Walking Speed Adaptability and Speed-related Changes in Spatiotemporal Gait Parameters, Symmetry, and Variability of Hemiplegic Gait in Patients following Stroke

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Purpose: Walking speed adaptability is essential in activities of daily living. We investigated walking speed adaptability and walking speed associated changes in spatiotemporal characteristics of gait parameters, symmetry, and stride-to-stride variability in hemiplegic gait of stroke patients. **Methods:** Nineteen patients following a single onset of stroke walked at their comfortable, fast, and slow speeds for six trials each without using any assistance or device. Walking speed, spatiotemporal gait parameters, step length asymmetry index (a spatial asymmetry index), single support time asymmetry index (a temporal asymmetry index), and stride-to-stride variability of spatiotemporal gait parameters were investigated for each walking speed condition. **Results:** The fast, comfort, and slow walking speeds of the subjects were 1.01±0.30, 0.66±0.18, and 0.43±0.19 m/sec, respectively, and were significantly different from each other ($p<0.017$). There were also significant differences in the majority of the investigated spatiotemporal gait parameters, except for stride width, across the three speed conditions ($p<0.017$). The stride-to-stride variability of all investigated gait parameters, except for stride width, and the single support time asymmetry index were significantly greater in the slow-speed walking condition than in the other two speed conditions ($p<0.017$). **Conclusions:** Walking speed adaptability is preserved, but limited, in hemiplegic patients following mild to moderate stroke. These patients are able to modulate spatiotemporal gait parameters of both unaffected and affected legs to achieve such adaptability. Patients presented the greatest temporal asymmetry and stride-to-stride variability in most of the spatiotemporal gait parameters while walking at slow speed, compared to walking at the other two speeds. We suggest that to enhance walking speed adaptability, symmetry, and stride-to-stride consistency, patients with stroke may practice walking at their comfortable and fast speeds, instead of at a slow speed cautiously. (FJPT 2011;36(1):9-19)

Key Words: Cerebrovascular accident, Adaptability, Gait speed, Symmetry, Variability

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Walking speed adaptability is essential in activities of daily living.[1] Patients with stroke typically walk at a slower speed compared to age-matched healthy adults.[2-6] These patients also show a smaller range of achievable walking speeds than healthy adults.[3,6] The comfortable and fastest walking speeds of these patients are in general slower than those of healthy adults.[3,6] These phenomena suggest that stroke patients present a decreased ability to alter walking speed according to environmental or task demands. Insufficient walking speed adaptability may render these patients at a higher risk of falls or injuries when they face sudden changes in environmental or task demands.

When healthy individuals change their walking speed, the spatiotemporal characteristics of gait parameters change concurrently.[6-8] Turnbull et al.[6] found that similar to healthy adults, patients with stroke achieved different walking speeds also by adjusting their stride time and stride length. However, little is known regarding whether stroke patients have difficulty modulating other spatiotemporal gait parameters, such as the stance and swing time, or whether they would modulate the gait parameters of both the affected and unaffected lower extremities differently when they adopt various walking speeds. Given the asymmetric nature of hemiplegic gait[2,5,9-11] and that left-right temporal and spatial asymmetry may serve as a good indicator for the functional level of hemiplegic gait,[9,10] it would be important to know how adopting different walking speeds affect left-right symmetry in hemiplegic gait.

In addition to left-right asymmetry, stride-to-stride variability is another gait parameter that is of functional and safety relevance and may also show speed-related changes within the same hemiplegic individuals. Brandstater et al.[9] demonstrated that patients with stroke who could walk faster also presented less variable gait patterns. Many researchers have suggested that variability of gait parameters is highly associated with the history or likelihood of falls in older adults,[12-16] with cognitive dysfunction in older adults,[17,18] or with the severity of disease in patients with Parkinson's disease.[19,20] These research findings imply that stride-to-stride consistency in spatiotemporal gait parameters is an important indicator of steadiness, function, and safety of ambulation in older adults and in patients with neurologic disorders.

Therefore, we conducted this study to further understand walking speed adaptability and walking speed associated changes in spatiotemporal characteristics of gait parameters, symmetry, and stride-to-stride variability in patients with stroke. Stroke patients who were able to walk independently without using any assistive device were tested when they walked at their fast, comfortable, and slow speeds. We hypothesized that these patients could modulate all spatiotemporal characteristics of gait parameters of the unaffected leg, but not those of the affected leg. We also hypothesized that the left-right symmetry and stride-to-stride consistency would be the best in the slow-speed condition and worst in the fast-speed walking condition. While the examination of walking speed related changes in spatiotemporal gait parameters may shed light on the mechanisms through which hemiplegic patients achieve walking speed adaptability, the investigation of left-right asymmetry and stride-to-stride variability would lead to better understanding of speed related changes in function and safety of hemiplegic gait.

