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Prefrontal over-activation during walking in people with mobility deficits: interpretation and functional implications

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Abstract

Background—Control of walking by the central nervous system includes contributions from executive control mechanisms, such as attention and motor planning resources. Executive control of walking can be estimated objectively by recording prefrontal cortical activity using functional near infrared spectroscopy (fNIRS).

Objective—The primary objective of this study was to investigate group differences in prefrontal/executive control of walking among young adults, older adults, and adults post-stroke. Also assessed was the extent to which walking-related prefrontal activity fits existing cognitive frameworks of prefrontal over-activation.

Methods—Participants included 24 adults post-stroke with moderate to severe walking deficits, 15 older adults with mild gait deficits, and 9 young healthy adults. Executive control of walking was quantified as oxygenated hemoglobin concentration in the prefrontal cortex measured by fNIRS. Three walking tasks were assessed: typical walking, walking over obstacles, and walking while performing a verbal fluency task. Walking performance was assessed by walking speed.

Results—There was a significant effect of group for prefrontal activity ($p < 0.001$) during typical and obstacles walking tasks, with young adults exhibiting the lowest level of prefrontal activity,

followed by older adults, and then adults post-stroke. In young adults the prefrontal activity during typical walking was much lower than for the verbal fluency dual-task, suggesting substantial remaining prefrontal resources during typical walking. However, in older and post-stroke adults these remaining resources were significantly less ($p < 0.01$). Cumulatively, these results are consistent with prefrontal over-activation in the older and stroke groups, which was accompanied by a steeper drop in walking speed as task complexity increased to include obstacles ($p < 0.05$).

Conclusions—There is a heightened use of prefrontal/executive control resources in older adults and post-stroke adults during walking. The level of prefrontal resource utilization, particularly during complex walking tasks like obstacle crossing, may approach the ceiling of available resources for people who have walking deficits. Prior cognitive research has revealed that prefrontal over-activation combined with limited prefrontal resources can lead to poor cognitive performance. The present study suggests a similar situation influences walking performance. Future research should further investigate the extent to which prefrontal over-activation during walking is linked to adverse mobility outcomes.

Keywords

Near-Infrared Spectroscopy; Stroke; Elderly; Prefrontal Cortex; Ambulation

1. Introduction

Control of walking by the central nervous system can be broadly viewed as a balance between automaticity and executive locomotor control (Clark, 2015; Yogev-Seligmann, Hausdorff, & Giladi, 2008). Automaticity refers to coordinated control of walking by lower levels of the neuraxis, including the spinal cord, brainstem, and cerebellum (Clark, 2015; Nielsen, 2003). Executive locomotor control refers to the use of attentional resources and motor planning to control walking, which serves to supplement automaticity under complex walking conditions such as obstacle crossing (Clark, Rose, Ring, & Porges, 2014; Maidan, Nieuwhof, et al., 2016). Executive resources may also be recruited as a compensatory mechanism in an attempt to preserve performance when other systems contributing to locomotion are impaired (Caliandro et al., 2012; Clark, 2015).

Functional near infrared spectroscopy (fNIRS) has emerged in the literature as a powerful tool to investigate cortical executive contributions to the control of walking (Holtzer, Epstein, Mahoney, Izzetoglu, & Blumen, 2014; Perrey, 2014). Heightened metabolic activity in the prefrontal cortex measured by fNIRS has been shown to be closely linked to the increased demand for planning and attention during motor and cognitive tasks (Clark, Rose, et al., 2014; Herrmann, Walter, Ehrlis, & Fallgatter, 2006; Holtzer et al., 2011; Maidan, Nieuwhof, et al., 2016; Ohsugi, Ohgi, Shigemori, & Schneider, 2013; Okamoto et al., 2004). However, when studying how the brain controls task performance, a notable complication is that either higher or lower levels of brain activity might convey a benefit depending on the context of the task and person. It is therefore necessary to work within a strong evidence-based framework. One such framework that has emerged from the cognitive aging literature is the Compensation-Related Utilization of Neural Circuits Hypothesis, or CRUNCH (Reuter-Lorenz & Cappel, 2008). The most prominent feature of CRUNCH with regard to brain activity in older (or neurologically impaired) individuals is brain over-activity at

submaximal levels of task difficulty, which brings these individuals closer to the “ceiling” of brain activation resources. This brain over-activation is viewed as compensatory and beneficial to preserving task performance at lower task difficulty levels (Cabeza, Anderson, Locantore, & McIntosh, 2002; Reuter-Lorenz & Cappell, 2008). However, as the brain activity ceiling is approached, performance suffers due to a lack of available remaining resources.

