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Neural Correlates of Obstacle Negotiation in Older Adults: An fNIRS Study

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Abstract

Older adults are less efficient at avoiding obstacles compared to young adults, especially under attention-demanding conditions. Using functional near-infrared-spectroscopy (fNIRS), recent studies implicated the prefrontal cortex (PFC) in cognitive control of locomotion, notably under dual-task walking conditions. The neural substrates underlying Obstacle Negotiation (ON), however, have not been established. The current study determined the role of the PFC in ON during walking in seniors. Non-demented older adults ($n=90$; mean age= 78.1 ± 5.5 years; %female=51) underwent fNIRS acquisition to assess changes in hemodynamic activity in the PFC during normal-walk [NW] and walk-while-talk [WWT] conditions with and without obstacles. Obstacles were presented as red elliptical shapes using advanced laser technology, which resemble potholes. Linear mixed effects models were used to determine differences in oxygenated hemoglobin (HbO_2) levels among the four task conditions. The presence of slow gait, a risk factor for dementia and falls, served as a predictor hypothesized to moderate the effect of obstacles on PFC HbO_2 levels. PFC HbO_2 levels were significantly higher in WWT compared to NW ($p < 0.001$) irrespective of ON. Slow gait moderated the effect of obstacles on HbO_2 levels across task conditions. Specifically, compared to participants with normal gait, PFC HbO_2 levels were significantly increased in ON-NW relative to NW ($p = 0.017$) and ON-WWT relative to WWT ($p < 0.001$) among individuals with slow gait. Consistent with Compensatory Reallocation, ON required greater PFC involvement among individuals with mobility limitations.

Keywords

fNIRS; aging; mobility; dual-tasking

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1. Introduction

Obstacle Negotiation (ON) requires individuals to scan the environment and adapt their walking patterns to avoid obstacles such as potholes. Older adults are less efficient at avoiding obstacles compared to younger adults, especially under dual-task (1) or timed (2) conditions. Older adults utilize a slower, more conservative, and stabilizing strategy when crossing obstacles compared to young adults (2). Among older adults, unsuccessful navigation of obstacles is a major fall risk (3).

The functional neural basis for gait is not well-understood due to limitations of traditional neuroimaging techniques, which require participants to lie motionless in a supine position. Functional near-infrared spectroscopy (fNIRS) is a relatively new optical imaging method that is well-suited to assess changes in the hemodynamic response during ambulation (4, 5). There is robust evidence for higher order cognitive control, notably attention and executive functions, in locomotion (5). Recent fNIRS studies have found increased bilateral oxygenated hemoglobin (HbO₂) in the prefrontal cortex (PFC), an area associated with executive functions, during dual-task compared to single-task walking conditions (6, 7).

Knowledge of the neural bases of ON, however, is very sparse. Consistent with dual-task studies, attention and executive dysfunction are associated with poor ON in both healthy older adults and patients with Parkinson's disease (PD) (8, 9). To date, task-based functional correlates of ON have not been established. One study examined PFC involvement in ON in healthy older adults and PD patients using fNIRS and found increased oxygenation during ON relative to normal walk in individuals with PD (10).

Recent research has shown that seniors with mobility limitations, attributed to peripheral causes, demonstrated greater PFC activations during dual-task walking compared to controls (11). Peripheral impairments are related to slow gait (12), which is a robust and relatively easy measure to assess, making it advantageous for both clinical and research settings. Slow gait is common among older individuals and has been associated with incidence of adverse outcomes including cognitive decline, falls, disability, and mortality (13–15). The effect of slow gait on the functional brain correlates of ON has not been reported.

Using fNIRS, we examined changes in PFC HbO₂ levels during ON assessed under single- and dual-task gait conditions in non-demented older adults. We hypothesized that HbO₂ levels would increase during ON relative to unobstructed walking. Furthermore, the current study was specifically designed to determine whether, consistent with compensatory reallocation (16), individuals with slow gait, an established risk factor for cognitive and mobility declines, would demonstrate greater increases in HbO₂ levels during ON compared to unobstructed walking conditions relative to healthy controls.

