Published in final edited form as:

Gait Posture. 2018 February ; 60: 148–153. doi:10.1016/j.gaitpost.2017.11.025.

Sympathetic nervous system activity measured by skin conductance quantifies the challenge of walking adaptability tasks after stroke

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Abstract

Background—Walking adaptability tasks are challenging for people with motor impairments. The construct of perceived challenge is typically measured by self-report assessments, which are susceptible to subjective measurement error. The development of an objective physiologically-based measure of challenge may help to improve the ability to assess this important aspect of mobility function. The objective of this study to investigate the use of sympathetic nervous system (SNS) activity measured by skin conductance to gauge the physiological stress response to challenging walking adaptability tasks in people post-stroke.

Methods—Thirty adults with chronic post-stroke hemiparesis performed a battery of seventeen walking adaptability tasks. SNS activity was measured by skin conductance from the palmar surface of each hand. The primary outcome variable was the percent change in skin conductance level (SCL) between the baseline resting and walking phases of each task. Task difficulty was measured by performance speed and by physical therapist grading of performance. Walking

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Conflicts of Interest

There are no conflicts to report.

function and balance confidence were measured by preferred walking speed and the Activities Specific Balance Confidence Scale, respectively.

Results—There was a statistically significant negative association between SCL and task performance speed and between SCL and clinical score, indicating that tasks with greater SNS activity had slower performance speed and poorer clinical scores. SCL was significantly greater for low functioning participants versus high functioning participants, particularly during the most challenging walking adaptability tasks.

Conclusion—This study supports the use of SNS activity measured by skin conductance as a valuable approach for objectively quantifying the perceived challenge of walking adaptability tasks in people post-stroke.

Keywords

Walking; Mobility Limitation; Self Efficacy; Stroke; Galvanic Skin Response

Introduction

Walking adaptability is defined as the ability to modify walking behavior to meet the demands of the environment and the objectives of the task [1]. Successful ambulation in the home and community requires walking adaptability, such as when walking on different surfaces, over various terrains, and with differing ambient conditions. Individuals who have had a stroke often report that walking adaptability tasks are challenging [2]. The construct of perceived challenge is generally measured by self-report assessments including mobility self-efficacy, balance confidence, and fear of falling. A number of studies have shown that these measures of perceived challenge are linked to fall risk, engagement in community mobility, and performance of life role activities [2–7]. Even after accounting for physical capabilities, balance/falls self-efficacy has been shown to be independently linked to activity and participation [3, 4, 8–11]. Accordingly, assessing the perceived challenge of walking may serve an important role when evaluating mobility deficits and recovery after neurological injury.

A drawback of self-report assessments of perceived challenge is that they are susceptible to subjective measurement error and bias [12–15]. The development of an objective physiologically-based measure of challenge may help to improve the ability to assess this important aspect of mobility function. One promising objective approach is to measure task-related increases in sympathetic nervous system (SNS) activity. Increased SNS activity is a physiological stress response (i.e., the ‘fight or flight’ response) that occurs under conditions of heightened attention, state anxiety, cognitive loading, and/or physical exertion [16, 17]. SNS activity can be robustly measured by recording changes in skin conductance on the palmar surface of the hands [18, 19]. Several prior studies have demonstrated that skin conductance is increased during walking tasks with greater task demands and/or perceived challenges. For instance, studies requiring participants to step over obstacles or to dual-task while walking have reported marked increases in skin conductance during performance of those tasks [17, 20]. Task demands are not the only factors contributing to perceived challenge. Other factors that may contribute to perceived challenge are the individual’s skill

level, past experience with a particular task (positive or negative), the consequences of success/failure, and trait anxiety. Prior studies have shown an increase in perceived challenge in the absence of a change in physical demands of a task. Most notably, self-reported anxiety and skin conductance have been reported to increase when the perceived challenge is increased by asking participants to perform walking or postural tasks on an elevated platform [20, 21]. Although the physical demands of walking/balancing on an elevated platform are identical to when performed at ground level, the consequences of falling are potentially much more serious and likely account for the perceived challenge.

