with SwT symmetry ratio. Spasticity measurement is commonly measured using the modified Ashworth Scale (MAS), although Lin et al used electromyography.

The different assessment tools used to measure stroke impairment include the Chedoke-McMaster Stroke Assessment, Fugl-Meyer Assessment, and Brunnstrom stages of stroke recovery (BSSR). These methods have been used to determine the relationship of stroke impairment with spatiotemporal asymmetrical ratio. However, only the BSSR assesses purely motor development and reorganization of the brain after stroke. The other assessment tools include sensory impairments, postural control balance, and ambulation. The findings regarding the correlation of BSSR with spatiotemporal symmetry ratio have been inconsistent. Öken and Yavuzer showed no correlation with SLST symmetry ratio, whereas Balasubramanian et al reported a negative correlation with step length symmetry ratio. However, to our knowledge, no study has determined the relationship of hemiparetic severity, the strength and level of spasticity of each lower extremity muscle group with gait speed, and the different symmetry ratio of step length, StT, SwT, and DLST. The current study hypothesized that motor impairments are predictors of gait velocity and spatiotemporal symmetrical ratio, which include step length, StT, SwT, SLST, and DLST. Motor impairments include BSSR; muscle strength of the affected lower extremity (except hip abductor and adductors); and spasticity of hamstrings, quadriceps, gastrocnemius, tibialis anterior, and hip adductors using MAS.

Methods

The study was performed at the Human Performance Laboratory of the University of Santo Tomas from July to December 2018. Ethical approval was provided by the Institutional Review Board of the University of Santo Tomas Hospital and conformed to the tenets of the Helsinki Declaration. Informed consent forms were signed by all participants before entering the study protocol. The study was designed as a cross-sectional, descriptive analysis study.
Participants

The differences and the variability in the stance time between stroke patients and healthy individuals reported in a study by Ng et al.\textsuperscript{20} were used to determine the sample size for the current study. A sample size of 56 was computed, with a power of 0.90 and an alpha level of 0.05.

The inclusion criteria for the participants were men or women with unilateral hemiparesis secondary to stroke aged between 30 and 75 years who were able to understand instructions and were ambulatory (either independently or with the use of a cane). Participants with a limited range of motion for the lower extremity joints (appendix 1), or any cardiopulmonary, musculoskeletal, or other neurologic conditions that prevented them from walking at least 10 meters without pain were excluded from the study.

Outcome measures

The demographic and anthropometric data recorded included sex, age, comorbidities, height in meters, weight in kilograms, and body mass index. Stroke data included the side of hemiparesis, stroke duration, and stroke classification.

The BSSR, which ranges from stage 1 to 6, was used to assess the severity of hemiparesis, indicating no voluntary movement to mild hemiparesis that allows patients to perform an isolated joint movement.\textsuperscript{21} Muscle strength of both lower extremities was assessed using the scoring system described by Collin and Wade (table 1).\textsuperscript{22} Spasticity of the lower extremity muscles was evaluated using MAS, which ranges from 0 (no increase in muscle tone) to 5 (joints are placed in rigid flexion or extension).\textsuperscript{23}

A Vicon motion capture system\textsuperscript{9} with 8 cameras was used to determine gait velocity and spatiotemporal asymmetry. Thirty-nine retroreflected markers were attached to the standard marker positions for data acquisition (fig 1). The Vicon motions were recorded using Nexus software\textsuperscript{8} and were directly imported to Microsoft Excel\textsuperscript{5} using a frame rate of 100 frames per second.

Data gathering procedure

Before the start of the study, the assessors conducted an orientation on the physical examination. Initially, participants answered questionnaires pertaining to demographic and stroke data. Participants then underwent assessments for blood pressure, pulse rate, anthropometric measures, muscle strength, sensory deficits, MAS, and BSSR.\textsuperscript{21-23} Next, gait performance was evaluated. The participants were asked to walk unassisted (use of a cane was permitted) at a self-selected speed along a 7-meter walkway 4 times.

