



Differences in paretic lower limb loading and fluidity in sit-to-walk according to selection of the leading limb in individuals with stroke

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ABSTRACT

Background: Sit-to-walk is an asymmetric task that is challenging for individuals with stroke, and paretic limb loading at seat-off and movement fluidity may change according to whether the non-paretic or paretic leg is used as the leading limb. This study aimed to investigate differences in paretic limb loading and fluidity depending on whether the non-paretic limb or paretic limb was used as the leading limb.

Methods: Thirty-eight individuals with stroke performed sit-to-walk with each leg as the leading limb, and their movements were measured using a 3D motion analysis system. The paired *t*-test or Wilcoxon signed-rank test was used to assess differences according to limb selection in paretic limb loading ratio at seat-off and fluidity (Fluidity Index: ratio of the lowest to peak forward velocity before first initial contact).

Findings: Twenty-two of 38 participants preferred to use the paretic limb as the leading limb. When leading with the paretic limb, the paretic limb loading ratio was significantly larger ($p = 0.002$), and the Fluidity Index was lower ($p = 0.007$).

Interpretation: Sit-to-walk with the paretic leading limb seems to be an adaptive movement because many participants preferred leading with the paretic limb. However, selection of the leading limb in sit-to-walk involves a biomechanical tradeoff between paretic limb loading at seat-off and movement fluidity in individuals with stroke. Use of the paretic leading limb requires loading capacity of this limb, and the non-paretic leading limb must have high balance ability to merge sit-to-stand and gait initiation.

1. Introduction

In daily life, walking can begin from a standing position (gait initiation [GI]) or a sitting position (sit-to-walk [STW]). STW is a transitional movement performed an average of 26 times a day by individuals with stroke (Kerr et al., 2017), because they spend a long time in a sedentary posture (i.e., sitting or lying) (English et al., 2016). Performing STW efficiently requires excellent balance control in order to merge rising and initiation of walking (Osada et al., 2015). In this challenging STW task, some individuals with stroke use the paretic leg as the leading limb and others use the non-paretic leg as the leading limb (Frykberg et al., 2009). The leading limb is responsible for the initial transfer of weight to the stance limb as well as the antigravity flexion required for forward swing (Brun et al., 1991). Thus, in healthy individuals, the maximum vertical force in STW is significantly greater on the leading limb

compared with the trailing limb, especially at seat-off (Magnan et al., 1996). This increase in maximum vertical force on the leading limb in STW may be due to anticipatory mediolateral postural adjustment before swing and has also been observed in individuals with stroke (Frykberg et al., 2012; Jones et al., 2019).

Training to enable greater loading on the paretic lower limb improves sit-to-stand performance in individuals with stroke (Cheng et al., 2001). If paretic limb loading can be increased by changing the selection of the leading limb in STW, paretic sensorimotor control may be improved. However, there is a clinical impression that using the non-paretic limb as the leading limb increases paretic limb loading (Davies, 2000). Weakness of the paretic lower limb is associated with less loading on the paretic limb at seat-off in sit-to-stand (Boukadida et al., 2015). Therefore, some patients with stroke may not prefer the method of overloading the paretic lower limb from the perspective of

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behavioral adaptation (Liepert et al., 2000).

The appropriate movement for individuals with stroke depends on their stage of recovery. Patients in the more chronic phase tend to require behavioral adaptation that is easier and less stressful rather than a restitutive approach to the sensorimotor system. Thus, if we can determine which leading limb enhances paretic limb loading at seat-off, we could make recommendations on use of the leading limb that increases loading on the paretic limb from the viewpoint of recovery of the sensorimotor system, or on the use of the other leading limb from the viewpoint of behavioral adaptation.