2. Method

2.1. Participants

The sample consisted of community-dwelling older adults enrolled in “Central Control of Mobility in Aging” (CCMA) (6, 11). Participants received a telephone interview prior to

inclusion in the study, which consisted of a medical history questionnaire, a mobility questionnaire, and cognitive screens to rule out dementia (17). Participants were at least 65 years of age, and English-speaking. Exclusion criteria were severe auditory or visual disturbances, inability to walk the length of a room or climb stairs without assistance, any medical/neurological history that may interfere with testing (e.g., acute or terminal illness, progressive neurodegenerative diseases, major psychiatric illnesses, traumatic brain injury, seizures), and a diagnosis of dementia (diagnosed via case conferences once the participant is enrolled). If participants were able to ambulate with a cane, they were eligible to participate in the walking paradigm, and were asked to place their cane outside the sensor-area.

2.2. Procedures

After meeting eligibility criteria, participants were invited for two three-hour visits at the research clinic. Participants completed a battery of neuropsychological tests, a neurological examination, walking and balance protocols, and standardized questionnaires. CCMA participants are followed annually. The slow gait status cuts (Men: age below 75 years = 86.2 cm/sec, and age above 75 years = 76.4 cm/sec; Women: age below 75 years = 84.7 cm/sec, and age above 75 years = 66.1 cm/sec) are based on age and sex specific stratification for the CCMA study during one straight walk (6.1 m $\times$ 0.61 m (L $\times$ W)), assessed using GAITRite independently of the experimental ON protocol (18). The method and sample specific cut-scores were recently published (19). Written informed consents were obtained in-person and approved by the Institutional Review Board.

2.3. Experimental Protocol

Quantitative Gait Assessment

Zenometrics: A 4 $\times$ 14 foot Zeno electronic walkway was utilized to assess quantitative measures of gait (Zenometrics, LLC; Peekskill, NY). The quantitative gait measure used in the current study, stride velocity(cm/sec), was assessed using the ProtoKinetics Movement Analysis Software (PKMAS), based on the location and mathematical parameters between footfalls on the instrumented walkway. Split-half intra-class correlations (ICC) for stride velocity(cm/sec) in NW and WWT were greater than 0.95 revealing excellent internal consistency (7).

Four separate task conditions were used for the purpose of the current study: 1) Normal Pace Walk (NW); 2) Walk While Talk (WWT); 3) Obstacle Negotiation during Normal Walk (NW + ON); and 4) Obstacle Negotiation during Walk While Talk (WWT+ ON). In the NW condition, participants were asked to walk around the electronic walkway at their “normal pace” for three consecutive loops. In the WWT condition, participants were instructed to walk around the walkway at their normal pace while reciting alternate letters of the alphabet, and they were reminded to pay equal attention to both tasks (6). For the ON conditions, participants were required to follow the same task instruction as for the NW and WWT conditions, while simultaneously circulating to the left of red elliptical-shaped obstacles produced using laser technology specifically developed for this project (Mobilaser™ ZenoMetrics LLC, MAP/CIRInc.) (Figure 1). Mobilaser is time-linked to both the PKMAS and fNIRS systems. Participants were instructed to not walk over the obstacles. The

elliptical shape was developed to resemble a pothole, which increases the ecological validity to our task. The appearance of each obstacle was triggered by participants' footfalls. Hence, an obstacle was presented (in a randomized order) only after the gait mat recognized that a participant was entering a new straight walk. This also ensured a fixed distance (from step to obstacle) irrespective of walking speed. The obstacles could appear between 0–2 times within each straight walk, but in total participants had to negotiate 6 obstacles during the entire course of each ON walking condition. Participants saw only one obstacle at a time.

2.4. Functional Near Infrared Spectroscopy (fNIRS) System

We used the fNIR Imager 1000 (fNIR Devices, LLC, Potomac, MD) to assess changes in hemodynamic activity in the PFC. The fNIRS system consists of a flexible circuit board that was placed on the participants' forehead using standard procedures, a control box for data acquisition and a computer for data collection and storage. The system can collect data at a sampling rate of 2Hz. The fNIRS sensor consists of 4 LED light sources and 10 detectors, which cover the forehead using 16 channels, with a source-detector separation of 2.5 cm (6). The fNIRS is placed on the forehead so that the horizontal symmetry axis central (y-axis) coincides with symmetry axis of the head, (i.e. in between the eyes). On the vertical axis, the sensor is positioned right above the eyebrows in relation to the international 10–20 system so that FP1 and FP2 marker locations are approximately positioned on the bottom channel row level.

