Walking through apertures and perceptual judgment in individuals with stroke

Dissertation by

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1. ABSTRACT

Walking through a narrow aperture requires unique postural configurations, i.e., body rotation in the yaw dimension. Stroke individuals may have difficulty performing the body rotations due to motor paralysis on one side of their body. The present study was therefore designed to investigate how successfully such individuals walk through apertures and how they perform body rotation behavior.

To achieve this purpose, I conducted six experiments to examine whether (a) individuals with stroke could walk through apertures safely (i.e., passage without contact) and efficiently (i.e., passage without taking too much of a conservative strategy) (Study 1: termed *a walking task* in this study), and (b) they could estimate passable/impassable space correctly (Study 2: termed *a perceptual judgment task*). In my study, stroke participants were categorized into two groups based on their fall history: stroke fallers and stroke non-fallers. This was because several previous studies had shown that significant gait characteristics of stroke individuals were more evident in those at high risk of falling (Bonnyaud et al. 2016; Isho et al. 2015). Moreover, Takatori et al. (2009) reported that stroke individuals with a history of falls showed a large gap between the visual estimation of a reachable distance and the actual reachable distance. If such a large gap between perception and action exists in various types of

behavior, then stroke fallers would show inaccurate judgment of the passability of an aperture, which could lead to accidental contact with the frame of an aperture.

In all experiments, participants performed a task of walking through the aperture (Walking task) or a task of perceptual judgment of aperture passability (Perceptual judgment task). In the walking task, participants walked for 4 m and passed through apertures of various widths (a range of 0.9–1.3 times the participant's shoulder width) in an effort to make no contact with the frame of an aperture. Accidental contacts with the frame and kinematic characteristics at the moment of aperture crossing were measured. In the perceptual judgment task, participants observed apertures of various widths and reported whether they believed they would be able to pass though the aperture without body rotation.

A brief summary of Study 1 (Experiments 1–3) and Study 2 (Experiments 4–6) is as follows. The results of Experiment 1 showed that stroke fallers made frequent contact on their paretic side. This was understandable because the stroke patients who had motor paralysis on one side of their body had difficulty controlling the paretic limb. Interestingly, however, the contacts were not frequent when participants penetrated the apertures from their paretic side. Although the minimum passable width was greater for stroke fallers, the body rotation angle was comparable between groups. This suggests that frequent contact by stroke fallers was due to insufficient body rotation.

The results of Experiment 2 supported our expectation. In this experiment, each participant performed the walking task under each of the two conditions: penetration from the paretic side and penetration from the non-paretic side. The tendency in stroke fallers to make more contact on the paretic side disappeared when they penetrated an aperture from their paretic side. These findings suggest that penetration from the paretic side was available for stroke fallers to successfully avoid accidental contact.

I conducted Experiment 3 to test the validity of these explanations by using a case-study experiment for three stroke participants who showed a dramatic decrease in contact rate when they penetrated an aperture from the paretic side. What I found was that the effectiveness of penetration from the paretic side was reduced from 67% to 25% when the walking task was performed under the dual task condition. These findings suggest that the involvement of spatial attention toward the paretic side of the body is a plausible explanation for the effectiveness of penetration from the paretic side.

One may assume that frequent accidental contact with the frame could be the result of inaccurate perception of aperture passability. To address the validity of such an assumption, three experiments were conducted as Study 2. The results of Experiment 4 showed that, when the judgments were made while participants were standing and observing from a remote place (a 3 m distance), there was no significant difference in the accuracy of the perceptual judgment between stroke participants and age- and gender-matched participants while they were standing.

The failure to show inaccurate perception of aperture passability in stroke fallers could be due to the fact that the perceptual judgment was made while standing. I therefore re-tested the same issue while participants were walking and while they were standing. The results of Experiment 5 showed that the perceptual judgment was significantly inaccurate for stroke fallers both when they were standing and walking. These results suggest that, contrary to the findings in Experiment 4, frequent accidental contact could be the result of inaccurate perception of aperture passability.

I investigated whether the inconsistent findings in Experiments 4 and 5 regarding accuracy of perceptual judgment in stroke fallers could be explained by the existence of time pressure in Experiment 5. Unfortunately, the results of Experiment 6 did not support my explanation; there was no significant influence of time constraint on the perceptual judgment of stroke fallers. An important finding, however, was that, consistent with the results of Experiment 5, perceptual judgment was significantly inaccurate for stroke fallers as compared with the controls. That is, the results of Experiments 5 and 6 indicated that the stroke fallers underestimated their spatial requirements. Although our findings on perceptual judgment tasks were not constant in Experiments 4–6, I tentatively concluded that perceptual judgment of aperture passability in stroke fallers is likely to be inaccurate.

Based on these findings, I concluded that stroke participants who had history of falls (i.e., stroke fallers) had difficulty avoiding accidental contacts on their paretic side when they passed through apertures. One of the reasons for this difficulty was likely their inaccurate perceptual judgement; these participants underestimated their spatial requirements for walking through the aperture. The most important finding was that stroke fallers showed a significant decrease in accidental contacts when they penetrated an aperture from the paretic side. A plausible explanation for this effect was that penetration from the paretic side was helpful to direct their spatial attention to the paretic side of the body, which resulted in accurate representation of the paretic side. These results suggest that measuring the behavior of walking through an aperture potentially provides new insight into the increased risk of instability during adaptive locomotion in stroke individuals.

2. INTRODUCTION & REVIEW OF LITERATURE

2.1 Introduction

Stroke is a disease caused by infarction, or hemorrhages of the blood vessels in the brain. Stroke is the major cause of neurological disabilities that affect many aspects of daily living. As one such issue, individuals with stroke often exhibit impaired walking, primarily due to motor paralysis on one side (typically the contralateral side of the affected side of the brain) of their body. A typical symptom indicating impaired walking is gait asymmetry. Gait asymmetry is the irregular coordination between the lower limbs and is produced mainly by differences in the magnitude of force displayed between the paretic and non-paretic limbs (Kim and Eng 2003). Walking with gait asymmetry is biomechanically inefficient for achieving forward progression and makes maintaining balance more challenging (Jørgensen et al. 2000; Patterson et al. 2008).

A particularly challenging aspect of maintaining balance becomes much more evident during adaptive locomotion, i.e., when basic movement patterns need to be modified adaptively in response to environmental constraints. Previous studies have shown that, as compared to control individuals, stroke individuals had difficulty stepping over an obstacle (Den Otter et al. 2005), walking fast while performing a cognitive task concurrently (Dennis et al. 2009), changing their walking speed in response to changes in the optic flow (Lamontagne et al. 2007), changing direction while walking (Lamontagne and Fung 2009; Hollands et al. 2010b; Lamontagne et al. 2010), and turning (Hollands et al. 2010a; Bonnyaud et al. 2016). In fact, the risk of falling is likely to increase when stroke individuals turn (Hyndman et al. 2002; Harris et al. 2005; Simpson et al. 2011).

The present study was designed to test the ability of stroke individuals to safely walk through apertures. The task of locomotion through apertures has been used to investigate perceptual-motor control of adaptive locomotion in healthy young adults (Warren and Whang 1987; Higuchi et al. 2004; Higuchi et al. 2006; Higuchi et al. 2012), older adults (Hackney and Cinelli 2011; Hackney and Cinelli 2013), inexperienced wheelchair users (Higuchi et al. 2006; Higuchi et al. 2009), and patients with Parkinson's disease (Cowie et al. 2010; Cohen et al. 2011; Cowie et al. 2012). To our knowledge, however, there has been no study testing the ability of stroke individuals to safely walk through an aperture.

Safely walking through a narrow aperture requires fine-tuning the walking direction toward the center of the aperture (Cinelli and Patla 2008; Cinelli et al. 2008) and, when necessary, adjusting the posture to avoid contact with the frame of the aperture. The dominant postural adjustment is the (upper-) body rotation in the yaw dimension because it effectively reduces the horizontal space necessary for passage (Warren and Whang 1987; Higuchi et al. 2006; Cowie et al. 2010; Higuchi et al. 2011; Franchak et al. 2012; Higuchi et al. 2012; Franchak and Adolph 2014; Hackney et al. 2014; Hackney et al. 2015a; Hackney et al. 2015b). Testing the ability to safely walk through an aperture has helped to describe the reason that controlling adaptive locomotion is difficult for some types of participants. Older adults had more variability in their body rotations at various aperture widths (Hackney and Cinelli 2011; Hackney and Cinelli 2013). Patents with Parkinson's disease (PD) showed sharply decreased walking speeds in front of an aperture, which could be caused by episodes of freezing (Cowie et al. 2010). When young adults used a manual wheelchair for the first time, contact with the frame of an aperture occurred more frequently with dramatically different spatial-temporal patterns of fixation (Higuchi et al. 2006; Higuchi et al. 2009).

Measuring the behavior of walking through an aperture potentially provides new insight into the increased risk of instability during adaptive locomotion in stroke individuals. Walking through a narrow aperture with body rotation results in unique postural configurations, i.e., the body is rotated in the yaw dimension, while the walking direction is maintained toward the center of the aperture. The uniqueness of the body rotation behavior becomes clear when it is compared with the turning behavior, which also involves individuals rotating their bodies, while its purpose is to change the direction of walking. Rotating the body to walk through an aperture usually involves a pivot-like turn, in which the body rotates about its vertical axis on the trailing limb at the moment it crosses the aperture. If stroke individuals penetrate an aperture from the paretic side (i.e., the trailing limb is non-paretic), then they would be able to perform a pivot-like turn. However, they would have difficulty maintaining their balance after the turn because they need to shift their body weight to the leading, or paretic, limb to progress forward. In contrast, if stroke individuals penetrate an aperture from the non-paretic side (i.e., the trailing limb is paretic), then an alternate strategy, rather than a pivot-like turn, would be selected for rotating their bodies. In both cases, taking multiple steps to rotate the body, which has been observed in the turning behavior performed of older adults (Thigpen et al. 2000; Dite and Temple 2002), was expected to occur. This was because it was effective, at least for stroke individuals, to avoid shifting their body weight onto the paretic limb for a relatively long time. However, because there has been no study, it remains unknown as to which strategy would be more preferable for strong individuals and which strategy would lead to safe walking through apertures without making any contact with the frame of an aperture. The rationale for conducting the present study was to clarify these issues.

In the present study, two groups of stroke individuals were recruited: stroke fallers and stroke non-fallers. Stroke fallers were identified as those having a history of falling history in the past for 1 year. A systematic review of the literature showed that a history of falling in the past year most strongly predicts the likelihood of future falls among community-living older adults (Tinetti and Kumar 2010). Several previous studies have shown that significant gait characteristics of stroke individuals were more evident in those at high risk of falling (Isho et al. 2015; Bonnyaud et al. 2016). Moreover, Takatori et al. (2009) reported that stroke individuals with a history of falls showed a large gap between the visual estimation of a reachable distance and the actual distance reachable (Takatori et al. 2009). If such a large gap between perception and action exists in various types of behavior, then stroke fallers would show inaccurate judgment of the passability of an aperture, which could lead to accidental contact with the frame of an aperture. To examine whether accidental contact was related to the inaccurate judgment of the passability of the aperture, participants in the present study performed both the behavioral task of walking through apertures and the perceptual judgment task of aperture passability. I conduct six experiments to examine if individuals with stroke could pass through apertures safely and efficiently, and whether they could estimate spatial requirements correctly.

2.2 Review of Literature

2.2.1 Falls among individuals with stroke

Falls are common among stroke survivors living in the community or hospital. A systematic review of the literature identified that an increased risk of falls was established among persons with diagnoses of stroke, dementia, and disorders of gait and balance in a neurology practice (Thurman et al. 2008). This study also showed that a history of falling in the past year strongly predicts the likelihood of future falls. Kerse et al. (2008) reported that approximately 37% of people with stroke have fallen within the 6 months after stroke onset. Individuals with stroke described the reasons for fall as a loss of balance, misjudgment, and a lack of concentration (Hyndman et al. 2002) (Table 1). They also showed that walking and turning was most frequently described as activities leading fall events. Moreover, most patients had sustained their fall at home (Kerse et al. 2008). Considering that 35–45% of the steps taken during everyday tasks occur while turning (Glaister et al. 2007), the ability to turn while walking was critical in regaining independence.