Treatment of data

Gait velocity was obtained from the Vicon results. Using the ankle marker, gait velocity was computed by calculating the mean of all computed velocities between frames. The average gait velocity was then computed by obtaining the mean of the 4 trials. Spatiotemporal asymmetrical ratios were obtained for the following parameters: step length, SwT, StT, SLST, and DLST. The temporal symmetry ratio was calculated using the following:\textsuperscript{5}

\[
\text{Temporal asymmetry ratio} = \frac{\text{Temporal parameter value of the affected side}}{\text{Temporal parameter value of the unaffected side}}
\]

To obtain the step length of the affected side, the distance between the paretic leg at the beginning of the stance phase and the unaffected leg at the end of the stance phase was measured. The step length symmetry ratio was calculated as follows:\textsuperscript{5}

\[
\text{Step length asymmetry ratio} = \frac{\text{Step length of the affected side}}{\text{Step length of the unaffected side}}
\]

Statistical analysis

All data were entered into a purpose-built MS Excel file. SAS software, version 9.2,\textsuperscript{6} was used for the analysis. The Kolmogorov-Smirnov test was used to test normality and showed that the data had normal distribution. Means and SD were used for the descriptive data. The Student t test was used to determine whether there was a significant difference in the anthropometric measures, stroke descriptors and assessments, gait velocity, and all spatiotemporal symmetry ratios between the sexes and laterality.
Results

A total of 66 participants were recruited for this study. Seven were excluded for gait assessment because of uncontrolled hypertension, and 59 participants underwent gait analysis. However, the data of 4 participants were excluded because of errors during analysis. Therefore, 55 participants were included in the final analysis of this study (fig 2).

Table 2 shows the participants’ demographics and stroke descriptors. The study included 34 men and 21 women with a mean age of 57.12±11.26 and 59.81±9.49 years, respectively. Thirty-three had left hemiparesis, and 22 had right hemiparesis. Spatiotemporal parameters, gait velocity, and spatiotemporal symmetry ratios are summarized in table 3. All spatiotemporal symmetry ratios were less than 1, except for the SwT symmetry ratio, which was 1.21±0.27. There were no sex- or laterality-related differences of demographics data, stroke descriptors, and spatiotemporal symmetry ratios, except for step length. For sex, the step length of the affected limb was statistically different, with men having a longer step length compared with women (0.43±0.09 vs 0.36±0.10 m; P=.018). Similar results were observed in the laterality of hemiparesis, in which the step length of both the affected and nonaffected limb was significantly longer for those with right hemiparesis (affected limb: right hemiparesis, 0.42±0.13m; left hemiparesis, 0.35±0.12m; P=.049; unaffected limb: right hemiparesis, 0.44±0.11m; left hemiparesis, 0.38±0.08m; P=.01). There was no correlation of the different anthropometric measures with step length for both sexes. The data of all participants were pooled for subsequent regression analysis.

Discussion

To the best of the authors’ knowledge, this is the first study to use clinical examination for assessing motor impairment in predicting gait velocity and spatiotemporal symmetry ratio among stroke community ambulators. Furthermore, muscles assessed were not limited to the ankle musculature, but also included hip and knee muscles. The study also assessed the subphases of the stance phase. Plantarflexor strength of the affected leg was a predictor of gait speed and all spatiotemporal symmetry ratio, whereas knee extensor strength was a negative predictor of DLST symmetry ratio. Spasticity of hip adductors and quadriceps was a positive predictor in SwT and step length symmetry ratio, respectively.

Motor impairment and spatiotemporal symmetry ratio

The current study demonstrated that plantarflexors contribute to decreasing asymmetry in SLS and DLST. Plantarflexors were found to be active from midstance to the beginning of preswing. During SLS, plantarflexors contribute to vertical support and cause the progression of the center of pressure when the foot is flat on the floor. During DLST, the plantarflexors generate power for forward acceleration of the center of mass.24 This could also explain why plantarflexors are predictors of step length symmetry ratio. In Balasubramanian et al’s study, the step length ratio had a negative correlation with paretic leg propulsion. It was postulated that hip flexor, hip extensor, and plantarflexor activities are important in generating propulsive forces to decrease step length asymmetry.16