The present study used fNIRS to assess prefrontal/executive control of typical walking and walking over obstacles in young adults, elderly adults, and adults post-stroke. The primary objective was to investigate possible group differences in prefrontal over-activation, and to assess the extent to which walking-related prefrontal activity fits the CRUNCH framework. The first hypothesis was that prefrontal activity would significantly differ among groups (stroke > elderly > young) for the typical and obstacles walking tasks, consistent with prefrontal over-activation in people with walking deficits. The second hypothesis was that the groups with walking deficits would have fewer remaining prefrontal resources during typical and obstacles walking (stroke < elderly < young), as calculated relative to a demanding dual-task walking condition. This would add additional evidence of prefrontal over-activation during walking. These primary hypotheses were also supplemented with additional analyses to assess behavioral implications of prefrontal over-activation and to explore the time course of prefrontal activity during walking task performance (earlier versus later time periods). This study seeks to provide important new evidence and interpretation of prefrontal brain activity during walking, in order to assist with future development of mechanistic and intervention studies to enhance walking function in impaired populations.

2. Methods

2.1 Participants

Participants included a convenience sample of twenty-four adults post-stroke with moderate to severe gait deficits, fifteen elderly adults with mild gait deficits, and nine young healthy adults (Table 1). Inclusion criteria for adults post-stroke were the occurrence of a single unilateral stroke in the previous four years, with accompanying hemiparesis (lower extremity Fugl-Meyer Motor Assessment (FMA) score < 30) and moderate to severe gait deficits including 10 meter walking speed less than 0.8 m/s. Inclusion criteria for elderly adults were age 65-85 years with mild gait deficits, as defined by 400-meter walking speed <1.1 m/s (no walking aids permitted) and agreement with the statement “I find it physically tiring to walk a quarter mile, or climb two flights of stairs or perform household chores.” Elderly and post-stroke volunteers were also required to have a Mini-Mental State Exam (MMSE) score of at least 21. Inclusion criteria for young adults were age 18-30 and self-report of being healthy with no conditions that affect mobility. Exclusion criteria for all groups included neurological diagnoses (with the exception of stroke for the post-stroke group), severe obesity (body mass index > 40), uncontrolled hypertension, myocardial infarction or heart surgery in the prior year, bone fracture or joint replacement in the prior six months, and diagnosis of a terminal illness. All participants provided written informed consent as

approved by the University of Florida Institutional Review Board and the North Florida/South Georgia Veterans Affairs Human Research Protection Program.

2.2 Protocol and Equipment

The experimental protocol took place during a single visit to a research laboratory located in an outpatient hospital setting. Participants performed multiple overground walking tasks in random order including *typical* walking (*typical* task), walking over obstacles (*obstacles* task), and walking with a verbal fluency task (*verbal* task). All tasks were performed at the individual's preferred speed. In order to encourage natural walking behavior, no special instructions were given regarding prioritization of task performance. For *obstacles*, the participant was instructed to step directly over six obstacles (shoes) evenly spaced along the walking path. For *verbal*, the participant walked while performing a verbal fluency task that required saying as many words as possible that began with a randomly selected letter (consonants excluding uncommon letters such as q, x, or z). To maintain a consistent level of cognitive effort over the duration of the task, a new letter was provided at the start of each lap.

Each task was performed during multiple consecutive laps on an 18-meter oval-shaped course. The floor surface was smooth tile with the exception of a 5.2 meter instrumented walkway (GAITRite, CIR Systems, Sparta NJ) that was used to acquire walking speed. Elderly and young participants walked five laps for a total walking distance of approximately 80 meters for each task. Post-stroke participants walked fewer laps (usually 2 or 3) in order to avoid fatigue and to maintain similar task time duration across groups as they had a slower walking speed. Prior to performing each task, the participants stood quietly at the start of the course to allow for a baseline measurement of prefrontal activity.