METHODS

Participants

Nineteen patients with hemiplegia or hemiparesis resulting from a single cerebral vascular accident recruited from the National Taiwan University Hospital (NTUH) participated in this study. The inclusion criteria were being able to communicate with others and to walk independently for at least 50 m with rest intervals, but without any assistive device or foot orthosis. The exclusion criteria were uncontrolled medical conditions, recurrent stroke attacks, cognitive disturbances, aphasia, perceptual disorders, and other known neurologic or musculoskeletal disorders.

The participants included 16 males and 3 females (Table 1.). The mean age and post-stroke onset days were 57.0± 10.1 years (range, 39.0-72.8y) and 99.8±107.6 days (range, 21-367d), respectively. Twelve of them were right hemiparetic and the remainder, left. The etiology was cerebral hemorrhage for 10 of the participants and ischemia for the others (Table 1.). The mean Fugl-Meyer motor scores[21] of the affected upper and lower extremities and balance were 45.0±18.7, 30.1±3.0, and 12.4±1.1, respectively, suggesting that these patients had mild to moderate motor and balance impairment. The mean Barthel Index[22] score was 87.6±12.1, suggesting that patients had mild

Table 1. Subject characteristics

Subject	Sex	Age (Yrs)	Post Onset (Days)	Hemiplegic Side	Etiology	FM-U	FM-L	FM-B	BI
1	M	68.0	339	R	Infarction	58	32	14	95
2	M	52.1	115	R	Hemorrhage	59	29	13	90
3	M	64.3	103	R	Hemorrhage	18	30	11	95
4	M	51.5	31	L	Hemorrhage	63	29	12	95
5	M	45.8	32	L	Hemorrhage	65	33	12	80
6	F	70.3	34	L	Infarction	40	30	11	75
7	M	50.3	367	R	Hemorrhage	58	28	12	100
8	M	58.2	28	R	Infarction	40	33	12	75
9	M	52.4	47	R	Hemorrhage	18	30	12	90
10	M	46.9	30	R	Infarction	15	28	12	85
11	M	64.2	62	R	Infarction	66	33	12	100
12	M	54.7	226	L	Infarction	59	33	14	95
13	M	72.8	21	R	Hemorrhage	65	29	13	90
14	M	70.0	68	R	Infarction	66	34	14	100
15	M	69.3	215	L	Hemorrhage	30	27	13	90
16	M	39.0	88	R	Hemorrhage	44	24	12	100
17	F	48.8	22	L	Hemorrhage	30	34	12	85
18	F	46.2	23	L	Infarction	18	24	10	70
19	M	58.1	45	R	Infarction	43	31	14	55

Abbreviations: FM-U, Fugl-Meyer motor score of affected upper extremity; FM-L, Fugl-Meyer motor score of affected lower extremity; FM-B, Fugl-Meyer balance score; BI, Barthel Index.

residual limitation in activities of daily living. All of the participants signed an informed consent form approved by the Ethics Committee of the NTUH.

Equipment

An instrumented gait mat (3.8m long x 0.6m wide) (GaitMat$^{\text{TM}}$II, E.Q. Inc., USA) was placed at the center of a 6-m-long walkway to record spatiotemporal information of gait. The mat was equipped with electronic pressure switches evenly arranged in 40 rows by 256 columns. The distance between adjacent switches was 1.5 cm, giving rise to a spatial resolution of 1.5 cm. The "on" and "off" signals registered by these switches indicated the location and time at which a subject's foot made a contact with and a release from the mat, respectively, as the subject walked on the mat. This spatiotemporal information of the switch signals was collected and recorded at 200 Hz with the GaitMat$^{\text{TM}}$II software. One dummy mat (1.1m long x 0.6m wide) with similar surface material to the gait mat, but not instrumented with pressure switches, was placed next to each end of the gait mat to make the beginning and ending parts of the 6-meter-long walkway, respectively. The use of the dummy mats was to ensure that when subjects walked onto the gait mat in a walking trial, they were already in the steady speed of walking; and thus the acceleration and deceleration phases of a walking trial were eliminated from walking speed calculation. The reliability and validity of using the GaitMat$^{\text{TM}}$II system in clinical gait analysis has been established previously.[23,24]

Procedures

In the walking experiment, subjects were asked to walk at their self-perceived comfortable, fastest, and slowest speeds, respectively, in the comfortable-, fast-, and slow-speed conditions. Six trials of walking at each speed condition were tested for all subjects. To minimize the influence of task and environment unfamiliarity on the walking performance, each subject undertook the comfortable-speed condition first, the fast-speed condition next, and the slow-speed condition last.

