Japanese Journal of Comprehensive Rehabilitation Science (2021)

Original Article

Effect of spasticity of the ankle plantar flexors on the walking speed of hemiplegic stroke patients after maximum walking speed exercises

Tatsuki Yamada, RPT, MS,[1] Mizuho Ohta, RPT,[2] Makoto Tamari, RPT, PhD[3]

[1]Inc.HL Support, Fukuoka, Japan
[2]Seiai Rehabilitation Hospital, Fukuoka, Japan
[3]International University of Health and Welfare Graduate School, Fukuoka, Japan

ABSTRACT
Yamada T, Ohta M, Tamari M. Effect of spasticity of the ankle plantar flexors on the walking speed of hemiplegic stroke patients after maximum walking speed exercises. Jpn J Compr Rehabil Sci 2021; 12: 64−69.
Objective: This study examined the effect of ankle plantar flexor spasticity on the walking speed of hemiplegic stroke patients immediately following maximum walking speed exercises.
Methods: A total of 23 hemiplegic stroke patients were divided into two groups based on the presence (n = 13) or absence (n = 10) of ankle plantar flexor spasticity on the paralyzed side. Gait speed, propulsive force during pre-swing, paretic side ankle plantar flexion movement during pre-swing, paretic side ankle dorsiflexion angle during the stance phase, angular velocity of paretic side dorsiflexion during the stance phase, paretic side trailing limb angle in the terminal stance, paretic side plantar flexion angle in the terminal stance, and the timing of maximum dorsiflexion of the ankle joint on the paretic side were measured before and after the maximum walking speed exercises, using a three-dimensional motion analyzer.
Results: In the spasticity group, no significant improvement was observed in any of the categories. In contrast, in the non-spasticity group, significant improvement was observed in all categories, except for the paretic side ankle dorsiflexion angle.
Conclusion: This study showed that maximum walking speed exercises immediately improved walking speed in hemiplegic stroke patients without ankle plantar flexor spasticity.

Correspondence: Tatsuki Yamada, RPT, MS
Inc.HL Support, 4−6−28 Chuo-ku, Fukuoka, Fukuoka 816−0956, Japan.
E-mail: t.y.104.ds.yrsk@gmail.com
Accepted: October 5, 2021.

This study received no outside funding. The authors report no conflict of interest.

doi.org/10.11336/jjcrs.12.64

Key words: maximum walking speed exercises, spasticity

Introduction

Stroke sequelae commonly include motor deficits, abnormal muscle tone, and disruptions in balance, leading to a reduced walking speed [1−3]. Walking speed can affect the activities of daily living (ADL) and has been associated with quality of life (QOL) [4−6] Therefore, improving walking speed is a vital rehabilitation goal for hemiplegic stroke patients.

Various parameters related to gait have been reported to change with an increase in walking speed in normal individuals [7−11]. The ankle joint plantar flexion moment movement during pre-swing also affects the walking speed of hemiplegic stroke patients [12], and the elastic energy of the triceps surae and Achilles tendons generated by sufficient ankle joint dorsiflexion motion during the monopodal support phase is necessary to exert the ankle joint plantar flexion moment [13]. Therefore, the dorsiflexion and ankle plantarflexion moment movement on the paralyzed side during the stance phase should be increased to improve the walking speed of hemiplegic stroke patients.

Walking speed exercises are essential for improving the walking speed of hemiplegic stroke patients [14−17]. Furthermore, increased walking speed improves step length and cadence compared to walking at a comfortable speed in such patients. However, previous studies on maximum walking speed exercises have been conducted only in patients with lower limb muscle tone below 1 on the Modified Ashworth Scale (MAS), with or without spasticity. It is considered that maximum walking speed exercises for hemiplegic stroke patients require more effort than walking at a comfortable speed, and the tone of the triceps surae muscle increases as the walking speed increases. Thus, improved ankle plantar flexor tone with increasing walking speed may prevent ankle movement during maximum walking speed exercises.

Hence, the purpose of this study was to classify patients with MAS of triceps surae on the paralyzed side of 1+ or more and those with MAS of 1 or less, and to examine the effect of maximum walking speed exercises on improvement of walking speed for each group.

Methods

1. Participants

The participants were first-stroke hemiplegia patients who were admitted to a convalescent rehabilitation hospital and were able to walk while being watched over without walking aids. This included 13 patients with MAS 1+ or higher on the paralyzed triceps surae (with spasticity) and 10 patients with MAS 1 or less (without spasticity). Patients with a resting heart rate of <40 or >100 bpm, resting blood pressure of <90/60 or >170/90 mmHg, higher brain dysfunction, impaired cognition that affected walking, ataxia, or orthopedic or cardiovascular disease were excluded (Table 1).