2.5. Preprocessing and Hemodynamic Signal Extraction

Data from each of the 16 fNIRS channels under the four walking experimental conditions were carefully inspected and removed if saturation or dark current conditions were identified. The raw intensity measurements were then low-pass filtered with a finite impulse response filter of cutoff frequency at 0.14Hz to eliminate possible respiration and heart rate signals and unwanted high frequency noise. This allowed for proper assessment and removal of artifact by identifying saturated and dark current measurements from signal levels. We additionally identified high frequency noise through visual inspection by an expert data analyst (M. Izzetoglu). HbO₂ signals were calculated using modified Beer-Lambert law (20) for each channel. HbO₂ values were used to characterize changes in the PFC since they are more reliable and sensitive to locomotion-related changes in cerebral blood flow (21). Relative changes in HbO₂ in each condition were obtained using the most proximal standing 10-second baseline, where participants were asked to remain still, fixate on the wall directly in front of them, and count silently in their head at a rate of about one number per second. For each condition the baseline levels were adjusted to a zero mean value. Hence, the changes in HbO₂ values in each condition were normalized to an individualized baseline. There were separate baselines prior to each trial. Mean HbO₂ levels for NW, WWT, NW +ON, and WWT+ON were calculated based on the 16 fNIRS channels as previously described (7, 11).

2.6. Covariates/Other Measures

Consistent with our previous studies (22), dichotomous rating (presence or absence) of physician diagnosed diabetes, chronic heart failure, arthritis, hypertension, depression,

stroke, Parkinson's disease, chronic obstructive lung disease, angina, and myocardial infarction was used to calculate a disease comorbidity summary score (range 0–10).

The Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) was used to assess overall cognitive function. The RBANS is a brief cognitive test that provides a global cognitive function score and is useful for the detection and characterization of dementia in older adults. The RBANS was used as a covariate due to literature suggesting a relationship between RBANS and neuroimaging (fMRI) outcomes (23). Additional covariates included age, education, and gender. Fear of falling was also assessed using a single question with a dichotomous rating ("yes" or "no"): "generally speaking, do you have a fear of falling."

2.7. Statistical Methods

Separate linear mixed effects models (LMEMs), each adjusted for age, gender, education, disease comorbidity (GHS), and RBANS total score, were used to examine the main effects of task on gait velocity and HbO₂ levels. Task conditions served as repeated measures variables. To avoid issues of multiple comparisons, we used one overall HbO₂ measure per walking task condition. However, in the context of the mixed effects models, we used information from all 16 channels taking into account their correlations and variable HbO₂ levels. The following four pre-specified contrasts were examined in the context of the LMEMs to directly evaluate the study predictions: a) NW vs. WWT; b) NW vs. NW + ON; c) WWT vs. WWT + ON; d) NW + ON vs. WWT + ON. The moderating effects of slow gait on these four pre-specified contrasts were examined via two-way interactions of slow gait status $\times$ task condition. All statistical analyses were run using IBM's Statistical Package for the Social Sciences (SPSS), Version 20.0 (Corp., 2011).

3. Results

Non-demented CCMA participants ($n=90$; mean age in years= 78 ± 15.5 ; %female=51) were included in the current study. The low mean disease comorbidity score ($GHS=0.7\pm0.9$) confirmed the relatively healthy nature of the sample. The mean RBANS Total Scale Index score (93.5 ± 12.8) was indicative of average cognitive ability overall. There were no observed differences in fear of falling between the slow gait (8 out of 26; 31%) and normal gait (17 out of 64; 27%) groups ($\chi^2(2) = 0.933$, $p = 0.627$). See Table 1 for sample characteristics.