In the current study, the hamstrings were found to be a predictor in improving SLS symmetry ratio. Neptune et al25 postulated that the hamstring muscle counteracted the deceleration of the forward movement of the body and leg and contributed the most force in accelerating the body forward in the stance phase. Furthermore,
knee flexion during preswing is essential in generating enough leg kinetic energy at toeoff.\(^8\) This is negated by the strength of the quadriceps of the affected side. Neptune et al showed that the vastus muscles and rectus femoris decelerated the forward motion of the leg during the beginning and the end of the stance phase, respectively.\(^25\) Therefore, an increase in quadriceps strength will further increase asymmetry during DLST. A similar finding by Hsu et al\(^11\) corroborated this and showed a significant positive correlation between SLST symmetry ratio and the total work of the ankle plantarflexor during walking comfortable speed. However, Lin et al\(^10\) suggested otherwise, indicating that dorsiflexor strength and joint position error were significant predictors of SLST symmetry ratio. Nevertheless, Hsu et al\(^10\) only evaluated the isokinetic strength of the hip flexors, knee extensors,
and ankle plantarflexors, whereas Lin et al.\textsuperscript{11} evaluated the isometric strength of ankle plantarflexors and dorsiflexors using a dynamometer. Although the assessment tools used in the previous studies were not the same as those used in the current study, a systematic review by Cuthbert and Goodheart\textsuperscript{26} suggested that manual muscle testing, on which the scoring system by Collin and Wade was based, has good concurrent validity when compared with a handheld dynamometer.\textsuperscript{26} At the same time, there is an underestimation of the severity of muscle weakness in the knee and ankle compared with isokinetic dynamometry.\textsuperscript{27}

Plantarflexor strength was a negative predictor of SwT symmetry ratio, which suggests that a stronger gastrocsoleus is associated with a more symmetrical SwT ratio. Previously, it was shown that leg kinetic energy at toeoff, which is generated by the plantarflexor and hip flexor, was reduced in the paretic limb of the stroke patients, which increased the SwT and energy cost to propel the leg.\textsuperscript{8} Although the plantarflexors’ excitation time is from midstance to preswing, the mechanical energy that it generated was an important predictor in shortening the swing phase of the paretic limb.\textsuperscript{25}

In their study, Öken and Yavuzer showed poorer motor recovery using BSSR had a higher symmetry ratio in step length but no difference with the SLST symmetry ratio.\textsuperscript{18} The difference in the results may be owing to the fact that we had only 6 participants with poor motor recovery.

**Spasticity and spatiotemporal symmetrical ratio**

In the current study, spastic muscles (ie, hip adductor and quadriceps) were significant predictors in SwT

| Table 2 | Participants’ demographics and stroke characteristics |
| --- | --- |
| Characteristics | Value |
| Sex, n (%) |  |
| Men | 34 (61.8) |
| Women | 21 (38.2) |
| Weight, kg |  |
| Men | 64.66±8.24 P = .017* |
| Women | 59.95±24.23 |
| Height, cm |  |
| Men | 160.75±6.67 P = 8.3989E-08* |
| Women | 149.68±6.00 |
| Body mass index, kg/m\(^2\) |  |
| Men | 25.10±3.47 P = .60 |
| Women | 26.97±12.61 |
| Stroke duration, mo | 56.84±94.24 |
| Laterality of stroke, n (%) |  |
| Right hemiparesis | 22 (40) |
| Left hemiparesis | 33 (60) |
| BSSR |  |
| Stage of recovery, n (%) |  |
| 1 | 1 (1.8) |
| 2 | 0 (0.0) |
| 3 | 5 (9.1) |
| 4 | 10 (18.2) |
| 5 | 19 (34.5) |
| 6 | 20 (36.4) |

| Table 2 (continued) | Muscle strength |
| --- | --- | --- |
| Muscle | Motricity Index | No. | Percentage |
| Knee extensor | 14.00 | 1 | 1.8 |
| 19.00 | 9 | 16.4 |
| 25.00 | 22 | 40.0 |
| 33.00 | 23 | 41.8 |
| Knee flexor | 19.00 | 6 | 10.9 |
| 25.00 | 23 | 41.8 |
| 33.00 | 26 | 47.3 |
| Ankle dorsiflexor | 0.00 | 7 | 12.7 |
| 9.00 | 2 | 3.6 |
| 14.00 | 11 | 20.0 |
| 19.00 | 7 | 12.7 |
| 25.00 | 16 | 29.1 |
| 33.00 | 12 | 21.8 |
| Ankle plantarflexor | 0.00 | 6 | 10.9 |
| 9.00 | 2 | 3.6 |
| 14.00 | 5 | 9.1 |
| 19.00 | 10 | 18.2 |
| 25.00 | 16 | 29.1 |
| 33.00 | 16 | 29.1 |

* Indicates significance.