Prefrontal activity was measured by the change in oxygenated hemoglobin (O₂Hb) concentration of the left and right anterior prefrontal cortices (Brodmann Area 10) using a commercially available 2-channel fNIRS monitor (Niro 200NX, Hamamatsu Photonics, Japan). Each set of probes (i.e., left and right channels) was placed high on the forehead and sufficiently lateral from the midline to avoid the superior sagittal sinus (Al-Rawi & Kirkpatrick, 2006; Tisdall et al., 2009). Optode spacing was maintained at 3 centimeters by a rubber probe holder (S type A10963, Hamamatsu Photonics, Japan) that was secured firmly to the forehead with double-sided adhesive tape. The leads from each probe were secured to both the head and the back of the participant's shoulder with sufficient slack to allow for head movement/turning without pulling on the wires. The combination of adhesive on the forehead and securing of leads helps to reduce the occurrence of movement related artifact. A diode emitted infrared light at wavelengths of 735 nm and 810 nm. Changes in O₂Hb and deoxygenated hemoglobin (HHb) concentrations, which are driven primarily by synaptic activity, were estimated with the modified Beer-Lambert law. Data were sampled at 2 Hz and saved to a memory card in the data acquisition unit. O₂Hb concentration was used as the primary outcome measure because it is sensitive to walking-related changes in cortical activity (Harada, Miyai, Suzuki, & Kubota, 2009; Miyai et al., 2001).

2.3 Clinical assessments

Participants in the elderly and stroke groups were evaluated with clinical assessments, including preferred 10-meter walking speed, MMSE, Activities-Specific Balance Confidence (ABC) Scale, and lower extremity Fugl-Meyer Motor Assessment (FMA, stroke group only). The MMSE is a commonly used questionnaire to screen for cognitive impairment (Folstein, Folstein, & McHugh, 1975). The ABC Scale is a self-report questionnaire that asks participants how confident they feel about their balance ability if asked to perform various common tasks (Powell & Myers, 1995). The FMA is a clinical test of paretic limb impairment that grades reflex activity, movement coordination, and ability to perform joint movements in isolation and in multi-joint patterns (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975).

2.4 Data Analysis

Data analysis was conducted with custom programs created with Matlab version R2015a (The Mathworks, Natick, MA, USA). All data were inspected for signal artifact based on the recommendations of Cooper et al. (Cooper et al., 2012). Artifacts were identified automatically as an amplitude offset of the O₂Hb signal exceeding 1 μ M within a 2-second period, and/or a 2-second sliding window standard deviation of the O₂Hb signal that exceeded 3 standard deviations of the original full signal. All automatically detected artifacts were visually confirmed by a trained team member. The occurrence of artifacts was relatively infrequent (less than one per trial, on average) and were observed to be brief and transient in accordance with prior reports (Cooper et al., 2012). Artifacts were removed and replaced with linear interpolation to the surrounding data points. In order to standardize the analysis across participants and to minimize the potential influence of variable task duration on prefrontal oxygenation, only the initial 67 s of walking were analyzed for each task.

Prefrontal O₂Hb and HHb were measured during a 10-second period of quiet standing immediately preceding each walking task. These variables were also measured for both a 30-second “early” period (7 – 37 seconds after the initial walk command) and a 30-second “late” period (37 – 67 seconds after the initial walk command). The purpose of separating early and late periods was to assess possible differences in acute versus persistent prefrontal activity. The primary outcome measure for prefrontal activity during each task was the change in oxygenated hemoglobin concentration (O₂Hb) from the resting baseline period to each walking period (early and late).

2.5 Statistics

Statistical analysis was conducted with JMP Pro software version 11.0.0 (SAS, Cary, NC, USA). Group differences in participant characteristics (e.g., age, MMSE score) were tested with t-tests. To assess the effect of hemisphere and the hemisphere $\times$ task interaction in prefrontal O₂Hb, a two-way repeated measures ANOVA (Hemisphere, Task) was conducted separately for each group and each time period (early and late). In the young and elderly, left and right hemisphere were compared whereas injured versus non-injured hemisphere readings were compared in the stroke group. For the stroke group, an additional two-way repeated measures ANOVA (Stroke Side, Task) was run to determine if prefrontal O₂Hb in people with left-sided strokes differed from people with right sided strokes. Also

assessed was the potential effect of gender, as well as gender interactions with task or group using a three-way repeated measures ANOVA (Gender, Task, Group).

