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Punt, Michiel; Bruijn, Sjoerd M.; Wittink, Harriet; van de Port, Ingrid G.; Wubbels, Gijs; van Dieën, Jaap H.

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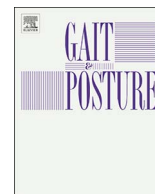
Original article

Virtual obstacle crossing: Reliability and differences in stroke survivors who prospectively experienced falls or no falls

Michiel Punt[a,*], Sjoerd M. Bruijn[b,c], Harriet Wittink[a], Ingrid G. van de Port[d], Gijs Wubbels[a], Jaap H. van Dieën[b]

[a] Research Group Lifestyle and Health, Utrecht University of Applied Sciences, Utrecht, The Netherlands
[b] Move Research Institute Amsterdam, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[c] Department of Orthopedics, First Affiliated Hospital of Fujian Medical University, Fuzhou, Fujian, PR China
[d] Revant Rehabilitation Center Breda, Breda, The Netherlands

A B S T R A C T

Introduction: Stroke survivors often fall during walking. To reduce fall risk, gait testing and training with avoidance of virtual obstacles is gaining popularity. However, it is unknown whether and how virtual obstacle crossing is associated with fall risk.
Aim: The present study assessed whether obstacle crossing characteristics are reliable and assessed differences in stroke survivors who prospectively experienced falls or no falls.
Method: We recruited twenty-nine community dwelling chronic stroke survivors. Participants crossed five virtual obstacles with increasing lengths. After a break, the test was repeated to assess test-retest reliability. For each obstacle length and trial, we determined; success rate, leading limb preference, pre and post obstacle distance, margins of stability, toe clearance, and crossing step length and speed. Subsequently, fall incidence was monitored using a fall calendar and monthly phone calls over a six-month period.
Results: Test-retest reliability was poor, but improved with increasing obstacle-length. Twelve participants reported at least one fall. No association of fall incidence with any of the obstacle crossing characteristics was found.
Discussion: Given the absence of height of the virtual obstacles, obstacle avoidance may have been relatively easy, allowing participants to cross obstacles in multiple ways, increasing variability of crossing characteristics and reducing the association with fall risk.
Conclusion: These finding cast some doubt on current protocols for testing and training of obstacle avoidance in stroke rehabilitation.

1. Introduction

About 30 to 50% percent of all chronic stroke survivors report at least one fall each year [1] and these falls often result in injuries and medical costs [2]. One of the causes of a fall may be unsuccessful negotiation of an obstacle, resulting in a trip. Indeed, it has been found that obstacle crossing is challenging for elderly and for stroke survivors, as it often results in tripping [3,4].

Crossing obstacles demands adequate gait adjustments. Several gait adjustments during obstacle crossing in an over ground setting were found to be different in stroke survivors compared to age matched controls [5–7]. For instance, stroke survivors showed a reduced toe clearance of the affected limb while crossing the obstacle and they also placed their foot at a less favorable position behind the obstacle [6].

Moreover, during over ground obstacle crossing, the peak velocity of the center of mass (CoM) in the medio-lateral (ML) direction was higher in stroke survivors as compared to controls [5,7]. These gait changes may reduce safety, and it has been shown that the ability to negotiate obstacles successfully is reduced in stroke survivors compared to age matched control groups [5,8–10]. Although these differences in over ground obstacle crossing may to some extent explain the higher fall rates in stroke survivors compared to the general older population [5,7,9,11], at present it remains largely unknown whether measures derived from over ground obstacle crossing are associated with falls in stroke survivors. Only one study did find that fall prone stroke survivors were indeed less successful in obstacle crossing as compared to non-fallers [12].

In recent years, obstacle crossing using a virtual environment has

gained popularity for testing and training during rehabilitation after a stroke [13,14]. Training generally aims to enhance the ability to perform stepping adjustments and thereby the ability to walk safely through more complex environments and as such perhaps prevent falls. However, little is known about the reliability and validity of virtual obstacle crossing as a diagnostic tool for fall risk, or as a model for daily life gait. Finally, results found in over ground obstacle crossing may be not transferable to virtual obstacle crossing due to the differences in the experimental set up. For instance, virtual obstacles are two dimensional, and there is no penalty when hitting the obstacle whereas hitting a real obstacle will result in a trip. Therefore, the main aims of the present experiment were to assess test-retest reliability of characteristics of virtual obstacle crossing and assess differences between stroke survivors who experienced falls or no falls. We note here that the data reported were obtained from participants of a previous study that found that steady-state gait characteristics were associated with fall risk [15].