3.1. Effects of dual-tasking and ON on gait velocity (see Table 1 for mean gait velocity for each task)

3.1.1. Dual vs. Single Task—Gait velocity in WWT was significantly reduced compared to NW during both unobstructed (estimate = -7.96 ; 95%CI = -9.40 to -6.52 ; $p < 0.001$) and obstructed gait conditions (estimate = -6.77 ; 95%CI = -8.07 to -5.46 ; $p < 0.001$ (Table 2, Panel A).

3.1.2. Obstructed vs. Unobstructed Walking—For the single task, gait velocity in ON-NW was significantly reduced compared to NW (estimate = -5.87 ; 95%CI = -6.88 to

−4.86; $p < 0.001$). For the dual task, ON-WWT was significantly lowered compared to WWT (estimate = −4.68; 95%CI = −5.62 to −3.73; $p < 0.001$ (Table 2, Panel A).

3.1.3. Moderation effect of slow gait on Obstructed vs. Unobstructed walking

—Slow gait status attenuated the decrease in gait velocity in ON-NW compared to NW (interaction of slow gait $\times$ task estimate = 4.50; 95%CI = 3.33 to 5.68; $p < 0.001$), and in ON-WWT compared to WWT (interaction of slow gait $\times$ task estimate = 2.32; 95%CI = 1.10 to 3.55; $p < 0.001$) for individuals with slow gait, compared to their normal gait counterparts (Table 2, Panel A and Figure 2, Panel A).

3.2. Effects of dual-tasking and ON on PFC HbO₂ levels (see Table 1 for mean HbO₂ levels for each task)

3.2.1. Dual Task vs. Single Task—Consistent with previous findings overall HbO₂ levels were significantly higher in WWT compared to NW in both unobstructed (WWT vs. NW; estimate = 0.79; 95%CI = 0.67 to 0.90; $p < 0.001$) and obstructed gait conditions (ON-WWT vs. ON-NW; estimate = 0.89; 95%CI = 0.78 to 1.01; $p < 0.001$) (Table 2, Panel B).

3.2.2. Moderation effect of slow gait on HbO₂ levels in Obstructed vs. Unobstructed walking—Slow gait status moderated the increase in HbO₂ levels in ON-NW compared to NW (interaction of slow gait $\times$ task estimate = 0.31; 95%CI = 0.06 to 0.57; $p = 0.017$), and in ON-WWT compared to WWT (interaction of slow gait $\times$ task estimate = 0.60; 95%CI = 0.34 to 0.85; $p < 0.001$). Greater increases in HbO₂ levels obstructed vs. unobstructed walking conditions were observed among individuals with slow gait compared to participants with normal gait (Table 2, Panel B and Figure 2, Panel B).

4. Discussion

Consistent with recent studies (6, 7), we found that PFC oxygenation levels were significantly higher in WWT compared to NW conditions, irrespective of the presence or absence of obstacles. Furthermore, confirming the study hypothesis, slow gait moderated the effect of obstacles on oxygenation levels across task conditions. Specifically, compared to individuals with normal gait, PFC oxygenation levels were significantly increased in ON-NW relative to NW, and in ON-WWT relative to WWT, among individuals with slow gait (see Figure 2, Panel B for visual depiction). For individuals with slow gait, ON may have presented a greater challenge requiring increased PFC recruitment to support the task demands. These results are consistent with a previous study, reporting that PFC HbO₂ levels were increased during ON relative to normal walk in individuals with PD (10). Motor imagery studies have also found that PD patients appear to require additional visuospatial and attention resources, relative to healthy adults (24, 25). An alternative explanation is that individuals with slow gait may attend to the obstacles more due to a greater fear of falling. However, fear of falls frequency did not vary as a function of slow gait.

The effect of obstacles on the change in PFC HbO₂ levels during walking is notable in light of the behavioral findings. As expected, gait velocity was significantly slower as a function of dual-task interference and the presence of ON. Our results support previous findings that older adults approach obstacles more slowly and conservatively, utilizing a more stabilizing

approach, particularly when they are required to divide their attention (1, 2). In addition, we found that individuals with slow gait manifested smaller obstacle-related task costs (differences between ON-NW and NW velocities and between ON-WWT and WWT velocities) compared to individuals with normal gait. This finding may be attributed to the fact that individuals with slow gait already demonstrated much slower walking in the unobstructed conditions compared to older adults with normal gait. Alternatively, the increased utilization of cognitive resources, operationalized using PFC HbO₂ levels, among individuals with slow gait may have contributed to their reduced gait speed costs compared to participants with normal gait. An additional study found that PFC activity was elevated during complex walking tasks relative to a control task, which the authors posited to reflect preserved quality of gait during obstacle negotiation tasks (26).