The primary analysis for this study was a three-way, repeated-measures ANOVA (Group, Task, Time Period), with tasks limited to the *typical* and *obstacles* conditions. For the first hypothesis, post hoc testing of the group effect was conducted with independent t-tests to assess differences between pairs of groups for each walking task. A separate exploratory subgroup analysis was also conducted with a two-factor ANOVA (Subgroup and Task) to compare higher and lower functioning stroke participants based on FMA scores. The late time period was used for this analysis because it reflects the persistent demands of each task.

For the second hypothesis, O_2Hb from the *typical* and *obstacles* tasks were compared to O_2Hb during the *verbal* task. Specifically, the remaining prefrontal resource measure was calculated for *typical* as [*verbal* O_2Hb - *typical* O_2Hb], and for *obstacles* as [*verbal* O_2Hb - *obstacles* O_2Hb]. The late time period was used for this analysis because it reflects the persistent demands of each task. These remaining resources were compared across groups with a one-way ANOVA, with post hoc analysis of pairs of groups conducted using independent t-tests.

To assess the effect of early versus late time period, post hoc analysis of the main effect of Time Period from the primary analysis was conducted using paired t-tests within each group and task.

The change in walking speed between *typical* and *obstacles* walking tasks (*typical* - *obstacles*) was calculated for each individual and compared between groups with two-sided t-tests.

3. Results

3.1 Participant characteristics and effect on prefrontal activity

Group differences in participant characteristics are presented in Table 1. Prefrontal O_2Hb did not show any significant effect of hemisphere, nor hemisphere $\times$ task interaction for any group ($p > 0.40$). Prefrontal O_2Hb was also not significantly different when comparing subgroups of people with left and right hemisphere strokes (side of stroke, and side $\times$ task interaction; $p > 0.22$). Based on these results, O_2Hb was averaged across hemispheres for each person for subsequent analyses. The effect of gender on O_2Hb was also not significant in the young, elderly, or post-stroke groups during the early time period ($p = 0.09$, $p = 0.58$, $p = 0.24$ respectively) or the later time period ($p = 0.60$, $p = 0.91$, $p = 0.31$ respectively).

3.2 Effect of group on prefrontal activity

Group mean O_2Hb by task and by time period are reported in Figure 1 and Table 2. Likewise, mean HHb is presented in Table 3. The first hypothesis tested whether prefrontal O_2Hb during the *typical* and *obstacles* tasks differed significantly among groups. The primary analysis found a significant main effect of Group ($p < 0.001$). For the early walking period, prefrontal O_2Hb in the elderly was greater than the young for *typical* ($p = 0.003$) and *obstacles* ($p = 0.052$). Likewise, there was significantly greater prefrontal O_2Hb in the

stroke group compared to the young for *typical* ($p=0.001$) and *obstacles* ($p=0.001$). The elderly and stroke groups did not differ significantly for either task during the early time period, though a trend for greater O_2Hb in the stroke group was observed for *obstacles* (effect size = 0.60 and $p=0.09$).

For the late time period, prefrontal activity in the elderly group was significantly greater than the young for *typical* ($p=0.009$), but not for *obstacles*. The stroke group had significantly greater prefrontal activity compared to young for *typical* ($p=0.002$) and *obstacles* ($p=0.001$). Between elderly and stroke, there was a significant difference during *obstacles* ($p=0.002$).

A secondary analysis was conducted to evaluate potential differences in prefrontal O_2Hb for stroke participants dichotomized into higher and lower functioning subgroups with the FMA (Figure 2). The FMA scores for each subgroup were 28.4 ± 2.4 and 22.3 ± 3.8 points, respectively. There was a significant main effect of subgroup on O_2Hb ($p=0.01$), with greater O_2Hb for the low FMA subgroup. The interaction between subgroup and task was non-significant ($p=0.60$). Preferred 10-meter walking speed did not differ between the higher and lower FMA subgroups (0.69 m/s versus 0.66 m/s, $p=0.77$).