2. Methods

Participants were community dwelling persons after stroke in the chronic phase, recruited via flyers in hospitals, physical therapy practices, general practitioners and national peer group meetings. Prior to the study, all participants gave written informed consent and the medical ethical committee 'Noord Brabant', The Netherlands approved the research protocol (NL49126.028.14).

Participants were excluded if their Functional Ambulation Category (FAC) was lower than three [16], Mini Mental State Examination (MMSE) was lower than 24 [17] and if they had severe cardiovascular, respiratory, musculoskeletal or other neurological disorders that could affect gait performance. Furthermore, stroke survivors who were institutionalized in for instance a nursing home were excluded as well. The measurements were performed during a single visit at the rehabilitation center Revant, Breda, The Netherlands.

2.1. Experimental set up

Data collection was performed using the Gait Real-time Analysis Interactive Lab (GRAIL, Motekforce Link b.v., The Netherlands). The GRAIL is equipped with ten infrared cameras (Bonita B10, Vicon Motion Systems, Oxford, UK), a dual belt treadmill with two embedded force platforms (Motekforce Link b.v., The Netherlands) and a synchronized virtual environment. A custom-developed application to control the GRAIL was written in DFlow software (Motekforce Link b.v., The Netherlands). Light planes projected on the treadmill, created with the DFlow software, functioned as obstacles to be crossed. Full-body kinematics were collected by tracking forty-seven markers on anatomical landmarks [18].

2.2. Obstacle crossing protocol

For safety reasons, participants wore a fall harness that did not restrict motion, nor provided body weight support. All participants first familiarized themselves with treadmill walking, and were instructed to walk without support of the treadmill sidebars and a walking aid. The obstacle crossing task was executed at a gait speed of 0.41 m/s (1.5 km/h) to make sure that the perturbation size was the same among all participants, moreover, 0.41 m/s was feasible for all participants.

The obstacle crossing task contained five virtual obstacles. The virtual obstacles were two-dimensional, and had no height. The width of the obstacle was equal to the width of the treadmill, the length of the first out of five obstacles was 7 cm, each of the subsequent obstacles increased in steps of 7 cm towards 35 cm. The appearance of the obstacle (in both time and position) was determined by the mid-swing phase position of the right limb, plus three times the stride time and stride length based on three previously performed strides, see Fig. 1A. Given the provided time and space between obstacle appearance and

actual obstacle crossing, participants were free to decide whether to cross the obstacle with their paretic or non-paretic limb. To improve the ecological validity of our experiment, the only instruction given was to cross the obstacle, no instruction was given on how to cross the obstacle. Finally, after a break of ten minutes the experiment was repeated to assess test-retest reliability. To assess differences between fallers and no fallers, we used data from the first set of 5 obstacles.

2.3. Data analysis

Gait events (foot contacts (FC), foot off) were detected based on the trajectory of the center of pressure [19]. The whole body CoM was determined using a 14 body segment model [20]. Subsequently dynamic stability expressed as the Margin of Stability (MoS) in forward (FW) and mediolateral (ML) directions, was determined at FC [21]. All crossing attempts were included for all analysis regardless of whether the attempt was successful or not.

We calculated several measures that reflect how, and how well, participants performed the obstacle crossing tasks, further referred to as crossing characteristics. First, we determined two dichotomous variables; 1) lead limb, i.e. the limb which first crossed the obstacle (paretic or non-paretic limb) further referred to as 'Leading Limb Preference'(LLP) and 2) success rate. Since some participants placed their foot in the middle of the obstacle, it was not always clear whether an unsuccessful foot placement was intended as a crossing step, or a last step before crossing. We defined a crossing step, as a step wherein the anterior-posterior (AP) position of the toe marker was beyond the midline of the obstacle. A crossing step was defined unsuccessful if the position of the virtual obstacle in the progression direction overlapped with the position of the foot during the stance phase. Both dichotomous variables were determined for each obstacle length. Second, we determined seven continuous crossing characteristics, (Fig. 1B): (1) toe clearance (i.e. vertical distance between lead limb toe and the ground halfway crossing the obstacle), (2) pre-obstacle-distance (i.e. the distance between the toe marker of the final foot placement prior to obstacle crossing and the beginning of the obstacle), (3) post-obstacle-distance (i.e. the distance between the end of the obstacle and the heel marker of the leading limb). (4) crossing length (i.e. the step length of the lead limb, when crossing the obstacle) (5) crossing speed (i.e. the crossing step length divided by the step time of the leading limb), (6 and 7) MoS in ML and FW direction at FC directly after obstacle crossing.