Failure to accommodate changes in environmental constraints can result in fall. Previous studies showed that the frequency of falls in daily activities in stoke individuals are relatively high. One study reported that 51% of community-dwelling stroke survivors experienced falls between 1 and 6 months post-stroke (Yates et al. 2002), while another study showed that 37% of patients with acute stroke experienced falls in the 6 months following their stroke (Kerse et al. 2008). This study also showed that 37% of stroke fallers sustained an injury that required medical treatment (Kerse et al. 2008). The bone mineral density in the lower extremity of the paretic side was low, and the bone loss was dependent on the patient's ambulatory level (Jørgensen et al. 2000). The risk of femoral neck fracture is 1.4–7 times higher in individuals with stroke than in healthy elderly people (Ramnemark et al. 1998; Kanis et al. 2001). This suggests that the risk of fracture could be increased as a result of stroke. Therefore, preventing falls is critical important for individuals with stroke in order to spend a life safety and independently.

The majority of individuals with stroke experiences fall during walking and turning (Hyndman et al. 2002; Harris et al. 2005; Simpson et al. 2011). A motor factor is considered as one of the reasons to explain falls during walking and turning. The reason is a motor factor includes a tendency of the loss of balance during locomotion. To effectively make body rotation during turning, healthy individuals are likely to use spin turns. Spin turns involve the change in direction of motion toward the same side as the stance limb. Turning offered less stability compared to strait walking (Segal et al. 2008), because the center of gravity (CoG) was likely to displace outside of the stance limb during walking with turns (Taylor et al. 2005). In addition, the risk of injury by falling among the older adults further increases when they involve turning (Cumming and Klineberg 1994). Providing that individuals with stroke had difficulty maintaining balance while performing turns (Bonnyaud et al. 2016). Walking with gait asymmetry is biomechanically inefficient for achieving forward progression and makes maintaining balance more challenging (Jørgensen et al. 2000; Patterson et al. 2008). For these reasons, a particularly challenging aspect of maintaining balance becomes much more evident while turning.

Table 1. Circumstances of falls and near falls among people with stroke (Hyndman et al., 2002)

Circumstance	Falls (n)	Near Falls (n)
Location (total)	51	
Garden	13	
Bedroom	9	
Lounge	9	
Activity (total)	55	50
Walking	20	27
Turning	8	6
Sit to stand	7	3
Cause (total)	57	51
Losing balance	20	13
Misjudgment/lack of concentration	14	11
Foot dragging	4	11
Landing (total)	51	
Sideways	16	
On hands and knees	16	
Backward	10	
Saving reactions (total)		50
Recovery by arm movements		25
Recovery by leg movements		6
Recovery of balance		6

* The 3 most common answers for each category are shown.

2.2.2 Adaptability of individuals with stroke in response to environmental constraints during walking

Challenging aspect of maintaining balance in stroke individuals becomes much more evident during adaptive walking, i.e., when basic movement patterns need to be modified adaptively in response to environmental constraints. For example, it becomes more difficult for individuals with stroke to avoid an obstacle by stepping over it (Said et al. 1999; Den Otter et al. 2005). These studies showed that the frequency of fails (contacted the obstacle, required assistance from the tester or the rail, or failed to step over the obstacle) in participants with stroke was significantly higher than the elderly. The reason of the fails with wide obstacle, individuals with stroke may have difficulty making the required alteration in step length to avoid the wide obstacle. In contrast, the reason of fails with high obstacle, they may have difficulty maintaining balance during stepping over the obstacle. For a subgroup of more severely affected and more slowly walking patients, a maladaptive movement execution of the crossing stride and post crossing stride under time pressure, leading to errors in the avoidance maneuver (Den Otter et al. 2005). These findings suggest that individuals with stroke need more time to implement changes to locomotor patterns in order to response to changes in the environment constraints.

Increased attentional load can be a factor that makes it difficult to maintain balance during walking. Individuals with stroke often mention that walking in complex situations requires their full attention in order not to fall. For example, individuals with stroke stop walking when talking (Hyndman and Ashburn 2004). Thus, online gait adaptation may be associated with higher attentional demands in individuals with stroke than in non-disabled persons. Higher attentional demands during gait adaptations may lead to an increased fall risk in individuals with stroke while performing dual tasks (Hollands et al. 2014). Therefore, not only a reduced capacity to avoid an obstacle but also increased attentional load to maintain the gait pattern may contribute to the increased fall risk in individuals with stroke.

2.2.3 Control and coordination of whole-body kinematics during turning in individuals with stroke

Individuals with stroke also showed impaired temporal and spatial coordination between the gaze, head, trunk, and pelvis during turning (Lamontagne et al. 2007; Lamontagne and Fung 2009). In the study by Lamontagne and Fung (2009), the temporal coordination of gaze and body kinematics was investigated in eight stroke and seven healthy individuals while walking and turning in response to a visual cue. The results showed that the healthy participants commenced with the gaze, followed by segmental reorientation of the head, thorax, and pelvis. This was the typical and ideal pattern of the temporal coordination (e.g., Imai et al. 2001). On the other hand, the stroke participants (particularly those with poor walking capacity) showed disrupted temporal coordination. These findings suggest that it is difficult for the stroke participants to coordinate gaze and body kinematics temporally while walking and turning.

2.2.4 Literature on walking through apertures

When individuals need to fit through narrow spaces such as doorways during walking, adaptive movement changes are observed prior to door crossing. These changes include rotation of the body or a decrease walking speed. The task of locomotion through apertures has been used to investigate visuo-motor control of adaptive locomotion in young healthy adults (Warren and Whang 1987; Higuchi et al. 2004; Higuchi et al. 2006; Higuchi et al. 2012), older adults (Hackney and Cinelli 2011; Hackney and Cinelli 2013), wheelchair users (Higuchi et al. 2009), and patients with Parkinson's disease (Cowie et al. 2010; Cohen et al. 2011; Cowie et al. 2012).

One of the most important information is the necessity of body-scaled information for adaptive locomotion. Young adults generally rotate their body when an opening is narrower than1.1–1.3 times their shoulder width (Warren and Whang 1987; Higuchi et al. 2006; Franchak et al. 2012; Higuchi et al. 2012). On the other hand, older adults produce shoulder rotations when an opening is narrower than 1.4–1.6 times their shoulder width, and more variable in shoulder rotations at each aperture width (Hackney and Cinelli 2011). These findings indicate that older adults adopt a more cautious approach than young adults when walking through apertures.

The task of walking through apertures is applicable to people with disabilities, such as participants with Parkinson's disease and participants with tetraplegic, have been studied for adapting locomotion. In patients with Parkinson's disease who experienced freezing behavior, the tasks have been used to investigate the effect of doorway size on gait before reaching the doorway (Almeida and Lebold 2010; Cowie et al. 2010; Cowie et al. 2012). These studies showed that patients with Parkinson's disease who experienced freezing behavior dramatically decreased the walking speed and step length when they walked through the narrow aperture. Moreover, Cowie et al. (2012) found that patients with Parkinson's disease could accurately judge the width of doorway they could just pass through the aperture. These findings suggest that an investigation of the behavior of walking through apertures is helpful to understand visuo-motor control of adaptive locomotion.

Higuchi et al. (2009) used the task of locomotion through apertures to investigate whether wheelchair users with the tetraplegic participants showed enhanced ability to estimate the space required for locomotion with familiar and unfamiliar wheelchairs. The results showed that the tetraplegic participants accurately estimated about the space required for both familiar and unfamiliar wheelchairs. The control, young-aduult participants showed less accuracy for the wheelchair condition than for the walking condition. The findings suggest that adaptation to altered body dimensions occurred in a short time only under a well-learned, familiar form of locomotion.

Overall, various researchers have demonstrated that the task of locomotion through apertures has been used to investigate visuo-motor control of adaptive locomotion Surprisingly, however, to our knowledge, no study has examined passing through the apertures in individuals with stroke. Considering that it is difficult for stroke individuals to adapt to the environment constraints during walking, it is possible that measuring the behavior of walking through an aperture potentially provides a new insight into the increased risk of instability in stroke individuals.

3. OVERVIEW OF THIS STUDY

3.1. Purpose & hypotheses

The purpose of this study was to investigate how individuals with stroke rotate their bodies when they pass through narrow apertures. Our particular interest was to understand the side of the body that penetrated an aperture and whether the selection of the body side for penetration was related to safely walking through apertures without making contact. As explained in the previous section (2.2.4), various types of individuals (e.g., the participants with Parkinson's disease or participants with tetraplegic) have been tested using the task of locomotion through apertures. To date, however, it remains unclear whether individuals with stroke could pass through apertures safely and efficiently.

According to the previous studies on the task of stepping over obstacles, the contact rate was higher in individuals with stroke than in healthy controls (Said et al., 1999; Den Otter et al., 2005). Moreover, Den Otter et al. (2005) found that individuals with stroke lengthen their steps more often than controls, which might reflect an attempt to reduce movement complexity, even when a shortening of the step would be spatially more efficient. For a subgroup of patients, more severely affected and walking more slowly, the execution of these lengthened steps led to larger disturbances in the locomotor rhythm than in controls. These results suggest that the ability to adequately modify the movement pattern in response to imposed spatiotemporal constraints was impaired in individuals with stroke. Considering these findings, it is possible that individuals with stroke who have a high risk of falls may not have passed through apertures safely and efficiently.

Another purpose of the present study was to investigate whether individuals with stroke could accurately estimate the space required for locomotion. Considering that individuals with stroke who had a history of falls showed a large gap between visual estimation of reachable distance and actual reachability (Takatori et al., 2009), there was also the gap between visual estimation of passable width and actual passability. To test this hypothesis, individuals with stroke who had history of falls could not correctly perceive the size of aperture relative to the size of their locomotion.

Totally six experiments have been conducted to examine whether (a) individuals with stroke could walk through apertures safely (i.e., passage without contact) and efficiently (i.e., passage without taking too much conservative strategy) (Study 1: termed *a walking task* in this study), and (b) they could estimate passable/impassable space correctly (Study 2: termed *a perceptual judgment task*).

3.2. General method

3.2.1 Participants

Participants in the stroke group were patients in a subacute hospital or had been discharged from a subacute hospital. Participants had residual hemiparesis. The inclusion criteria ensured that participants had been walking for at least one month after a first-time stroke and that they were able to walk independently for more than 100 m with or without an assistive device. The exclusion criteria ensured that none of the participants had any indications of the following symptoms: (a) neurological, orthopedic, or other disorders that could affect walking, (b) history of visual deficits, (c) visual field deficits and visual spatial neglect, and (d) a score of less than 24 on the Mini Mental State Examination (MMSE) (Holsinger et al, 2007).

All stroke participants were asked whether they had fallen in the past 12 months. A fall was defined as an event that results in a person coming to rest unintentionally on the ground or other lower level (Clark et al, 1993). Falls resulting from uncommon environmental factors (e.g., traffic accidents or while riding a bicycle) were excluded.

3.2.2 Apparatus

The experiment was performed along a straight 6.0-m path. A door opening was located 4.0 m in front of the location where participants started walking. A door-like aperture was created as a space between two projector screens (see Fig 1). Each screen was attached with an aluminum frame (2.2 m wide × 2.0 m high) so that the screens were located perpendicularly to the floor. The width of an aperture was easily adjustable by changing the location of the edge of each screen. After finishing the adjustment, the upper edge of each screen was fixed to the horizontal aluminum frame so that the width of an aperture remained immobile. In Experiments 1–3, Whole-body kinematics were measured with a three-dimensional motion analysis system (OQUS 300, Qualisys, Sweden) at a sampling frequency of 60 Hz. Six (Experiment 1) or Nine (Experiment 2 and 3) cameras tracked passive retroreflective markers attached to participants. In Experiment 1, the participants were attached three passive retroreflective markers: one marker for both the left and right shoulders (the lateral border of the spine of the scapula) and one marker for the spinous process of the 7th thoracic vertebrae (T7). In Experiments 2 and 3, twenty-two passive retroreflective markers were attached: one marker for both the left and right side of the head, shoulders, olecranons, head of ulnas, posterior superior iliac spines, great trochanters, lateral tibial condyles, lateral malleolus, heel, toe, and one marker for top of the head and 7th thoracic vertebrae. Two additional markers were placed on the inner edge of the doorframes to measure the position of the door opening.

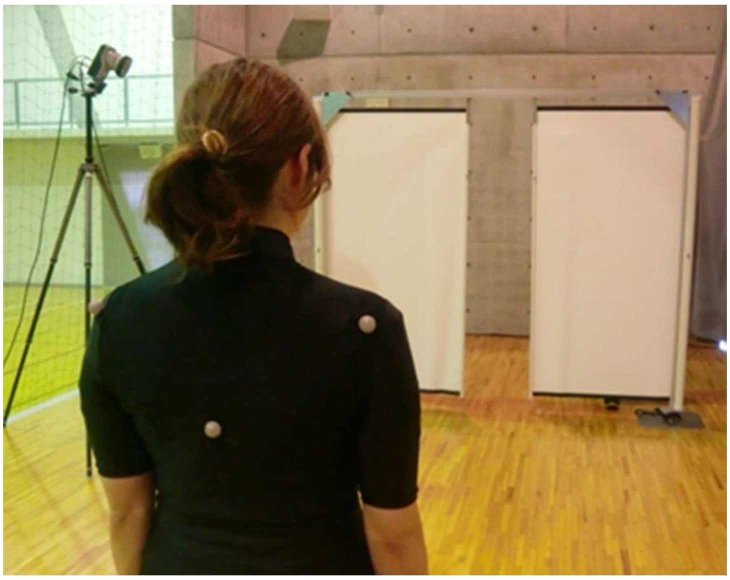


Fig 1. An experimental task. A participant walks toward a door-like aperture.