To evaluate STW, it is also necessary to analyze overall motion fluidity (Dion et al., 2003; Osada et al., 2015). Individuals with stroke tend to divide STW into rising and initiation of walking because they start walking from a less stable posture in STW than in GI (Dion et al., 2003; Malouin et al., 2003). Thus, fluid STW may indicate a high level of balance performance for merging the two locomotor tasks of sit-to-stand and GI (Malouin et al., 2003). If we can determine whether using the non-paretic limb as the leading limb enhances the fluidity of STW, we could make recommendations on the use of a leading limb for fluid STW from the viewpoint of recovery of balance ability. Conversely, if an adaptive approach is required for the individuals with lower balance ability, a leading limb with less fluid STW can be selected.

Although some previous studies have investigated differences in selection of leading limb for GI (Brunt et al., 1995; Hesse et al., 1997; Ko et al., 2011), few studies have done so for STW. No studies have examined which leading limb induces more paretic limb loading and motion fluidity during STW in individuals with stroke. The aim of this study was to investigate the biomechanical differences in STW according to selection of the leading limb in individuals with stroke and to infer the appropriate leading limb in STW from the viewpoints of recovery of sensorimotor function or behavioral adaptation. Our hypothesis is that leading with the paretic limb would be an adaptive movement in STW, namely, that leading with the paretic limb in STW would place less loading of the paretic limb with less fluency than leading with the non-paretic limb because most individuals with stroke tend to use paretic limb as the leading limb in STW (Frykberg et al., 2009). If the biomechanical differences in STW according to selection of the leading limb are found, we can instruct individuals with stroke on the appropriate first step for different purposes: an adaptive approach that is easier and less stressful on the leading limb and a restitutive approach that is harder and more stressful on the leading limb.

2. Methods

2.1. Participants

Thirty-eight individuals with stroke (mean age, 60 years) participated in this cross-sectional study. Participant characteristics are shown

Table 1
Participant characteristics.

	Patients (N = 38)
Age [years], mean \pm SD	59.5 \pm 10.1
Weight [kg], mean \pm SD	59.2 \pm 11.0
Height [cm], mean \pm SD	163.9 \pm 7.4
Sex (female/male)	11/27
Paretic side (right/left)	17/21
Time since onset (days), median (IQR)	92 (98)
BRS: lower extremity score, n (%)	III: 7 (18); IV: 9 (24); V: 18 (47); VI: 4 (11)
FMA: lower extremity score, median (IQR)	28 (3.75)
FMA: balance score, median (IQR)	10 (3.75)
FIM: transfer to the bed score, n (%)	V: 4 (13); VI: 18 (47); VII: 16 (42)
FIM: locomotion (walking) score, n (%)	IV: 4 (11); V: 10 (26); VI: 15 (39); VII: 9 (24)

BRS, Brunnstrom Recovery Stage; FMA, Fugl-Meyer Assessment; FIM, Functional Independence Measure; IQR, interquartile range.

in Table 1. All participants were patients in a convalescent rehabilitation ward who met the following inclusion criteria: (1) age 18 years or older; (2) hemiparesis secondary to a cerebrovascular accident; (3) first unilateral stroke; (4) sub-acute phase and hospitalized in a convalescent rehabilitation ward; (5) ability to stand up from a chair without using their arms; and (6) ability to follow simple instructions and walk at least 10 m at their preferred speed without manual assistance. Individuals were excluded if they had other neurological or musculoskeletal deficits that would influence gait and sit-to-stand. This study was approved by the ethics committees of the International University of Health & Welfare (17-10-22) and Nakaizu Rehabilitation Center (28-007). Participants provided written informed consent before enrollment in the study.

