Gait initiation is dependent on the function of the paretic trailing limb in individuals with stroke

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Abstract

The purposes of this study were to compare the gait initiation task between individuals with chronic stroke and age-matched healthy controls, to determine whether the observed differences between groups could be attributed to the presence of a stroke or to differences in gait initiation speed, and to establish the gait initiation variables that relate with a faster gait initiation speed. All subjects initiated gait at their preferred speed, while control subjects were also asked to initiate gait at a speed that was comparable to the stroke group. It was found that while many temporal and kinetic differences were observed between the two groups, most were simply due to differences in gait initiation speed. Two variables that remained different when speed was controlled were the magnitude of the antero-posterior impulse generated by the paretic limb when it was used as either the leading or trailing limb. Kinetic parameters of the trailing limb (i.e. peak antero-posterior force and impulse) were also found to correlate with the gait initiation speed for the non-paretic lead limb condition. The results suggest that the propulsive function of the paretic limb when used as the trailing limb is a key area to address in the rehabilitation of gait initiation for individuals with stroke.

Keywords

cerebrovascular accident; gait speed; kinetics

Introduction

Gait initiation, the transition period from upright stance to steady-state gait, can be considered a unique and challenging task. Unlike steady-state gait, gait initiation requires each limb to have distinctive responsibilities depending on the choice of leading limb. For example, the leading limb is used for the first step and is responsible for applying a large vertical force in order to lift its foot from the ground¹. Conversely, the trailing (i.e. the non-

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Conflict of interest statement

There were no financial and personal relationships that could inappropriately influence our work.

stepping) limb is responsible not only for body support during the initial swing phase but also for the majority of forward propulsion, as this limb applies approximately three times greater propulsive forces than the leading limb^{2,3}. These asymmetrical limb requirements may thus provide additional insight about the way in which individuals with walking difficulties, such as those with chronic stroke, achieve gait.

While it has been shown that individuals with chronic stroke tend to walk at a slower speed⁴, take shorter strides⁵, and rely more heavily on the non-paretic limb⁴ during steady-state gait, the manner in which these individuals initiate gait has received much less focus. To our knowledge, only two studies have examined gait initiation in individuals with acute stroke; none have examined the chronic stroke population. One study has found that when individuals with acute stroke initiate gait with their non-paretic limb, the center of mass moved forward prior to the initial toe-off of the leading limb⁶. In contrast, when these individuals led with their paretic limb, there was a delay in the body's forward acceleration, where greater body movements, such as the lifting of the leading limb as well as a forward push from the trailing limb, were necessary to initiate gait⁶. Brunt et al.⁷ also found the propulsive forces from the trailing limb to be important during gait initiation in subjects with acute stroke, and this may be a reason why these individuals prefer to lead with the paretic limb⁶.

While these previous studies find differences in the way in which individuals with acute stroke initiate gait, several issues remain unanswered. The first purpose was to determine the differences in gait initiation between a group of individuals with chronic stroke compared to a group of healthy adults. We hypothesized that individuals with chronic stroke would exhibit differences in the gait initiation strategy when compared to healthy adults, with greater changes occurring during the non-paretic lead limb condition. The second purpose was to establish whether the between-group differences were due to the effects of the stroke or to the slower gait initiation speed. It was hypothesized that these differences can be primarily attributed to the effects of stroke and these between-group differences would remain even after controlling for the effects of gait initiation speed. Finally, the study was conducted to determine the factors that are related with faster gait initiation speeds. It was hypothesized that parameters of the paretic limb when used as the trailing limb would have the strongest relationship with the ability to initiate gait faster, as this condition requires the greatest contribution from the weakest limb.

Methods

Subject characteristics of the 13 individuals with chronic stroke and 13 healthy adults who participated in the study can be found in Table 1. To be eligible for the stroke group, participants were required to be a minimum of 6 months post-stroke, have hemiparesis secondary to a cerebrovascular accident, and have no other musculoskeletal or neurologic conditions. The functional disability was assessed using the leg and foot dimensions of the Chedoke-McMaster Stroke Assessment scale, where scores were rated on separate 7-point scales for a maximum total of 14 (higher scores indicating better recovery)⁸. All subjects consented to the study in accordance with the local university ethics policies.

Prior to each trial, participants were asked to stand with each foot on a separate force platform (Bertec model K71003, Bertec Corporation) that was flush mounted to the ground. Participants were then instructed to walk at their comfortable speed, without the use of any walking aid for a distance of five meters. While 7 of the 13 subjects with stroke used canes for community ambulation, all subjects were comfortable moving about their home or walking short distances without their cane. Two subjects with stroke wore their ankle foot orthosis during the testing as they used it on a regular basis. While spotters were always available in the event that the subject required immediate assistance, no physical help was given during the testing trials. The choice of leading limb was determined randomly by the experimenter. Subjects landed with their leading foot on a third platform that was situated directly in front of the starting position. Rest periods were given between trials to minimize fatigue effects. Three trials were collected from each lead limb condition.