Based on the evidence discussed above, it is known that SNS activity is elevated by heightened task demand and under walking conditions that are perceived as challenging. However, it is not known whether the specific amplitude of this response closely corresponds to task difficulty, or if instead it is a generic response that is similar across many tasks. Furthermore, the potential influence of walking function and balance confidence on SNS activity during walking are not known. The objective of the present study is therefore to (1) quantify SNS activity level measured by skin conductance during a battery of walking adaptability tasks after stroke, (2) investigate the association between task difficulty and skin conductance, (3) assess the effect of functional status on the task-related increase of skin conductance, and (4) assess the effect of self-reported balance confidence on the task-related increase of skin conductance. The primary hypotheses are that greater task difficulty will be associated with higher skin conductance during walking, and that participants with better walking function and balance confidence will exhibit lower skin conductance during walking.

Methods

Participants

Inclusion criteria were prior occurrence of a single stroke primarily affecting motor function on one side of the body, no other major neurological diagnoses, no major visual impairment, able to walk at least 10 meters independently (the use of a cane or an orthotic device was acceptable), age 18 years or older, able to follow verbal commands, and willing to provide informed consent. All participants provided written informed consent as approved by the local university Institutional Review Board.

Walking adaptability tasks

Each participant performed the study procedures during a single visit to a research laboratory. All testing was led by a licensed physical therapist with research experience, with assistance from trained research staff. Participants performed a battery of walking adaptability tasks (Table 1) in random order. Two consecutive trials of each task were performed. The tasks were selected to represent a broad range of walking adaptability domains [1, 22].

Measurement of sympathetic nervous system activity with skin conductance

SNS activity was measured with skin conductance during each walking adaptability task using a commercially available portable data acquisition unit (Flexcomp Infinity, Thought

Technologies Ltd., QC, Canada). Data acquisition procedures were consistent with the recommendations of the 2012 committee report from the Society For Psychophysiological Research Ad Hoc Committee On Electrodermal Measures [23]. Adhesive electrodes (10mm Ag/AgCl recording surface) with conductive paste (0.5% saline in a neutral base) were placed on the palmar surface of the proximal phalanges of the index and ring fingers. Skin conductance signals were acquired separately from both hands for each participant, sampled at 32 Hz, and saved directly to an onboard flash memory card.

Analysis of skin conductance data was performed with Matlab version R2015a (The Mathworks, Natick MA) using Ledalab v3.4.7 [24] and custom analysis programs. The raw skin conductance data were downsampled to 8 Hz and visually examined for the presence of motion artifact, as indicated by high frequency fluctuations in the signal amplitude. The relatively few artifacts that were identified were replaced using linear interpolation. Continuous decomposition analysis [24] was performed to separate the tonic component (skin conductance level, or SCL) and the phasic component (skin conductance response, or SCR) of the signal using an amplitude criterion of 0.04 microsiemens (μS) for defining SCRs. The SCL signal was used for data analysis. For each walking task, three values were extracted from the SCL data. The first value was the minimum SCL that occurred during the baseline period of quiet standing that preceded each walking task. The other values were the maximum SCL occurring during each of the two consecutive trials of walking adaptability tasks. Exemplar data are shown in Figure 1. The primary outcome variable for SCL is the percent change in SCL (denoted by ΔSCL) between the resting and walking phases of each task:

$$\Delta\text{SCL} = [(\text{Walking Maximum} - \text{Resting Minimum}) / \text{Resting Minimum}] * 100.$$

Calculating the percent change from rest reduces the confounding influence of inter-individual differences in the absolute amplitude of skin conductance.

Estimating difficulty of walking adaptability tasks

The difficulty level of walking adaptability was estimated by calculating task performance speed and by assigning a clinical performance grade. Task performance speed was calculated by dividing the performance time by the length of the walking course. Task performance speed was calculated only for those tasks that were performed at a continuous preferred walking speed. The tasks that were omitted from the analysis were *Opening Door*, *Change Speed*, *Fast*, *Stairs*, and *Fast Obstacles*. The clinical grade was scored according to an ordinal scale, similar to other established instruments of mobility function. Scoring was based on a set of qualifying statements, as shown below, that could be used across the diverse set of walking tasks tested here.. If qualifiers were spread across scores, the lowest applicable score was assigned. Clinical grading was performed by a licensed physical therapist with advanced expertise and training in neurologic physical therapy.