2. Measurement of maximum walking speed and comfortable walking speed

The maximum walking speed exercises were performed 10 times over a distance of 15 m, with a 10 s interval between trials. Patients were instructed to "walk as fast as you safely can." They walked three times at the optimal walking speed for 10 m, and measurements were obtained before and after the exercise. Then, the participants were provided the following instruction verbally: "Please walk at a comfortable walking speed." No walking cane or brace was used.

3. Measurement equipment and environment

Patients walked barefoot at a self-determined speed over a distance of 8 m. Instrumented gait analysis was performed using a 14-camera motion-capture system (100 Hz) with three synchronized force plates (1,000 Hz) and a measurement section of 8 m. Additionally, infrared reflective markers with a diameter of 14 mm were attached according to the Helen Hayes marker set (Figure 1).

4. Data analysis

For the optimal walking speed before (PRE) and after exercise (POST), the average of three exercise trials that involved accurate foot placement on a ground reaction force (GRF) meter was used. For the maximum walking speed exercises, the average of 10 exercise trials that involved accurate foot placement on the GRF meter was used. Filter processing with a cutoff frequency of 8 Hz was performed on the coordinate data of the infrared reflection marker. The vertical component of the GRF was used to define the walking cycle. Frames with GRF vertical component values ≥20 N were defined as foot contact, and frames with vertical component values <20 N were defined as foot off.

We extracted data on gait speed, propulsive force, paretic side ankle plantar flexion moment, paretic side trailing limb angle (TLA), paretic side ankle dorsiflexion angle, angular velocity of paretic side dorsiflexion, paretic side plantar flexion angle, and the timing of maximum dorsiflexion of the ankle joint on the paretic side. For the walking speed, the center of gravity was calculated from a rigid body model by differentiating the displacement on the sagittal plane with respect to time. For the paretic side propulsive force and plantarflexion moment movement, the maximum paralyzed pre-swing phase (non-paralyzed side foot contact - paralyzed side foot off) values were used. For the TLA [18], the angle between the vertical axis and the line that connected the GRF on the sagittal plane and the greater trochanter in the terminal stance (0.01 s before the non-paralyzed side foot contact) on the paralyzed side was used. The ankle plantar flexion angle of the paralyzed side was used as the ankle joint angle

Table 1. Patient characteristics.

	Spasticity group (*n*=13)	Non-spasticity group (*n*=10)	*p*-Value	
Ankle plantar flexors MAS	1+: 5 2: 6 3: 3	0: 4 1: 6		
Type of stroke (Hemorrhage/Infarction)	7/6	6/4		
Paralyzed side (R/L)	5/8	8/2		
Age (years)	61.0 ± 10.9	55.4±14.3	0.40*	n.s
Sex (M/F)	7/6	4/6	0.81*	n.s
Time from onset to hospitalization (days)	148.0±32.8	126.0±48.5	0.39‡	n.s
FMA-LE (Maximum 34)	24.4±2.8	28.4±5.4	0.06‡	n.s

Mean ± SD. n.s, Not significant; *, Fisher's exact test; ‡, Mann-Whitney *U* test; MAS, Modified Ashworth Scale; FMA, Fugl Mayer Assessment.

Figure 1. Using a modified Helen Hayes marker set for the lower limbs, 29 reflective markers were placed on the patient's parietal, frontal, and occipital lobes; both shoulders, lateral epicondyle, midpoint of the ulnar radius of both sides, both anterior superior iliac spines, sacral center; and the acromion, thighs, external knee joints, internal knee joints, lower limbs, lateral and medial malleoli, second metatarsal heads, and heels of both sides.

in the terminal stance (0.01 s before the non-paralyzed side foot contact). The maximum angle of the ankle joint and angular velocity values of the paretic side dorsiflexion were used during the stance phase. The time taken to reach maximum dorsiflexion of the ankle joint on the paralyzed side was normalized to one gait cycle before calculation.

5. Statistical analyses

Statistical analyses were performed using SPSS Statistics version 24 (SPSS Inc., Chicago, IL, USA, 2016). As a comparison of the preconditions, the Wilcoxon signed-rank test was performed to compare the walking speed before and during the maximum walking speed exercises in both the spasticity and non-spasticity groups. The Mann-Whitney *U* test was used to compare the walking speed and speed difference between the two groups with and without spasticity before and during the maximum walking speed exercises. We performed the Wilcoxon signed-rank test to compare the PRE and POST data in each group. The Mann-Whitney *U* test was performed to compare the amount of change in the extracted data before and during the maximum walking speed exercises between the two groups, the group with spasticity and the group without spasticity. The significance level was set at 5%.