3.3 Remaining prefrontal resources during walking

The second hypothesis was that walking impaired groups (older and post-stroke) would have fewer remaining prefrontal resources during *typical* and *obstacles* walking, as expressed relative to the *verbal* walking task. These remaining resources differed significantly, with a main effect of group for both the *typical* and *obstacles* tasks ($p=0.013$ and $p=0.003$, respectively). For *typical*, post hoc analysis revealed that remaining resources were significantly different between the young and the elderly groups (1.81 ± 0.91 versus $0.45 \pm 0.79 \mu\text{mol/L}$, $p=0.002$) and between the young and stroke groups (1.81 ± 0.91 versus $0.63 \pm 0.98 \mu\text{mol/L}$, $p=0.005$). Similarly for *obstacles*, post hoc analysis revealed that remaining resources differed significantly between the young and the elderly groups (1.43 ± 0.81 versus $0.37 \pm 0.84 \mu\text{mol/L}$, $p=0.009$) and between the young and stroke groups (1.43 ± 0.81 versus $0.26 \pm 0.81 \mu\text{mol/L}$, $p=0.008$). Remaining resources did not significantly differ for the elderly and stroke groups for either the *typical* or *obstacles* tasks.

To quantify performance decrements during the *obstacles* task, the percent change in walking speed was calculated relative to *typical* (Figure 3). Within each group there was a significant reduction in walking speed for the obstacles task. The young group slowed by $7.3 \pm 5.6\%$ ($p=0.013$), the older group by $14.7 \pm 8.5\%$ ($p<0.001$), and the stroke group by $35.5 \pm 27.4\%$ ($p<0.001$). This change in walking speed was significantly different for each pair of groups ($p<0.05$).

4. Discussion

The primary finding from this study is that older adults and people post-stroke exhibit over-activation of prefrontal cortex during typical and obstacles walking tasks. For Hypothesis 1, prefrontal activity quantified as O_2Hb was highest in the post-stroke group, followed by elderly adults, and lowest in young healthy adults. Also noteworthy is that the elderly and stroke groups generally exhibited the expected reduction in HHb (coinciding with

increasing O_2Hb) that is a signature of cortical activation with fNIRS assessment. The young group did not exhibit this reduced HHb during walking, which further supports the lack of prefrontal resource recruited during walking in this group. For the second hypothesis, the remaining prefrontal resources during *typical* (calculated as the difference in O_2Hb from the *verbal* task) was found to be significantly greater for the young healthy group compared to the elderly or stroke groups. This finding implies that young adults have more remaining prefrontal resources for attending to complex walking conditions and/or secondary cognitive tasks during walking. Furthermore, Figure 1 shows that in elderly and stroke groups, a substantial proportion of the limited prefrontal resources are consumed by the added demand of walking over obstacles. In particular, prefrontal activity is comparable between the *verbal* and *obstacles* tasks in the early period for the elderly group, and for both the early and late periods in the stroke group. These findings are consistent with and expand upon prior studies that have reported greater prefrontal activity during walking in impaired populations relative to healthy controls, including elderly adults (Chen et al., 2017; Mirelman et al., 2017), post-stroke ataxia (Mihara, Miyai, Hatakenaka, Kubota, & Sakoda, 2007), cerebellar ataxia (Caliandro et al., 2012), multiple sclerosis (Hernandez et al., 2016), and Parkinson's disease (Maidan, Nieuwhof, et al., 2016; Maidan, Rosenberg-Katz, et al., 2016).

The findings from Hypotheses 1 and 2, as well as the aforementioned related literature, demonstrate prefrontal over-activation in populations with walking impairments. However, the causes and interpretation of this over-activation remain unclear. In the cognitive literature, the concepts of “compensation” and “dedifferentiation” have been used to interpret heightened recruitment of brain resources. Compensation is viewed in a positive light, such that it counteracts neural deficits to preserve task performance (Cabeza et al., 2002). Dedifferentiation is viewed in a negative light, such that it indicates inefficient and non-specific neural processing that leads to impaired task performance (Cabeza et al., 2002; Li, 2002). These concepts may not be mutually exclusive. In the CRUNCH framework (Reuter-Lorenz & Cappell, 2008), inefficient neural processing can lead to increased recruitment of resources (i.e., over-activation) at submaximal levels of task difficulty. This over-activation can help to preserve task performance above what would be possible without over-activation (i.e., consistent with positive compensation). However, as the individual reaches the ceiling of available neural resources, task performance levels cannot be sustained and may drop precipitously (consistent with negative dedifferentiation). Before considering how these cognitive concepts and frameworks may interface with control of walking, it is also important to consider that walking also involves extensive control at other levels of the neuraxis. This includes spinal and brainstem circuitry that process sensory afferent signals, control locomotor pattern generation, and thereby produce the signature “automaticity” of healthy walking (Clark, 2015). Brain over-activation during walking may therefore not only indicate inefficient neural processes in the brain, but may also (or instead) reflect impairments below the level of the brain. This fact does not invalidate the potential utility of cognitive frameworks for understanding the brain's contribution to walking, but does require taking a more global view when interpreting the causes of altered brain activity across tasks or groups. For instance, our prior work showed that prefrontal brain activity was lower in older adults when wearing textured shoe insoles versus typical shoe insoles (Clark, Christou,