The subjects wore their comfortable walking shoes without using any assistive device or foot orthosis during the walking experiment. They were given at least three practice trials of each speed condition to familiarize themselves with the tasks and the experimental setting. In each trial, the subjects walked along the 6-m-long walkway at the designated self-perceived speed. Subjects were reminded of walking at the same perceived speed as much as they could across the 6 trials of the same walking-speed condition. A rest of 2 to 5 minutes was given between different waking-speed conditions.

Data Analysis

Walking speed and twelve spatiotemporal gait parameters, including cadence, stride length, stride width, double support time, as well as step length, stance time, swing time, and single support time of both legs, were calculated and recorded for each walking trial by using the GaitMat^{TM}II software. The left-right spatial and temporal asymmetry was quantified by calculating the step length asymmetry index (= $\left|1- \frac{\text{step length of affected leg}}{\text{step length of unaffeceted leg}}\right|$) and single support time asymmetry index (= $\left|1- \frac{\text{single support time of affected leg}}{\text{single support time of unaffected leg}}\right|$), respectively.[25] The greater these indices were, the more the asymmetry. The stride-to-stride variability of all, but cadence, of the spatiotemporal gait parameters in each walking-speed condition was calculated using the coefficients of variance (CV) (= standard deviation/mean x 100%) equation across all the gait cycles collected from the six walking trials.

Statistical Analysis

Separate one-way repeated measures analysis of variance (ANOVA) was performed to investigate differences in walking speed, spatiotemporal gait parameters, spatial and temporal asymmetry indices, and stride-to-stride variability across the three walking-speed conditions using the SPSS for Windows, version 15.0 (SPSS Inc., Chicago, Illinois 60606, USA). Statistical significance for all analyses was set at $p<0.05$. Post-hoc analyses were performed with Bonferonnie adjustments.

RESULTS

Walking Speed Adaptability

Figure 1. shows the three walking speeds of 19 individual subjects. Statistical results revealed that walking speed in the fast-speed condition (1.01±0.30 m/sec) was significantly faster than that in the comfortable-speed condition (0.66±0.18 m/sec) ($p<0.017$), which in turn, was significantly faster than that in the slowest-speed condition (0.43±0.19 m/sec) ($p<0.017$) (Table 2.). Thus, the subjects were able to change walking speed according to the experimenter's instructions. The mean range of achievable walking speed (fast walking speed minus slow walking speed) of all subjects was 0.58±0.21 m/sec (range= 0.28 -0.96 m/sec). When analyzing the relationships of the range of achievable walking speed with the slow, comfortable, and fast speeds of these patients, we found Pearson correlations of 0.10 (p=0.68), 0.48 (p=0.04), and 0.78 ($p<0.0001$), respectively, indicating that stroke patients who had quicker comfortable and fast walking speeds also had a wider available range of walking speed or better walking speed adaptability.

Speed-Related Changes in Spatiotemporal Parameters

Table 2. presents the values of spatiotemporal gait parameters of the three walking-speed conditions for all subjects. All these parameters, but the stride width, were significantly

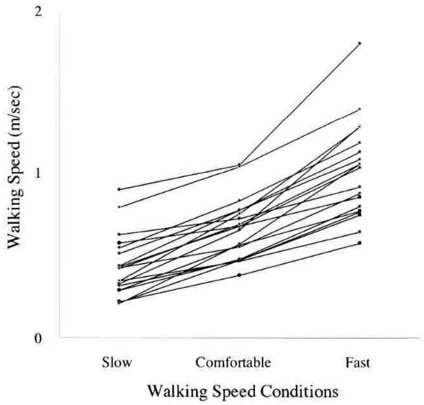

Fig 1. Plot of the slowest, comfortable and fastest walking speeds of each subject. A dot (•) indicates the speed for each subject in a walking speed condition.

Table 2. Walking speed and spatiotemporal gait parameters in three walking speed conditions

Gait Parameters	Slow	Comfortable	Fast
Walking speed (m/sec)	0.43±0.19	0.66±0.18[*]	1.01±0.30[*,†]
Cadence (steps/sec)	1.17±0.25	1.48±0.25[*]	1.83±0.27[*,†]
Stride length (m)	0.72±0.20	0.89±0.14[*]	1.10±0.21[*,†]
Stride width (m)	0.17±0.03	0.17±0.04	0.16±0.04
Step length (m)			
Unaff. side	0.35±0.10	0.44±0.08[*]	0.54±0.13[*,†]
Aff. side	0.37±0.10	0.44±0.07[*]	0.55±0.09[*,†]
Stance time (sec)			
Unaff. side	1.35±0.38	0.99±0.21[*]	0.75±0.14[*,†]
Aff. side	1.22±0.30	0.90±0.16[*]	0.69±0.11[*,†]
Swing time (sec)			
Unaff. side	0.45±0.07	0.42±0.07[*]	0.38±0.04[*,†]
Aff. side	0.58±0.12	0.50±0.10[*]	0.44±0.07[*,†]
Single support time (sec)			
Unaff. side	0.58±0.12	0.50±0.10[*]	0.44±0.07[*,†]
Aff. side	0.45±0.07	0.42±0.07[*]	0.38±0.04[*,†]
Double support time (sec)	0.38±0.15	0.24±0.07[*]	0.15±0.05[*,†]

Abbreviations: unaff, unaffected; aff, affected.