“Compensatory reallocation” and “neural inefficiency” are two hypotheses providing a conceptual framework for our findings. Compensatory reallocation (16) suggests that older adults demonstrate bilateral activations in the PFC in cognitively demanding tasks compared to more structurally circumscribed and unilateral activations in young adults. According to this model the bilateral increase in brain activation in the PFC has a compensatory function among older adults that is expected to enhance cognitive performance. Given that relative to individuals with normal gait, those with slow gait had smaller ON-related task costs in performance (i.e., velocity) and greater PFC activation, our results appear to provide an explanation that is consistent with the compensatory reallocation hypothesis. On the other hand, neural inefficiency (27) posits that due to age-related changes in structure and function, the brain does not efficiently allocate resources to support cognitive task demands. According to this scenario, greater brain activation levels are associated with equivalent or worse behavioral performance. Since the slow gait group had slower velocities across all task conditions compared to the normal control group, it is impossible to rule out the interpretation that individuals with slow gait may have also exhibited an overall inefficient brain responses during ambulation.

Study limitations

Given the relatively healthy nature of the CCMA sample, the generalizability of our findings to populations with cognitive and motoric impairments should be examined. Though our study used PFC oxygenation to assess change in utilization of cognitive resources, it is important to note that attention is a multidimensional concept. Besides the PFC, other cortical and subcortical areas are implicated in different aspects of attention (28). Therefore, the involvement of other brain regions in walking during ON was not captured by our fNIRS system. Nevertheless, the PFC is vital in the top-down control of attention. Furthermore, oxygenated hemoglobin was solely examined because it is more reliable and more sensitive to locomotion-related oxygenation changes compared to de-oxygenated hemoglobin (21). Future studies should investigate whether inclusion of deoxygenated hemoglobin would yield a different pattern of results.

5. Conclusion

Individuals with mobility limitations utilized more cognitive resources when navigating around obstacles. Such utilization of cognitive resources, whether compensatory or inefficient, may put individuals with gait limitations at greater risk for falling and other adverse outcomes.

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Highlights

- We examined brain activity in prefrontal cortex (PFC) in 90 healthy older adults.
- PFC oxygenation was higher in walk while talk (WWT) compared to normal walk (NW).
- Slow gait moderated effect of ON on PFC oxygenation.
- PFC oxygenation was higher in ON during NW and WWT among people with slow gait.
- Overall, ON required greater PFC involvement in those with mobility limitations.

Figure 1. Picture of Obstacle Negotiation Experimental Setup

Note. The picture displays all possible positions of the laser obstacles, which are ellipses with a length of 13.5' and a width of 9.75.

Figure 2. Average levels of gait velocity (panel A) and HbO₂ (panel B) by task and by slow gait status as moderator

Note. (A) Gait velocity is the dependent measure and depicted on the vertical axis, and (B) HbO₂ is the dependent measure and depicted on the vertical axis. NW: Normal Walk; WWT: Walk While Talk; ON-NW: Obstacle Negotiation – Normal Walk; ON-WWT: Obstacle Negotiation – Walk While Talk; Error bars = mean±SEM.