3.2.3 Tasks and procedures

Walking task

A main experimental task was walking through apertures of various widths. Participants were asked to approach and walk through an aperture without making any contact with a screen. There were various different aperture widths (cf. 0.9, 1.0, 1.1, 1.2, and 1.3 times the width of participants' shoulders). To ensure participants' safety of the participants while they were attempting to pass through an aperture, two therapists stood beside the door apparatus while participants performed the task.

For each trial, participants stood at the starting position (i.e., 4 m in front of the aperture), while visual information about the aperture was occluded by a large plate placed 20 cm in front of them. After the width of the aperture was adjusted, the visual occlusion was removed. Participants then started walking. They were allowed to rotate their bodies when necessary to avoid contact.

Prior to performing the main trial, participants performed three pretrial practices to familiarize themselves with the task. Aperture widths narrower than 1.1 times their shoulder widths were presented in at least two of these three trials. The order of the aperture width presented was randomized. After the pretrial practice, participants performed main trials (three trials for each aperture widths). The order of the aperture widths presented was randomized. Participants were able to rest between trials when they felt it to be necessary.

Perceptual judgment task

Another experimental task was to judge the passability of an aperture. Participants stood at the starting position. The floor was covered with a white cloth to prevent participants from obtaining any information from the floor around the door apparatus to aid in estimating the width of the aperture. They observed apertures of various widths and reported whether they believed they would be able to pass though the aperture without making any contact. A series of apertures was presented to participants using the staircase method. In this method, a series of opening widths was presented in either an ascending or descending order with consecutive 2-cm intervals. The presentation of the ascending (descending) series was started with an aperture selected randomly from those that were 15–20 cm wider (narrower) than the width of participants' shoulders. The presentation of the series was terminated when the participants alternated their response (i.e., from passable to impassable, or from impassable to passable) a total of six times. Each participant performed one ascending series and one descending series. They were required to close their eyes during the intervals between the trials, during which the size of the aperture was changed. After finishing this task, participants' actual minimum passable widths were measured. The actual minimum passable width was defined as the minimum width that a participant could pass through the aperture twice consecutively without body rotation.

3.2.4 Dependent measures and statistical analysis

Characteristics of participants, clinical measurements, and stroke participant details

In all experiments, except for Experiments 2 and 3, the characteristics of participants (gender, age, height, shoulder width, and minimum passable width) and the results of clinical tests (MMSE and TUG) were compared statistically among the three groups (stroke fallers, stroke non-fallers, and control participants). A non-parametric test, the Kruskal-Wallis test, was used as the statistical test for all but gender. A significant main effect in the Kruskal-Wallis test was analyzed further using the Mann-Whitney U test with Bonferroni corrections. A Pearson's chi-square test was used for gender. Statistical comparisons between stroke fallers and stroke non-fallers were also made in terms of the time since the stroke, mRS, upper extremity BRS, lower extremity BRS, stroke type, hemiplegic type, and the use of a walking aid. A Mann-Whitney U test was used to measure the time since the stroke, whereas a Pearson's chi-square test was used for the other measurements. The software package SPSS (version 21.0) was used.

Walking task

Dependent measures were categorized as one of two types: contact with the frame of an aperture and kinematic characteristics at the moment of aperture crossing.

To explain the characteristics of contact with the frame of an aperture, I calculated the contact rate, i.e., the percentage of contacts with the door's edges in the trials; the contact frequency based on the number of contacts, i.e., no contact, single contact, or multi contacts; and the contact frequency based on the body side where the contact occurred. Contact with the frame of an aperture was detected by three experimenters. To correctly detect contact, participants were asked to inform experimenters whenever they touched the door. Contact frequency according to body side where the contact occurred, was measured separately in three situations of body rotations: no rotation, penetration from the paretic side, and penetration from the non-paretic side. The distribution of the percentage data was not normal. Therefore, I transformed the data used in the current study (i.e., the percentage of contact) by means of angular transformation (also known as arcsine transformation) prior to performing a two-way or a three-way ANOVA. A Pearson's chi-square test was used to analyze the contact frequency and the side of the body where contact occurred.

Kinematic characteristics at the moment of aperture crossing were described in terms of three measurements: the absolute body rotation angle, the body side to penetrate an aperture, and the absolute deviation of the upper-body midpoint from the center of the doorway.

The body rotation angle in the yaw dimension was defined as the angle created between the aperture, represented by the two reflective markers on the edges of the screen, and the body, represented by two markers on the left and right shoulders (values larger than zero indicate counterclockwise rotation). Absolute values of the rotation angles were used as dependent measures.

The body side that penetrated the aperture was checked only for stroke fallers and stroke non-fallers because the purpose of this measurement was to investigate whether stroke participants penetrated from the paretic side or non-paretic side when body rotation occurred.

For all measurements, except in those which the body side penetrated an aperture, statistical analysis was conducted using ANOVA. Partial eta-squared values (η_p^2) were calculated as an unbiased estimate of the effect size in an ANOVA. Significant main and interaction effects in the ANOVA were analyzed further using Bonferroni-corrected pairwise comparisons. A Pearson's chi-square test was used to statistically analyze the body side that penetrated the aperture for each comparison.

<u>Perceptual judgment task</u>

The dependent variable was the perceived minimum passable width relative to the minimum passable width (referred to as the *relative perceptual boundary*). The perceived minimum passable width was calculated as the average of twelve aperture-width values with which participants alternated their responses in each stage of an ascending and descending series (i.e., six values were obtained from each series). The relative perceptual boundaries were analyzed in an ANOVA. A one-sample t-test was also carried out to examine whether the results of each condition would be significantly different from a value of 1.0. A value of 1.0 meant that their judgment was accurate, and values smaller than 1.0 meant that participants overestimated their passability (i.e., they underestimated the space necessary for passage).

4. EXPERIMENTS

<u>Study 1.</u> Do stroke fallers walk through apertures safely and efficiently? (Walking task)

4.1 Experiment 1

The present study was designed to test the ability of stroke individuals to safely walk through apertures. Our particular interest was to understand the side of the body that penetrated an aperture and whether the selection of the body side for penetration was related to safe walking through apertures without making contact.

4.1.1 Participants

Twenty-three individuals with stroke (eleven females) participated. The mean age was 60.7 years (SD = 10.1). Twenty-three age- and height-matched healthy individuals also participated as control participants. Testing was approved by the ethics committee of the Kameda Medical Center. All participants gave written informed consent prior to participation.

Participants in the stroke group were patients in a subacute hospital or had been discharged from a subacute hospital. The mean time from the onset of stroke to testing was 15.2 ± 21.1 months (ranging from 1 to 78 months). All stroke participants were asked whether they had fallen in the past 12 months. A fall was defined as an event that results in a person coming to rest unintentionally on the ground or other lower level (Clark et al. 1993). Based on this definition, 10 participants were referred to as stroke fallers in this study. Six of these participants had fallen two or more times. The other 13 participants were referred to as stroke non-fallers in this study. Characteristics of participants are summarized in Tables 2 and 3.

Table 2. Characteristics of participants

	Stroke fallers (n = 10)	Stroke non-fallers (n = 13)	Control participants (n = 23)	p value
Participant details				
Gender (male/female) b)	6 / 4	6 / 7	11 / 12	n.s
Age (y) a)	63.1 ± 9.0	58.8 ± 10.8	61.0 ± 9.7	n.s
Height (cm) a)	160.0 ± 20.9	158.8 ± 10.9	160.9 ± 9.0	n.s
Shoulder width (cm) a)	45.7 ± 4.0	46.7 ± 4.7	44.4 ± 2.3	n.s
Minimum passable width a)	1.13 ± 0.05	1.09 ± 0.04	1.08 ± 0.04	0.048*
Clinical tests				
MMSE a)	28.7 ± 1.9	28.8 ± 1.9	29.6 ± 0.9	n.s
TUG (s) a)	16.8 ± 6.4	11.6 ± 5.5	6.23 ± 0.9	< 0.001*†
Stroke participants' details				
Time after stroke (months) c)	19.4 ± 21.5	12.0 ± 21.1		n.s
mRS (score 2/score3) b)	3 / 7	10 / 3		n.s
Upper extremity BRS (stages 3/4/5/6) b)	3 / 6 / 1 / 0	1 / 4 / 7 / 1		n.s
Lower extremity BRS (stages 3/4/5) b)	1 / 7 / 2	0 / 6 / 7		n.s
Stroke type (hemorrhagic/ischemic) b)	5 / 6	6 / 7		n.s
Hemiplegic side (right/left) b)	5 / 6	8 / 5		n.s
Use of walking aid (no/yes) b)	6 / 4	7 / 6		n.s

a) Kruskal-Wallis test, b) Pearson's chi-square test, c) Mann-Whitney U test

Note. MMSE = Mini Mental State Examination, BRS = Brunnstrom Recovery Stage, mRS = modified Ranking Scale

* Significant difference between stroke fallers and control participants

† Significant difference between stroke non-fallers and control participants

Table 3. Participant information

Participant	Gender	Age (years)	Time since stroke (months)	Paretic side	Fall history	BRS Lower extremity score	Mean TUG time (s)	Use of walking aid	modified Ranking Scale	Mean relative perceptual boundaries
01	M	40	67	Right	Faller	4	15.5	SPS	3	1.15
02	F	72	12	Left	Faller	4	14.5	AFO	3	0.81
03	F	66	50	Right	Faller	3	31.8	AFO, SPS	3	0.83
04	M	64	5	Left	Faller	4	18.3	AFO, SPS	3	0.92
05	F	66	14	Left	Faller	4	19.1	None	3	1.03
06	M	64	3	Left	Faller	5	20.3	SPS	3	0.92
07	F	66	12	Left	Faller	5	10.2	SPS	2	1.02
08	M	59	12	Right	Faller	4	7.7	None	2	1.10
09	M	62	16	Right	Faller	4	10.3	AFO	2	0.82
10	M	72	3	Right	Faller	4	16.1	SPS	3	1.06
11	F	48	78	Left	None	4	16.9	AFO, SPS	3	0.96
12	F	70	2	Right	None	5	10.2	None	2	0.96
13	M	56	1	Right	None	5	6.5	None	2	1.14
14	F	43	2	Left	None	5	7.2	None	2	1.09
15	F	62	4	Right	None	4	12.3	None	2	1.31
16	M	56	3	Right	None	4	11.1	AFO, SPS	3	0.94
17	F	75	9	Right	None	4	25.3	SPS	2	1.27
18	F	70	10	Left	None	4	12.5	SPS	2	0.97
19	M	69	2	Right	None	5	7.4	None	2	1.13
20	M	53	21	Right	None	4	13.7	AFO, SPS	2	0.73
21	M	64	21	Right	None	5	10.6	SPS	2	1.02
22	M	41	1	Left	None	5	5.2	None	2	0.77
23	F	58	2	Left	None	5	10.4	SPS	3	1.04

SPS (Single-point stick)

AFO (Ankle Foot Orthosis)

4.1.2 Tasks and procedures

The experiment consisted of three parts, which included (a) taking clinical measurements and some measurements of participants' characteristics, (b) performing the walking task, and (c) performing the perceptual judgment task regarding aperture passability. Clinical measurements and measurements of participants' characteristics were conducted first; however, the measurement of the minimum passable width was conducted after performing the two tasks to avoid the possibility that the experience of measuring could affect their performance in these tasks.

Walking task

Participants were asked to approach and walk through an aperture without making any contact with a screen. There were five different aperture widths: 0.9, 1.0, 1.1, 1.2, and 1.3 times the width of participants' shoulders. Participants performed a total of 15 main trials (three trials for each of five aperture widths). The order of the aperture widths presented during the 15 trials was randomized.

4.1.3 Dependent measures and data analysis

Kinematic characteristics at the moment of aperture crossing were described in terms of three measurements: the absolute body rotation angle, the body side to penetrate an aperture, and the absolute deviation of the upper-body midpoint from the center of the doorway. For all measurements, except in those which the body side penetrated an aperture, statistical analysis was conducted using a group (stroke fallers, stroke non-fallers, or age-matched controls) × an aperture width (0.9, 1.0, 1.1, 1.2, and 1.3 times the shoulder width) with repeated measures analysis of variance (ANOVA) of aperture width. The relative perceptual boundaries were analyzed in a one-way (group) ANOVA.