2.2. Study protocol

During two STW tasks involving initiating walking with either the paretic or non-paretic limb as the leading limb, data were measured using a 3D motion capture system comprising eight Vicon MX cameras (Vicon Motion System Ltd., Oxford, UK) and six AMTI force plates (600 mm \times 400 mm; Advanced Mechanical Technology Inc., Phoenix, AZ). Participants were positioned in a standardized static sitting position with each buttock and foot placed on a force plate (Fig. 1). Chair height was adjusted to the height of the right lateral knee joint space, and participants sat on the chair with a depth equal to half the length of the thigh. Each foot was placed at pelvis width. Because this study aimed to analyze natural daily movements, the participants were allowed to freely coordinate their arms and feet to accomplish the STW task comfortably (Frykberg et al., 2009; Osada et al., 2015). A previous study found that there were no differences between using dominant and non-dominant legs as leading limbs (Jones et al., 2016), so the participant's dominant leg was not considered. To ensure uniform STW conditions for each of the participants with maximum performance, a behavioral constraint was applied by instructed to start walking as quickly as possible from a static sitting position toward a line 3 m ahead (Ko et al., 2011) upon receiving a cue from an audible buzzer synchronized with an LED light placed 5 m ahead. Following the protocol of previous studies (Hesse et al., 1997; Sharma et al., 2015), participants wore normal low-heeled shoes; no ankle-foot orthosis nor walking aid was used. Guarded assistance from physiotherapists during the task prevented the participants from falling. After some trial attempts to acclimate to the experimental situation, the participants performed STW three times with no instruction on which limb should be used as the leading limb; then, the participants were instructed to use opposite leading limb for three trials. This procedure was chosen because random determination of the leading limb tended to cause the patients to freeze and move unnaturally. The remaining three STW trials were instructed to use the designated leading limb so that data could be obtained three times for each task, even for participants who were inconsistent in their initial selection.

Thirty-four reflective markers were attached to the participants at various landmarks, following a protocol used in previous studies (Osada et al., 2015; Wu et al., 2002). The marker trajectories and force plate data were synchronized at a sampling frequency of 120 Hz and low-pass filtered using a second-order Butterworth filter with cutoff values of 6 Hz and 18 Hz, respectively (Robertson and Dowling, 2003). Center of mass (CoM) and joint centers were calculated using anthropometric data for each segment of a link-segment model. Joint kinematics and kinetics were calculated using an inverse dynamic model according to the Vicon Plug-in Gait model computed with a biomechanics analysis program (Visual3D, version 5; C-Motion Inc., Kingston, ON, Canada).

2.3. Parameters

To analyze differences in STW between each leading limb, we extracted the paretic limb loading ratio. The vertical floor reaction forces on the paretic side (F_P) and non-paretic side (F_N) at seat-off during

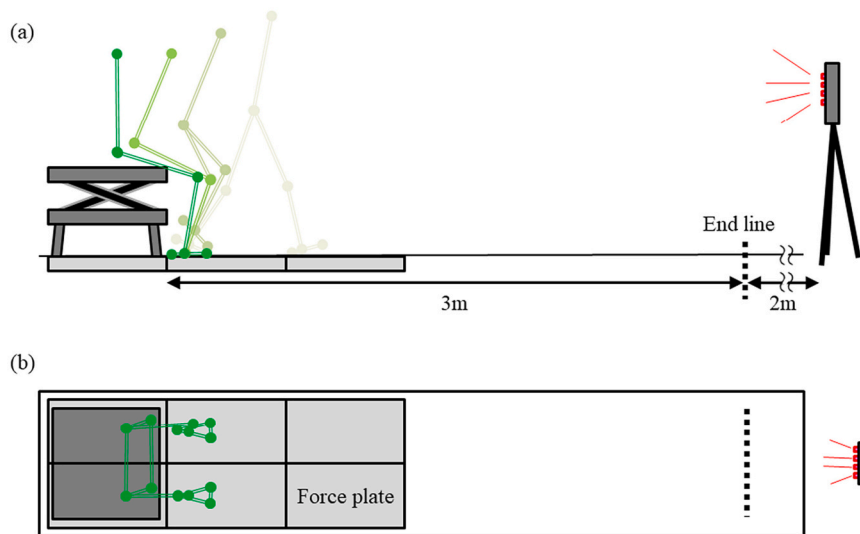


Fig. 1. Experimental setup for STW: (a) sagittal plane and (b) horizontal plane. Two adjustable chairs were set on each force plates. Chair height was adjusted to the height of the right lateral knee joint space. Participants sat on the chair with a depth equal to half the length of the thigh and were positioned in a standardized static sitting position with each buttock and foot placed on a force plate. The participants were instructed to start walking as quickly as possible from a static sitting position toward an end line 3 m ahead upon receiving a cue from an audible buzzer synchronized with an LED light placed 5 m ahead.

