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Prefrontal Activation During Inhibition of a Balance Recovery Step

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PREFRONTAL ACTIVATION DURING INHIBITION OF A BALANCE RECOVERY STEP

by

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ABSTRACT

The ability to quickly step is an important strategy to avoid a fall. However, real-world settings often constrain a stepping path. Such constraints necessitate response inhibition to prevent an inappropriate step and select a new course of action to ultimately recover balance. The present study investigated neural mechanisms that underlie this ability to stop a highly automatic balance recovery step. In the field of cognitive neuroscience, response inhibition has typically been researched using focal hand reaction tasks performed by seated participants. This approach combined with neuroimaging has revealed a neural stopping network, which includes the right Inferior Frontal Gyrus (right IFG) as a key node in this network. It is unclear if the same brain-based stopping networks suppress a prepotent balance reaction since compensatory balance reactions are subcortically triggered, multi-segmental responses that are much faster than voluntary reactions. To test this, functional near-infrared spectroscopy (fNIRS) was used to measure brain activity in 21 young adults (ages 18-30) as they performed a balance recovery task that demanded rapid step suppression following postural perturbation. The hypothesis was that the right IFG would show heightened activity when suppressing an automatic balance recovery step. A lean and-release system was used to impose temporally unpredictable forward perturbations by releasing participants from a supported forward lean. For most trials (80%), participants were told to recover balance by quickly stepping forward. However, on 20% of trials at random, a high-pitch tone was played immediately after postural perturbation signaling participants to suppress a step and fully relax into a catch harness. This allowed us to target the ability to cancel an already initiated step in a balance recovery context. Average Oxygenated hemoglobin (HbO_2) changes were contrasted between step and stop trials, 1-6 seconds post perturbation. A two-way repeated measures ANOVA tested for main effects with condition

(Step, Stop), and hemisphere (right, left) and for the interaction. Post hoc analysis was performed using paired t-test comparisons between Step and Stop trials for each channel (Bonferroni correction applied). Two-way, repeated measures ANOVA showed no significant interaction ($F_{1, 20} = 1.212$, $p = 0.284$) between factors and no significant main effect for hemisphere ($F_{1, 20} = 0.282$, $p = 0.601$). However, there was a significant main effect for condition where Stop trials produced a greater response compared to Step trials ($F_{1, 20} = 31.617$, $p < 0.001$). Follow-up analysis revealed a significant increase in three of the seven channels on each hemisphere. Consistent with the hypothesis, the results showed a greater prefrontal response during stopping trials, supporting the idea that executive brain networks are active when suppressing a balance recovery step. Contrary to our hypothesis, a similar increased response for stop trials was observed in both hemispheres indicating that step suppression was not limited to right IFG control, at least not as currently measured. This study demonstrates one way in which higher brain processes may help us prevent falls in complex environments where behavioral flexibility is necessary. This study also presents a novel method for assessing response inhibition in an upright postural context where rapid stepping reactions are required.

1.0 INTRODUCTION

A quick step, a type of a highly automatic reaction can be used with the goal of preventing a fall (Mille et al., 2013). Neural mechanisms in the spinal cord and brain stem afford highly automatic reactions that are useful when faced with simple settings; however, as we face more complex situations, there is a need for higher brain control to adapt these highly automatic reactions (Fiorio et al., 2022; Takakusaki, 2017). In balance recovery, stepping is one important way we avoid a fall and individuals who have difficulty executing an effective step are susceptible to a fall (Maki & McIlroy, 1997; Mansfield et al., 2013; Okubo et al., 2021). However, in some instances, it will be necessary to suppress an automatic tendency to step based on environmental conditions (e.g., preventing a step that would land on a slippery or unstable surface and thus increase the odds of falling).