2.4. Fall status

For six months after the lab visit, fall status was determined by monthly phone calls, and a fall diary was used to report when, and how the fall occurred. We defined a fall as 'any unanticipated event that results in a participant coming to the ground, floor or lower level' [22]. We excluded falls that had a clearly different cause than a loss of balance, such as fainting or an epileptic seizure. Participants that experienced at least one fall were classified as fall prone stroke survivors.

2.5. Statistics

For all crossing characteristics, we determined the test-retest reliability. For both dichotomous crossing characteristics, Kappa statistics were used. Reliability of continuous crossing characteristics was determined through intra-class correlation (ICC), absolute agreement [23], single measures. Reliability of dichotomous crossing characteristics was defined as moderate for kappa between 0.41–0.6, substantial for kappa between 0.61–0.8, or almost perfect for kappa between 0.81–1 [24] and reliability for continuous crossing characteristics was considered adequate if ICC was ≥ 0.75 [25].

Demographic and stroke specific characteristics between fallers and non-fallers were compared using a Mann Whitney *U* test. Between
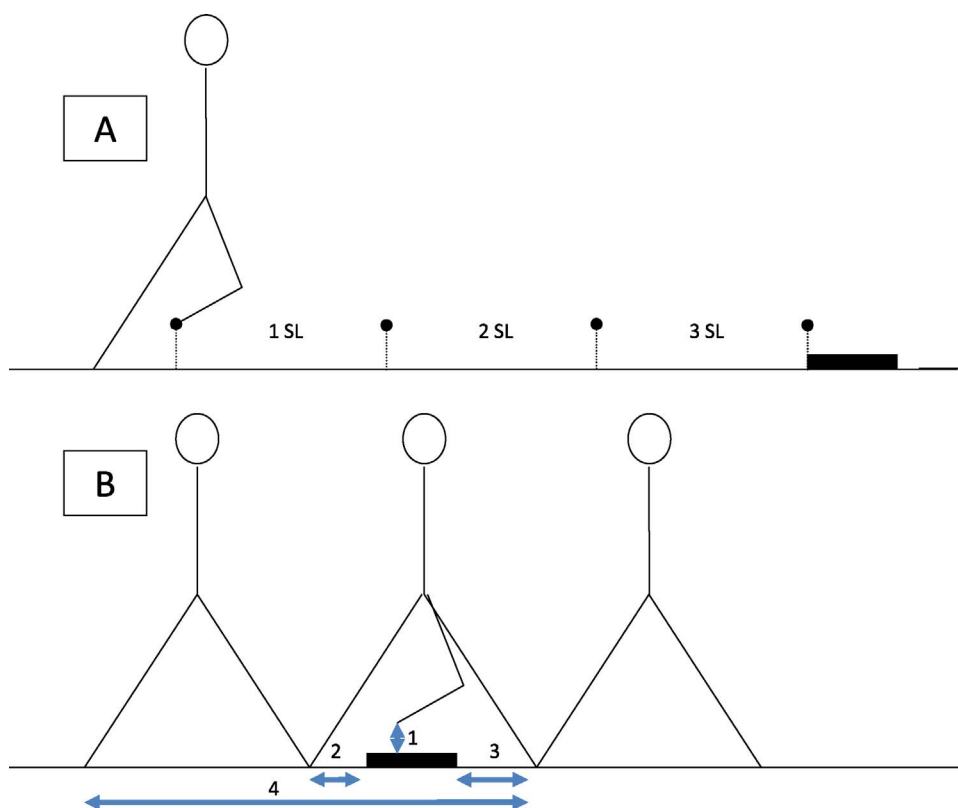
Fig. 1. (A) Time and place of the appearance of the obstacle. SL is stride length. (B) spatial crossing characteristics.

group differences for the dichotomous variables LLP and success rate were examined using a Chi square test. Normality of the continuous variables was examined using a Kolmogorov-Smirnov test. We used a mixed model ANOVA with group as between and obstacle length as within factors. If an interaction with group was found, independent samples *t*-tests were used to determine which condition(s) differed between groups.