To address issues dealing with speed differences between the two groups, the control subjects were also asked to complete an additional set of trials, where they initiated gait at a slower than normal speed. The experimenter demonstrated the desired speed and verbal instruction was given as “stepping at about one step per second”, which represented a speed similar to that chosen by the stroke group.

All force platform data were sampled at 600 Hz, and low-pass filtered (second order zero-phase lag Butterworth filter with a cutoff frequency of 50 Hz). From the three force platform data, variables that were extracted consisted of gait initiation speed, duration of gait initiation, backward displacement of the center of pressure (COP), initial loading of the limbs during quiet stance, the peak vertical and antero-posterior (A-P) forces from the leading and trailing limbs, and the A-P impulses from the leading and trailing limbs.

The duration of gait initiation was defined as the period between the first 4 mm shift in the baseline COP until the toe-off of the trailing limb, where baseline COP was determined as the mean value prior to the “start” command. Speed of the subject’s center of mass in the A-P direction was determined by first dividing the A-P force data from all platforms by the subject’s body mass to yield the total acceleration. The acceleration profile was then integrated in order to determine the subject’s velocity. The use of ground reaction forces to compute the kinematics of the center of mass yields similar results as those obtained through kinematic methods during slow steady-state gait speeds¹⁰.

While some consider the toe-off event to signify the achievement of steady-state gait², individuals with stroke may require more time to attain steady-state gait. Hence, the speed at toe-off of the trailing limb has been termed the “gait initiation speed”. Impulses in the A-P direction were calculated by integrating the A-P force data from the first two platforms, between the period of onset of gait initiation and toe-off of each limb. All force and impulse data were normalized to the individual’s body mass.

Preliminary analysis between the left and right lead limb conditions for the control group exhibited minimal differences and thus, only the right lead limb condition from the control group has been presented. Data were statistically analyzed with ANOVAs, using post-hoc Tukey’s tests to detect differences among the three lead limb conditions (i.e. control, paretic

and non-paretic). Paired t-tests were used to compare between the fast and slow speed conditions in the control group in order to determine whether the selected variables were important determinants of gait initiation speed. To determine the relationship between the biomechanical variables and the final gait initiation speed, Pearson correlation coefficients were performed. All statistical analyses were conducted at an alpha value of 0.01.

Results

Magnitude differences between the stroke and control groups were found for the majority of the gait initiation variables (Table 2). Regardless of whether individuals with stroke led with their paretic or non-paretic limb, they took almost twice as long to initiate gait, the magnitude of postural adjustment (as expressed by the change in COP in the backward direction) was approximately two and one-half times smaller, and the peak A-P force on the trailing side was more than two times smaller when compared to the self-paced trials of the control group. Three lead limb variables during the paretic lead limb condition (i.e. peak vertical force, peak A-P force and peak A-P impulse) were also reduced ($p < 0.01$) from the control condition. Conversely, when leading with their non-paretic limb, the A-P impulse generated by the trailing limb was less than half of that of the controls ($p < 0.01$). Finally, regardless of whether individuals led with their paretic or non-paretic limb, they stood in a more asymmetrical manner compared to the healthy controls (57% of body weight on the non-paretic limb and 42% of body weight on the paretic limb versus 49% for the control condition, $p < 0.01$).

The effect of gait initiation speed was also determined in both the control and stroke groups. In the controls, it was found that eight of the ten variables were deemed to be altered by gait initiation speed (Table 2). This confirmed the use of our pre-selected variables and thus, comparisons between the control and stroke groups were performed.

Although many group differences were found between the normal speed of the controls and the stroke group, most of these differences could be attributed to differences in gait initiation speed. Fewer between-group differences emerged when comparisons were conducted with the slower speed of the control subjects (Table 2). It was found that only the magnitude of A-P impulse generated by the paretic limb was different than normal. When the paretic limb was used as the trail limb, the impulse was about half the value of the control condition, whereas when the paretic limb was used as the lead limb, the impulse was almost non-existent.

To determine whether a relationship existed between the final gait initiation speed and the measured variables, correlations were conducted and the results are presented in Table 3. Only the magnitude of the peak A-P force and impulse of the trailing limb for the non-paretic limb and normal speed control groups were significant related to initiation speed ($r = 0.76\text{--}0.93$, $p < 0.01$).