Score 0 – Severe Impairment: Loss of balance and severe difficulty adapting to the task.

Score 1 – Moderate Impairment: Loss of balance and some/no difficulty adapting to the task OR no loss of balance but severe difficulty adapting to the task.

Score 2 – Mild Impairment: no loss of balance and some/no difficulty adapting to the task OR no loss of balance but appears unsafe.

Score 3 – No Impairment: no loss of balance, no difficulty adapting to the task, and appears safe.

Measures of walking function and balance confidence

Walking function for each individual was assessed with the 10-meter walk test. The test was performed at each individual's preferred overground speed and timed with a stop watch by a trained examiner. Balance confidence was measured with the Activities-specific Balance Confidence (ABC) Scale. The ABC Scale is a set of sixteen questions related to confidence in one's ability to perform common household and community mobility tasks [25]. Each question is scored on a scale of 0-100% based on the individual's self-reported confidence that he/she "would not lose balance or become unsteady" when performing the specified task. The total score is calculated as the average of the sixteen responses.

Statistics

Statistical analysis was conducted using JMP software (JMP® 11. Cary, NC: SAS Institute Inc.). Correlation analysis was used to make comparisons of the data acquired from the multiple trials of each task and multiple recording sites (i.e., paretic and nonparetic hands). Associations between SCL, task performance speed, and clinical grading were assessed with Pearson's product-moment correlation coefficient. For assessing the effects of walking function and balance confidence, the participants were divided into subgroups and compared statistically using two-tailed t-tests for differences in skin conductance outcomes.. Effect size (d) and probability (p) values are reported for subgroup analyses. The significance threshold for all analyses was set at $p < 0.05$.

Results

Participants

Thirty adults with chronic post-stroke hemiparesis participated in this study, including nineteen males and eleven females. The average age was 60.5 ± 13.3 years and the average time since stroke was 23.3 ± 16.7 months. The paretic side of the body was the right side for nineteen participants and left side for the remainder.

Comparison of multiple trials and multiple recording sites

For all participants and tasks pooled together, SCL from trials 1 and 2 were very strongly associated ($r=0.91$, $p < 0.0001$). Similarly, the pooled data showed a very strong association between paretic and nonparetic SCL ($r=0.80$, $p < 0.0001$). When each task was assessed separately, the associations between trials and between sides ranged from $r=0.54$ ($p=0.003$) to $r=0.97$ ($p < 0.0001$). Given these associations, the data from each trial and each side were averaged together for some analyses and figures.

Associations between SNS activity and task difficulty

Group mean values for SNS activity, task performance speed, and clinical grading for each walking task are shown in Table 2. Correlation analysis revealed a strong negative association between task performance speed and SCL recorded from both the non-paretic side (Figure 2A; $r = 0.76$, $p = 0.005$) and paretic side (Figure 2B; $r = 0.69$, $p = 0.01$), indicating that tasks with greater SNS activity had lower speed of performance. For task difficulty based on clinical grading, there was a moderate negative association between clinical score and SCL recorded from both the non-paretic side (Figure 2C; $r = 0.52$, $p = 0.03$) and paretic side (Figure 2D; $r = 0.44$, $p = 0.07$), supporting that tasks exhibiting greater SNS activity had poorer clinical scores.