STW were extracted to calculate the paretic limb loading ratio as follows:

$$\text{Paretic limb loading ratio} = \frac{F_p}{F_p + F_N} \times 100\%.$$

A ratio of 50 indicates perfect symmetry, while a ratio of less than 50 (resp., greater than 50) indicates that the distribution of weight-bearing is higher on the non-paretic side (resp., non-paretic side).

The index of movement fluidity was the Fluidity Index (FI), which is the gold standard for evaluating efficiency in STW (Åberg et al., 2010; Asakura and Usuda, 2013; Dion et al., 2003; Malouin et al., 2003; Osada et al., 2015). The FI value indicates the ability to merge sit-to-stand and GI, and a higher value indicates that the participant can start walking efficiently while rising. The FI value is calculated as the percentage change in the forward velocity of the CoM from initial peak just before seat-off to the first step (ratio of the lowest to peak value) (Malouin et al., 2003). High balance coordination is required for STW with a high FI value (Osada et al., 2015).

Additionally, duration and step length were also obtained as in previous studies of STW (Buckley et al., 2009; Chen and Chou, 2013; Jones et al., 2021). Movement duration is separated into four phases (Osada et al., 2015): the rise phase, from a change of vertical force >2 SD from the mean in 1 s of static sitting to seat-off (defined as when the buttocks force <5 N); the postural phase, from seat-off to first foot-off (defined as when the foot force <5 N); the single support phase, from first foot-off to first initial contact (defined as when the first force acts on the swing leg); and the double support phase, first initial contact to second foot-off. Step length was calculated as the anteroposterior distance between the heel markers at initial contact.

2.4. Statistical analysis

Differences in paretic limb loading ratio, FI, duration, and step length were compared between the paretic and non-paretic leading limbs in STW. All indices were extracted as the average of three trials for each task. The Shapiro–Wilk test was used to confirm the normality of all data. Normally distributed data were compared using the paired t -test, and non-normally distributed data were compared using the Wilcoxon signed-rank test (SPSS, version 24.0; IBM Corp., Armonk, NY). The significance level was set at $\alpha = 0.05$, and the power was computed for each outcome variable to assess effect size using G*Power (version 3.1.9.2). The effect size dz was calculated for each index (Lakens, 2013). The formula for calculating the effect size dz was.

$$dz = \frac{t}{\sqrt{n}}.$$

where t is the t value and n is the number of pairs.

3. Results

In the first three trials, 22 participants used the paretic leg consecutively as the leading limb and 8 used the non-paretic leg. Eight participants did not select a specific leading limb in consecutive trials; that is, the same leading limb was not selected in all of the first three trials. The paretic limb loading ratio at seat-off, duration of the single support phase, and step length were the only normally distributed data. Differences in the kinetic and kinematic data are presented in Table 2. There were significant differences in the paretic limb loading ratio, FI, and the durations of the postural phase and single support phase. The paretic limb loading ratio at seat-off was larger when leading with the paretic limb compared with the non-paretic limb (mean difference = 3.07%; 95% confidence interval 1.19–4.94, $p = 0.002$, effect size $dz = 0.54$).

Table 2

Differences between using the paretic and non-paretic limb as the leading limb (N = 38).

