Constraints on perception of information from obstacles during foot clearance in people with chronic stroke

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Abstract

The aim of this study was to examine effects of different types of task constraints on coupling of perception and action in people with chronic stroke when crossing obstacles during a walking task. Ten participants with hemiplegic chronic stroke volunteered to walk over a static obstacle under two distinct task constraints: simple and dual task. Under simple task constraints, without specific instructions, participants walked at their preferred speed and crossed over an obstacle. Under dual task constraints the same individuals were required to subtract numbers whilst walking. Under both distinct task constraints, we examined emergent values of foot distance when clearing a static obstacle in both affected and unaffected legs, measured by a 3D motion tracking system. Principal Component Analysis was used to quantify task performance and discriminant analysis was used to compare gait performance between task constraints. Results suggested that patients, regardless of affected body side, demonstrated differences in perception of distance information from the obstacle, which constrained gait differences in initial swing, mid-swing and crossing phases. Further, dual task constraints, rather than hemiplegic body side, was a significant discriminator in patients' perceptions of distance and height information to the obstacle. These findings suggested how performance of additional cognitive tasks might constrain perception of information from an obstacle in people with chronic stroke during different phases of obstacle crossing, and thus may impair their adaptive ability to successfully manoeuvre around objects.

Keywords: gait, perception, cognitive task constraints, obstacle crossing, stroke.

Introduction

One of the most common problems in people with stroke is increased risk of falling (Wagner et al. 2009). Incidence of falls is a complex phenomenon and the ability of a person to use different compensatory mechanisms, underpinned by perception and action, is a key determinant of physical rehabilitative strategies (Rensink et al. 2009; Nyberg and Gustafson 1995). For example, a person's functional capacity to cope with key task constraints, such as surfaces, barriers and external objects, are important limiting factors that shape movement organisation (Sanchez-Caballero et al. 2016). An important aim of neuro-rehabilitation is to improve the capacity of patients to re-organise movement patterns with respect to contextual constraints that, in turn, will improve the adaptive mechanisms during ambulation.

The dynamic and multifactorial interaction between a patient and the surrounding environment can be conceptualised according to the constraint-led approach (Newell 1989) and the coupling of perception and action (Gibson 1979). From these points of view, an individual's actions are directly related to the perceived environment and the role of perception and action is to re-organise intentional behaviours during interactions with key environmental and task constraints. Therefore, emphasis on the complex interactions between an individual and a performance environment is important in the design of therapeutic exercises. Information for affordances from the environment guides the organisation of required actions (Withagen et al. 2012) to be utilised in a perceptual-motor landscape. Dysfunction of the integration of sensory-motor systems may lead to attentional deficits and thus constrain task performance in people with neurological disorders (House et al. 1990; Langhorne et al. 2000). This in turn, could affect the perception of information for affordances (e.g. obstacle physical properties, surface, etc.). There are different ways to assess the ability of a patient to adapt to constraints that emerge in a dynamic performance context. For example, walking in a challenging environment could include obstacle negotiation (stepping over a barrier) and simultaneously multi-tasking during problem solving (walking while engaged in planning). These could be framed by intentionality in the form of adopting specific safety margins when stepping over an obstacle and are typical task constraints used in studies of older adults and patients with neurological conditions in order to understand the nature of their adaptive capacities (Balasubramanian et al. 2014). Biomechanical and behavioural parameters are the most common variables studied to assess adaptations (Liao et al. 2014; Novak and Deshpande 2014; Lowrey et al. 2007; MacLellan et al. 2015; Yogev et al. 2005; Springer et al.

2006). During walking, a number of compensatory mechanisms have been reported in people with motor disorders when required to negotiate an obstacle (MacLellan et al. 2015). These include greater variation in central pressure placement in a medial-lateral direction (Novak and Deshpande 2014), reduced crossing step velocity, shorter landing distance, emergence of a narrow base of support (Lowrey et al. 2007), and a frontal plane strategy as a form of increased knee flexion, along with greater vertical hip elevation.