Values reported as mean±SD.

[*] Significantly different from the slow-speed condition at $p<0.017$ level.

[†] Significantly different from the comfortable-speed condition at $p<0.017$ level.

Table 3. Coefficients of variance of gait parameters in three walking speed conditions

Gait Parameters	Slow	Comfortable	Fast
Stride length	0.08±0.03	0.06±0.02[*]	0.05±0.02[*]
Stride width	0.11±0.04	0.12±0.04	0.16±0.06[*,†]
Step length			
Unaff. side	0.11±0.05	0.08±0.04[*]	0.07±0.04[*]
Aff. side	0.10±0.04	0.08±0.03	0.07±0.02[*]
Stance time			
Unaff. side	0.08±0.03	0.07±0.03	0.06±0.02[*]
Aff. side	0.08±0.03	0.07±0.03	0.06±0.03[*]
Swing time			
Unaff. side	0.14±0.07	0.09±0.05[*]	0.08±0.05[*]
Aff. side	0.11±0.05	0.08±0.03[*]	0.07±0.03[*]
Single support time			
Unaff. side	0.11±0.05	0.08±0.03[*]	0.07±0.03[*]
Aff. side	0.14±0.07	0.09±0.05[*]	0.08±0.05[*]
Double support time	0.15±0.04	0.16±0.06	0.16±0.05

Abbreviations: unaff, unaffected; aff, affected.

Values reported as mean±SD.

[*] Significantly different from the slow-speed condition at $p<0.017$ level.

[†] Significantly different from the comfortable-speed condition at $p<0.017$ level.

different across the three walking-speed conditions ($p<0.05$). Cadence, stride length, and step length were the greatest in the fast-speed condition and smallest in the slow-speed condition ($p<0.017$). The stance time, swing time, single support time, and double support time were shortest in the fast-speed condition and longest in the slow-speed condition ($p<0.017$).

Speed-Related Changes in Spatial and Temporal Asymmetry Indices

Figures 2. and 3. present the step length and single support time asymmetry indices in the three walking-speed conditions, respectively. There was no significant difference in the step length asymmetry index among the three walking conditions. The single support time asymmetry index was significantly greater in the slow-speed walking condition than in the other two conditions ($p<0.017$). No significant difference was found in single support time asymmetry index between the comfortable- and fast-speed conditions.

Speed-Related Changes in Stride-to-Stride Variability

Table 3. presents the values of the CVs of eleven spatiotemporal gait parameters. Most of the spatiotemporal gait parameters showed the greatest stride-to-stride variability in the slow-speed condition and smallest variability in the fast-speed condition, except for stride width and double support time. The CVs were greater in the slow-speed condition than in the fast-speed condition for nine of the eleven investigated variables ($p<0.017$, Table 3.). There were no significant differences in the CVs between the comfortable- and fast-speed conditions for the same nine variables ($p>0.017$). Six of these nine variables, including stride length, step length of the unaffected leg, as well as swing time and single support time of both legs, also showed significantly greater CVs in the slow-speed condition than in the comfortable-speed condition ($p<0.017$). In contrast, the CV of stride width in the fast-speed condition was significantly greater than those in the comfortable- and slow-speed conditions ($p<0.017$). There was no significant difference in stride-to-stride variability of double support time across the three conditions.

DISCUSSION

This study investigated walking speed adaptability and walking speed associated changes in spatiotemporal gait parameters, left-right asymmetry and stride-to-stride variability in independently ambulatory stroke patients. We targeted at this patient group because with their independence walking ability, these patients also face a high challenge of walking adaptability in their daily living. Our results demonstrated that these patients were capable of adapting different walking speeds when instructed to walk at their comfortable, fastest and slowest speeds. Contrary to our hypothesis, these patients were able to change walking speeds through adjusting the spatiotemporal gait parameters of both the affected and unaffected legs. How-

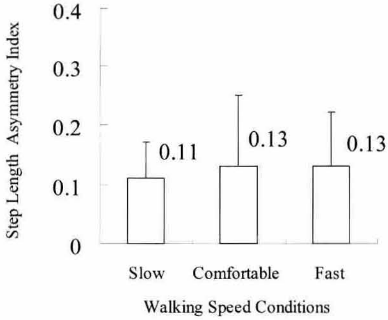

Fig. 2. Means and standard deviations of the step length asymmetry indices for the slow-, comfortable- and fast-speed conditions.