4.1.4 Results

Characteristics of participants, clinical measurements, and stroke participants' details

With regard to the characteristics of participants and clinical measurements, a significant main effect of the group was found in the minimum passable width ($H = 6.09$, $p = 0.048$) and the TUG ($H = 27.16$, $p < 0.001$). Multiple comparisons with Bonferroni corrections showed that the minimum passable widths were significantly wider for stroke fallers than for controls. The time required for the TUG was significantly slower for stroke fallers and non-fallers than for controls. There were no significant differences among the three groups regarding other characteristics of participants and clinical measurements. Measurements of the stroke participants' details showed that each mRS score was either 2 (slight disability: unable to carry out all previous activities but able to look after own affairs without assistance) or 3 (moderate disability: requiring some help but able to walk without assistance). Because our inclusion criteria in the present study ensured that participants were able to walk independently for more than 100 m, no participants were evaluated as having scores of 4 and 5. A significant main effect of the group was found in mRS (($\chi2$ (1) = 5.06, p = 0.024). The upper and the lower extremity BRS were either stage 3 (spasticity increases: gaining voluntary control of movement in synergy patterns), stage 4 (spasticity decreases: the beginning of voluntary movement without synergy patterns), stage 5 (spasticity continues to decline: capable of more complex natural movements), or stage 6 (spasticity disappears, except for when fatigued: movement of individual joints is almost normal) for all participants. No significant main effect of the group were found in the upper extremity BRS (($\chi2$ (3) = 6.62, p = 0.085), and lower extremity BRS (($\chi2$ (2) = 3.52, p = 0.17).

Walking task

The mean contact rate in each group is shown in Fig 2. The main effect of the group was significant (F (2, 43) = 21.18, p < 0.001, η_p^2 = 0.50). Post-hoc multiple comparisons showed that the mean contact rate was significantly higher in stroke fallers than in stroke non-fallers and control participants. The main effect of the aperture width was significant (F (4, 172) = 4.81, p = 0.0011, η_p^2 = 0.10). The percentage was significantly higher when the relative aperture widths were 0.9 and 1.0 than when it was 1.3. The interaction between the group and the aperture size was also significant (F (8, 172) = 3.18, p = 0.0022, η_p^2 = 0.13). When the aperture width was relatively narrow (i.e., 0.9 and 1.0 times the participant's shoulder width), stroke fallers experienced contact significantly more frequently than did stroke non-fallers and controls. When the relative aperture width was 1.1, stroke fallers experienced contact significantly more frequently than did controls.

Table 4 shows the contact frequency, classified as no contact, single contact, or multi contacts, in stroke fallers and non-fallers. A chi-squire analysis showed a significant difference (χ^2 (2) = 10.57, p = 0.0051). Multiple contacts with the door edges were made by 6 of 22 stroke participants. In addition, six people who had multiple contacts all were fallers.

Figure 3 shows the contact frequency classified according to the frequency of the body side where contact occurred in stroke fallers and non-fallers. A chi-square analysis showed a significant difference in stroke fallers ($\chi 2$ (5) = 15.50, p = 0.0056) but not a significant difference in stroke non-fallers ($\chi 2$ (5) = 2.00, p = 0.85). Multiple comparisons with Bonferroni corrections showed that, for stroke fallers, contact occurred more frequently in the affected side of the body when participants showed no body rotation and showed penetration from the non-paretic side. For stroke non-fallers, there was no significant difference regarding the body side where contact occurred.

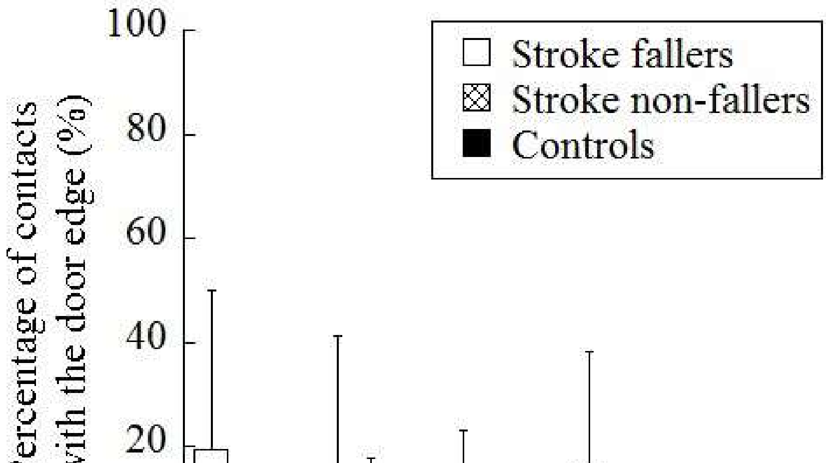
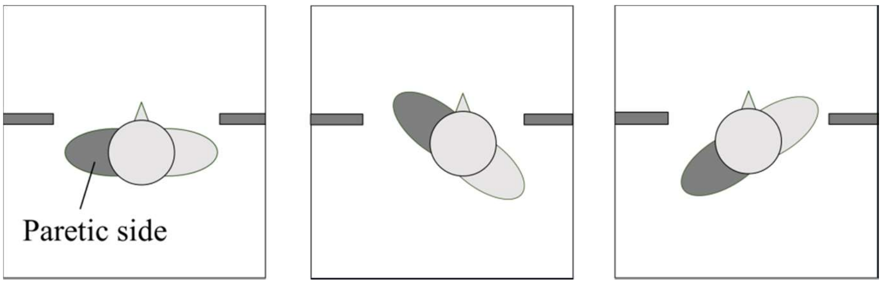


Fig 2. The mean percentage of contacts with the frame of an aperture in each group

Table 4. Contact frequency classified as no contact, single contact, or multi contacts

	No contact	Single contact	Multi contacts
Stroke fallers	**2**	**2**	**6**
Stroke non-fallers	**7**	**6**	**0**

	No body rotation		Penetration from paretic side		Penetration from non-paretic side	



Body side	Paretic	Non-paretic	Paretic	Non-paretic	Paretic	Non-paretic
Stroke fallers	2.3	0	0.6	0.6	2.6	0.9
Stroke non-fallers	0.3	0.3	0.3	0.6	0.3	0

Fig 3. Percentage of contact frequency classified according to the body side where contact occurred

The mean absolute angles of body rotation for all aperture widths in each group are shown in Fig 4. The main effect of the group was not significant (F (2, 43) = 0.31, *ns*). The main effect of the aperture width was significant (F (4, 172) = 204.21, $p < 0.001$, $\eta_p^2 = 0.83$). Multiple comparisons showed that the absolute angle of body rotation of each pair of five aperture widths was significantly different. A significant interaction between the two factors (F (8, 172) = 3.75, $p < 0.001$, $\eta_p^2 = 0.15$) indicated that the absolute body rotation angle was significantly smaller in stroke fallers than in stroke non-fallers when the aperture width was 1.0.

The frequency with which each body side penetrated a narrow aperture (i.e., 0.9, 1.0, and 1.1) for each stroke participant is shown in Fig 5. Except for four participants (Ss. 3, 6, 7, and 19), participants had preferences regarding with which body side to penetrate a narrow aperture. Twelve of 23 stroke participants (52%) penetrated an aperture with one side of the body throughout the 15 trials. As a whole, penetration of an aperture from the non-paretic side was 45.8 %, and penetration from the paretic side was 54.2%.

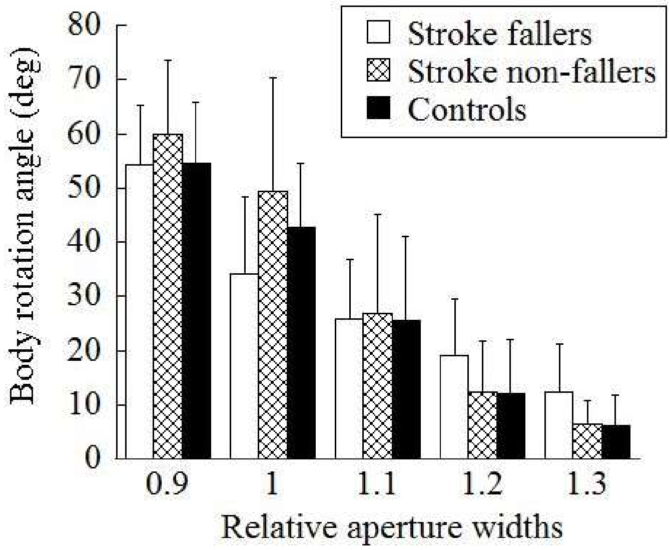


Fig 4. The mean absolute angle of body rotation for each aperture width in each group

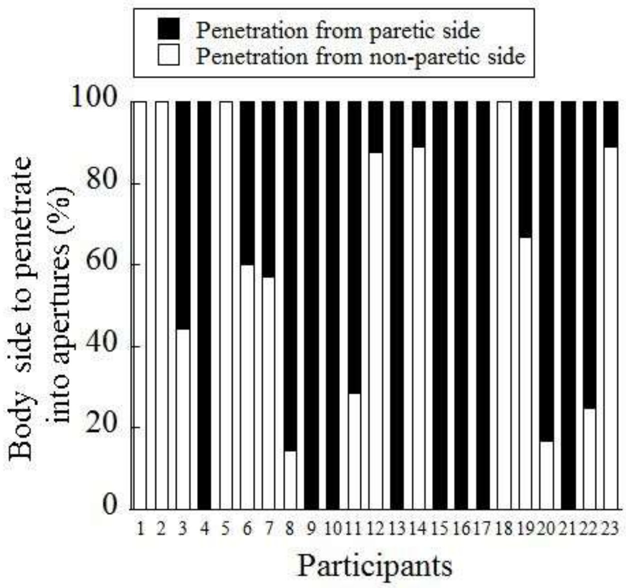


Fig 5. Frequency with which the body side penetrated an aperture in stroke fallers and non-fallers

Table 5 shows the frequency with which the body side penetrated the aperture in stroke fallers and non-fallers. A chi-squire analysis showed no significant differences ($\chi2$ (1) = 0.31, $p = 0.45$).

Table 5. The frequency of each body side penetrated the aperture in stroke fallers and non-fallers

	Fallers	Non-fallers
Penetration from the paretic side	5	8
Penetration from the non-paretic side	5	5

The absolute deviation of the upper-body midpoint from the center of the doorway is shown in Fig 6. The main effect of the group was not significant (F (2, 43) = 1.73, *ns*). The main effect of the aperture width was significant (F (4, 172) = 17.4, $p < 0.001$, $\eta_p^2 = 0.29$). The absolute deviation of the upper-body midpoint from the center of the doorway became significantly larger as the aperture width narrowed. There was a significant interaction between the two factors (F (8, 172) = 2.09, $p = 0.039$, $\eta_p^2 = 0.09$). When the relative aperture width was 1.3, the absolute deviation of the upper-body midpoint from the center of the doorway was significantly larger in stroke fallers than in stroke non-fallers and controls.

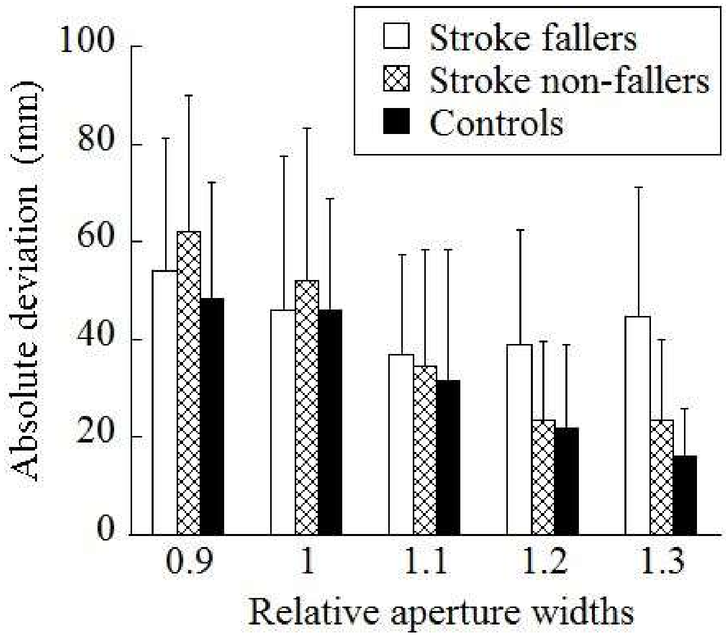


Fig 6. The mean of the absolute deviation from the center of the aperture at the time of aperture crossing under each experimental condition (SD in parenthesis) (mm)

4.1.5 Discussion

The main purpose of Experiment 1 was to test the ability of stroke individuals to safely walk through apertures. Our particular interest was to understand the side of the body that penetrated an aperture and whether the selection of the body side for penetration was related to safe walking through apertures without making contact. The results showed that the contact with the frame of an aperture occurred more frequently in stroke fallers than in both stroke non-fallers and control participants. Interestingly, the tendency to make more contact on the paretic side in stroke fallers disappeared when they penetrated an aperture from the paretic side.