Influence of walking function and balance confidence on SNS activity

To assess the effect of walking function and balance confidence on SNS activity, the sample was divided into subgroups of participants. For walking speed, the lower functioning subgroup were those who walked slower than 0.90 m/s, which was the closest round number to approximately evenly separate slower walkers from faster walkers (fourteen and sixteen participants, respectively). To summarize SCL, the tasks were collapsed into three categories: Lower SNS Activity, Moderate SNS Activity, and Higher SNS Activity, as reported in Table 2. SCL in the slower and faster walkers did not significantly differ for *Lower SNS Activity* tasks, ($d=0.08$, $p=0.42$), but was significantly different for *Moderate SNS Activity* tasks ($d=0.23$, $p=0.03$) and *Higher SNS Activity* tasks ($d=0.42$, $p<0.001$). Data are shown in Figure 3A. For the balance confidence subgroups, a score of 75 on the ABC scale was the closest round number to approximately evenly separate study participants with lower balance confidence from those with higher balance confidence (fourteen and sixteen participants, respectively). SCL for the balance confidence subgroups did not differ significantly for any of the task challenge levels (*Lower SNS Activity* tasks: $d=0.07$, $p=0.54$; *Moderate SNS Activity* tasks: $d=0.08$, $p=0.48$; *Higher SNS Activity* tasks: $d=0.17$, $p=0.17$). Data are shown in Figure 3B.

Discussion

The findings from this study provide preliminary support that SNS activity measured by skin conductance is a valuable approach for objectively quantifying the perceived challenge of walking adaptability tasks in people post-stroke. Table 2 lists the task in order of lowest to highest skin conductance values, and assigns each to a category of lower, moderate, and higher SNS activity. The tasks that were categorized as having “lower SNS activity” included, for example, walking in dim lighting, or on an outdoor sidewalk, or on a ramp. These tasks introduce only minor deviations in task demands relative to a typical controlled walking environment. In the “moderate SNS activity” category were tasks that required a more overt increase in task demands, including adaptation of the walking pattern or increased use of cognitive/attentional resources. These included such tasks as opening a door, stepping over an obstacle, or answering questions while walking. The “higher SNS activity” category of tasks generally involved postural adaptations or increased speed/temporal demands including walking on stairs, bending to pick up an object from the floor, or walking quickly over multiple obstacles. These types of tasks, particularly stairs, have

previously been noted as being challenging [26–28], and have been linked to avoidance of community mobility [29].

The first hypothesis was that SCL during walking adaptability tasks would be higher for task that were more difficult. Task difficulty was estimated in two ways: task performance speed and clinical grading. A negative association across tasks was found for both SCL versus task performance speed and for SCL versus clinical grade, indicating that tasks eliciting higher SCL also exhibit evidence of being more difficult to perform. Performing walking tasks with added task demands generally results in slower speed [30, 31]. For instance, a prior study of over 1200 participants confirmed that increasing task difficulty by layering on various additional task demands led to marked reductions in walking speed [32]. However, using task performance speed to estimate task difficulty is not ideal when the task instructions require a deviation from usual speed (i.e., usual versus fast pace) or that might involve momentary stopping (e.g., stairs or opening a door). For this reason we excluded some walking tasks from the correlation analysis (Table 2A and 2B) as described in the Results section. For clinical grading, it should be acknowledged that our scale has not been previously validated. It was necessary to create a new scale for this study because no existing assessment is designed to fit the wide variety of walking tasks that we conducted. Despite its shortcomings, clinical grading conducted by a physical therapist with expertise in neurological motor impairment can provide valuable insight into the difficulty that the participants experienced performing each task.

SNS activity measured by skin conductance was also hypothesized to be lower for people who have a faster preferred walking speed or who have higher self-reported balance confidence. The assumption in this case is that with poor physical function and/or poor balance confidence should exhibit a greater SNS response when faced with challenging walking tasks. SNS activity was found to be higher in the subgroup of participants with slower preferred walking speed (Figure 3A), especially for tasks that were categorized as *Higher SNS Activity*, as listed in Table 2. Slow walking speed is a global indicator of mobility deficits, disability, and loss of independence [33]. Accordingly, people who walk slowly under typical walking conditions are more likely to be challenged by walking adaptability tasks. This challenge may elicit feelings of anxiety and a fear of falling during task performance, which then manifests as heightened SNS activity. However, when the subgroups were defined based on the ABC score, there was no significant group difference in SNS activity during adaptability tasks (Figure 3B). This finding might indicate that self-reported balance confidence does not adequately reflect the physiological stress response of performing challenging walking tasks. Other factors may also explain this lack of agreement between SNS activity and self-reported confidence. For instance, the adaptability tasks in our protocol are different from the tasks included on the ABC Scale questionnaire, and the ABC Scale does not require participants to actually perform the tasks.