Results

1. Comparison of walking speed before and during practice between the two groups and within each group

The pre-practice walking speeds were 0.60 ± 0.23 m/s and 0.92 ± 0.23 m/s for the spasticity and non-spasticity groups, respectively. During practice, the walking speeds were 0.77 ± 0.25 m/s and 1.17 ± 0.30 m/s for the spasticity and non-spasticity groups, respectively. Walking speed before and during practice was significantly faster in the non-spasticity group. In the within-group comparison, both groups showed a significant increase in walking speed during practice. However, there was no significant difference in walking speed before and during exercise (Tables 2 and 3).

2. Comparison between PRE and POST exercises in the spasticity and non-spasticity groups

There was no significant improvement in any category in the spasticity group. However, there was a statistically significant improvement in walking speed, step length (on both the affected and unaffected sides), paretic side forward propulsion, paretic side TLA, and paretic side ankle plantar flexion angle in the non-spasticity group. The maximum dorsiflexion angular velocity and the timing of maximum dorsiflexion of the ankle joint on the paralyzed side significantly increased ($p<0.05$), but there was no significant change in other data (Table 4).

3. Comparison of the amount of change in extracted data before and during exercises between the two groups

The amount of change in propulsive force, TLA, ankle joint plantar flexion angle, angular velocity of ankle joint maximum dorsiflexion, and timing of ankle joint maximum dorsiflexion in the spasticity group were significantly lower than those in the non-spasticity group ($p<0.05$). No significant changes were observed in other data (Table 5).

Discussion

First, the walking speed of both the groups significantly increased during the maximum walking speed practice compared to that before the practice. However, a comparison of the speed difference between the two groups showed no significant difference. This suggests that both groups could withstand the load of maximum walking speed, and there was no difference in the amount of load in either

Table 2. Comparison of gait speed PRE and during exercises and speed between the two groups.

	Spasticity group (n=13)	Non-spasticity group (n=10)	p-Value	
PRE gait speed (m/s)	0.60±0.23	0.92±0.23	0.01	*
EX gait speed (m/s)	0.77±0.25	1.17±0.30	0.00	*
speed difference (m/s)	0.17±0.07	0.26±0.12	0.07	n.s

Mean±SD. $p < 0.05$.
*, Items with significant differences between groups; n.s, Not significant; PRE gait speed, Gait speed during comfort speed walking before maximum speed walking exercises; EX gait speed, Gait speed during maximum speed walking exercises; Speed difference, Gait speed during maximum speed walking practice − gait speed during comfortable speed walking before maximum speed walking exercises.

Table 3. Comparison of gait speed before and during exercises within two groups.

	PRE gait speed	EX gait speed	p-Value	
Spasticity group	0.60±0.23	0.77±0.25	0.00	*
Non-spasticity group	0.92±0.23	1.17±0.30	0.00	*

Mean ± SD. $p < 0.05$.
n.s, Not significant; *, Items with significant differences within each group; PRE gait speed, Gait speed during comfort speed walking before maximum speed walking exercises; EX gait speed, Gait speed during maximum speed walking exercises.

group during the maximum walking speed exercises.

This study showed that when the pre- and post-practice data were compared, the non-spasticity group showed significant improvement in gait speed, whereas the spasticity group showed no significant improvement. The propulsive force on the paralyzed side is closely related to the walking speed of hemiplegic stroke patients, and the TLA in the late stance phase contributes more to the propulsive force on the paralyzed side than the plantar flexion moment of the ankle joint [19]. In addition, significant improvements in propulsive force and TLA were observed in the non-spasticity group, whereas no significant improvements in ankle plantar flexion movement, propulsive force, and TLA were observed in the spasticity group. These results indicated that the non-spasticity group, which showed an increase in the TLA, demonstrated an improved walking speed after practice. In contrast, the spasticity group, which did not show an increase in the TLA, did not show any improvements in walking speed.