Kinematic analyses showed that the main reason for failing to avoid contact in stroke fallers was likely to be insufficient body rotation. The measurement of the minimum passable width showed that stroke faller participants required wider space than did stroke non-fallers and control participants (Table 2). This suggests that lateral sway during walking was larger for stroke fallers, quite possibly due to their motor paralysis. Given such a larger minimum passable width, a larger magnitude of body rotation would be necessary for stroke fallers to avoid contact. However, the angle of body rotation at the moment of aperture crossing was not significantly different from other groups of participants (Fig 4); rather, their body rotation angle was significantly smaller for the 1.0 aperture than those of other groups of participants. Therefore, insufficient body rotation is likely to be a cause of frequent accidental contact.

4.2 Experiment 2

One of the important findings in Experiment 1 was that, for stroke fallers, who showed a greater number of accidental contact, penetration of an aperture from the paretic side could be an effective method to reduce the rate of contact. To obtain clearer evidence for this possibility, I conducted Experiment 2, in which stroke participants were asked to walk through an aperture with penetrating from the paretic side in one condition and with penetration from the non-paretic side in the other condition.

4.2.1 Participants

Twenty four individuals with stroke (ten females) participated. Mean age was 66.9 years (SD = 5.7). The mean time from the onset of stroke to testing was 25.9 months (ranging from 1 to 123 months). Participants had residual hemiparesis. Testing was approved by the Ethics Committee of the Kameda Medical Center (approval number 16-160), and all subjects gave written informed consent.

All stroke participants were asked whether they had fallen in the past 12 months. Twelve participants were regarded as fallers (referred to as stroke fallers in this study). The other 13 participants, who had not fallen, were referred to as stroke non-fallers in this study. Characteristics of participants were summarized in Table 6, and detailed participant information is shown in Table 7.

Table.6 Characteristics of participants

	Stroke fallers (n = 12)	Stroke non-fallers (n = 13)	p value
Participant details			
Gender (male/female) [a)]	8 / 4	7 / 6	n.s
Age (y) [b)]	67.9 ± 4.0	65.2 ± 7.1	n.s
Height (cm) [b)]	160.7 ± 11.2	159.8 ± 11.8	n.s
Shoulder width (cm) [b)]	46.3 ± 2.6	44.9 ± 3.5	n.s
Minimum passable width[b)]	1.13 ± 0.04	1.11 ± 0.03	n.s
Clinical tests			
MMSE[b)]	27.4 ± 2.2	29.2 ± 1.5	n.s
TUG (s) [b)]	13.0 ± 5.0	11.7 ± 4.7	n.s
Stroke participants' details			
Time after stroke (months) [b)]	20.4 ± 20.5	29.2 ± 34.2	n.s
mRS (score 2/score3) [a)]	8 / 4	8 / 5	n.s
Upper extremity BRS (stages 3/4/5) [a)]	3 / 1 / 8	2 / 2 / 9	n.s
Lower extremity BRS (stages 3/4/5) [a)]	0 / 6 / 6	0 / 6 / 7	n.s
Stroke type (hemorrhagic/ischemic) [a)]	6 / 6	9 / 4	n.s
Hemiplegic side (right/left) [a)]	6 / 6	7 / 6	n.s
Use of walking aid (no/yes) [a)]	5 / 7	4 / 9	n.s

a) Pearson's chi-square test, b) Mann-Whitney U test

Table 7. Participant information

Participant	Gender	Age (years)	Time since stroke (months)	Paretic side	Falls history	BRS Lower extremity score	Mean TUG time (s)	Use of walking aid	modified Ranking Scale
01	F	74	2	Right	None	5	7.8	None	3
02	M	73	2	Right	None	5	9.8	None	3
03	F	65	48	Right	None	5	10.8	None	2
04	M	57	2	Left	None	5	8.7	None	3
05	M	66	43	Right	Faller	4	9.9	SPS	2
06	M	61	35	Right	None	4	6.3	None	2
07	M	59	46	Right	None	4	10.7	None	2
08	M	62	5	Left	Faller	5	11.4	SPS	2
09	M	65	24	Left	Faller	4	12.2	SPS, AFO	3
10	M	68	9	Right	Faller	4	24.8	SPS, AFO	3
11	M	66	46	Left	Faller	4	15.8	None	2
12	F	73	1	Right	Faller	5	10.0	None	2
13	M	68	12	Right	Faller	5	8.8	None	2
14	M	67	50	Left	None	4	14.9	SPS, AFO	2
15	M	63	1	Right	Faller	5	8.6	None	3
16	F	68	36	Left	Faller	5	11.3	None	2
17	F	70	22	Right	None	4	25.4	SPS, AFO	3
18	M	71	9	Right	None	4	10.9	None	2
19	F	52	123	Left	None	4	14.7	SPS, AFO	2
20	M	71	8	Left	Faller	4	17.3	SPS, AFO	2
21	F	72	35	Left	None	5	11.0	SPS	2
22	F	69	59	Left	Faller	4	18.0	None	2
23	F	69	4	Left	None	5	10.7	None	2
24	F	76	1	Right	Faller	5	8.4	None	3
25	M	58	1	Left	None	5	10.3	None	3
Average		66.5	25.0				12.3		
SD		5.9	28.4				4.8	SPS (Single-point stick) AFO (Ankle Foot Orthosis)	

4.2.2 Apparatus, tasks, and procedures

The same apparatus as in Experiment 1 was used. The same experimental task as a walking task in Experiment 1 was used. The only differences were that the participants were instructed on the direction of penetration in advance and that the 1.3-time aperture was not included. Each participant performed this task under each of the two conditions: penetration from the paretic side, and penetration from the non-paretic side. Participants performed a total of 12 main trials (three trials for each of four aperture widths), and a total of 24 trials were conducted under the two conditions.

4.2.3 Dependent measure and data analysis

Characteristics of participants, clinical measurements, and stroke participants' details

A Pearson's chi-square test was used for gender, mRS, upper extremity BRS, lower extremity BRS, stroke type, hemiplegic type, and the use of a walking aid. A Mann-Whitney U test was used for the other measurements.

Walking task

For all measurements, except which body side penetrated an aperture, statistical analysis was conducted using a group (stroke fallers, or stroke non-fallers) × an aperture width (0.9, 1.0, 1.1, and 1.2 times the shoulder width) × direction of penetration (paretic side, or non-paretic side) with repeated measures analysis of variance (ANOVA). For the body side that penetrated the aperture, except when not rotated, statistical analysis was conducted using a Pearson's chi-square test for each comparison. This was because the experiment was a comparison of penetration from the paretic side and non-paretic side, therefore the frequency of no body rotation was different.

4.2.4 Results

Characteristics of participants, clinical measurements, and stroke participants' details

Characteristics of participants and clinical measurements are summarized in Table 6. No significant main effect of the group was found in any of the measurements (Table 6).

Walking task

The mean contact rate in each group is shown in Fig 7. Both the main effect of the group ($F(1, 23) = 3.00$, $p = 0.097$, *ns*) and the direction of body rotation failed to reach significance (F (1, 23) = 3.00, p = 0.097, *ns*; and F (1, 23) = 3.45, p = 0.076, *ns, respectively*). The main effect of the aperture width was not significant (F (3, 69) = 1.91, *ns*). The interaction between the group and the direction of body rotation was significant (F (1, 23) = 5.43, p = 0.029, η_p^2 = 0.19). Multiple comparisons showed that, for the stroke fallers, percentage of contacts was significantly smaller in when they penetrated from the paretic side than from the non-paretic side. In the condition in which participants penetrated from non-paretic side, stroke fallers experienced significantly more frequent contacts than stroke non-fallers. Any other interaction was not significant (group × aperture width: F (3, 69) = 0.37, *ns*; direction × aperture width: F (3, 69) = 1.17, *ns*).

Figure 8 shows the percentage of contact frequency classified according to the body side in stroke fallers and non-fallers. A chi-square analysis showed a significant difference in stroke fallers ($\chi 2$ (3) = 27.71, $p < 0.001$) but not a significant difference in stroke non-fallers ($\chi 2$ (3) = 2.11, p = 0.55). Multiple comparisons with Bonferroni corrections showed that, for stroke fallers, contact occurred more frequently in the affected side of the body when participants showed penetration from the non-paretic side.

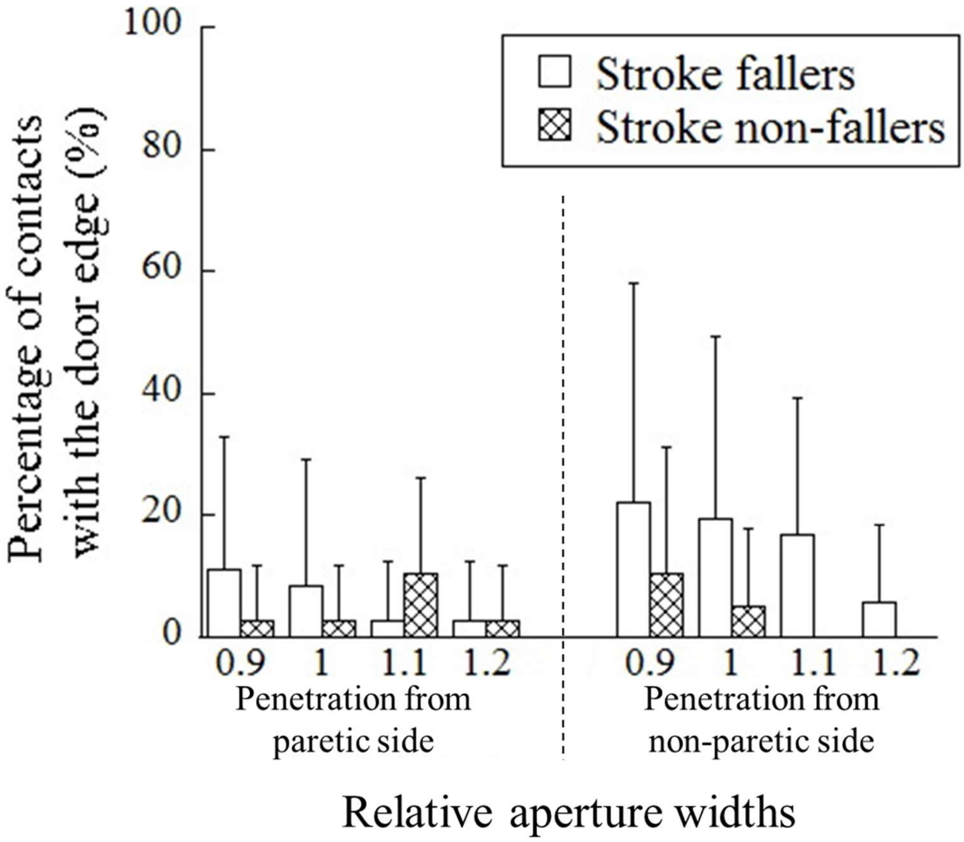
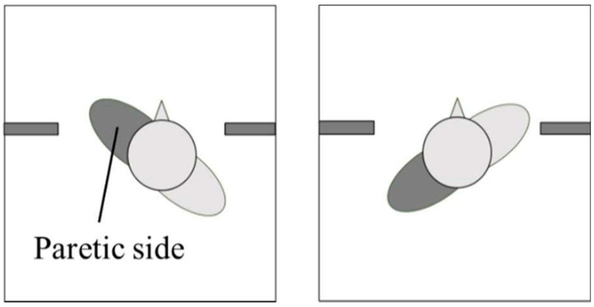


Fig 7. The mean percentage of contacts with the frame of an aperture in each group



	Penetration from paretic side		Penetration from non-paretic side	
Body side	Paretic	Non-paretic	Paretic	Non-paretic
Stroke fallers	0.5	0.7	3.4	0.4
Stroke non-fallers	0.4	0.4	0.7	0.2

Fig 8. Percentage of contact frequency classified according to the body side where contact occurred in stroke fallers and non-fallers

The mean absolute angles of body rotation for all aperture widths in each group are shown in Fig 9. Neither the main effect of the group nor the direction of penetration were significant (group: $F (1, 23) = 0.18$, *ns*; direction: $F (1, 23) = 0.21$, *ns*). The main effect of the aperture width was significant ($F (3, 69) = 115.51$, $p < 0.001$, $\eta_p^2 = 0.75$). Multiple comparisons showed that the absolute angle of body rotation of each pair of four aperture widths was significantly different. The interaction between the group and the direction of body rotation was not significant ($F (1, 23) = 1.27$, *ns*). A significant interaction between the group and the aperture widths ($F (3, 69) = 3.08$, $p = 0.033$ $\eta_p^2 =$

0.12) indicated that, for stroke non-fallers, the absolute angle of body rotation between each pair of four aperture widths was significantly different. For stroke fallers, the absolute angle was significantly different between each pair of four aperture widths, except between the 0.9 and 1.0 apertures. The interaction between the direction of body rotation and the aperture width was not significant ($F(3, 69) = 0.30$, *ns*). A significant interaction among three factors ($F(3, 69) = 4.24$, $p = 0.0082$ $\eta_p^2 = 0.16$) indicated that, when the aperture width was 0.9, the absolute body rotation angle was significantly smaller in stroke fallers than in stroke non-fallers. Multiple comparisons also showed that, when stroke fallers penetrated from paretic side, the absolute angle was significantly different between each pair of four aperture widths, except between the 0.9 and 1.0 apertures.