	Paretic leading limb	Non-paretic leading limb	P-value	Effect size (dz)
Limb loading ratio at seat-off				
Paretic limb (%), mean \pm SD	41.3 \pm 9.0	38.2 \pm 9.1	0.002	0.54
Movement fluidity				
FI (%) ^a , median (IQR)	37.0 (70.8)	39.6 (71.8)	0.007	−0.35
Duration (s)				
Rise phase ^a , median (IQR)	0.77 (0.36)	0.73 (0.38)	0.780	−0.30
Postural phase ^a , median (IQR)	0.76 (0.88)	0.90 (1.13)	0.001	−0.34
Single support phase, mean \pm SD	0.49 \pm 0.14	0.25 \pm 0.06	<0.001	1.38
Double support phase ^a , median (IQR)	0.25 (0.22)	0.25 (0.19)	0.290	−0.23
Step length (cm/Ht), mean \pm SD				
1st step	0.20 \pm 0.09	0.19 \pm 0.09	0.578	0.12
2nd step	0.18 \pm 0.11	0.21 \pm 0.09	0.115	−0.32

^a Non-normally distributed; FI, Fluidity Index; Ht, height; IQR, interquartile range; rise phase, onset to seat-off; postural phase, seat-off to first foot off; single support phase, first foot off to first initial contact; double support phase, first initial contact to second foot off.

Differences in the paretic limb loading ratio between the paretic leading limb and non-paretic leading limb from seat-off to first foot-off in STW are shown in Fig. 2. The paretic limb loading ratio was maintained for a while after seat-off in the task using the paretic limb as the leading limb.

In our examination of movement fluidity, FI was significantly smaller when leading with the paretic limb compared with the non-paretic limb. Specifically, CoM velocity at seat-off tended to decrease more to start walking when leading with the paretic limb compared with the non-paretic limb. The median value of FI in STW tended to be positive regardless of which leg was used as the leading limb. However, there were 11 participants with 0% FI values when leading with the paretic limb, meaning that their CoM moved backward after standing up before initiating walking. In contrast, only 3 participants had 0% FI values when leading with the non-paretic limb.

Regarding the additional indices, duration of the postural phase was shortened (median difference = 0.14 s; $p = 0.001$, effect size $d_z = -0.34$) and the single support phase was prolonged (mean difference = 0.24 s; $p < 0.001$, effect size $d_z = 1.38$) when leading with the paretic limb compared with the non-paretic limb.

4. Discussion

This is the first study to clarify the differences in lower limb loading and fluidity in STW according to selection of the leading limb in individuals with stroke. The purpose of this study was to investigate the biomechanical differences in STW according to selection of the leading limb in individuals with stroke and to infer the appropriate leading limb in STW from the viewpoints of behavioral adaptation and recovery of sensorimotor function. In other words, we sought to determine the adaptive leading limb that was easier and less stressful on the sensorimotor system for an adaptive approach, and the restitutive leading limb that was harder and more stressful on the sensorimotor system for a restitutive approach. Our hypothesis was that the paretic limb would be the adaptive leading limb in STW. However, some of the results were contrary to our hypothesis. Loading on the paretic limb at seat-off was larger when leading with the paretic limb than when the non-paretic limb was used as the leading limb.

To adapt to the environment with an impaired sensorimotor system, individuals with stroke tend to reduce loading on the paretic limb, which

is associated with gait deviation and kinematic abnormalities (Szopa et al., 2017). Contrary to this adaptive movement, many physiotherapists select the stressful restitutive approach to promote recovery of the sensorimotor system, for example, weight-bearing on the paretic limb in sit-to-stand by changing foot position or putting the non-paretic foot on a solid block (Gray and Culham, 2014; Noh et al., 2020). We found that the paretic limb loading ratio at seat-off can be increased by simply trying to take a step with the paretic leading limb. This increase in loading on the leading limb before swing seems to be an anticipatory mediolateral postural adjustment to transfer weight to the stance limb. This increase in the maximum vertical force on the leading limb in STW has also been reported in several previous studies (Frykberg et al., 2012; Jones et al., 2019; Magnan et al., 1996). However, these studies did not report specific statistical data for changes in paretic limb loading. Our study is the first to reveal a significant difference in the paretic limb loading at seat-off when using the paretic limb as the leading limb in STW. We expected that paretic limb loading would be greater when the non-paretic leading limb was used, because a previous study found that anticipatory postural adjustments were more frequent and the CoM shifted more to the paretic side when the non-paretic limb was used as the leading limb in GI (Rajachandrakumar et al., 2017). Using the paretic limb as the leading limb has the merit of being able to control the forward velocity during the first step by the non-paretic stance limb (Frykberg et al., 2012). To effectively use the non-paretic limb as the first stance limb, the CoM should be moved toward the non-paretic side by the antigravity extension activity of the paretic lower limb before the antigravity flexion for swing. This may be one of the reasons for the increased loading on the paretic swing limb until first foot-off. This tendency may have strengthened by instructing the participants to complete the STW task as quickly as possible.