Intentionality and cognitive activity are undoubtedly involved in performing everyday actions and dual-tasking is a method for assessing their influence when organising two different tasks at the same time. These task constraints have been well studied in patients with neurological disorders, particularly as secondary tasks added to walking (Chisholm et al. 2014; Yang et al. 2007; Haggard et al. 2000; Plummer-D'Amato et al. 2012; Plummer-D'Amato et al. 2008; Manaf et al. 2015). These studies have demonstrated clearly the interference effects of dual-tasking on spatiotemporal gait parameters such as walking speed, step and stride duration, step and stride length, double-support time, and cadence. A few studies have examined the effect of dual task performance on variability of gait pattern. Two such studies suggested that variability in gait patterns may also depend on the phase of recovery, being greater in the earlier phases (Chisholm et al. 2014; Haggard et al. 2000). Kizony et al. (2010) reported adaptive gait speed changes in people with stroke during dual-task performance. By using a virtual functional environment for examining effects of dual tasks on gait patterns, they showed that stride duration variability was greater in stroke patients than in a healthy group, and that overall gait speed was increased in a dual-task condition without decrements in stability. Similar effects on gait speed were reported in another stroke population, but not in spatial parameters (Manaf et al. 2015). These results suggest that different gait strategies, including an increasing or decreasing gait speed, could be functionally adaptive behaviours for coping with increased constraints on cognition in dual task performance. In another study of people with hemiplegic stroke under dual-task performance constraints, Takatori et al. (2012) showed that obstacle crossing was accompanied by an increase in crossing performance time and an increased risk of heel-obstacle contact after crossing. However, not all studies have revealed significant effects from dual-task constraints on gait behaviour. For example, Smulders et al. (2012) reported that dual-task constraints did not affect crossing performance in people with stroke because they probably used a 'posture-first' strategy signifying that patients traded off greater stability when walking for poorer performance in the accompanying cognitive task.

A possible mechanism to explain dual-task constraint effects on gait performance relates to the mutual co-influence of the two tasks as a coupled dynamic system (Saltzman and Kelso 1987; Saltzman and Munhall 1992; Sternad et al. 1998). This theoretical explanation suggests that one task shares its functional attractive state with another task or that a re-organisation of task dynamics emerges resulting in a new single functional system (Neumann 1987) with new parameters. From this perspective, the main challenge for the motor system is to maintain a preferred attractor (stable) state among limbs or to utilise other solutions within the perceptual-motor landscape in order to adapt to the dual-task performance constraints. In fact, it is possible that participants require the emergence of a conditionally coupled system between the body and an obstacle to accommodate an action continuously (van Geert 1994). The functional adaptability of such a re-configured coupled system would rely on information from a participant's perceptual system to continuously regulate gait with information on relative distance and velocity to an object. Thus, a comparison of gait under simple and dual- task constraints during walking performance could yield data on how performance is predicated on the continuous, cyclic interaction of perception and action. This experimental design may provide valuable insights on how a disabled motor system might re-organize movement patterns in order to adapt to changing task demands.

The aim of this study was to examine the effects of dual-task performance constraints on the perception of candidate perceptual variables, such as relative distance to a target, providing insights on the adaptive mechanisms during obstacle crossing in people with chronic stroke. Unlike traditional methods to quantify movement patterns using compressed (aggregated) group data (e.g. average, SD, coefficient of variations), in this study we used principal component analysis which included all the data points from an entire time series (e.g. data from the whole gait cycle). This method has advantages over other reductionist methods in that we could track the effects of dual-task constraints on performance at different moments of the swing phase, allowing us to investigate sources of task variability in the swing sub-phases along a time series.

Methods

Participants

Ten people with chronic stroke (Age=57.8±11.4 yrs) were recruited from a hospital rehabilitation clinic to voluntarily participate in the study. All patients were able to consent themselves, were right side dominant and had hemiplegic gait patterns that affected postural balance and ambulation. Demographic and clinical information is presented in table 1. The ethics boards of Sheffield Hallam University and Noor Afshar hospital approved all stages

of the study. As a part of the selection process, all participants were assessed on motor ability (Motor Assessment Scale; MAS), balance (Timed Up and Go; TUG) and cognitive function (Mini-Mental Status Examination; MMSE). Inclusion criteria included the ability to walk (with or without assistive devices) independently for 6 minutes in a straight line; absence of orthopaedic problems or significant pains in the lower extremities, and weakness in the right or left sides of the body. Patients with poor visual depth perception, inability to control their posture or legs (MAS score <24), poor dynamic balance and walking ability (TUG >150s), and poor memory recall (MMSE <20) were excluded from the study.