3. Results

A group of twenty-nine stroke survivors derived from a larger cohort [15] participated in the obstacle crossing task. After a six-month follow up, twelve stroke survivors (41%) reported at least one fall, and were classified as fall prone stroke survivors (F). The remaining seventeen stroke survivors (59%) were classified as non-fall prone stroke survivors (NF). None of the reported falls were excluded due to the fall exclusion criteria. The participants in the fall prone group were significantly older and used a walking aid more often, see Table 1 for statistics. Due to missing marker data, we were not able to estimate center of mass position for all participants, therefore results regarding the MoS are based on twenty-four participants, including nine participants with prospective falls.

Table 1
Mean and SD and between group differences i demographic and stroke specific characteristics. Significant between group differences are printed in bold.

Demographic characteristics	NF-SS (17)	F-SS (12)	p-value
Age (years)	55.5 (12.3)	64.6 (8.2)	**0.03**
Height (cm)	171.8 (10)	169.9 (11)	0.64
Weight (kg)	90.2 (20)	76.9 (16)	0.07
Male (%)	50%	66%	0.39
Use walking aid (%)	25%	66%	**0.03**
Use of medication (%)	87%	83%	0.75

3.1. Reliability of crossing characteristics

Dichotomous crossing characteristics LLP and success rate were not reliable (Table 2). Test-retest reliability of pre- and post-obstacle distance was inadequate for the smaller obstacles but was adequate (0.65–0.78) for obstacles with a length of 21 cm or higher. Reliability of crossing step length, and crossing speed was inadequate with ICC values around 0.4. Test-retest reliability of toe clearance was around 0.7 across the obstacle lengths. Reliability of MoS in the ML direction ranged between 0.6 and 0.8, while reliability for MoS in FW direction was inadequate.

3.2. Differences between fallers and no fallers

Dichotomous crossing characteristics LLP and success rate were not different between groups (see Table 3 for percentages and Table 4 for p-values per obstacle length). No interaction effect with group or main effect of group was found for any of the crossing characteristics. Pre-obstacle-distance decreased and step length and FW MoS increased when obstacle length increased (main effect of obstacle length, Table 4).

4. Discussion

As virtual obstacle crossing has gained popularity in stroke rehabilitation for training and testing, and since falls occur during obstacle negotiation in daily life [3,4], we explored whether a virtual obstacle crossing task can function as a diagnostic tool for fall risk. Specifically, the main purpose of the present experiment was to determine test-retest reliability of obstacle crossing characteristics and differences between stroke survivors who prospectively experienced falls or no falls. Contrary to our expectations, the results indicated no differences between groups, neither for the dichotomous, nor for the

Table 2

Test-retest reliability for dichotomous and continuous obstacle crossing characteristics for all five obstacle lengths. LLP is leading limb preference, MoS is margins of stability, FW is forward, ML is medio-lateral.

Obstacle	7 cm obstacle	14 cm obstacle	21 cm obstacle	28 cm obstacle	35 cm obstacle
Crossing characteristics	Kappa	Kappa	Kappa	Kappa	Kappa
Success rate	0.32	0.51	0.81	0.51	0.31
LLP	0.40	0.17	0.26	0.51	0.24
Crossing characteristics	ICC (CI)	ICC (CI)	ICC (CI)	ICC (CI)	ICC (CI)
Pre obstacle distance	0.41 (0–0.71)	0.57 (0.24–0.79)	0.70 (0.41–0.86)	0.65 (0.33–0.84)	0.72 (0.42–0.87)
Post obstacle distance	0.39 (0–0.69)	0.48 (0.12–0.74)	0.67 (0.36–85)	0.79 (0.57–0.91)	0.78 (0.57–90)
Step length	0.39 (−0.01 to 0.69)	0.16 (−0.26 to 0.5)	0.28 (−0.15 to 0.62)	0.16 (−0.24 to 0.52)	0.36 (0–0.66)
Crossing speed	0.46 (0.06–0.73)	0.21 (−0.2 to 0.55)	0.26 (−0.1 to 0.6)	0.21 (0.01–0.54)	0.63 (0.3–0.82)
Toe clearance	0.74 (0.45–0.88)	0.71 (0.43–0.86)	0.74 (0.49–0.88)	0.62 (0.30–0.82)	0.76 (0.52–0.89)
MoS ML	0.59 (0.21–0.81)	0.80 (0.56–0.91)	0.63 (0.24–0.84)	0.62 (0.25–0.83)	0.66 (0.29–0.85)
MoS FW	0.45 (0.05–0.73)	0.14 (−0.25 to 0.52)	0.22 (−0.19 to 0.58)	0.26 (−0.22 to 0.62)	0.40 (−0.05 to 0.72)