Discussion

Individuals with chronic stroke were found to be different from control subjects from the start of each trial, as they stood in a more asymmetrical manner. While the control subjects

stood with half of their weight on each limb, individuals with stroke relied less (only 42%) on their paretic limb. Others have found similar levels of weight-bearing asymmetry during upright stance^{11,12}. This increased dependence on the non-paretic limb may result from sensory loss, spasticity, impaired balance and muscle weakness¹¹, and is one factor that can affect an individual's walking performance¹³.

When individuals with stroke posturally adjusted for the initial stepping movement, they exhibited a reduced response, where the backward displacement of the COP was smaller by a factor of approximately 2.5. While it is possible that this was due to a change in initial posture, this cannot be determined from the present study as no kinematic data were collected. However, it is also likely that the reduced COP displacement was an indication of poorer body stability in individuals with stroke, since smaller postural shifts can minimize the upcoming body disequilibrium¹⁴. Additional postural compensations may have also occurred in the medio-lateral direction, as individuals with acute stroke exhibit greater lateral shifts when leading with their non-paretic limb⁶. Although we did not report the displacement of the medio-lateral COP specifically, the observed increase in the vertical force, which affects the displacement of the medial-lateral COP, on the non-paretic leading limb is a comparable result to those found previously⁶.

Regardless of whether individuals with stroke initiated with their paretic or non-paretic limb, the magnitude of push-off (as determined by the A-P force and impulse) was most reduced on the paretic side. Studies have shown that individuals with stroke exhibit decreased plantarflexor, hip flexor and hip extensor strength on the paretic side^{15,16}, which may underlie their inability to generate as large a force and impulse as the controls. In contrast, the contralateral non-paretic limb exhibited only one difference when compared to the controls: it did not produce as large a peak A-P force when used as the trailing limb. This may be due to two reasons. First, although motor impairments are usually affected on the side contralateral to the lesion, the strength on the ipsilateral side has also been found to be moderately impaired¹⁷. Greater muscle fiber atrophy due to a more sedentary lifestyle may also contribute to the decreased torque generation on the non-paretic side. Second, the gain on the non-paretic side may have simply been down-regulated such that individuals with stroke do not compensate with the non-paretic limb for the reduced propulsion on the paretic side. Although the lack of compensation may have reduced the magnitude of body propulsion, it would have also minimized the total body instability. This is likely to be a major consideration for individuals with stroke, as they are reluctant to shift their body weight onto the paretic limb and to a lesser extent onto their non-paretic limb^{5,11}.

Individuals with stroke achieved a slower gait initiation speed when leading with their non-paretic limb, but were able to walk at a similar pace when starting with their paretic limb. Because the trailing limb is relied upon more heavily for forward propulsion^{2,3}, initiating with their paretic limb enabled these individuals to use the non-paretic limb as the main propulsion generator and thus, were able to achieve a comparable gait initiation speed. In contrast, the inability to achieve a fast gait initiation speed when leading with the non-paretic limb is not surprising since it is the weakened paretic limb which is primarily responsible for forward propulsion.

To control for the possible confounding effect of speed, the control subjects were also asked to initiate gait at a slower pace. From these trials, it was evident that contrary to our hypothesis, many of the differences observed between groups can be attributed to differences in gait initiation speed. However, variables concerning the A-P impulse from the paretic limb still remained smaller and again indicates that the stroke impairment on the paretic side had a negative effect on gait initiation. This result can be thought to be in agreement with Brunt et al.⁷, who found that the function of the paretic limb was strongly related to the ability to generate vertical and A-P forces in individuals with acute stroke.

Whether the decreases in the magnitude of the gait initiation variables were detrimental to the ability to attain steady-state gait in individuals with stroke cannot entirely be deduced by comparing group differences. Instead, correlational analyses were conducted to better determine the variables that are related to functional performance (i.e. gait initiation speed). In agreement with our hypothesis, correlational analyses determined that the greater the ability an individual with stroke has to produce a larger peak A-P force and magnitude of A-P impulse with the paretic limb when used as the trailing limb, the faster the gait initiation speed they are able to achieve. This finding suggests that training the paretic limb for generating large magnitudes of push-off is a key area in which to focus on in order to improve upon gait initiation speed. Improving the abilities of the paretic limb could also potentially serve to minimize the risk of falls, since this lack of momentum generation may be responsible for falls or the direction of falls in the elderly¹⁸.