-------------Insert Table 1 here---------------

Materials

The task was walking on a flat walkway (L: 270cm, W: 55cm) and turning at the end. For safety reasons, two adjustable handrails were placed on the right and left sides of the walkway and a therapist accompanied them during performance of the walking task. Each participant was required to walk up and down the line ten times and cross over a foam obstacle placed 195cm from the start line. The obstacle was a right-angled, foam triangle (L:55cm, W:8cm, H:8cm) with the hypotenuse side oriented towards the participants. A 3D motion analysis system was used to analyse movement regulation. The system used three digital high speed cameras (Casio Exlim EX F1, Japan), with a 6 megapixel resolution and 240 fps recording speed. Cameras were installed on the sides of the walkway (60 degrees from each other), 265cm from the walkway boundary at a height of 50cm from the floor.

Two reflective-adhesive markers were attached on the first and fifth metatarsal joints of both feet. The laboratory coordinate system was determined according to the walkway (X: length, Z: width and Y: height). The 3D motion data were analysed by Simi motion software (Simi Co, Germany). Raw data were smoothed using a Butterworth 2nd order low pass (dual-pass) filter at 6Hz frequency.

The stride cycle was defined for each leg separately. For the purpose of this study, leg swing time was calculated as the time from toe-off to heel-contact. It was also divided in two parts: (i) crossing time, the time from toe-off to obstacle crossing, and (ii), landing time, the time from obstacle crossing to heel-contact. For the purpose of this study only crossing time data were analysed. The candidate perceptual variables in this study were relative distance in X (horizontal) and Y (vertical) axes to the target. Relative distance was defined as the distance gap between each foot and the static obstacle in X and Y axes. Negative values indicated that the foot position was behind (X axis) and

under (Y axis) the obstacle. The resultant displacement trajectory during obstacle crossing was calculated by the Euclidean method:

$$d = \sqrt{(x_{n+1} - x_{n1})^2 + (y_{n+1} - y_{n1})^2}$$
Equation 1

Where n_1 is position data in a given point and n_{+1} is position data in next point at entire time series. Perceptual variables in the X axis represent perception of an obstacle's depth or continuous foot horizontal distance changes to the obstacle, and in the Y axis represents the perception of an obstacle's height or continuous foot vertical distance to the edge of the obstacle. The candidate perceptual variables distance$_{horizontal}$, distance$_{vertical}$ and foot trajectory are calculated through average and standard deviation scores. For the purpose of this analysis, only the organisation of stride parameters when clearing the obstacles was considered for analysis. A stride during obstacle clearance requires significant foot adjustments for unimpeded swing and a concomitant reduction in the risk of falls (Said et al., 2005). In addition, values of these variables were calculated in the affected and unaffected leg separately in the group of patients. Participants were able to select any leg as the leading leg to cross the obstacle when walking.

Procedures

Participants met a qualified physiotherapist individually for clinical assessments. MAS was used for assessing limb functions in different tasks. The MAS is a functional test for assessing performance of everyday movement tasks in patients with stroke (Carr, et al., 1985). It includes eight different movements such as supine to side lying, supine to sitting, balanced sitting, sit to stand, walking, upper arm function, hand movements and advanced hand activities. For each movement there are six different scales based on the difficulty of the task. Dynamic balance was assessed with the TUG test, a valid and reliable test for assessing balance and walking abilities (Shamay and Hui-Chan 2005). Participants sat on a chair, then stood up and walked a distance of 3 m and returned to the initial sitting position. The time taken to complete this movement was recorded in seconds. Each participant performed one trial after familiarisation with the procedures. The MMSE was used to assess memory and cognitive function in participants. It is a validated tool for screening cognitive function in patients with dementia and stroke (Bour et al. 2010). In addition, before the walking test, participants were asked to count backwards from 500 by subtracting 3 numbers each time, as required in the secondary task in this study (e.g. 500, 497, 494, etc.). The threshold for number or errors made sequentially by participants, inside 1 minute, was 3 errors.

Two types of constraints were assessed the in walking task: simple and dual-task constraints. Under the simple task constraints, participants were required to walk independently along the walkway and when they approached the obstacle they had to step over it without any collision. There were no pre-determined instructions provided regarding the specific task of obstacle crossing and participants could decide to use the affected or unaffected leg as the leading leg during performance. They were required to use both legs to cross over the obstacle to complete a walking trial. This method was chosen because it provided freedom in using perception and action processes during walking to simulate everyday life settings, reflecting how the emergence of a gait pattern is (re)shaped under task constraints in both affected and unaffected legs. This protocol was similar under both simple task and dual task constraints. The preferred speed during 20 trials was determined by each participant. Under the dual-task constraints, participants were also asked to count backward from 500, each time subtracting 3 digits, while walking. If the participant made more than five errors, the trial was terminated and a new trial was initiated after a short break. It is worth noting that, in this study, all participants completed the walking task successfully and the task protocol allowed us to observe how they solved this task problem, given their new system condition (one side of the body affected by stroke and the other unaffected). Half the patients experienced the simple task constraints first and the other half completed the dual-task condition first, before switching tasks.