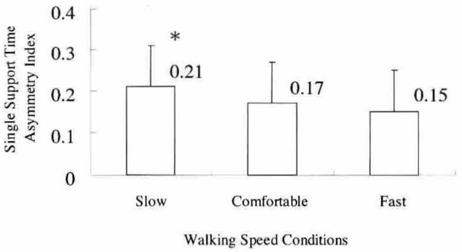

Fig. 3. Means and standard deviations of the single support time asymmetry indices for the slow-, comfortable- and fast-speed conditions. Asterisk (*) indicates significant difference compared to the fast- and comfortable-speed conditions ($p<0.017$).

ever, changes of walking speed significantly affected temporal asymmetry between legs and stride-to-stride variability in these patients. In particular, in the slow-speed condition, the single support time asymmetry index and stride-to-stride variability of most the spatiotemporal parameters were the greatest, compared to the other two conditions. These results suggest that as stroke patients change their walking speed, there are associated changes in the left-right temporal symmetry and stride-to-stride variability of their gait patterns. Accordingly, the function and safety of their walking may be jeopardized when they are performing such adaptive behaviors.

Limited Walking Speed Adaptability in Stroke Patients

Generally speaking, patients in this study were able to increase and decrease their walking speeds by approximately 0.35 m/sec (50%) and 0.23 m/sec (33%) from the comfortable walking speed, respectively. Similarly, Bohannon[3] found that independently ambulatory stroke patients who could walk with or without a device and whose mean comfortable walking speed was 43.5 m/sec were able to safely and significantly increase walking speed by approximately 48% of their comfortable walking speed. The mean range of achievable walking speed of our patients was 0.58 m/sec, a value similar to what Turnbull, Charteris, and Wall reported.[6] This range of achievable walking speed was much smaller compared to those of healthy older adults of similar age (0.90-1.10 m/sec).[26]

When further examining the nature of the decreased walking speed adaptability in our stroke patients, it was found that these patients presented greater difficulty with speeding up than with slowing down to the walking speed comparable to those of healthy adults. Leiper & Craik[26] reported that the slowest, comfortable, and fastest walking speeds of healthy older adults were approximately 0.38-0.47 m/sec, 0.89-1.03 m/sec, and 1.29-1.49 m/sec, respectively. Thus, whereas the slow walking speed of our patients was comparable to that of healthy older adults, their comfortable and fast walking speeds were much slower. In fact, the fast walking speed of our stroke subjects approximates the comfortable speed of healthy older adults. Since we found that stroke patients who had quicker comfortable and fast walking speeds also had a wider available range of walking speed, it was therefore the comfortable and fast walking speeds, not the slow walking speed, that primarily contribute to walking speed adaptability in patients with stroke. It is important to note that the comfortable walking speed of our patients only allows them to perform limited community ambulation.[27] Only when they walked at their fast speed, were they possible to achieve the walking speed required for unlimited community walking- 0.80 m/sec.[27]

Speed-associated Changes in Spatiotemporal Gait Parameters

Similar to the findings of Turnbull et al.,[6] we also found that patients with mild to moderate stroke, who were able to walk independently, can modulate spatiotemporal gait parameters when they adopt different walking speeds. However, our investigation of speed-associated changes in spatiotemporal gait parameters of both legs allowed further understanding of whether stroke patients were able to modulate movement of the affected and unaffected legs to achieve different walking speeds. The results rejected our hypothesis and suggested that these patients achieved walking speed adaptability by modulating the spatiotemporal gait parameters of both the unaffected and affected lower extremities, rather than by the sole effort of the unaffected leg. We therefore speculated that the mechanisms through which these patients were able to adopt different walking speeds may come from the modulation of the descending central drives that are involved with interhemispheric and interlimb coordination. This speculation needs further investigation. In addition, the only gait parameter that did not reveal speed-associated changes was stride width, suggesting that when these patients adopted different walking speeds, they primarily modulated the forward progression movements, not the lateral movements, of the two lower extremities.

Speed-associated Changes in Spatial and Temporal Asymmetry

Our results showed that changes of walking speed significantly affected temporal asymmetry, but not spatial asymmetry, between the two lower extremities in these patients. The finding that the single support time asymmetry index was the greatest in the slow-speed walking condition was contrary to the conventional belief in clinical practice that walking at a consciously controlled slow speed may reduce gait abnormalities, such as asymmetry, of hemiplegic gait.[28] We speculated that subjects' inability to maintain a sufficient single support time (>0.5 sec) with affected leg in the slow-speed condition may cause the increased temporal asymmetry in this condition.