Ring, Williamson, & Doty, 2014). This finding suggests that prefrontal over-activation during walking may be due in part to age-related deficiencies in somatosensory afferent feedback to the central nervous system. This is just one example of many potential peripheral factors that could contribute to brain over-activation during walking (Clark, 2015).

A secondary analysis for this study was to assess whether subgroups of post-stroke participants with higher and lower motor impairment (based on FMA) differed in their use of prefrontal resources during walking. Prefrontal activity was significantly greater during the *typical* and *obstacles* tasks in the low FMA subgroup compared to the high FMA subgroup. This finding suggests that people with poorer voluntary control of limb movement have to dedicate more executive control resources to the task of walking. Interestingly, steady state walking speed did not differ for the high and low FMA subgroups. This might be an example of over-activation serving in the role of beneficial compensation, such that prefrontal over-activation helped to preserve walking speed in people with more severe motor impairment. A clinically important implication of this finding is that traditional walking tests (e.g., 10-meter walk speed) may not be fully effective for assessing walking function because performance deficits are masked by the recruitment of additional executive control resources. This increased reliance on executive control resources may place individuals at increased risk of falls (Fasano, Plotnik, Bove, & Berardelli, 2012; Herman, Mirelman, Giladi, Schweiger, & Hausdorff, 2010; Springer et al., 2006). The present result is also consistent with a prior study of older adults, which showed that individuals who exhibited a larger increase in prefrontal activity when performing complex walking tasks also showed fewer adverse changes in walking parameters (e.g., speed; step length variability) relative to typical walking (Clark, Rose, et al., 2014).

Another secondary analysis examined the decline in walking speed for *obstacles* relative to *typical*. There was a significant difference between groups, such that younger adults showed the least slowing, followed by older adults who exhibited moderate slowing, and adults post-stroke with the most slowing of walking speed. As task complexity increases, such is the case with *obstacles*, it is expected that performance will suffer to some extent in all groups. According to the CRUNCH framework, the ability to perform well as task complexity increases is dependent on the availability of neural resources. As discussed in the findings from Hypothesis 2, the young adults had considerable remaining resources available above what was required for the *obstacles* task. In contrast, the older group and particularly the post-stroke group had few remaining prefrontal resources. This is clearly visible as a plateau in prefrontal activity across tasks for the latter two groups in Figure 1, and may explain the steeper drop in walking speed during *obstacles*.

A novel aspect of this study is the assessment of both an early period (7-37 seconds after the start command) and late period (37-67 seconds after the start command) for each walking task. Nearly all prior studies have reported data from only a single time period that approximately corresponds to our early period. In all three groups, the *typical* and *obstacles* tasks showed a reduction in prefrontal activity from the early period to the late period. This finding indicates that the demand for executive resources diminishes somewhat during prolonged performance of walking. The reason for this finding is not fully clear, but may

due to familiarization with the task leading to reduced cognitive arousal and less executive resources dedicated to the task over the extended period of performance. However, the stroke group exhibited a significantly smaller reduction in prefrontal activity than did the young or elderly groups (Figure 1 and Table 2C). This finding suggests that the post-stroke group exhibits less familiarization with the task, perhaps due to their more severe motor control impairments, and therefore requires a more persistent demand for executive resources throughout the duration of the trial.