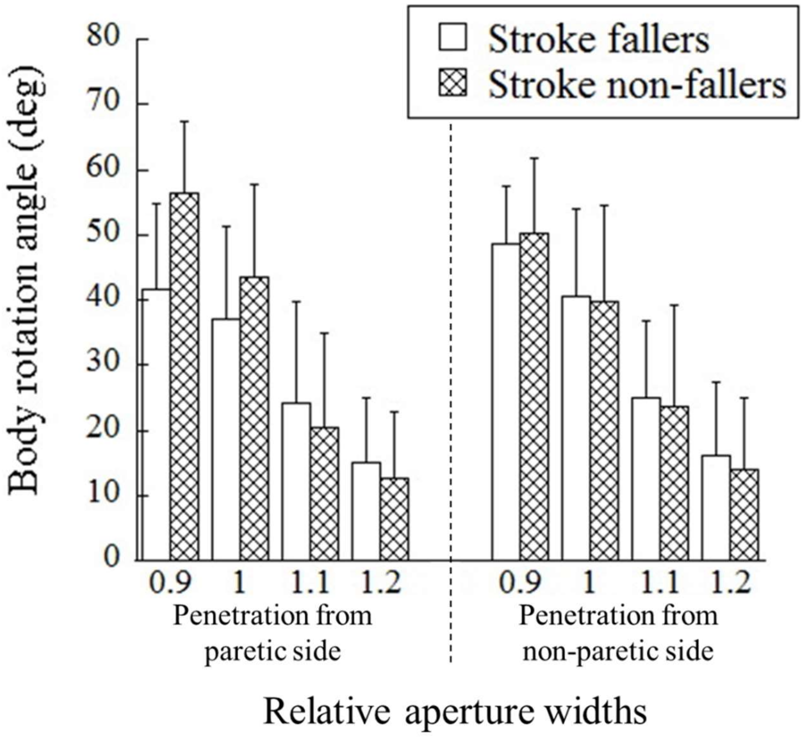


Fig 9. The mean absolute angle of body rotation for each aperture width in each group

The absolute deviation of the upper-body midpoint from the center of the doorway is shown in Fig 10. Neither the main effect of the group nor the direction of penetration were significant (group: $F(1, 23) = 0.31$, *ns*; direction: $F(1, 23) = 3.09$, $p = 0.092$). There was a tendency that the absolute deviation was smaller in the penetration from the paretic side, but the effect did not reach a significant level. The main effect of the aperture width was significant (F (3, 69) = 16.58, p < 0.001, η_p^2 = 0.42). Multiple comparisons showed that the absolute deviation became significantly larger as the aperture width was narrower, except between the 0.9 and 1.0 apertures, and the 1.1 and 1.2 apertures. All of interactions were not significant (group × direction: F (1, 23) = 0.007, *ns*; group × aperture width: F (3, 69) = 2.24, p = 0.091; direction × aperture width: F (3, 69) = 0.84, *ns*; group × direction × aperture width: F (3, 69) = 1.06, *ns*).

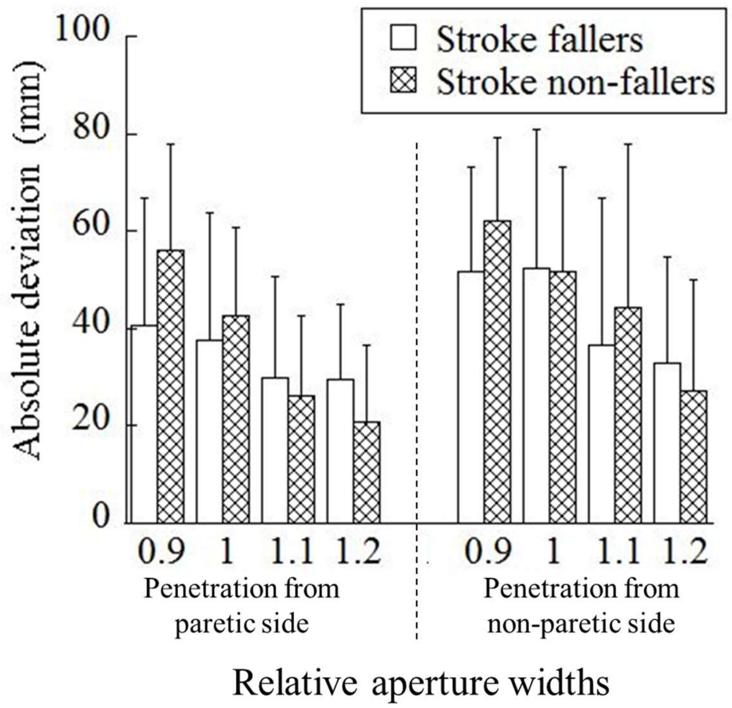


Fig 10. The mean of the absolute deviation from the center of the aperture at the time of aperture crossing under each experimental condition (SD in parenthesis) (mm)

4.2.5 Discussion

The findings of Experiment 2 generally supported those of Experiment 1. The results showed that, the tendency in stroke fallers to make more contact on the paretic side disappeared when they penetrated an aperture from their paretic side. This suggests that penetration from the paretic side was helpful for stroke fallers in order to pass through apertures safely.

One of the main findings in Experiments 1 and 2 was that, when stroke fallers penetrated an aperture from the paretic side, contact on the paretic side did not occur frequently. Two possibilities explain this result, i.e., the availability of vision and/or the availability of spatial attention to represent the paretic side of the body. First, vision may have been available to represent the paretic side of the body. When stroke participants penetrated an aperture from their paretic side, the location of the paretic side of the body was visible through the lower visual field. Second, spatial attention may have been directed more toward the paretic side of the body. Higuchi et al. (2012) demonstrated that, when walking through an aperture, the magnitude of the angle of body rotation is determined so that it creates a constant spatial margin between the frame of an aperture and the edge of the body side from which individuals penetrated the aperture.

4.3 Experiment 3

A case-study experiment (Experiment 3) was conducted to address the plausible explanation for a significant decrease in contact rate when stroke fallers penetrated an aperture from the paretic side. Three stroke fallers who had participated in Experiment 2 and showed a dramatic decrease in contact rate when penetrating from the paretic side took part in this experiment.

4.3.1 Participants

Three individuals with stroke who had more than five contacts, and whose contact rate was reduced by more than 50% due to penetration from paretic side in Experiment 2 were recruited as participants. Participants had residual hemiparesis. Testing was approved by the Ethics Committee of the Kameda Medical Center (approval number 17-100), and all participants gave written informed consent. Detailed participant information is shown in Table 8.

Table 8. Participant information

Participant	Gender	Age (years)	Time since stroke (months)	Paretic side	Falls history	BRS Lower extremity score	Mean TUG time (s)	Use of walking aid	modified Ranking Scale
01	M	66	34	Left	None	4	11.6	SPS, AFO	2
02	M	72	17	Left	None	4	20.0	SPS, AFO	2
03	M	69	19	Right	None	4	25.5	SPS, AFO	2

SPS (Single-point stick)
AFO (Ankle Foot Orthosis)

4.3.2 Apparatus, tasks, and procedures

The same apparatus as in Experiments 1 and 2 was used. The walking task itself was identical to that used in Experiments 1 and 2. However, the experimental condition and protocol were altered in response to the purpose of this experiment. Two experimental conditions (visual occlusion and calculation) were added to examine two possible explanations for the effect of penetration from the paretic side on the contact rate. In the visual occlusion condition, participants performed the walking task while wearing goggles with a sponge attached to the bottom rims of the goggles (see Figure 11). Participants were unable to see the body through lower peripheral vision while wearing the goggles

In the calculating condition, the participants performed the walking task while simultaneously performing serial 3 subtractions from a given number (any number from 60 to 100) (Manaf et al. 2015). For example, if the given number was 80, participants verbally reported “77, 74, 71,” etc. The participants were instructed to continue the verbal report until they passed through the aperture.

Other differences in the protocol from Experiments 1 and 2 were as follows: The aperture width was only 1.0 times the width of participants’ shoulders. Each participant performed this task under each penetration condition: penetration from the paretic side and penetration from the non-paretic side. Twenty-four trials were conducted under the two experimental conditions in one day. The participants performed 12 main trials (three trials for each penetration condition and with or without the experimental condition).

Fig 11. The goggles used in the visual occlusion condition. Participants were unable to see the body through peripheral vision.

4.3.3 Dependent measure and data analysis

The dependent measure was the contact frequency under each experimental condition. The statistical analysis for the dependent measure was not conducted because this experiment was designed on the basis of a case-study experiment.

4.3.4 Results and discussion

The contact frequency under each experimental condition is shown in Table 9. Consistent with the findings in Experiments 1 and 2, the tendency in stroke participants to make more contact on the paretic side disappeared when they penetrated an aperture from their paretic side. The effectiveness of penetration from the paretic side was reduced from 67% to 25% when the walking task was performed under the dual (calculation) task condition. Two out of three participants made contact when they penetrated from the paretic side while carrying out the calculation task. That is, the contact frequency was comparable between penetration from the paretic side and the non-paretic side. In contrast, under the visual occlusion condition, the reduced contact rate was maintained when participants penetrated from their paretic side; thus, the availability of the lower visual field to obtain spatial information on the body is not likely to be involved in the effect. Taken collectively, the findings of Experiment 3 suggest that the availability of the paretic side penetration for reducing the contact rate is likely to be explained on the basis of the availability of spatial attention to represent the paretic side of the body.

Table 9. Contact frequency under each constrained condition

a) The visual occlusion condition

	Constrained condition		Non-constrained condition	
Penetration direction	Paretic	Non-paretic	Paretic	Non-paretic
Contact frequency	2	5	1	4

b) The calculation condition

	Constrained condition		Non-constrained condition	
Penetration direction	Paretic	Non-paretic	Paretic	Non-paretic
Contact frequency	3	4	1	3

<u>Study 2.</u> How stroke fallers estimated their spatial requirements when they imagined themselves walking through the aperture? (Perceptual judgment task)

4.4 Experiment 4

The results of Experiments using the walking task showed that the contact with the frame of an aperture occurred more frequently in stroke fallers than in both stroke non-fallers and control participants. One may assume that frequent contact with the frame could be the result of inaccurate perception of aperture passability. To test the assumption, the purpose of Study 2 (Experiments 4–6) was to investigate how stroke fallers estimated their spatial requirements when they imagined themselves walking through the aperture.

4.4.1 Participants

The participants were same as Experiment 1 (see section 4.1.1). Twenty-three individuals with stroke (10 fallers, and 13 non-fallers) and twenty-three age- and height-matched healthy individuals participated. Testing was approved by the ethics committee of the Kameda Medical Center. All participants gave written informed consent prior to participation.

4.4.2 Tasks and procedures

Perceptual judgment task

Participants stood 3 m in front of an aperture. They observed apertures of various widths and reported whether they believed they would be able to pass though the aperture without making any contact.

4.4.3 Dependent measures and data analysis

The dependent variable was the perceived minimum passable width relative to the minimum passable width. The relative perceptual boundaries were analyzed in a one-way (group) ANOVA. A one-sample t-test was also carried out to examine whether the results of each condition would be significantly different from a value of 1.0. A value of 1.0 meant that their judgment was accurate, and values smaller than 1.0 meant that participants overestimated their passability (i.e., they underestimated the space necessary for passage).

4.4.4 Results

Characteristics of participants, clinical measurements, and stroke participants' details

The results of participants' information were the same as in Experiment 1 (see section 4.1.4).