Furthermore, we found no significant difference in step length and single support time asymmetry indices between the comfortable-speed and fast-speed walking conditions. Thus, walking fast does not exacerbate hemiplegic gait asymmetry. Our results were in congruent with research findings which suggest that walking speed and symmetry in fact may measure different features of gait control in stroke patients.[25,29,30]

Speed-associated Changes in Stride-to-stride Variability

A previous study showed that nondisabled children and children with cerebral palsy presented an optimal walking control, indicated by least variability in intra-limb and inter-limb coordination, while walking at a model-derived preferred stride frequency at comfortable speed on a treadmill.[31] Those results were made in comparison to non-preferred lower and higher stride frequency. Our subjects performed overground walking and selected their own comfortable, fast, and slow speeds, as well as their preferred stride frequency. Our results showed that most of the investigated spatiotemporal gait parameters demonstrated the greatest stride-to-stride variability in the slow-speed condition. The increased stride-to-stride variability while these patients walk at their slow speed has clinical implications for severity of hemiparesis and for walking safety. In a recent study investigating the relationship between variability in spatiotemporal gait parameters and degree of hemiparesis in stroke patients, Balasubramanian et al.[32] found that greater step length, swing time, and stride time variability was associated with more severe hemiparesis. Our findings of slow-speed walking associated greater stride-to-stride variability imply that walking slowly may limit patients' ability to fully exploit the muscle strength that they have already regained during the recovery course. Furthermore, previous research has also shown that high stride-to-stride variability of gait parameters is significantly associated with risks of falls in older adults and in patients with neurologic diseases.[12-20] Slow walking, therefore, does not necessarily guarantee a safer walking strategy for stroke patients.

Another interesting finding was these patients presented the highest stride-width variability while walking at the fast speed, a trend different from other gait parameters. Similarly, Balasubramanian et al.[32] reported that decreased stride width variability was associated with more severe hemiparesis in chronic stroke patients. We speculated that the greater stride width variability while walking at fast speed may indicate a subject's ability to manage more degrees of freedom, in both the anteroposterior and lateral directions, as they were aiming to move forward at fast speed. On the other hand, as these patients were walking slowly, they may reduce the variability in stride width as a trade off to manage the greater variability in the progression direction, that is, in step length, stance time, and swing time.

One important issue is- what causes the better stride-to-stride consistency in fast-speed walking? We speculated that this could be due to increased descending motor drive,[33] increased joint stiffness,[34] or increased activation of cortical areas involved with motor planning and programming.[35] Using a near-infrared spectroscopic imaging technique, Suzuki and colleagues recently found that as healthy adults walked faster, the level of oxygenated hemoglobin in bilateral prefrontal and premotor cortices also increased.[35] Therefore, we postulate that walking at comfortable and fast speeds may also increase the activation of bilateral prefrontal and premotor cortices in stroke patients; which then leads to better locomotion programming and hence better stride-to-stride consistency of hemiplegic gait patterns. However, further testing of all these possibilities is needed.

Clinical Implications

Contrary to the common clinical belief that gait abnormalities may be exacerbated when stroke patients walk at fast speed,[28] our results showed no increase in gait asymmetry or stride-to-stride variability for most of the spatiotemporal gait parameters as these patients walked at their fast speed, compared to walking at their comfortable speed. In contrast, the temporal asymmetry, as well as stride-to-stride variability in the majority spatiotemporal gait parameters, was the greatest in slow-speed walking compared to fast- and comfortable-speed walking. Given that patient's comfortable and fast walking speeds were positively related to patient's range of achievable walking speed, we speculated that patients who practice comfortable- and fast-speed walking often will be likely to improve their comfortable and fast walking speeds, which in turn will improve their range of achievable walking speed. Indeed, past research has shown that stroke patients who receive treadmill walking training at higher than their comfortable speed, with[35] or without partial body weight support,[36] better improve their overground walking speed than those who are trained to walk at or below their comfortable walking speed. Consistent with this previous research, our findings also suggest that in terms of walking speed adaptability, symmetry, and consistency, comfortable- and fast-speed walking would be recommended for stroke patients. However, kinematic, kinetic, and elecrtromyographic data are still needed to fully explore the biomechanical changes with walking speed in stroke patients and to investigate whether walking at comfortable and fast speeds is also associated with better dynamic stability during walking.