more reliable continuous crossing characteristics. This is in contrast with results from an previous study which found that fall prone stroke survivors were more likely to fail an over ground obstacle crossing task [12]. Additionally, previous studies found a greater ML velocity of the CoM during over ground obstacle crossing in fallers than in non-fallers [5,7]. This greater velocity requires a greater deceleration after obstacle crossing, which may hamper safety. However, we found that despite this greater velocity, fall prone stroke survivors were equally able to regulate their MoS in ML direction compared to non-fallers. While stroke survivors generally compensate their increased ML trunk displacement by an increased step width compared to a general older population [26,27], these differences were not found between fallers and non fallers, neither during steady-state gait [Punt 2017B], nor during obstacle crossing tasks as step-width after obstacle was similar between both groups (17.4 cm versus 17.5 cm for non-fallers versus fallers).

Interestingly, test-retest reliability for pre and post obstacle distance improved when obstacle length increased from 21 cm onwards, and these ICC values are similar to earlier findings [28]. Furthermore, poor reliability of leading limb preference and success rate has also been reported previously [8]. Reliability of toe clearance was lower in our study as compared to a previous report [28], where ICCs were around 0.8. Previous studies assessed real obstacle crossing in over ground walking, we assessed crossing of virtual obstacles on a treadmill. There are several differences between virtual and actual obstacle crossing which have to be taken into account when interpreting the results. While over ground obstacle crossing of a real obstacle can actually result in a trip, which may result in some degree of fear, this is not the case when using a virtual obstacle. Another important limitation of a virtual obstacle is the absence of height of the obstacles. This latter difference may explain the limited test-retest reliability of toe clearance in our study. It may also be that obstacle crossing was relatively easy

Table 4

Chi square *p*-values per obstacle length for success rate and leading limb preference. Main and interaction effects for continuous crossing characteristics. Significant Values are printed in bold.

Obstacle length	7 cm	14 cm	21 cm	28 cm	35 cm	
Success rate (P-value)	0.87	0.22	0.26	0.12	0.12	
LLP (P-value)	0.46	0.64	0.18	0.30	0.49	
Main effects	Obstacle length		group		Interaction	
Crossing characteristic	F-value	P-value	F-value	P-value	F-value	P-value
Pre-obstacle-distance	29.2	**< 0.001**	0.19	0.66	0.97	0.41
Post-obstacle-distance	2.80	**0.04**	1.79	0.19	2.47	0.07
Step length	**16.3**	**< 0.001**	0.15	0.69	0.35	0.79
Crossing speed	0.95	0.42	0.99	0.33	1.87	0.14
Toe clearance	1.59	0.20	0.0	0.99	0.65	0.58
MoS ML	0.54	0.65	1.51	0.23	1.08	0.36
MoS FW	**3.47**	**0.03**	1.48	0.23	2.84	0.07

due to the absence of obstacle height. Such a relatively easy task may not perturb gait enough, so that participants maintain their regular gait pattern. To successfully overcome more challenging obstacles, participants are forced to optimize pre-obstacle-distance, which will limit the possibility of varying crossing characteristics. This may lead to smaller variation within participants, and thus more reliable crossing characteristics. Note that in our experiment, the obstacles with greater length resulted in more reliable crossing characteristics. Obviously, more reliable crossing characteristics can be more sensitive to differentiate between fallers and non-fallers, because true differences do not get buried in noise. Moreover, our results support this suggestion as we did find a nearly significant interaction between group and obstacle length on post-obstacle-distance (see Table 4, p = 0.07). We highly recommend future studies to carefully read these recommendations and

Table 3

Mean and standard deviation (SD) from continuous crossing characteristics for both groups. Success rate as percentage of successful crossings attempts per group for each LPO size. In addition Leading limb preference (LLP) as percentage of crossing attempts leading with the paretic leg per group for each LPO size. Significant differences for dichotomous crossing characteristics based on Chi Square statistics are printed in bold. NF is the none fall prone group. F is the fall prone group. cm is millimeter. Dis is distance.