Data analysis

Dependent variables in this study were foot displacement trajectories for perceived distance to the obstacle height and depth. Because of the variability in swing times between trials, within and between participants, a spline interpolation method was used to normalise raw data of a stride cycle. Variables were normalised from toe-off (0%) to crossing the obstacle (100%) for all trials. The average of value of trials was used as a mean score for each participant. Thus, normalised data points in each walking time series were 100 data points per dependent variable. Principal Component Analysis (PCA) was used to examine the nature of variability and similarity in a time series (e.g. swing phase). This method has been used frequently in previous gait analyses (Deluzio et al. 2014) as a way to explore the similarity between variables through reduction in the number of variables into components (factors). The advantage of PCA over other methods is that it can extract relevant information from all points in time of the action and classify them into related components based on common variance. This advantage allows it to capture all data points of a gait cycle, rather than reducing the data by averaging or selecting max/min values of a time series. PCA is not the only way to analyse an entire time series and there are other ways to analyse the gait cycle for this

purpose, such as Functional Data Analysis (Ramsay and Dalzell 1991) and Spatial Parameter Mapping (Pataky et al. 2013). Information about PCA is briefly described in this study and detailed information about using PCA could be found in Chau (2001) and Deluzio et al. (2014).

In this study for a comparison between task conditions and affected-unaffected limbs, all data of participants, under both simple and dual-task conditions, and for affected and unaffected legs, were used at the same time for each PCA-such that separate PCAs were performed for relative distance $_{horizontal}$, relative distance $_{vertical}$ and foot trajectory. In total 40 time series (for each participant there were 4 time series: affected limb-simple task, affected limb-dual task, unaffected limb -simple task, unaffected limb-dual task) were included in each PCA in each swing time points for each dependent variable. After factor extraction by orthogonal varimax rotation, the total variance was calculated from all components in swing time series. Then, Principal Component (PC) loads that represent the weight of correlation between each PC and a dependent variable (e.g. distance$_{horizontal}$) in each point of time series were calculated and a PC load was allocated to each participant for group comparisons. Saturation level for total variance is typically between 90% and 95% (Deluzio et al. 2014) and in this study it was set above 95%. In order to interpret the nature of PCs for each dependent variable, raw data of time series were reconstructed by a difference between high and low values of mean waveform ($\overline{X}$) ±1SD of the PC scores ($\vec{z}$) times the loading vector ($\vec{u}$) for each PC (Deluzio et al. 2014):

$$\vec{X} = \overline{X} \pm SD(\vec{z}) \times \vec{u} \hspace{3cm} \text{Equation 2}$$

In order to compare PCs between tasks and body sides a discriminant function analysis was used. This method, as a regression model, can predict group differences based on the weighting (strength) of predictors. In this study the predictors were PCs extracted from each perceptual variable over the entire swing time before crossing. Canonical correlation coefficients were calculated to test the nature of the relationship between all predictors and task constraints. A standardised discrimination coefficient was used to associate between each predictor and task constraints. In this study, Fisher's linear coefficient is used to transform the values into an interval ranging from -1 to 1 to facilitate the interpretation of group differences on PC loads. The assumptions of discriminant analysis in terms of normality, homogeneity of variance and independency of groups and dependent variables were checked before using.

Results

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In order to control the effect of learning in successive trials paired-t tests were used to assess performance changes in all variables and in both legs over time. Results showed a statistically, non-significant difference between the first and last trials in the affected and unaffected legs.

Principal Component Analysis

Results of the PCA are presented in Figures 1 to 3 for relative distance $_{horizontal}$, relative distance$_{vertical}$ and foot trajectory, respectively. In all perceptual variables, the swing phase could be determined by all 3 components. More specifically, 3 principal components (PC) could determine 97% of total variance in relative distance$_{horizontal}$ (PC1=69%, PC2=23%, PC3=5%), 96% of total variance in relative distance$_{vertical}$ (PC1=72%, PC2=20%, PC3=4%) and 98% of total variance in foot trajectory (PC1=71%, PC2=22%, PC3=5%). The suggestion was that PC1, PC2 and PC3 could determine variance of the relative distance to target at the initial swing phase, mid-swing phase and time before crossing, respectively. As shown in Figures 1, 2 and 3 (b), PC1 in all perceptual variables had the highest variance in the initial part of swing. On the other hand, PC1 represents the variability in the initial swing phase and its role is related to resistance against gravity. PC2 determines the variability in mid-swing phase that is mainly responsible for maintaining the postural balance. PC2 had the highest variance in mid-swing, as shown in Figures 1, 2 and 3 (d). PC3 determines the variability in the time before crossing and plays as an important role for foot adjustment before clearance. The highest variance in PC3 was at crossing time (see Figures 1, 2 and 3, f).