There are a number of methodological factors and other observations that warrant additional discussion. The three experimental groups differed in walking speed, which could potentially have an influence on task complexity (e.g., slower walking could make the task less complex). Despite slower walking speeds in elderly and post-stroke participants, these groups nevertheless showed heightened prefrontal activity. Group differences may have been even more pronounced, particularly for the *obstacles* task, if we had made walking relatively more challenging for the elderly and stroke participants by matching speed across groups, such as by using a treadmill. Furthermore, the literature is consistent in reporting that the speed of typical steady state walking does not significantly influence prefrontal cortical activity within group. (Harada et al., 2009; Meester, Al-Yahya, Dawes, Martin-Fagg, & Pinon, 2014; Metzger et al., 2017; Suzuki et al., 2004). For these reasons, differences in walking speed between groups does not diminish the present findings. An observation from our study that warrants discussion is that O2Hb often exhibits a negative value, meaning less prefrontal activity during walking than during baseline standing (although this was not the case for the stroke group). This finding is consistent with prior literature showing reduced or very small increases in prefrontal activity during walking relative to baseline (Clark, Rose, et al., 2014; Holtzer et al., 2015; Koenraadt, Roelofsen, Duysens, & Keijsers, 2014; Lin & Lin, 2016), which may be explained by a number of factors. It may be that higher O2Hb levels during baseline standing reflect heightened levels of attention and planning during task preparation, which then dissipates as automatic control processes at lower levels of the neuraxis take over during task performance (Clark, Rose, et al., 2014; Holtzer et al., 2015). Another possible factor is that O2Hb delivery to the prefrontal cortex is reduced as blood is diverted to other regions (e.g., motor and visual cortex) that are important for locomotion (Beurskens, Helmich, Rein, & Bock, 2014). A methodological weakness of this study is that only a small region of cortical activity was recorded. Other cerebral regions also contribute to executive control of walking (Maidan, Rosenberg-Katz, et al., 2016; Yogev-Seligmann et al., 2008) and should be assessed more thoroughly in future studies. Study outcomes might be influenced by stroke site, type, chronicity, and recovery. Future larger studies with sufficient statistical power will be needed to investigate potential interactions with prefrontal activity. Eliminating age differences between groups would also aid interpretation. Since elevated prefrontal cortical activity has been previously noted in older adults during cognitive tasks, it is possible that age may be responsible for the lack of significant difference in O2Hb between the elderly and stroke groups. The limited sample size of this study warrants caution when generalizing the results to a larger population.

5. Conclusions

There is a heightened use of executive control resources in elderly and post-stroke adults during walking, as measured by prefrontal cortical oxygenation. The level of prefrontal resource utilization, particularly during complex walking tasks like obstacle crossing, might approach the ceiling of available resources for compromised populations and thereby exacerbate walking deficits. The present findings fit within the CRUNCH framework, but further research is warranted to more definitively establish this assertion. Prior research indicates that excessive reliance on prefrontal/executive control of walking may pose a risk for adverse mobility outcomes including dyscoordination, tripping, and falling (Fasano et al., 2012; Herman et al., 2010; Springer et al., 2006). This raises questions about whether some individuals have inadequate resources for meeting the executive demands of walking safely in complex environments, including in the home and community (Balasubramanian, Clark, & Fox, 2014). Therefore, future research should further investigate the functional implications of prefrontal over-activation.

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Fig. 1. Group mean prefrontal activity by walking task

Prefrontal activity for each group, quantified by fNIRS as ΔO_2Hb , is shown for the *typical*, *obstacles*, and *verbal* walking tasks. Error bars indicated standard error of the mean. Black lines are from the early phase of each walking task and gray lines are from the late phase. Young, elderly, and stroke groups are shown in Panels A, B and C, respectively. Significant differences in elderly group relative to young are shown with *. Significant differences in the stroke group relative to elderly are shown with †. Significant differences in the stroke group relative to young are shown with ‡.

Figure 2. Stroke subgroup mean prefrontal Δ O₂Hb by walking task

Prefrontal activity for subgroups of post-stroke participants, quantified by fNIRS as Δ O₂Hb, is shown for the *typical* (squares) and *obstacles* (triangles) walking tasks. Error bars indicate standard error of the mean. Subgroups were defined based on lower extremity Fugl-Meyer Assessment score (FMA). The asterisk indicates a significant main effect of subgroup.