Perceptual judgment task

Figure 12 shows the relative perceptual boundaries obtained for each group. An ANOVA showed no significant main effect of group ($F(2, 43) = 0.88$, $p = 0.42$). The one-sample t-tests showed that the relative perceptual boundaries obtained from each group were not significantly different from the value 1.0.

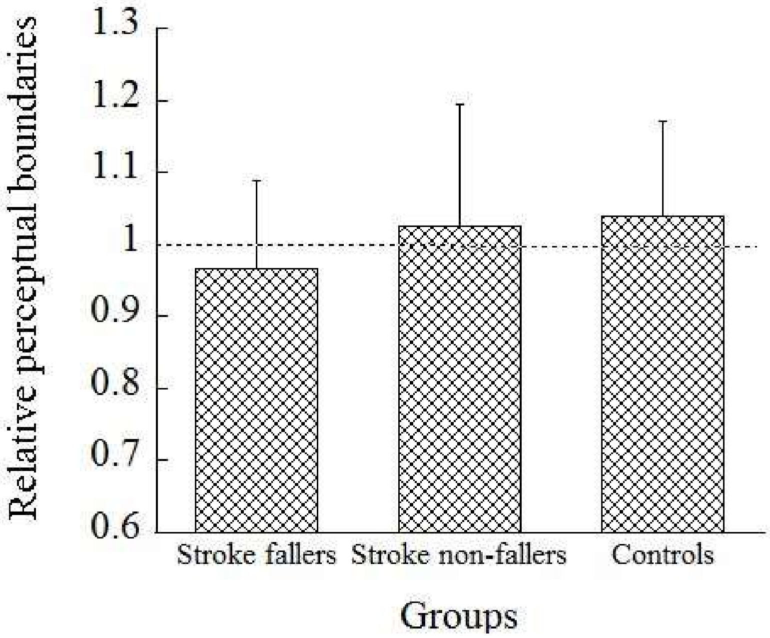


Fig 12. The mean relative perceptual boundaries obtained from the perceptual judgment task in each group. A relative value less than 1.0 indicates that the participants underestimated their body width

4.4.5 Discussion

Inconsistently with my assumption, the results showed that there was no significant group difference in the perceptual judgment of aperture passability (Fig 12). Considering the protocol of the task, this suggests that the perceptual judgment of aperture passability of stroke fallers was comparable to that of stroke non-fallers and control participants, at least when they observed an aperture from a remote place while standing still. In fact, this was consistent with a previous study that showed no relationship between the behavior of walking through an aperture and the perceptual judgment of aperture passability in patients with PD (Cowie et al. 2010).

It is still possible to assume that the perceptual judgment of stroke fallers may have been inaccurate if it is measured during walking. Hackney et al. has shown that age-related differences in action capabilities (i.e., older adults have more body rotation for wider apertures than do younger adults) were related to perceptual judgment under dynamic conditions (i.e., judgment of passability while walking toward an aperture) but not under static conditions (i.e., judgment of passability while standing still) (Hackney and Cinelli 2013). According to this finding, future studies would need to examine whether stroke fallers would show inaccurate perceptual judgment while they are walking. The rationale to conduct the next experiment was to test this issue.

4.5 Experiment 5

The purpose of Experiment 5 was to test whether the relative perceptual boundaries obtained from the walking condition was significantly inaccurate for stroke fallers as compared with stroke non-fallers and control participants.

4.5.1 Participants

Twenty individuals with stroke (nine females) participated. The mean age was 63.9 years (SD = 8.3). Eleven healthy individuals also participated as control participants. Testing was approved by the Ethics Committee of the Kameda Medical Center (approval number 15-080), and all subjects gave written informed consent.

Participants in the stroke group were patients in a subacute hospital or had been discharged from a subacute hospital. The mean time from the onset of stroke to testing was 22.0 months (ranging from 1 to 110 months).

All stroke participants were asked whether they had fallen in the past 12 months. Ten participants were regarded as fallers (referred to as stroke fallers in this study). Five of these participants had fallen two or more times. The other 10 participants, who had not fallen, were referred to as stroke non-fallers in this study.

Characteristics of participants are summarized in Table 10. Not significant difference between stroke faller and stroke non-fallers.

Table.10 Characteristics of participants

	Stroke fallers (n = 10)	Stroke non-fallers (n = 10)	Control participants (n = 11)	p value
Participant details				
Gender (male/female) b)	5 / 5	6 / 4	5 / 6	n.s
Age (y) a)	65.8 ± 5.8	61.8 ± 9.5	64.1 ± 3.8	n.s
Height (cm) a)	160.5 ± 7.4	158.5 ± 11.2	159.2 ± 7.1	n.s
Shoulder width (cm) a)	44.6 ± 4.5	46.9 ± 2.2	45.0 ± 2.2	n.s
Minimum passable widtha)	1.16 ± 0.08	1.10 ± 0.05	1.09 ± 0.03	n.s
Clinical tests				
MMSEa)	28.8 ± 1.3	28.1 ± 2.8	29.1 ± 0.9	n.s
TUG (s) a)	13.2 ± 3.4	12.0 ± 2.7	6.70 ± 1.2	< 0.001*†
Stroke participants' details				
Time after stroke (months) c)	18.6 ± 13.5	27.5 ± 30.9		n.s
mRS (score 2/score3) b)	7 / 3	8 / 2		n.s
Upper extremity BRS (stages 3/4/5) b)	1 / 3 / 6	2 / 5 / 3		n.s
Lower extremity BRS (stages 3/4/5) b)	0 / 9 / 1	0 / 8 / 2		n.s
Stroke type (hemorrhagic/ischemic) b)	6 / 4	6 / 4		n.s
Hemiplegic side (right/left) b)	5 / 5	5 / 5		n.s
Use of walking aid (no/yes) b)	7 / 3	6 / 4		n.s

a) Kruskal-Wallis test, b) Pearson's chi-square test, c) Mann-Whitney U test

Note. MMSE = Mini Mental State Examination, BRS = Brunnstrom Recovery Stage, mRS = modified Ranking Scale

* Significant difference between stroke fallers and control participants

† Significant difference between stroke non-fallers and control participants

4.5.2 Apparatus, tasks, and procedures

The same apparatus as in Experiment 4 was used. The same experimental task as a visual estimation task in Experiment 4 was used. In this task, participants observed the aperture at a predetermined position (1 m or 4 m, which was different among the visual conditions). The width of the aperture ranged from 30 cm to 80 cm with 2-cm intervals (See below for details). Participants were asked to verbally report whether the aperture presented was passable.

Each participant performed this task under each of four observation conditions: observe while walking, observe while standing at 4 m in front of the aperture, observe while standing at 1 m in front of the aperture, and observe while being assisted in a wheelchairs. During the walking condition, they stood facing down at the 4 m in front of the aperture without vision. After the signal of the experimenter, the participants raised the head, and moved forward until 1 m in front of the aperture. Their vision was occluded 1 m from the aperture by large white board (42-cm × 58-cm). The participants judged whether the aperture was passable immediately after stopping. Under the 4 m or 1 m standing condition, participants kept standing at the starting position (4 m or 1 m in front of the aperture) and observed the aperture for the same time as the walking conditions. After the observation, their vision was occluded by white board. Participants were then asked to judge whether they could pass through the aperture without touching it if body rotation was not allowed. Under the wheelchair condition, the protocols were almost the same as those under the walking condition. The only exception was that participants had a sheet on the wheelchair and got by pushing the wheelchair at the same speed as the walking condition. In each visual condition, the methods of presentation of the apertures were same as in Experiment 4.

4.5.3 Dependent measures and data analysis

The dependent variable was same (the perceived minimum passable width as compared to the actual minimum passable width) as in Experiment 4. The relative perceptual boundaries were analyzed in a two-way (group × observational conditions) ANOVA. I also conducted one-sample t-test in order to examine accuracy of judgement.

4.5.4 Results and discussion

Characteristics of participants, clinical measurements, and stroke participants' details

With regard to the characteristics of participants and clinical measurements, a significant main effect of the group was found in the TUG (H = 18.30, $p < 0.001$).

Multiple comparisons with Bonferroni corrections showed that the time required for the TUG was significantly slower for stroke fallers and non-fallers than for controls. There were no significant differences among the groups regarding other characteristics of participants and clinical measurements.

Perceptual judgment task

Figure 13 shows the relative perceptual boundaries obtained from each visual condition. A two-way ANOVA showed that the main effect of each group was significant (F (2, 28) = 7.66, $p < 0.005$, $\eta_p^2 = 0.35$). A follow-up test indicated that the relative perceptual boundary for the stroke fallers smaller than for the stroke non-faller and controls. The main effect of the visual conditions was not significant (F (3, 84) = 1.60, *ns*). There was no significant interaction between the two factors (F (6, 84) = 0.77, *ns*). A one-sample t test showed that the relative perceptual boundaries for stroke fallers were significantly smaller than 1.0 of all visual conditions. This meant that the stroke faller could not correctly perceive the size of aperture relative to the size of their locomotion in all of the observed condition.

The results of Experiment 5 showed that the perceptual judgment was significantly inaccurate for stroke fallers both when they were standing and walking.

These results suggest that, contrary to the findings in Experiment 4, frequent accidental contact could be the result of inaccurate perception of aperture passability. A possible explanation for the discrepancy of the results on the accuracy of perceptual judgment in stroke fallers would be related to the existence of time constraint for the judgment. While there was no time constraint in the task of Experiment 4, there was a time limit of 4–7 seconds in Experiment 5. The time constraint was necessary for Experiment 5 to control the time for the judgment between the standing condition and walking condition. A previous study showed that, when stroke participants were pressured for time, errors during stepping over obstacles increased (van Swigchem et al. 2013). Considering this result, stroke faller's performance might have been negatively affected by time constraint.

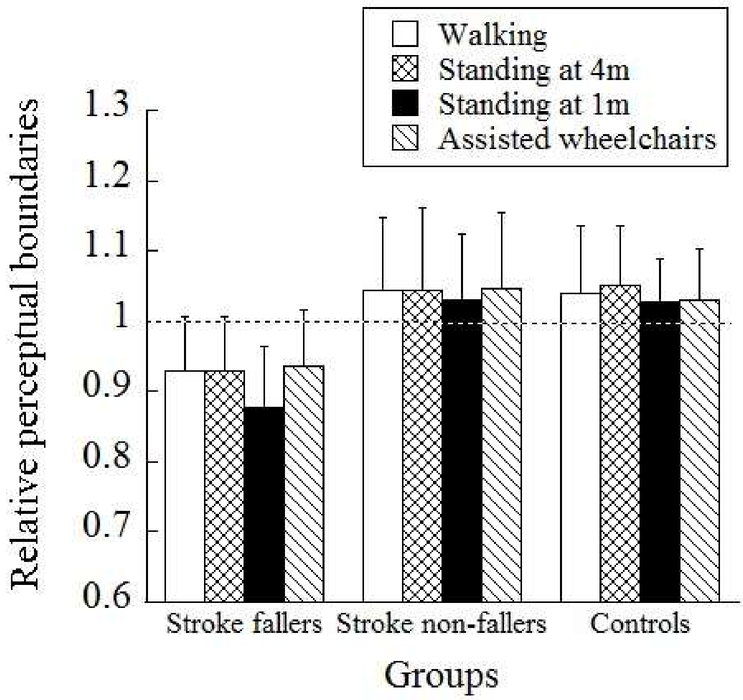


Fig 13. The mean relative perceptual boundaries obtained from each visual condition. A relative value less than 1.0 indicates that the participants underestimated their body width.

4.6 Experiment 6

The purpose of Experiment 6 was to test whether the relative perceptual boundaries in stroke fallers would be inaccurate when time constraint was introduced for the judgment.

4.6.1 Participants

Twenty five individuals with stroke (ten females) participated. Mean age was 66.5 years (SD = 5.9). The mean time from the onset of stroke to testing was 25.0 months (ranging from 1 to 123 months). Participants had residual hemiparesis. Nineteen healthy individuals also participated as control participants. Testing was approved by the Ethics Committee of the Kameda Medical Center (approval number 16-160), and all subjects gave written informed consent.

All stroke participants were asked whether they had fallen in the past 12 months. Twelve participants were regarded as fallers (referred to as stroke fallers in this study). The other 13 participants, who had not fallen, were referred to as stroke non-fallers in this study. Characteristics of participants are summarized in Table 11. Not significant difference between stroke faller and stroke non-fallers.