There is growing evidence that the cerebral cortex plays an important role in the control of balance, and this includes compensatory reactions to unanticipated challenges to upright posture (Bolton, 2015; Mihara et al., 2008). Consistent with a cortical role in balance, there is a positive correlation between increased fall-risk and a decline in cognitive ability, especially executive function and this is true even in healthy older adults (Zhang et al., 2019; Mirelman et al., 2012). Executive function, also known as executive control, refers to a family of mental processes that enable us to concentrate, focus attention and juggle multiple tasks successfully and these processes are especially critical when acting automatically is insufficient or impossible (Diamond, 2013). It is widely accepted that there are three core executive functions: inhibition, working memory, and cognitive flexibility (Lehto et al., 2003). Age-related changes in executive functions are associated with fall history among older adults (Herman et al., 2010). Even though

fall-risk, and deterioration in cognitive function are often viewed as distinct and different domains, severe cognitive impairment is known to increase the risk of falls (Amboni et al., 2013; Mirelman et al., 2012; Muir et al., 2012). Studies like that of Mirelman and colleagues (2012), illustrate that executive function measures at baseline were associated with fall rates in community-dwelling seniors during a five-year prospective follow-up period. The executive function index they used was based on a test of response inhibition (i.e., computerized versions of the Go-No-Go and the Stroop interference tests). They found that those with better executive function over time rarely fell and they were at a low risk of fall compared to their counterparts with worse executive function, who fell more and were at a greater risk of falling. Similarly in another study, Sparto et al. (2013) demonstrated a potential mechanism for how response inhibition deficits with age could translate into higher fall risk. Using a step reaction task that stressed both motor and perceptual inhibition, they found deficient inhibitory control in old versus young stating that increased errors in step performance may be related to increased fall risk. Therefore, executive function's inhibitory control may have a vital role in balance (Sparto et al., 2013; Mirelman et al., 2012).

Inhibitory control is the ability to suppress goal-irrelevant stimuli and behavioral responses (Diamond, 2013). It is the cognitive process that allows an individual to suppress their impulses and natural, habitual or dominant behavioral responses to stimuli in order to select a more suitable behavior that is reliable for completing their goal. Inhibitory control is not a uniform process but rather spans across perceptual and motor processes (Germain & Collette, 2008; Rey-Mermet & Gade, 2018). Perceptual inhibition is the process that allows a suppression of environmental stimuli that are irrelevant to a complex task in progress while motor inhibition is the process that involves the voluntary cancellation or suppression of unwanted movement

(Katharine & Jeffrey, 2003). There are two broad forms of motor inhibition according to motor control literature. The inhibition of dominant, yet unwanted motor responses referred to as action restraint and the cancellation of prepared or ongoing movement referred to as action cancellation (Barkley, 1997; Rubia et al., 2001; Schachar et al., 2007). Action cancellation, the focus of this study, enables a cessation of a rapid step already underway which becomes inappropriate in an event of a tone stimulus.

The prefrontal cortex (PFC) is critical for inhibitory control and this has been established over the years in traditional cognitive neuroscience outside the domain of gait and posture research (Aron et al., 2003, 2007; Liotti et al., 2005; Picton et al., 2007; Rubia et al., 2001; Swick et al., 2008; Wager et al., 2005). The Inferior Frontal Gyrus (IFG) is one particular part of the PFC that is implicated in inhibitory control and this has been shown in patients with circumscribed brain lesion studies and in various neuroimaging studies. For instance, Rieger et al. (2003), observed a more obvious deficit in response inhibition in patients with frontal lesions compared to patients with non-frontal lesions. Aron et al. (2004), built upon this finding and they were able to identify the right Inferior Frontal gyrus (right IFG) as a key area in response inhibition. They found a high correlation between lesion volume within the right IFG and performance in inhibition tests, suggesting that the right IFG is critical to inhibitory control (Aron et al., 2004; Jana et al., 2020; Rubia et al., 2003). Likewise, across several functional magnetic resonance imaging (fMRI) studies, Rubia et al. (2000, 2001, 2003) found the right IFG activation to be correlated with successful inhibition.

The evidence for a relationship between inhibitory capacity and falls is accumulating (Fung et al., 2018; Herman et al., 2010), and this relationship has been shown with inhibition test

performance studies where the lower they scored on the test, the higher the risk of a fall (Anstey et al., 2009; Mirelman et al., 2012; Nagamatsu et al., 2011). As mentioned previously, one of the potentially important ways that inhibitory capacity may influence fall risk is by suppressing an automatic, but unwanted balance recovery step. In certain contexts of reactive stepping, a higher degree of inhibition correlates with the initiation of the required correct preparatory movement for stepping (Cohen et al., 2011) but this control varies and worsens with age (Cohen et al., 2011; Schoene et al., 2017). In the study by Cohen et al. (2011), anticipatory postural adjustment errors on a choice-reaction stepping task correlated with performance on a Stoop test (a classic test of response inhibition). Overall, older adults were much slower and made more errors on this task and this seemed to be related to deficiency in response inhibition. Therefore, any stepping tasks where inhibition is required to successfully navigate through the world will put older adults at a disadvantage, and increase their potential fall risk.