(continued on next page)
symmetrical ratio and step length ratio. Finley et al. studied heteronymous reflexes in stroke patients, and their results showed that hip abduction perturbation caused an excitatory response in the adductor longus and rectus femoris, which could be owing to the descending coactivation of the motor neuron pools of both muscles. The response to stretch is reciprocal; such a stretch of the rectus femoris caused reflex excitation of the adductor longus, and findings are consistent with increased facilitation of heteronymous reflexes after neurologic conditions. In stroke patients, there is an increase in the amplitude of hip abduction during the swing phase to assist in the foot clearance in the swing phase that could trigger an excitatory response of adductor longus and rectus femoris. Spasticity of the adductors could cause problems in the advancement of the paretic limb and its clearance during the swing phase, thereby increasing the SwT asymmetry.

On the other hand, quadriceps spasticity was a positive predictor for step length asymmetry ratio. Our participants had a gait speed of 62 cm/s, which is approximately 57% of the speed of Filipinos between the ages of 40 and 59 years (102-108 cm/s) in our laboratory results. This classifies them as a fast walker group among stroke patients, which is approximately 44% of normal gait speed.

Study limitations

Our study only included patients who are community ambulators with mild to moderate motor impairment and did not include patients with acute stroke. The results may not be generalizable to this subset of patients.

### Table 3  Spatiotemporal parameters, gait velocity, and spatiotemporal symmetry ratios

| Spatiotemporal Parameters | Nonaffected Limb | Affected Limb | P Value |
|---------------------------|------------------|---------------|---------|
| Stance time, s            | 0.75±0.32        | 0.63±0.27     | 1.1739×10⁻⁷ |
| Swing time, s             | 0.46±0.10        | 0.55±0.13     | 0.000003 |
| Step length, m            | 0.40±0.10        | 0.38±0.13     | .21     |
| SLST, s                   | 0.55±0.12        | 0.47±0.11     | .000016 |
| DLST, s                   | 0.21±0.25        | 0.16±0.18     | .000279 |
| Gait speed                | 0.66±0.26 m/s    |               |         |
| Stance time symmetry ratio| 0.85±0.15        |               |         |
| Swing time symmetry ratio | 1.21±0.27        |               |         |
| Step length symmetry ratio| 0.94±0.22        |               |         |
| SLST symmetry ratio       | 0.87±0.19        |               |         |
| DLST symmetry ratio       | 0.88±0.30        |               |         |

### Table 4  Multiple logistic regression model of BSSR, MAS, and muscle strength of individual muscles for gait speed and spatiotemporal symmetry ratios

| Gait Parameter/Dependent Variable | Predictors                        | Unstandardized Coefficients | t     | P Value |
|----------------------------------|-----------------------------------|-----------------------------|-------|---------|
| Gait speed (Constant)            |                                   | 0.57                        | 10.97 | 2.999E⁻¹⁵ |
|                                  | Ankle plantarflexor strength      | 0.16                        | 2.39  | 2.04E⁻⁰²  |
| Stance time symmetry ratio (Constant) |                                  | 0.73                        | 32.09 | 2.10E⁻³⁶  |
|                                  | Ankle plantarflexor strength      | 0.21                        | 6.93  | 5.74E⁻⁰⁹  |
| Swing time symmetry ratio (Constant) |                                  | 1.34                        | 26.01 | 1.77E⁻¹¹  |
|                                  | Ankle plantarflexor strength      | -0.25                       | -3.81 | 3.67E⁻⁰⁴  |
|                                  | Hip Adductor Spasticity           | 0.24                        | 2.18  | 3.35E⁻⁰²  |
| Step length symmetry ratio (Constant) |                                  | 0.74                        | 15.59 | 3.06E⁻¹¹  |
|                                  | Ankle plantarflexor strength      | 0.28                        | 4.80  | 1.36E⁻⁰⁵  |
|                                  | Quadriceps spasticity             | 0.29                        | 3.72  | 4.91E⁻⁰⁴  |
| SLST symmetry ratio (Constant)   |                                   | 0.62                        | 9.35  | 1.01E⁻¹²  |
|                                  | Ankle plantarflexor strength      | 0.14                        | 2.83  | 6.60E⁻³³  |
|                                  | Knee flexor strength              | 0.19                        | 2.42  | 1.90E⁻⁰²  |
| DLST symmetry ratio (Constant)   |                                   | 0.94                        | 10.98 | 3.64E⁻¹⁵  |
|                                  | Ankle plantarflexor strength      | 0.29                        | 3.80  | 3.80E⁻⁰⁴  |
|                                  | Knee extensor strength            | -0.29                       | -2.89 | 5.50E⁻³³  |
Furthermore, the researchers were not able to include trunk and pelvic parameters, which could have affected the spatiotemporal asymmetry.