Next, in terms of the difference between the extracted data before and during the maximum walking speed exercises, the changes in propulsive force, TLA, ankle joint plantar flexion angle, angular velocity of ankle joint maximum dorsiflexion, and timing of ankle joint maximum dorsiflexion were significantly lower in the spasticity group compared to the non-spasticity group. It is known that the forward propulsive force during the stance phase is obtained by sufficient dorsiflexion of the ankle joint to move the axis of rotation of the lower leg from the heel to the forefoot [20]. Additionally, the angular velocity of ankle joint dorsiflexion during the monopodal support phase increases with an increase in walking speed in healthy subjects, and the timing of maximum ankle joint dorsiflexion moves forward and the ankle joint plantar flexion angle in the late stance phase increases [7, 8]. Furthermore, the ankle plantar flexion angle in the late stance period is thought to affect the TLA [18], according to a model encompassing the three joints of the lower extremities. These results suggest that an increase in the angular velocity of ankle dorsiflexion during the monopodal support phase may affect the TLA in the late stance phase. However, as spasticity increases muscle tension in a speed-dependent manner, the increase in the angular velocity of ankle dorsiflexion during the maximum walking speed exercises may have been lower in the spasticity group than in the non-spasticity group. Therefore, the spasticity group, which showed a small increase in the ankle plantar flexion angle in the late stance phase during maximum walking speed practice, did not demonstrate a sufficient increase in the propulsive force of the paralyzed leg as they could not perform the walking practice with a higher TLA. Therefore, the TLA and propulsive force did not improve even after practice.

Finally, our study has some limitations. First, the walking speed during the maximum walking speed practice was set to the subjective maximum effort speed of the participant, and the amount of practice (walking distance) was set to the amount that the participant could perform based on the researchers' clinical experience. Therefore, different results may be obtained based on the setting of these conditions. Second, cardiopulmonary function and muscular endurance may affect maximum

Table 4. Comparison between PRE and POST in each group with and without spasticity.

	Spasticity group (*n*=13)				Non-spasticity group (*n*=10)			
	PRE	POST	*p*-Value		PRE	POST	*p*-Value	
Speed (m/s)	0.60±0.23	0.63±0.24	0.50	n.s	0.92±0.23	1.13±0.16	0.01	*
A/P GRF (N/kg)	0.06±0.04	0.06±0.03	0.45	n.s	0.11±0.06	0.12±0.06	0.05	*
Ankle Moment (N・m/m・kg)	0.91±0.23	0.88±0.21	0.38	n.s	1.08±0.2	0.88±0.21	0.49	n.s
TLA (Deg)	6.61±2.87	6.68±3.26	1.00	n.s	10.76±3.47	11.77±3.53	0.02	*
Mst Ankle DF angle (Deg)	4.80±3.15	4.76±4.13	0.11	n.s	8.93±4.30	8.16±4.74	0.13	n.s
Tst Ankle PF angle (Deg)	−3.96±3.23	−3.18±3.81	0.07	n.s	−6.73±3.85	−5.63±7.41	0.05	*
DF angular velocity (Deg/s)	62.78±23.71	62.04±23.60	0.75	n.s	79.23±33.49	86.23±36.60	0.03	*
Timing (%)	46.15±6.53	48.85±11.65	0.06	n.s	44.50±4.40	42.70±5.12	0.03	*

Mean ± SD. $p < 0.05$.

*, Items that showed significant differences within each group; n.s, Not significant; PRE, Comfortable speed walking before maximum speed walking exercise; POST, Comfortable speed walking after maximum speed walking exercise; A/P GRF, Anterior/posterior ground reaction force; TLA, Trailing Limb Angle; Mst Ankle DF angle, Maximum ankle dorsiflexion angle during single leg stance on paretic side; Tst Ankle PF angle, Terminal stance Ankle plantar flexion; DF angular velocity, Dorsiflexion angular velocity; Timing, The timing of the maximal dorsiflexion of the ankle joint.

Table 5. Amount changed during maximum walking exercise from pre between the two groups.

	Spasticity group (*n*=13)	Non-spasticity group (*n*=10)	*p*-Value	
A/P GRF (N/kg)	0.01±0.02	0.03±0.02	0.04	*
Ankle Moment (N・m/m・kg)	0.03±0.12	−0.12±0.23	0.47	n.s
TLA (Deg)	0.91±1.07	2.10±1.59	0.04	*
Mst Ankle DF angle (Deg)	−0.03±0.14	−1.27±1.87	0.19	n.s
Tst Ankle PF angle (Deg)	−0.46±2.03	−4.30±4.04	0.01	*
DF angular velocity (Deg/s)	8.75±7.74	18.97±8.75	0.00	*
Timing (%)	1.00±3.24	4.30±4.30	0.04	*

Mean ± SD. $p < 0.05$.