Regarding motion efficiency, 11 of the 38 participants had 0% FI values when leading with the paretic limb. This means that about one-third of the participants safely kept the CoM within the base of support and stopped moving forward after standing up before starting to walk when leading with the paretic limb. However, when leading with the non-paretic limb, most participants had a high FI value and thus fluently merged sit-to-stand and GI. Previous studies have also found that an inefficient CoM movement occurs when leading with the paretic limb in STW (Dion et al., 2003; Osada et al., 2015). In normal STW, large

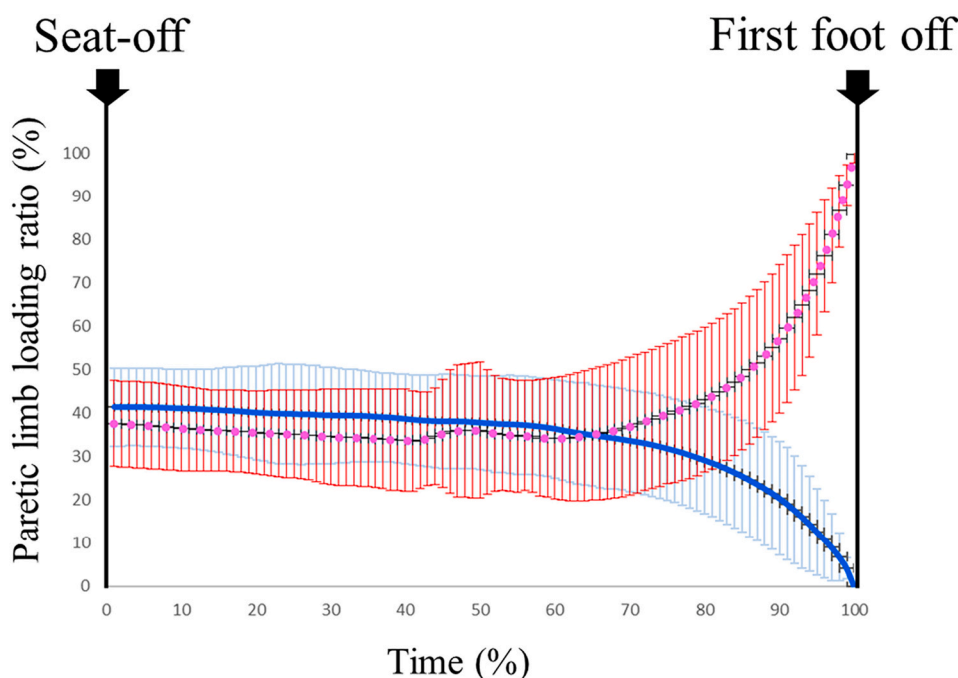


Fig. 2. Differences in paretic limb loading ratio between the STW tasks using either the paretic limb or non-paretic limb as the leading limb ($N = 38$). The solid line shows changes in averaged paretic limb loading ratio when leading with the paretic limb. The dotted line shows changes in averaged paretic limb loading ratio when leading with the non-paretic limb. The thin lines are the standard deviation. The trajectories were obtained for the averaged trials of each participant in which STW was performed as quickly as possible from a static sitting position. The horizontal axis is time (%), which is normalized to 100 from seat-off to first foot off. The vertical axis is the paretic limb loading ratio, calculated as the vertical floor reaction force on the paretic side divided by the sum of vertical floor reaction forces on the paretic and non-paretic sides (%).