Conclusions

Our study determined the motor predictors of spatiotemporal parameters using clinical assessment for a better comprehension of how motor deficits could contribute to stroke gait abnormality. In patients with mild to moderate deficits, intensive mobility training composed of graded strengthening using functional tasks, aerobic exercise, and walking activities with postural control demands will be an effective rehabilitation strategy.

Suppliers

a. Vicon motion capture system; Vicon Industries.
b. Nexus software; Nexus Software LLC.
c. Excel; Microsoft Corp.
d. SAS software, version 9.2; SAS Institute, Inc.

Corresponding author

Consuelo B. Gonzalez-Suarez, MD, PhD, Research Center for Health Research, Medicine Building, University of Santo Tomas, Espana Blvd, Sampaloc, Manila, Metro Manila, Philippines 1008. E-mail address: cgsuarez@ust.edu.ph.

Acknowledgment

The authors thank Jason Jake Tan, MS, for technical support and Francisco delos Reyes, MS, for his statistical work for this study.

Appendix 1

| Joint       | Normal Range of Motion |
|-------------|------------------------|
| Hip         |                        |
| Flexion     | 0 to 110-120           |
| Extension   | 0 to 10-15             |
| Internal Rotation | 0 to 30-40         |
| External Rotation | 0 to 40-60        |
| Abduction   | 0 to 30-50             |
| Adduction   | 0 to 25-30             |
| Knee        |                        |
| Flexion     | 0-140                  |
| Extension   | 0-15                   |
| Ankle       |                        |
| Dorsiflexion| 0-20                   |
| Plantarflexion | 0-50                  |
| Inversion   | 0-20                   |
| Eversion    | 0-10                   |