Limitations

There are three major limitations of this study. First, the order of the walking-speed conditions was not randomized across the subjects due to the concern of subjects' safety and familiarity with the tasks. This testing order may cause an undesirable order effect on the results. However, we speculate that the fixed sequence should not have a significant impact on our results because sufficient resting time (2-5 minutes) was given between conditions, at least three practice trials were given before the testing of each condition, and there were significant differences on almost all spatiotemporal parameters across the three walking-speed conditions. Nevertheless, randomization of the testing order of different walking-speed condition is suggested to future studies of this type. Second, the subjects in this study all had mild to moderate stroke and were able to walk independently without any assistance and device. Generalization of our results to patients with more severe stroke needs to be made with caution. Last, we only investigated spatiotemporal gait parameters in this study. Future research that simultaneously acquires kinematics, kinetics, and electromyographic data will provide more in-depth insight into the mechanisms through which the walking speed adaptability is achieved.

CONCLUSIONS

The present study showed that patients with stroke who are able to walk independently without using any assistance or assistive device preserve partial walking speed adaptability. They were able to achieve such adaptability by modulating the spatiotemporal gait parameters of both the affected and unaffected legs. However, the slower comfortable and fast walking speeds of these patients, compared to healthy adults, may still render these patients at a high risk of danger in emergency situations. Patients presented the greatest temporal asymmetry and stride-to-stride variability in most of the spatiotemporal gait parameters while walking at slow speed, compared to walking at the other two speeds. We suggest that to enhance walking speed adaptability, symmetry, and stride-to-stride consistency, patients with stroke may practice walking at their comfortable and fast speeds, instead of at a slow speed cautiously.

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REFERENCES

1. Patla AE. Adaptability of human gait: Implications for the control of locomotion. In: Advances in Psychology. Vol. 78. Amsterdam: Elsevier Science Publishers; 1991.
2. Bohannon RW. Gait performance of hemiparetic patients with stroke: Selected variables. Arch Phys Med Rehabil 1987;68:777-81.
3. Bohannon RW. Walking after stroke: Comfortable versus maximum safe speed. Int J Rehabil Res 1992;15:246-8.
4. Olney SJ, Richards CL. Hemiparetic gait following stroke. Part I: Characteristics. Gait Posture 1996;4:136-48.
5. Olney SJ, Richards CL. Hemiparetic gait following stroke. Part II: Recovery and physical therapy. Gait Posture 1996;4:149-62.
6. Turnbull GI, Charteris J, Wall JC. A comparison of the range of walking speeds between normal and hemiplegic subjects. Scand J Rehabil Med 1995;27:175-82.
7. Bilney B, Morris M, Webster K. Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. Gait Posture 2003;17:68-74.
8. McDonough AL, Batavia M, Chen FC, Kwon S, Ziai J. The validity and reliability of the GAITRite system's measurements: A preliminary evaluation. Arch Phys Med Rehabil 2001;82:419-25.
9. Brandstater ME, de Bruin H, Gowland C, Clark BM. Hemiplegia gait: Analysis of temporal variables. Arch Phys Med Rehabil 1983;64:583-7.
10. Roth EJ, Merbitz C, Mroczek K, Dugan SA, Suh WW. Hemiplegic

gait: Relationships between walking speed and other temporal parameters. Am J Phys Med Rehabil 1997;76:128-33.