Figure 3. Change in walking speed for obstacles task

Percent change in walking speed relative to typical walking for the obstacles task. Error bars are standard deviation. All within-group and between-group comparisons of speed were statistically significant at $p < 0.05$.

Table 1

Participant Characteristics

	Sex	Age (years)	Walking speed (m/s)	MMSE Score (out of 30)	Fugl-Meyer LE Score (out of 34)	ABC Score (%)	Time Since Stroke (months)
Stroke Group	16M/8F	58.0±9.3 * [†]	0.51±0.27 * [†]	25.9±3.3	25.3±4.0	59.1±19.1 *	18.3±9.3
Elderly Group	7M/8F	77.2±5.6 [†]	1.07±0.16 [‡]	27.4±1.7	NA	83.0 ± 15.0	NA
Young Group	4M/5F	22.4±3.21	1.28±0.18	NA	NA	NA	NA

* different from elderly group at p<0.001;

[†] different from young group at p<.001;

[‡] different from young group at p<.05;

Abbreviations: M – male; F – female; Walking speed – 10-meter preferred walking speed; MMSE - Mini Mental State Exam; LE – lower extremity; ABC – Activities Specific Balance Confidence Scale; NA – not available/applicable

Table 2

Group and task comparisons of O2Hb. Statistical comparisons with moderate to large effects sizes with $p < 0.05$ are shown in bold font. Statistical comparisons with moderate to large effects sizes but with $p > 0.05$ are shown in bold italic font.

A. Early Walking Period			
<i>Group Means</i>		<i>Group Comparisons</i>	
Young	Elderly	Young vs. Elderly	Elderly vs. Stroke
Typical	-0.75 ± 0.81	0.10 ± 0.48	0.20 ± 0.58
Obstacles	-0.38 ± 1.12	0.36 ± 0.64	0.72 ± 0.59
Verbal	0.67 ± 1.16	0.51 ± 0.48	0.68 ± 0.98
B. Late Walking Period			
<i>Group Means</i>		<i>Group Comparisons</i>	
Young	Elderly	Young vs. Elderly	Elderly vs. Stroke
Typical	-1.23 ± 0.88	-0.43 ± 0.53	-0.03 ± 0.84
Obstacles	-0.85 ± 0.91	-0.34 ± 0.52	0.52 ± 0.90
Verbal	0.58 ± 0.83	0.02 ± 0.64	0.57 ± 1.19
C. Changes from Early to Late Period			
<i>Group Means</i>		<i>Group Comparisons</i>	
Young	Elderly	Young vs. Elderly	Elderly vs. Stroke
Typical	-0.48 ± 0.40	-0.53 ± 0.34	-0.24 ± 0.37
Obstacles	-0.47 ± 0.71	-0.70 ± 0.40	-0.18 ± 0.45
Verbal	-0.08 ± 0.44	-0.37 ± 0.34	-0.08 ± 0.45

Abbreviations: Typical – walking at usual preferred speed; Obstacles – walking over obstacles; Verbal – walking while performing a cognitive verbal fluency task.

Table 3

Group and task data for HHb

Early Walking Period			
	<i>Group Means</i>		
	Young	Elderly	Stroke
Typical	$0.21 \pm 0.21^*$	$-0.23 \pm 0.28^{\ddagger}$	$-0.17 \pm 0.24^{\ddagger}$
Obstacles	$0.25 \pm 0.35^*$	-0.11 ± 0.48	$-0.17 \pm 0.31^*$
Verbal	0.11 ± 0.33	$-0.25 \pm 0.38^*$	$-0.18 \pm 0.26^{\ddagger}$
Late Walking Period			
	<i>Group Means</i>		
	Young	Elderly	Stroke
Typical	$0.45 \pm 0.31^{\ddagger}$	-0.17 ± 0.38	-0.17 ± 0.41
Obstacles	$0.43 \pm 0.41^*$	0.005 ± 0.58	$-0.20 \pm 0.42^*$
Verbal	-0.05 ± 0.35	-0.16 ± 0.60	$-0.25 \pm 0.48^*$

*
p < 0.05; $\ddagger$
p < 0.01

HHb: change in deoxygenated hemoglobin between resting baseline and active walking periods