---------Insert Figure 1 here----------

---------Insert Figure 2 here----------

---------Insert Figure 3 here----------

Discriminant Analysis

Results of the discriminant function analysis (see Figure 4) also showed that the resultant principal components significantly affected by the type of task constraints, but not the affected side of the body. In fact, there were no significant effects of the affected and unaffected sides of the body on any principal components observed in this study, whereas the type of task constraint was a significant discriminator.

In addition, it seems that the cost of dual-tasking on the perception of information from the obstacle depended on the nature of the perceptual variable and the phase of swing. As shown in Figure 4, the best task discriminator on relative distance $_{horizontal}$ was PC3, whereas PC2 was a significant discriminator of type of task on relative distance$_{vertical}$ and foot trajectory.

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Discussion

The aim of this study was to examine the effect of dual-task constraints on gait patterns during obstacle crossing in people with chronic stroke. This method of simulation allows investigation of how people with stroke engage in everyday activities like walking, while undertaking another task. In this study perceptual variables, such as the distance to obstacle gap and height needed for foot clearance were measured in one stride during crossing. Results of the PCA showed that the nature of perception to crossing an obstacle depends on the phase of leg swing. For example, perception of distance to the obstacle in the swing phase is decomposed into three main components, closely associated with the sequence of swing sub-phases. We can term the three PCs as: *resistance against gravity* (PC1), *maintaining balance* (PC2) and *foot adjustment* (PC3) and associate them with a specific sub-phase of swing time. In fact, perception of information at the initiation of the swing phase is related to" *resistance against gravity"*. Perception of information at mid-swing is related to "*maintaining balance"* and before the crossing point is related to "*foot adjustment"*. This classification results from differences between high and low values of the mean waveform (see equation 2). This classification might be valid for foot trajectory, but for interpreting the principal components in both the relative distance both horizontally and vertically, the mechanism of foot adaptation is slightly different. On the other hand, a patients' capacity to cross an obstacle in a vertical direction is mainly constrained by their capacity to overcome gravitational forces by exploiting available reaction forces in the initial swing, maintaining balance in mid-swing and selecting a safe margin to cross an obstacle. Therefore, the swing components for height perception in pathologic gait play an important role for foot displacement at toe-off, keeping the flexed position in knee and hip (MacLellan et al. 2015) during single-leg support, and keeping a safe distance from the obstacle to avoid tripping (see Figure 2a for the slope of changes). The perception of depth when crossing an obstacle is interpreted as hesitation due to muscle weakness and spasticity in people with stroke.

The results of the current study suggest that perception of obstacle distance and accommodation of swing time to avoid collision and subsequent risk of tripping is a continuous process that uses a cyclic perception-action coupling. The nature of adaptations, as represented by sources of task variability, depends on the swing sub-phase. The important roles of obstacle perception are for aiding the swinging leg in meeting its movement requirements in different phases in terms of equilibrium and body adjustments. In fact, the swing phase is not a passive pendular

action. The moving limb tries to decrease the period of time spent in the single support phase by exploiting small muscular actions in order to reduce energy costs. This perception-action strategy will help the limb to select a velocity suitable for swing sub-phases (Whittlesey et al. 2000). This proposal could explain the nature of 3 different types of intra-task variability when approaching an obstacle. Variability in initiation of swing is necessary for forward displacement, but further changes in distance gap to the obstacle (see Figure 1a for the slope of changes) emerge because of hesitation when approaching an obstacle in mid-swing due to weakness in ankle dorsi-flexion and the need for a cautious strategy to avoid collision at crossing time.