References

1. Langhammer B, Lindmark B, Stanghelle JK. The relation between gait velocity, static and dynamic balance in the early rehabilitation of patients with acute stroke. Adv Physiother 2006;2:60-5.
2. Balaban B, Tok F. Gait disturbances in patients with stroke. PM R 2014;6:635-42.
3. Allen JL, Kautz SA, Neptune RR. Step length asymmetry is representative of compensatory mechanisms used in post-stroke hemiparetic walking. Gait Posture 2011;1(33):538-43.
4. Perry J, Garrett M, Gronley J, Mulroy SJ. Classification of walking handicap in the stroke population. Stroke 1995;26:982-9.
5. Patterson KK, Gage WH, Brooks D, Black SE, McIlroy WE. Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization. Gait Posture 2010;1(31):241-6.
6. Brandstater ME, de Bruin H, Gowland C, Clark BM. Hemiplegic gait: analysis of temporal variables. Arch Phys Med Rehabil 1983;64:583-7.
7. Roelker SA, Bowden MG, Kautz SA, Neptune RR. Paretic propulsion as a measure of walking performance and functional motor recovery post-stroke: a review. Gait Posture 2019;68:6-14.
8. Chen G, Patten C, Kothari DH, Zajac FE. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. Gait Posture 2005;22:51-6.
9. Beyaert C, Vasa R, Frykberg GE. Gait post-stroke: pathophysiology and rehabilitation strategies. Neurophysiol Clin 2015;45:335-55.
10. Lin PY, Yang YR, Cheng SJ, Wang RY. The relation between ankle impairments and gait velocity and symmetry in people with stroke. Arch Phys Med Rehabil 2006;87:562-80.
11. Hsu AL, Tang PF, Jan MH. Analysis of Impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. Arch Phys Med Rehabil 2003;84:1185-93.
12. Lauziere S, Betschart M, Aissaoui R, Nadeau S. Understanding spatial and temporal gait asymmetries in individuals post stroke. Int J Phys Med Rehabil 2014;2:201.
13. Patterson KK, Gage WH, Brooks D, Black SE, McIlroy WE. Changes in gait symmetry and velocity after stroke: a cross-sectional study from weeks to years after stroke. Neurorehabil Neural Repair 2010;24:783-90.
14. Patterson KK, Parafianowicz I, Danells CJ, et al. Gait asymmetry in community-ambulating stroke survivors. Arch Phys Med Rehabil 2008;89:304-10.
15. Dettmann MA, Linder MT, Sepic SB. Relationship among gait performance, postural stability, and function assessments of the hemiplegic patient. Am J Phys Med Rehabil 1987;66:77-90.
16. Balasubramanian CK, Bowden MG, Neptune RR. Paretic propulsion ratio in subgroups of patients with stroke. Eur J Phys Rehabil Neural Repair 2010;1(2):51-6.
17. Bovonsunthonchai S, Hiengkaew V, Vachalathiti R, Vongsirinavarat M. Gait symmetrical indexes and their relationships to muscle tone, lower extremity function, and postural balance in mild to moderate stroke. J Med Assoc Thai 2011;94:976-84.
18. Öken O, Yavuzer G. Spatio-temporal and kinematic asymmetry ratio in subgroups of patients with stroke. Eur J Phys Rehabil Med 2008;44(1):27-32.
19. Alexander LD, Black SE, Patterson KK, Gao F, Danells CJ, McIlroy WE. Association between gait asymmetry and brain lesion location in stroke patients. Stroke 2009;40:537-44.
20. Ng SS, Hui-Chan CW. The Timed Up & Go test: its reliability and association with lower-limb impairments and locomotor capacities in people with chronic stroke. Arch Phys Med Rehabil 2005;86:1641-8.
21. Brunnstrom S. Motor testing procedures in hemiplegia based on sequential recovery stages. Phys Ther 1966;46:357-75.
22. Collin C, Wade D. Assessing motor impairment after stroke: a pilot reliability study. J Neurol Neurosurg Psychiatry 1990;53:576-9.
23. Gregson JM, Leathley M, Moore AP, Sharma AK, Smith TL, Watkins CL. Reliability of the Tone Assessment Scale and the modified Ashworth scale as clinical tools for assessing poststroke spasticity. Arch Phys Med Rehabil 1999;80:1013-6.
24. Francis CA, Lenz AL, Lenhart RL, Thelen DG. The modulation of forward propulsion, vertical support, and center of pressure by the plantarflexors during human walking. Gait Posture 2013;38:993-7.
25. Neptune RR, Zajac FE, Kautz SA. Muscle force redistributes segmental power for body progression during walking. Gait Posture 2004;19:194-205.
26. Cuthbert SC, Goodheart GJ. On the reliability and validity of manual muscle testing: a literature review. Chiropr Man Therap 2007;15:4.
27. Andersen H, Jakobsen J. A comparative study of isokinetic dynamometry and manual muscle testing of ankle dorsal and plantar flexors and knee extensors and flexors. Eur Neurol 1997;37:239-42.
28. Finley JM, Perreault EJ, Dhaher YY. Stretch reflex coupling between the hip and knee: implications for impaired gait following stroke. Exp Brain Res 2008;188:529-40.
29. Kerrigan DC, Frates EP, Rogan S, Riley PO. Hip hiking and circumduction: quantitative definitions. Am J Phys Med Rehabil 2000;79:247-52.
30. Thibaut A, Chatelle C, Ziegler E, Bruno MA, Laureys S, Gossieres O. Spasticity after stroke: physiology, assessment and treatment. Brain Inj 2013;27:1093-105.
31. Li S, Francisco GE, Zhou P. Post-stroke hemiplegic gait: new perspective and insights. Front Physiol 2018;9:1021.
32. Boehm WL, Gruben KG. Post-stroke walking behaviors consistent with altered ground reaction force direction control advise new approaches to research and therapy. Translat Stroke Res 2016;7:3-11.
33. Eng JJ, Tang PF. Gait training strategies to optimize walking ability in people with stroke: a synthesis of the evidence. Expert Rev Neurother 2007;7:1417-36.
34. Dutton M. Dutton’s. Orthopaedic Examination, Evaluation and Intervention. 5th edition. New York City, New York: McGraw-Hill Education; 2020.