shock absorption is required at first initial contact because the CoM moves rapidly in the upward and forward directions after seat-off (Frykberg et al., 2012; Osada et al., 2015). Therefore, a participant who could not absorb the shock at first initial contact with the paretic foot may have attempted to soften the contact by reducing their forward velocity. When leading with the non-paretic limb, excessive momentum at first initial contact can be absorbed by the non-paretic limb, although the single support phase on the paretic side would be shortened and high balance ability would be required. From the above, we consider that when leading with the paretic limb in STW, the participants deliberately moved in a way that lowered the FI value—that is, they made movements that required less balance control—and adopted a strategy to reduce the shock in the first step.

Given that STW is a more difficult task than sit-to-stand and GI (Kouta et al., 2006), it was meaningful to analyze the differences in STW according to selection of the leading limb in individuals with stroke in order to promote recovery of the sensorimotor system and to suggest adaptive movements for safety. Similar to our results, Frykberg et al. (2009) reported that 60% of individuals with stroke always led with the paretic limb in STW, 20% of participants always led with the non-paretic limb, and 20% of participants did not habitually lead with either limb. A previous study revealed that individuals with stroke often lead with the paretic limb due to their asymmetrical standing posture with less limb loading on the paretic side (Brunt et al., 1995). Because 80% of individuals with stroke have a balance disability (Tyson et al., 2006), they may prefer to lead with the paretic limb, which reduces balance control during first stance phase but increases loading on the paretic limb. Therefore, we conclude that the paretic limb is the adaptive leading limb, though this may vary depending on the physical dysfunction of patients. The paretic limb may be the restitutive leading limb for patients with poor limb loading capacity, and similarly, the non-paretic limb may be the restitutive leading limb for patients with balance disability. In sum, selection in the leading limb in STW involves a biomechanical tradeoff between paretic limb loading until first foot-off and balance-controlled movement fluidity in individuals with stroke.

5. Study limitations

Because this study was conducted with limited evaluation indices, we could not analyze the results based on the participants' physical function, use of a walking aid, and other factors. To eliminate the effect of walking aids, even in those who usually use canes (17 participants) and orthoses (13 participants), STW tasks were measured without the use of walking aids. Accordingly, participants who tend to rely on walking aids might have produced movements with unusual patterns. Additionally, we could not analyze normal movement in our protocol because this study had no control group, so it was not possible to make comparisons with normal limb loading during STW. Also, sex differences may have affected our results. Despite these limitations, few studies have investigated the selection of the leading limb at the start of walking after rising from a sitting position, so the results of this study are expected to be useful for rehabilitation programs focusing on movements at the initiation of walking from a sitting position.

6. Conclusions

This study aimed to examine the biomechanical differences in STW according to selection of the leading limb in individuals with stroke and to infer the appropriate leading limb in STW from the viewpoints of recovery and adaptation of paretic limb loading and fluidity. The results showed that when leading with the paretic limb, the paretic limb loading ratio was significantly larger and movement fluidity was lower. In this study, many individuals with stroke preferred to lead with the paretic limb in STW. Therefore, we conclude that using the paretic limb is generally the adaptive leading limb. However, selection of the leading limb in STW involves a biomechanical tradeoff between paretic limb

loading at seat-off and movement fluidity at the start of walking in individuals with stroke. These results should aid physiotherapists in providing instruction on the appropriate first step for different purposes: an adaptive approach with the paretic limb as the leading limb for balance disability and with the non-paretic limb as the leading limb for poor paretic limb loading capacity, and a restitutive approach with stress on the paretic limb as the leading limb for patients with poor paretic limb loading capacity and with stress on the non-paretic limb as the leading limb for balance disability.

Declaration of Competing Interest

None declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.clinbiomech.2022.105639>.

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