11. Wall JC, Turnbull GI. Gait asymmetry in residual hemiplegia. Arch Phys Med Rehabil 1986;67:550-3.
12. Guimares RM, Issacs B. Characteristics of the gait in old people who fall. Int Rehabil Med 1980;2:177-80.
13. Hausdorff JM, Edelberg HK, Mitchell SL, Goldberger AL, Wei JY. Increased gait unsteadiness in community-dwelling elderly fallers. Arch Phys Med Rehabil 1997;78:278-83.
14. Maki BE. Gait changes in older adults: Predictors of falls or indicators of fear? J Am Geriatr Soc 1997;45:313-20.
15. Tinetti ME. Performance-oriented assessment of mobility problems in elderly patients. J Am Geriatr Soc 1986;34:119-26.
16. Wolfson LI, Whipple R, Amerman P, Tobin JN. Gait assessment in the elderly: A gait abnormality rating scale and its relation to falls. J Gerontol Med Sci 1990;45:M12-9.
17. van Iersel MB, Kessels RP, Bloem BR, Verbeek AL, Olde Rikkert MG. Executive functions are associated with gait and balance in community-living elderly people. J Gerontol A Biol Sci Med Sci 2008;63:1344-9.
18. Verghese J, Robbins M, Holtzer R, Zimmerman M, Wang C, Xue X, et al. Gait dysfunction in mild cognitive impairment syndromes. J Am Geriatr Soc 2008;56:1244-51.
19. Blin O, Ferrandez AM, Serratrice G. Quantitative analysis of gait in Parkinson patients: Increased variability of stride length. J Neurol Sci 1990;98:91-7.
20. Hausdorff JM, Cudkowicz ME, Firtion R, Wei JY, Goldberger AL. Gait variability and basal ganglia disorders: Stride-to-stride variations of gait cycle timing in Parkion's disease and Huntington's disease. Mov Disord 1998;13:428-37.
21. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. Scand J Rehabil Med 1975;7:13-31.
22. Mahoney FI, Barthel DW. Functional evaluation: The Barthel Index. Md State Med J 1965;14:56-61.
23. Barker S, Craik R, Freedman W, Herrmann N, Hillstrom H. Accuracy, reliability, and validity of a spatiotemporal gait analysis system. Med Eng Phys 2006;28:460-7.
24. Pomeroy VM, Chambers SH, Giakas G, Bland M. Reliability of measurement of tempo-spatial parameters of gait after stroke using GaitMat II. Clin Rehabil 2004;18:222-7.
25. Hsu AL, Tang PF, Jan MW. Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. Arch Phys Med Rehabil 2003;84:1185-93.
26. Leiper CI, Craik RL. Relationships between physical activity and temporal-distance characteristics of walking in elderly women. Phys Ther 1991;71:791-803.
27. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. Stroke 1995;26:982-9.
28. Bobath B. Adult Hemiplegia: Evaluation and Treatment. 3rd ed. Oxford: Butterworth-Heinemann, Ltd.; 1990.
29. 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.
30. Titianova EB, Tarkka IM. Asymmetry in walking performance and postural sway in patients with chronic unilateral cerebral infarction. J Rehabil Res Dev 1995;32:236-44.
31. Jeng SF, Holt KG, Fetters L, Certo C. Self-optimization of walking in nondisabled children and children with spastic hemiplegic cerebral palsy. J Mot Behav 1996;28:15-27.
32. Balasubramanian CK, Neptune RR, Kautz SA. Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke. Gait Posture 2009;29:408-14.
33. Hesse S, Werner C, Paul T, Bardeleben A, Chaler J. Influence of walking speed on lower limb muscle activity and energy consumption during treadmill walking of hemiparetic patients. Arch Phys Med Rehabil 2001;82:1547-50.
34. Simonsen EB, Dyhre-Poulsen P. Amplitude of the human soleus H reflex during walking and running. J Physiol 1999;515:929-39.
35. Suzuki M, Miyai I, Ono T, Oda I, Konishi I, Kochiyama T, et al. Prefrontal and premotor cortices are involved in adapting walking and running speed on the treadmill: An optical imaging study. Neuroimage 2004;23:1020-6.
36. Sullivan KJ, Knowlton BJ, Dobkin BH. Step training with body weight support: Effect of treadmill speed and practice paradigms on poststroke locomotor recovery. Arch Phys Med Rehabil 2002;83:683-91.
37. 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.

步行速度適應力及與步行速度相關之中風偏癱步態空間—時間參數、對稱性、與變異性之變化

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背景與目的：在日常活動中，步行速度的適應能力是必要的。本研究探討中風病患的步行速度適應能力以及其偏癱步態空間—時間步態參數、對稱性、步與步間變異性是否隨步行速度而改變。**方法：**19位單次中風、可不用輔具而獨立行走的病患參與本研究。受試者在舒適速度、快速、及慢速下行走六回。分析並比較受試者在每種步行速度情境下步行速度、空間—時間步態參數、單腳支撐時間不對稱指數（時間不對稱指數）、步長不對稱性指數（空間不對稱性指數）、以及步與步間空間—時間步態參數的變異性。**結果：**受試者的快速、舒適、及慢速步行速度分別為1.01±0.30、0.66±0.18、0.43±0.19公尺/秒，且相互間有顯著差異（$p<0.017$）。除了步寬以外，其餘空間—時間步態參數在三種步行速度情境間皆有顯著差異（$p<0.017$）。除了步寬外之所有步態參數的步與步間變異性及左右單腳支撐時間不對稱指數，在慢速步行時皆大於在快速及舒適步行時（$p<0.017$）。**結論：**輕度到中度中風病患雖有保留部份的步行速度適應能力，但仍受到限制。這些病患能夠藉由調節健側及患側腳的空間—時間步態參數，而達成不同的步行速度。中風病患慢速步行時，其單腳支撐時間不對稱性以及大部分空間—時間步態參數的步與步間變異性皆比在快速及舒適速度步行時為大。依據本研究結果，建議中風病患以舒適速度及快速進行步行練習，而非在小心謹慎的慢速下練習，以加強其步行速度適應能力、對稱性、以及步與步間穩定性。（物理治療 2011;36(1):9-19）

關鍵詞：腦中風、適應能力、步行速度、對稱性、變異性

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