Despite determining some of the factors that are associated with faster initiation speeds, it is possible that other variables may also be of importance. For example, Nadeau et al.¹⁵ have recently suggested that during steady-state gait, sensation of the lower limbs was an important variable to predict maximal gait speed. This is likely to be of importance during gait initiation as well, since the task requires body disequilibrium and thus, correct and reliable sensory feedback would certainly aid in this accomplishing this task. A second limitation may be the large age variability present within each of the groups. Although the groups had similar age ranges and previous research has shown that parameters of gait initiation are not affected by age,¹⁹ it is still possible that the large age range may have introduced a variety of movement strategies which in turn, may have weakened our correlations. It would be beneficial to determine whether younger individuals with stroke are better able to compensate for the presence of a stroke. Finally, it is important to consider the impairment levels of our subjects with stroke. All were self-ambulatory, and could be classified as those with mild to moderate impairment levels based on the Chedoke-McMaster Stroke Assessment leg scores and thus the data cannot be generalized to individuals with more severe impairments or those who need assistance with walking. However, it is important to note that independent ambulators do constitute a large proportion (80%) of individuals with chronic stroke²⁰.

In summary, when speed was controlled, it was found that only the magnitude of A-P impulse from the paretic limb, regardless of whether it was leading or trailing, was still reduced in the stroke group. Similarly, correlational analyses showed that when subjects with stroke initiated with their non-paretic limb, the A-P force and impulse generated by the trailing limb were strongly related to the magnitude of the final gait initiation speed. These

results suggest that the propulsive function of the paretic limb when used as the trailing limb may be a key area to address in the rehabilitation of gait initiation in individuals with stroke.

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Table 1

Subject characteristics for the control and stroke groups.

	Control Group	Stroke Group
Gender	8 males, 5 females	8 males, 5 females
Age (mean±SD, in years)	64.69±7.81	59.31±9.16
Mass (mean±SD, in kg)	71.58±15.10	71.14±13.63
Height (mean±SD, in cm)	171.46±9.79	164.31±12.49
Time since injury (mean±SD, in years)	-	4.04±4.03
Chedoke-McMaster scale (median, with range)	-	8 (5–10)
Paretic side	-	7 right, 6 left

Table 2

Mean (SD) for each of the gait initiation variables.

Variable	Controls Normal Speed	Controls Slow Speed	Paretic Lead Limb	Non-Paretic Lead Limb
Gait initiation speed (m/s)	1.07 (0.13)	0.73 (0.08) ^a	1.04 (0.23) ^{b,c}	0.71 (0.26) ^a
Duration (s)	1.18 (0.14)	1.65 (0.43) ^a	2.19 (0.50) ^a	2.00 (0.59) ^a
Change in COP (cm)	-5.19 (1.72)	-2.74 (1.37) ^a	-2.00 (1.01) ^a	-1.66 (0.90) ^a
Initial load on lead limb (% body mass)	0.51 (0.06)	0.51 (0.07)	0.43 (0.06) ^{a,c}	0.56 (0.07)
Peak vertical force (lead limb) (N/kg)	7.05 (1.19)	6.42 (1.20) ^a	5.63 (1.01) ^a	6.37 (0.98)
Peak vertical force (trail limb) (N/kg)	10.34 (0.47)	10.03 (0.39)	10.03 (0.26)	9.95 (0.37)
Peak A-P force (lead limb) (N/kg)	-0.51 (0.23)	-0.27 (0.17) ^a	-0.20 (0.22) ^a	-0.32 (0.11)
Peak A-P force (trail limb) (N/kg)	-1.72 (0.33)	-1.11 (0.21) ^a	-0.96 (0.29) ^a	-0.86 (0.26) ^a
A-P impulse (lead limb) (Ns/kg)	-0.13 (0.07)	-0.07 (0.07) ^a	0.00 (0.12) ^{a,b,c}	-0.13 (0.10)
A-P impulse (trail limb) (Ns/kg)	-0.88 (0.09)	-0.73 (0.08) ^a	-0.79 (0.16) ^c	-0.38 (0.22) ^{a,b}

^a different than control (normal speed) (p<0.01)

^b different than control (slow speed) (p<0.01)

^c different than non-paretic lead (p<0.01)

Correlations with the final gait initiation speed. Negative correlations with A-P force or impulse indicate that faster gait initiation speeds were associated with greater backward forces or impulses.

Table 3

Variable	Controls Normal Speed	Controls Slow Speed	Paretic Lead Limb	Non-Paretic Lead Limb
Duration	-0.335	-0.833 ^a	0.061	-0.289
Change in COP	-0.579	-0.645	-0.033	-0.326
Initial load on lead limb	0.437	0.052	0.249	-0.673
Peak vertical force (lead limb)	0.504	0.319	0.053	-0.146
Peak vertical force (trail limb)	0.278	-0.058	0.639	0.153
Peak A-P force (lead limb)	-0.649	-0.269	-0.011	-0.089
Peak A-P force (trail limb)	-0.927 ^a	-0.628	-0.576	-0.903 ^a
A-P impulse (lead limb)	-0.685	-0.023	0.268	0.078
A-P impulse (trail limb)	-0.761 ^a	-0.221	-0.707	-0.854 ^a

^a correlation is significant at the 0.01 level