Human Movement Science 59 (2018) 46–55

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

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

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A R T I C L E I N F O

Keywords:
Near-infrared spectroscopy
Stroke
Elderly
Prefrontal cortex
Ambulation

A B S T R A C T

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

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https://doi.org/10.1016/j.humov.2018.03.010
Received 12 July 2017; Received in revised form 2 March 2018; Accepted 20 March 2018
0167-9457/ Published by Elsevier B.V.

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.

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 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 et al., 2014; Herrmann, Walter, Ehlis, & Fallgatter, 2006; Holtzer et al., 2011; Maidan 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 & Cappell, 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.

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

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.

* Different from elderly group at $p < .001$.

† Different from young group at $p < .001$.

‡ Different from young group at $p < .05$.