Obstacle	7 cm obstacle		14 cm obstacle		21 cm obstacle		28 cm obstacle		35 cm obstacle	
Group	NF	F	NF	F	NF	F	NF	F	NF	F
Success rate (%)	50	50	62	41	68	50	68	41	68	41
LLP (%)	50	33	44	50	44	33	25	41	31	41
Crossing characteristic										
Pre-obstacle-dis (cm)	33 (14.4)	29.1 (13.7)	23.3 (14.2)	21.2 (9.1)	17.7 (6.7)	21.1 (14.2)	14.5 (7.7)	11.8 (10.6)	12.7 (6.3)	10.7 (9.1)
Post-obstacle-dis (cm)	−4 (7.2)	−2 (8.9)	4.5 (7.6)	3 (9)	5.1 (6.2)	−1 (12.9)	2.7 (6)	−3.0 (12.9)	1.4 (7.0)	−1.9 (11.5)
Step length (cm)	59.3 (10)	46.8 (15.2)	60.3 (7.7)	51.2 (14.3)	65.2 (12)	53.1 (17.1)	67.7 (8.2)	57.8 (15)	70.7 (9.6)	60.5 (13.4)
Crossing speed (cm/s)	63.4 (18.9)	63.7 (33.8)	72.7 (22.8)	59.5 (22.3)	76 (13.8)	60.7 (24.5)	70.2 (14.5)	69.1 (25.8)	71.7 (16)	66.6 (24.1)
Toe clearance (cm)	11.9 (4.1)	12.3 (4.3)	11.3 (4.3)	11.3 (2.9)	11.5 (3.9)	12.1 (3.9)	11 (3.5)	10.7 (2.4)	12 (3.7)	11.1 (3.1)
MoS ML (m)	0.19 (0.05)	0.20 (0.04)	0.19 (0.04)	0.22 (0.05)	0.18 (0.04)	0.21 (0.05)	0.19 (0.03)	0.20 (0.05)	0.19 (0.03)	0.20 (0.05)
MoS FW (m)	0.53 (0.07)	0.44 (0.09)	0.51 (0.04)	0.51 (0.11)	0.54 (0.05)	0.57 (0.11)	0.53 (0.04)	0.48 (0.10)	0.56 (0.05)	0.50 (0.07)

follow along as we still think that this paradigm can reveal relevant information for evaluation and diagnostic purposes during rehabilitation, especially because we are not the first to report large variance in obstacle crossing behavior [29].

In contrast to previous studies, we did not separately analyze obstacle crossing with the affected and unaffected limb as leading limb. During a pilot experiment, we discovered that not all stroke survivors were able to follow instructions on which limb should be leading during obstacle crossing. This may be related to constraints imposed by the treadmill, as this requires the participant to maintain gait speed in contrast to over ground walking. Although this may appear to be a disadvantage, it may more realistically reflect daily-life situations, where time to adapt may be limited and may not allow crossing an obstacle with the preferred limb. Furthermore, a previous study indicated that obstacle crossing characteristics between affected and unaffected limb appear to be small, and thus there may be no or very limited information to be obtained with respect to fall risk [28]. Yet, at present it remains unknown if a separation of paretic and non paretic limb on obstacle crossing characteristics will reveal other insights in regard to evaluation and diagnostic assessments in stroke survivors. A final comment on the obstacle crossing protocol is the possibility of cueing. Although between each light plane obstacle was approximately 15 s of general steady state walking the light plane obstacle could have functioned as cueing which may explain the slight increase in success rate in the non fall prone group.

Despite the fact that training with virtual obstacles holds promise as a few pilot studies did find improvements in the ability to adjust step placements [13,14], our findings suggest that caution may be needed regarding implementation of these interventions. More successful virtual obstacle avoidance or improved avoidance characteristics on the treadmill may not reflect reduced fall risk in daily life.

A limitation in our study design was that we explored test-retest reliability of crossing characteristics during a single visit rather than two separate visits. On average, participants improved their success rate by 20% during the second trial. Although this improvement was not significant, a learning effect may have affected our reliability results. Another limitation is that our study did not explore variability of pre-obstacle distance over multiple trials, a variable that was recently reported to discriminate older from younger adults [30]. Finally, our limited sample size might have not revealed small between group differences. However, for the purpose of fall prediction at an individual level, such small group differences are not meaningful.

In conclusion, obstacle crossing characteristics in chronic stroke survivors, as determined in our protocol, are neither suitable for evaluation of the ability to make step adjustments nor for the prediction of fall risk among stroke survivors, because test-retest reliability was poor and no differences in obstacle crossing characteristics were found between fallers and non-fallers. However, it is worth to explore reliability of crossing characteristics and their potential in discriminating fallers from non fallers in a set of more challenging obstacles, as more challenging obstacles may improve reliability and sensitivity of the crossing characteristics.

Conflict of interest

Acknowledgements

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