It is also important to acknowledge that stroke might lead to abnormal SNS responses in some people, and may vary based on the site, side, and severity of the lesion. This might have introduced variability to the study though the statistical strength of our findings support that the SNS response to walking adaptability tasks remains relatively robust even after a stroke. A weakness of measuring SNS activity is that it cannot distinguish between the

potential sources of task difficulty that contributed to the stress response. For example, relative to typical walking, stair climbing requires a combination of increased physical exertion, attention to leg movement, and potential fear of falling. The relative contributions of each of these factors to changes in the SCL value are not known. There is value in using multiple approaches to gauge mobility function, including physical assessments, self-report, and novel measures like the SNS activity approach used here. Accordingly, our approach should not be viewed as a replacement to any existing assessment but rather as a new tool to enhance measurement of mobility function and recovery.

Based on the results of this study, SNS activity measured by skin conductance may be a useful approach for objectively assessing the perceived challenge of walking adaptability tasks in people post-stroke. Future larger studies should further validate this approach, as well as examine whether SNS activity provides predictive ability over and above self-report assessments in accounting for falls, loss of participation, effectiveness of rehabilitation, and other important mobility outcomes.

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Figure 1. Skin conductance signal and analysis

This figure shows skin conductance recording during two consecutive trials of a walking adaptability task. The gray regions are rest periods of quiet standing, and the white regions are periods of walking. The unprocessed skin conductance signal is shown as a gray line. The tonic component of this signal, which is called the skin conductance level (SCL), is shown as a black line. The main outcome variable is the percent change in SCL (SCL) between the lowest SCL value during the initial resting period (white circle) and the highest SCL value of each walking trial (black circles).

Figure 2. Associations between TSCl and measures of task difficulty

The values graphed here are group means for TSCl, task speed (Panels A and B), and clinical grading score (Panels C and D). Results from paretic and non-paretic sides are shown separately. There was a significant negative association between task speed (i.e., walking speed for each task) and TSCl, and between clinical scores and TSCl. The task speed analysis included only the walking tasks performed at continuous preferred pace.

Figure 3. SNS activity in subgroups with higher and lower walking function and balance confidence

The seventeen walking adaptability tasks are collapsed into three categories as shown on Table 2: *Lower SNS Activity*, *Moderate SNS Activity*, and *Higher SNS Activity*. In Panel A, participants are divided into *Faster* and *Slower* groups based on a threshold of 0.90 m/s for the 10-meter walk test. The *Slower* group exhibited significantly higher SCL for the *Moderate SNS Activity* and *Higher SNS Activity* categories of walking tasks, consistent with greater perceived challenge of the tasks for lower functioning individuals. In Panel B, participants are divided into *Higher* and *Lower* groups based on a threshold of 75% for ABC score. The groups did not significantly differ for SCL within any of the categories of SNS activity.