Negotiating an obstacle requires adaptive ability for successful crossing (Balasubramanian et al. 2014). The adaptations in both affected and unaffected legs emerge through mechanical and perceptual changes (Novak and Deshpande 2014; Lowrey et al. 2007; MacLellan et al. 2015). For example, Novak and Deshpande (2014) reported that increased deviations in centre of pressure in a medial-lateral direction were a common adaptation strategy in stroke patients. Lowrey et al. (2007) emphasised the importance of crossing step velocity, using a shorter landing distance and a narrower base of support. MacLellan et al. (2015) showed that using a frontal plane strategy as a form of increased knee flexion, along with greater vertical hip elevation, were the main compensatory mechanisms in people with motor disorders when faced with an obstacle. In terms of perceptual adaptations, Paquette and Vallis (2010) proposed that older adults display a cautious strategy during obstacle crossing due to spending more time looking at the obstacle. Menuchi and Gobbi (2012) indicated that visual information from self-motion provided by the optic flow was crucial for estimating distance from and height of an obstacle to cross.

When considering the results of the discriminant analysis and linking them to the PCA findings, it seems that the effect of satisfying two task constraints during obstacle crossing is costly for patients in terms of foot adjustments before the crossing point and maintenance of balance during single-leg support. This interpretation of the data is supported by the discrimination coefficient values (see Figure 4)[1]. It seems that by adding a secondary task constraint, the perception of an obstacle's depth, significantly regulated foot adjustments, whereas perception of an obstacle's height influenced the maintenance of balance.

In the extant literature, there are some contradictory findings regarding the effect of dual-tasking on obstacle crossing performance. Takatori et al. (2012) showed that a cognitive dual-task performance constraint was accompanied by an increase in crossing performance time and a risk of heel-obstacle contact after crossing, whereas Smulders et al. (2012) reported that dual-task costs did not affect crossing performance in people with stroke. Our

findings support the former and show that walking over an obstacle under dual task constraints requires additional perceptual effort in some sub-phases of the swing. Differential effects of task constraints on balance control and foot adjustments could be explained by the nature of the coupled system that (re)emerged in interactions between the walking task (primary) and the cognitive task (secondary). Such a coupled system has to adapt to a key feature of the task constraint (e.g. an obstacle) to re-organise itself as a conditionally-coupled system (van Geert 1994). Actually, the continuous adaptations during dual-task performance are constrained at two levels: the organismic level and environmental level. This notion might explain why the leg swing, generally, is not a passive pendular movement that is controlled by gravity and its sub-phases need to be constrained by the organisation of active muscle action (Whittlesey et al. 2000). It may also explain why adding another task can increase the cost of walking over an obstacle at the mid-swing and crossing point more than at the initiation of the swing.

Dual-task interference has been implemented as a training method to increase balance and gait in people with stroke. While its effectiveness depends upon several training factors, it may prove a superior rehabilitative technique for falls prevention (Wang et al. 2015).

Our findings also failed to show any significant differences in effects of the affected and unaffected sides of the body on perception to obstacle during walking. Similarly, additional data analysis revealed no major effects depending on the side of dominance or which side led obstacle clearance.

The implication of this study for gait re-training is that dual-task constraints could be used to provide a therapeutic simulation that is useful for encouraging stroke patients to undertake adaptations in dynamic situations such as obstacle clearance. Due to a limitation of this study in terms of training duration (only short-term gait training) it was not possible to examine durability (long-term adaptations) and transferability (generalisation to other conditions) effects of the testing procedures. In addition, the role of cognitions and intentions in performing the obstacle crossing task, for example with regards to adopting different safety margins, were not formally quantified in this study. Ecological psychology proposes that, successful/unsuccessful experiences in this task continually re-shape intentionality as participants adopt individualised approaches to functionally adapt to the constraints of obstacle crossing. Lastly, we did not measure proprioceptive deficits in patients. This variable could have affected the distance to obstacle perception during walking in individual participants. Future studies could include proprioceptive deficits as a part of a clinical assessment in this task and seek qualitative information on perceptions of safety margins adopted in obstacle crossing task performance.

In conclusion, the findings of this study show that people with chronic stroke exhibit different types of perception of an obstacle before and during obstacle clearance. Constraining a motor task by adding a cognitive task could be a way to explore the perceptual-motor landscape in order to help patients find a functional strategy to cope with the contextual demands of everyday life. A conditionally coupled system that emerges when performing a cognitive task while walking is best reflected in continuous adaptations of the swinging leg, in terms of ability to resist against gravitational forces, maintaining balance, and spatially adjusting the foot. These kinds of movement variability emerged independently of the affected and dominant sides of the body.

Note

[1] Foot adjustments as a source of swing variability was attributed to PC3 in relative distance$_{horizental}$, PC2 in foot trajectory. All of them determined the variability at crossing point sub-phase. Maintaining the balance as another source of variability was attributed to PC2 in relative distance$_{vertical}$ that constraint the variability at single-leg support balance.

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