*, Items with significant differences between groups; n.s, Not significant; A/P GRF, Anterior/posterior ground reaction force; TLA, Trailing Limb Angle; Mst Ankle DF angle, Maximum ankle dorsiflexion angle during single leg stance on paretic side; Tst Ankle PF angle, Terminal stance Ankle plantar flexion; DF angular velocity, Dorsiflexion angular velocity; Timing, The timing of the maximal dorsiflexion of the ankle joint.

walking speed. In this study, participants with diseases directly related to cardiopulmonary function were excluded, and their vitals were constantly checked during the maximum walking speed practice. Hence, the effects of cardiopulmonary function and muscular endurance on maximum walking speed require further research.

Acknowledgments

In carrying out this research, We also express our deepest gratitude to Seiai Rehabilitation hospital Dr. Ibayashi, Dr. Nagao, and the patients who cooperated with the data measurement.

References

1. De Quervain IA, Simon SR, Leurgans S, Pease WS, Mcallister D, Ohjo C. Gait pattern in the early recovery period after stroke. J Bone Joint Surg Am 1996; 78: 1506–14.
2. Kim CM, Eng JJ. Symmetry in vertical ground reaction force is accompanied by symmetry in temporal but not distance variables of gait in persons with stroke. Gait Posture 2003; 18: 23–8.
3. 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.
4. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. Stroke 1995; 26: 982–9.
5. Peurala SH, Karttunen AH, Sjogren T, Paltamaa J. Evidence for the effectiveness of walking training on walking and self-care after stroke: a systematic review and meta-analysis of randomized controlled trials. J Rehabil Med 2014; 46: 387–99.
6. Schmid A, Ducan PW, Studenski S, Lai SM, Richard L, Perera S, et al. Improvements in speed-based gait classifications are meaningful. Stroke 2007; 38: 2096–100.
7. Mentiplay BF, Banky M, Clark RA, Kahn MB, Williams G. Lower limb angular velocity during walking at various speeds. Gait Posture 2018; 31: 190–6.
8. Lewek MD. The influence of body weight support on ankle mechanics during treadmill walking. J Biomech 2011; 44: 128–33.
9. Murray MP, Mollinger LA, Gardner GM, Sepic SB. Kinematic and EMG patterns during slow, free, and fast walking. J Orthop Res 1984; 2: 272–80.
10. Hsiao HY, Knarr BA, Higginson JS, Blinder-Macleod SA. The relative contribution of ankle moment and trailing limb angle to propulsive force during gait. Hum Mov Sci 2015; 39: 212–21.
11. Jonsdottir J, Recalcati M, Rabuffetti M, Casiraghi A, Boccardi S, Ferrarin M. Functional resources to increase gait speed in people with stroke: strategies adopted compared to healthy control. Gait Posture 2009; 29: 355–9.
12. Olney SJ, Griffin MP, McBride ID. Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. Phys Ther 1994; 74: 872–85.
13. Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. *In vivo* behavior of human muscle tendon during walking. Proc Biol Sci 2001; 268: 229–33.
14. Pohl M, Mehrholz J, Ritschel C, Ruckriem S. Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: a randomized controlled trial. Stroke 2002; 33: 553–8.
15. Lau KW, Mak MK. Speed-dependent treadmill training is effective to improve gait and balance performance in patients with sub-acute stroke. J Rehabil Med 2011; 43: 709–13.
16. Lee IH. Does the speed of the treadmill influence the training effect in people learning to walk after stroke ? A double-blind randomized controlled trial. Clin Rehabil 2015. 29: 269–76.
17. Yoshimoto T, Shimizu I, Hiroi Y, Kawai M, Sato D, Nagasawa M. Feasibility and efficacy of high-speed gait training with a voluntary driven exoskeleton robot for gait and balance dysfunction in patients with chronic stroke: nonrandomized pilot study with concurrent control. Int J Rehabil Res 2015; 38: 338–43.
18. Peterson CL, Cheng J, Kautz SA, Neptune RR. Leg extension is an important predictor of paretic leg propulsion in hemiparetic walking. Gait Posture 2010; 32: 451–6.
19. Hsiao HY, Knarr BA, Higginson JS, Blinder-Macleod SA. Mechanisms to increase propulsive force for individuals post stroke. J Neuroeng Rehabil 2015; 12: 40.
20. Yamamoto S, Ibayashi S, Fuchi M, Yasui T. Immediate-term effects of use of an ankle-foot orthosis with an oil damper on the gait of stroke patients when walking without the device. Prosthet Orthot Int 2015; 39: 140–9.