Table 1

Task *	Domain †	Description
Fast	Temporal	Walk as fast as possible without running.
Change Speed	Temporal	Walk at normal pace. When the therapist says, “go,” walk as fast as possible. When the therapist says “slow,” walk as slow as possible.
Obstacle	Obstacle negotiation	Walk at normal pace while stepping over a 12.5cm obstacle.
Fast Obstacles	Obstacle negotiation; Temporal	Walk quickly while stepping over two obstacles (the first 5cm tall, and the second 30cm tall).
Up Ramp	Terrain demands	Walk up a wheelchair ramp (7.6% grade).
Down Ramp	Terrain demands	Walk down a wheelchair ramp (7.6% grade).
Foam	Terrain demands	Walk normally while approaching a foam cushion, step onto cushion then step off and continue walking.
Grass	Terrain demands; Ambient demands	Walk on grass.
Stairs	Terrain demands	Walk up 3 stairs and then walk back down.
Step Up and Over	Terrain demands	Walk towards a riser (20cm height), step up and over it, and continue walking.
Dim Lighting	Ambient demands	Walk while wearing sunglasses to replicate dim lighting.
Outside	Ambient demands	Walk outside on the sidewalk.
Answer Questions	Cognitive dual-tasking	Walk and answer a continuous series of brief questions, such as how to spell a short word backwards.
Carry Package	Motor dual-tasking	Walk at a normal pace while carrying a large, lightweight package that obstructs the view of the feet.
Look at Target	Postural transitions	Walk at normal pace. When the therapist says “look”, turn head sideways to look at a target placed at eye level, fixate on target while walking past, and finally look ahead when told to.
Opening Door	Postural transitions	Walk towards the door, open it, and walk through.
Pick up Object	Postural transitions; Motor dual-tasking	Walk forward and pick up a bean bag from the floor, then continue walking.

* All tasks were conducted over a distance of approximately 10 meters unless stated otherwise.

† Domains were previously defined by Balasubramanian et al. (2014) and by Patla and Shumway-Cook (1999).

Table 2

Group mean data by task

	Walking Task	SCL Paretic	SCL Non-paretic	Rank: Paretic	Rank: Non-paretic	Task Speed (m/s)	Clinical Score (0-3)
Lower SNS Activity	Dim Lighting	3.9 ± 7.6	3.5 ± 6.9	1	1	0.89 ± 0.32	2.63 ± 0.72
	Grass	6.1 ± 5.3	5.6 ± 12.1	3	3	0.91 ± 0.35	2.67 ± 0.61
	Up Ramp	6.2 ± 10.1	5.6 ± 7.1	4	2	0.87 ± 0.31	2.76 ± 0.44
	Carry Package	6.0 ± 7.2	6.1 ± 6.2	2	4	0.69 ± 0.30	1.79 ± 0.82
	Outside	6.3 ± 4.7	7.4 ± 6.6	5	5	0.85 ± 0.37	2.23 ± 0.90
	Down Ramp	7.8 ± 10.7	8.2 ± 11.8	6	6	0.84 ± 0.31	2.60 ± 0.67
Moderate SNS Activity	Foam	8.0 ± 10.6	8.7 ± 9.5	7	7	0.81 ± 0.31	1.87 ± 0.86
	Open Door	8.2 ± 8.5	10.5 ± 9.7	8	8	N/A	2.63 ± 0.56
	Obstacle	9.7 ± 9.3	11.3 ± 9.4	9	10	0.81 ± 0.32	1.73 ± 0.87
	Look at Target	10.5 ± 9.7	11.4 ± 9.3	11	11	0.71 ± 0.27	1.53 ± 0.63
	Answer Questions	10.5 ± 9.9	11.5 ± 10.2	12	13	N/A	2.63 ± 0.72
	Change Speed	11.4 ± 10.5	10.8 ± 9.8	15	9	0.78 ± 0.28	1.48 ± 0.57
Higher SNS Activity	Fast	10.8 ± 6.3	11.4 ± 8.8	13	12	N/A	2.84 ± 0.52
	Stairs	10.1 ± 9.5	12.9 ± 9.5	10	15	N/A	2.00 ± 0.83
	Fast Obstacles	11.8 ± 8.8	12.4 ± 11.6	16	14	N/A	1.93 ± 0.75
	Pick up Object	10.8 ± 8.2	13.5 ± 9.2	14	17	N/A	2.00 ± 0.59
	Step up and Over	14.2 ± 9.5	13.4 ± 11.1	17	16	0.70 ± 0.30	1.55 ± 0.63

All values are group mean ± standard deviation; SCL is the change in skin conductance level between the resting baseline period and walking period of each task; Categorization of Lower/Moderate/Higher SNS Activity tasks is based on group mean SCL from both paretic and non-paretic sides; Task Speed is N/A (not applicable) for tasks that did not involve continuous walking at typical speed.