Table 1Summary of sample characteristics, gait velocity, and HbO₂ levels per task

	Total sample	Normal Gait	Slow Gait
Participants (n)	90	64	26
Women: number (%)	46 (51%)	36 (56.3%)	10 (38.5%)
Fear of Falling	25 (28%)	17 (27%)	8 (31%)
	<i>Mean (SD)</i>	<i>Mean (SD)</i>	<i>Mean (SD)</i>
Age years	78.01 (5.49)	78.31 (5.88)	77.58 (4.45)
Education years	14.86 (2.96)	15.00 (2.93)	14.50 (3.04)
Disease comorbidity index	0.70 (0.92)	0.67 (0.89)	0.77 (0.99)
RBANS standard index score	93.45 (12.77)	95.68 (12.55)	88.04 (11.83)
Gait velocity NW (cm/s)	62.60 (13.04)	66.10 (11.72)	53.99 (12.11)
Gait velocity WWT (cm/s)	54.68 (13.46)	58.18 (12.69)	46.07 (11.27)
Gait velocity ON-NW (cm/s)	56.67 (11.71)	58.84 (10.09)	51.31 (13.55)
Gait velocity ON-WWT (cm/s)	49.94 (12.00)	52.75 (11.15)	43.03 (11.20)
HbO ₂ levels NW	0.30 (1.21)	0.32 (1.04)	0.24 (1.55)
HbO ₂ levels WWT	1.08 (1.51)	1.10 (1.25)	1.04 (1.99)
HbO ₂ levels ON-NW	0.19 (1.35)	0.13 (1.28)	0.35 (1.50)
HbO ₂ levels ON-WWT	1.08 (1.57)	0.93 (1.35)	1.45 (2.00)

Note. SD: standard deviation; GHS: Global Health Score (range 0–10) obtained from dichotomous rating (presence or absence) of diabetes, chronic heart failure, arthritis, hypertension, depression, stroke, Parkinson's disease, chronic obstructive pulmonary disease, angina, and myocardial infarction; RBANS: Repeatable Battery for the Assessment of Neuropsychological Status; NW: Normal Walk; WWT: Walk While Talk; ON-NW: Obstacle Negotiation – Normal Walk; ON-WWT: Obstacle Negotiation – Walk While Talk.

Table 2

Linear mixed effect models with task as the four-level within person repeated measure (NW, WWT, ON-NW, ON-WWT), slow gait status as moderator, and gait velocity (panel A) and HbO₂ levels (panel B) as the dependent measures

Variable	Estimate	95%CI	t	P
(A) Task effects (total sample)				
WWT vs. NW	-7.96	-9.40 to -6.52	-10.94	<0.001
ON-WWT vs. ON-NW	-6.77	-8.07 to -5.46	-10.25	<0.001
ON-NW vs. NW	-5.87	-6.88 to -4.86	-11.49	<0.001
ON-WWT vs. WWT	-4.68	-5.62 to -3.73	-9.79	<0.001
Interaction effects with groups and task conditions				
Slow gait vs. normal gait × WWT vs. NW	0.48	-1.37 to 1.47	0.07	0.947
Slow gait vs. normal gait × ON-WWT vs. ON-NW	-2.13	-3.62 to -0.64	-2.81	0.005
Slow gait vs. normal gait × ON-NW vs. NW	4.50	3.33 to 5.68	7.51	<0.001
Slow gait vs. normal gait × ON-WWT vs. WWT	2.32	1.10 to 3.55	3.71	<0.001
(B) Task effects (total sample)				
WWT vs. NW	0.79	0.67 to 0.90	13.00	<0.001
ON-WWT vs. ON-NW	0.89	0.78 to 1.01	7.23	<0.001
ON-NW vs. NW	-0.11	-0.22 to 0.01	-1.75	0.08
ON-WWT vs. WWT	0.002	-0.12 to 0.12	0.03	0.98
Interaction effects with groups and task conditions				
Slow gait vs. normal gait × WWT vs. NW	0.006	-0.25 to 0.26	0.05	0.963
Slow gait vs. normal gait × ON-WWT vs. ON-NW	0.29	0.03 to 0.55	2.20	0.028
Slow gait vs. normal gait × ON-NW vs. NW	0.31	0.06 to 0.57	2.40	0.017
Slow gait vs. normal gait × ON-WWT vs. WWT	0.60	0.34 to 0.85	4.58	<0.001

Note. (A) Gait velocity is the dependent measure, and (B) HbO₂ is the dependent measure.

Both analyses are adjusted for age, gender, education, comorbidity status, and RBANS total index score. NW: Normal Walk; WWT: Walk While Talk; ON-NW: Obstacle Negotiation – Normal Walk; ON-WWT: Obstacle Negotiation – Walk While Talk.