Table.7 Characteristics of participants

	Stroke fallers (n = 12)	Stroke non-fallers (n = 12)	Control participants (n = 19)	p value
Participant details				
Gender (male/female) b)	8 / 4	6/ 6	12 / 7	n.s
Age (y) a)	67.9 ± 4.0	65.9 ± 7.0	61.0 ± 9.7	n.s
Height (cm) a)	160.7 ± 11.2	158.7 ± 11.6	160.2 ± 7.8	n.s
Shoulder width (cm) a)	46.3 ± 2.6	44.9 ± 3.7	45.2 ± 2.6	n.s
Minimum passable width a)	1.13 ± 0.04	1.11 ± 0.03	1.09 ± 0.04	0.040*
Clinical tests				
MMSE a)	27.4 ± 2.2	29.1 ± 1.6	28.4 ± 1.8	n.s
TUG (s) a)	13.0 ± 5.0	11.7 ± 4.7	6.65 ± 1.2	< 0.001*†
Stroke participants' details				
Time after stroke (months) c)	20.4 ± 20.5	31.4 ± 34.7		n.s
mRS (score 2/score3) b)	8 / 4	8 / 4		n.s
Upper extremity BRS (stages 3/4/5) b)	3 / 1 / 8	2 / 2 / 8		n.s
Lower extremity BRS (stages 3/4/5) b)	0 / 6 / 6	0 / 6 / 6		n.s
Stroke type (hemorrhagic/ischemic) b)	6 / 6	8 / 4		n.s
Hemiplegic side (right/left) b)	6 / 6	7 / 5		n.s
Use of walking aid (no/yes) b)	5 / 7	4 / 8		n.s

a) Kruskal-Wallis test, b) Pearson's chi-square test, c) Mann-Whitney U test

Note. MMSE = Mini Mental State Examination, BRS = Brunnstrom Recovery Stage, mRS = modified Ranking Scale

* Significant difference between stroke fallers and control participants

† Significant difference between stroke non-fallers and control participants

4.6.2 Apparatus, tasks, and procedures

The same apparatus as in Experiments 4 and 5 was used. The same experimental task as a visual estimation task in Experiments 4 and 5 was used. In this task, participants observed 4 m in front of the aperture. Each participant performed this task under conditions with or without time pressure. Under the condition with time pressure, the participants were asked to answer within 5 seconds. Participants were asked to judge whether they could pass through the aperture without touching it if body rotation was not allowed. In each condition, the methods of presentation of the apertures were same as in Experiments 4 and 5.

4.6.3 Dependent measures and data analysis

The dependent variable was same (the perceived minimum passable width as compared to the actual minimum passable width) as in Experiments 4 and 5. The relative perceptual boundaries were analyzed in a two-way (group × time constraints) ANOVA. I also conducted one-sample t-test in order to examine accuracy of judgement.

4.6.4 Results

Characteristics of participants, clinical measurements, and stroke participants' details

With regard to the characteristics of participants and clinical measurements, a significant main effect of the group was found in the minimum passable width (H = 6.44, p = 0.040) and the TUG (H = 27.63, p < 0.001). Multiple comparisons with Bonferroni corrections showed that the minimum passable widths were significantly wider for stroke fallers than for controls. The time required for the TUG was significantly slower for stroke fallers and non-fallers than for controls. There were no significant differences among the groups regarding other characteristics of participants and clinical measurements.

Perceptual judgment task

Figure 14 shows the relative perceptual boundaries obtained from each time pressure condition. A two-way ANOVA showed that the main effect of each group was significant ($F (2, 40) = 3.50$, $p < 0.05$ $\eta_p^2 = 0.15$). A follow-up test indicated that the relative perceptual boundary for the stroke fallers smaller than for controls. The main effect of the group was not significant ($F (1, 40) = 1.32$, *ns*). There was no significant interaction between the two factors (F (2, 40) = 1.40, *ns*). A one-sample t test showed that the relative perceptual boundaries for stroke fallers were not significant.

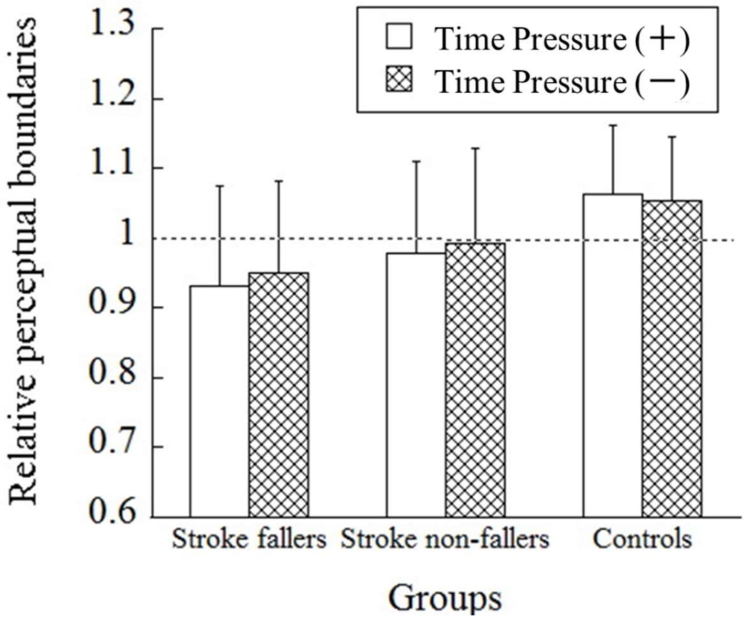


Fig 14. The mean relative perceptual boundaries obtained from each time pressure condition. A relative value less than 1.0 indicates that the participants underestimated their body width.

4.6.5 Discussion

Unfortunately, the results of Experiment 6 did not support my hypothesis that the relative perceptual boundaries in stroke fallers would be inaccurate when time constraint was introduced for the judgment. An important finding, however, was that, consistent with the results of Experiment 5, perceptual judgment was significantly inaccurate for stroke fallers as compared with the controls. That is, the results of Experiments 5 and 6 indicated that the stroke fallers underestimated their spatial requirements. Although our findings on perceptual judgment tasks were not constant in Experiments 4–6, I tentatively concluded that perceptual judgment of aperture passability in stroke fallers is likely to be inaccurate.

There are two reasons why there was no significant difference in Experiment 4. First, there were many variations of patients' characteristics in Experiment 4. In all experiments, no significant main effect of the group was found in the upper and lower extremity BRS. However, many stroke individuals with severe paralysis were included in the stroke fallers. On the other hand, the degree of paralysis was almost the same between stroke fallers and non-fallers in Experiments 5 and 6. Second, the variation in the perceptual boundaries of the control group was large in Experiment 4. It was found that the variations of control participants' perceptual boundaries in Experiments 4 and 5 were not equal variance in the F test (p = 0.023). The reason might be due to the fact that three control participants with a history of falls were included. For these two reasons, I judged that there is a high possibility that a significant difference was not likely to occur in Experiment 4. Considering these findings, the failure to avoid contact in stroke fallers is likely to be related to their difficulty in recognizing their behavior, and their difficulty in representing the affected side of their bodies.

5. GENERAL DISCUSSION

Summary of results

The present study was designed to investigate how successfully stroke individuals walk through apertures and how they perform body rotation behavior (Study 1: Walking task). It was also designed to investigate how they estimated their spatial requirements when they imagined themselves walking through the aperture (Study 2: Perceptual judgment task). The results obtained from the six experiments (Study 1: three experiments; Study 2: three experiments) showed that (a) Stroke fallers, but not stroke non-fallers, showed frequent contact with the frame of an aperture (Experiments 1 and 2). (b) Contact with the frame of an aperture occurred more frequently on the paretic side in stroke fallers (Experiments 1, 2, and 3). (c) When stroke fallers penetrated an aperture from the paretic side, contact on the paretic side did not occur frequently (Experiments 1, 2, and 3). (d) The involvement of spatial attention toward the paretic side of the body is a plausible explanation for the effectiveness of penetration from the paretic side (Experiment 3). (e) Stroke fallers underestimated their spatial requirements when they imagined themselves walking through the aperture (Experiments 5 and 6, but see Experiment 4 for different results).

The availability of the paretic side penetration

Our particular interest in the present study was to understand the side of the body that penetrated an aperture and whether the selection of the body side for penetration was related to safe walking through apertures without making contact. The results from Experiment 1 showed that there was no consistency among stroke participants with regard to selecting a body side to penetrate an aperture; 11 participants penetrated an aperture from the paretic side, while eight participants penetrated from the non-paretic side. There was no significant difference between stroke fallers and non-fallers.

Interestingly, the tendency among stroke fallers to make more contact on the paretic side disappeared when they penetrated an aperture from the paretic side. Clearer evidence was obtained from Experiment 2: the tendency among stroke fallers to make more contact on the paretic side disappeared when they penetrated an aperture from their paretic side. These findings suggest that penetration from the paretic side was available for stroke fallers to successfully avoid accidental contact.

There are two possible explanations for the advantage of penetration from the paretic side to avoid contact. First, vision may have been available to represent the paretic side of the body. While fixation is mainly directed toward a distant place during walking, visual information obtained from a lower visual field is important to perceive the spatial relationship between the environment and the body in the peri-personal space (Marigold and Patla 2008; Rietdyk and Rhea 2006). When stroke participants penetrated an aperture from their paretic side, the location of the paretic side of the body was visible through the lower visual field. Because the availability of proprioceptive input from the paretic side of the body is limited, the use of vision is helpful to represent the paretic side of the body and was, thus, helpful for perceiving the spatial relationship between the body and the aperture.

Second, spatial attention may have been directed more toward the paretic side of the body. A previous study (Higuchi et al. 2012) demonstrated that, when walking through an aperture, the magnitude of the angle of body rotation is determined so that it creates a constant spatial margin between the frame of an aperture and the edge of the body side from which individuals penetrated the aperture. Providing that spatial attention is involved in information processing to produce the constant spatial margin, this could help improve the representation of the paretic side of the body. In fact, when attention was not sufficiently allocated during obstacle avoidance, contact occurred more frequently (Menant et al. 2010).

The results of the case study in Experiment 3 supported the second explanation; the availability of paretic side penetration was canceled when participants performed the walking task under the dual (calculation) task condition. In contrast, under the visual occlusion condition, the reduced contact rate was maintained when participants penetrated from their paretic side. These findings suggest that the availability of paretic side penetration to reduce the contact rate can likely be explained by the availability of spatial attention to represent the paretic side of the body.

Is the cause of contact motor factors or perceptual factors?

Throughout the six experiments, I considered that accidental contact by stroke fallers was likely to occur due to both perceptual factors and motor factors. Previous studies have investigated whether maladaptive locomotion in obstacle avoidance was affected either by perceptual-motor or by locomotor factors in participants who had suffered a stroke and who had visuospatial neglect (Aravind and Lamontagne 2014) and PD (Cowie et al. 2010). Based on the results of the walking tasks in Experiments 1 and 2, kinematic analyses showed that the absolute body rotation angle was significantly smaller in stroke fallers than in stroke non-fallers when they walked a through narrow aperture. Measurement of the minimum passable width showed that stroke fallers required wider space than did stroke non-fallers and control participants. This suggests that lateral sway during walking was larger for stroke fallers, quite possibly due to their motor paralysis. Given this larger minimum passable width, a larger magnitude of body rotation would be necessary for stroke fallers to avoid contact. However, the angle of body rotation at the moment of aperture crossing was not significantly different from that of other participants. Therefore, insufficient body rotation is likely to be a cause of frequent accidental contact. These findings suggest that several motor factors could lead to the failure by stroke fallers to avoid contact.

Based on the results of the perceptual judgment tasks in Experiments 4–6, there is a high possibility that the judgment ability of stroke fallers is inaccurate. The reason there was no significant difference in Experiment 4 is considered to be that the variation in judgment values was larger in the stroke fallers and controls. Overall, there was a consistent tendency of stroke fallers to underestimate their spatial requirements when they imagined themselves walking through the aperture. Considering the fact that stroke fallers showed frequent contact with the frame of an aperture, there was a relationship between the behavior of walking through an aperture and the perceptual judgment of aperture passability with stroke fallers. This was different from the result of Cowie et al. (2010), targeting PD, suggesting that PD participants were not able to successfully pass through the aperture mainly due to motor factors. Considering these findings, the failure of stroke fallers to avoid contact is likely related not only to motor factors but also to cognitive factors, i.e., difficulty in estimating their spatial requirements when the individuals imagined themselves walking through the aperture.

6. CONCLUSION

Throughout these six experiments, I demonstrated that (a) stroke participants who had history of falls were not able to pass through apertures safely because they experienced many contacts on the paretic side (Study 1) and that (b) the failure to avoid contact was likely due to participants' underestimating their spatial requirements when they imagined themselves walking through the aperture (Study 2). However, there is a high possibility that penetration from the paretic side was available for stroke fallers in order to pass through apertures safely.

To our knowledge, this is the first report regarding an effective way for stroke individuals (particularly stroke fallers) to avoid accidental contact when walking through apertures. Measuring the behavior of walking through an aperture potentially provides new insight into the increased risk of instability during adaptive locomotion in stroke individuals.

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