Neuroimaging techniques have been used to study the neural correlates inherent to human balance control (Wittenberg et al., 2017). However, a standard imaging technique such as fMRI is limited in the study of upright and functional tasks because participants need to be confined to a scanner usually lying supine. This is a significant shortcoming with fMRI studies looking at balance control since they are limited to focusing on mental imagery of balance (Afrasiabi & Noroozian, 2015). Just a few functional neuroimaging studies have studied brain activation during maintenance of standing postures using positron emission topography (PET) (Ouchi et al., 1999) and motor imagery of locomotor-related task using fMRI and PET (Jahn et al., 2004; Malouin et al., 2003). Mihara et al. (2008), illustrated that functional near-infrared spectroscopy (fNIRS) could facilitate the evaluation of upright task-related responses and is not vulnerable to the subject's motion. Compared to fMRI and PET, fNIRS stands out for its robustness against

motion artifacts, portability, low cost, no general contraindications to its use (Cieśla et al., 2020), and a better temporal resolution allowing measurement of concentration changes in both oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HHb) (Sukal-Moulton et al., 2014). Using fNIRS, task-related responses that involve high levels of movement can be assessed. fNIRS is a non-invasive brain imaging modality, which uses near-infrared and visible (red) light to image changes in HbO_2 and HHb through sensors placed on the surface of the head (Cope et al., 1988). The fNIRS signal relies on optical absorption changes between oxygenated and deoxygenated hemoglobin in the blood and detects brain activity by measuring the dynamics of blood flow in the cortex (Sukal-Moulton et al., 2014).

Mihara et al., (2008) showed that the PFC is involved in reactive balance and that fNIRS can be successfully used to study neural responses in a reactive balance context. However, in their study, the participants did not step when perturbed as the small raised perturbation platform and test instruction did not allow a step. As a result of a using a paradigm where a step response was constrained, the engagement of the PFC in their study could be explained by a need for step suppression to maintain standing balance rather than a more general need to respond to a loss of balance. A significant difference between Mihara's original study and the present thesis is that in our study a balance recovery step is allowed on the majority of trials. We then contrast brain activity on stepping trials with infrequent stop trials.

The purpose of this current study is to determine if suppressing an automatic balance recovery step would elicit increased PFC activity. Therefore, to evaluate the role of the PFC in reactive balance, individuals performed a balance recovery task that demanded rapid step suppression following postural perturbation. We contrasted brain activity on stepping trials with the infrequent stop trials to illustrate the involvement of the PFC in inhibitory control. The

hypothesis is that by suppressing an automatic balance recovery step, heightened brain activity would be observed in the right IFG.

2.0 METHODS

2.1 Participants

A convenience sample of 24 young adults aged 18-30 years (average = 24 ± 2 years; 12 Females) were recruited from Utah State University and the surrounding Cache Valley, UT area through direct and indirect methods. Indirect methods included the Sona System Software and flyers placed around the university. Participants were screened for inclusion and exclusion criteria using a custom screening questionnaire through Research Electronic Data Capture (REDCap), a secure web-based data entry system hosted at Utah State University (Harris et al., 2009, 2019). The inclusion criteria included: age eligibility between 18-30 years, the ability to stand and step continuously for up to 15 minutes, normal hearing, no history (e.g., 6 months) of fainting, no neural and cognitive deficits, and no musculoskeletal and cardiovascular impairment. All individuals were provided written informed consent for experimental protocols as approved by the Utah State University Institutional Review Board and conducted in accordance with the Declaration of Helsinki. Note that two participant's test sessions were excluded due to equipment malfunction and a third participant stopped testing early leaving 21 participants total.

2.2 Data Acquisition

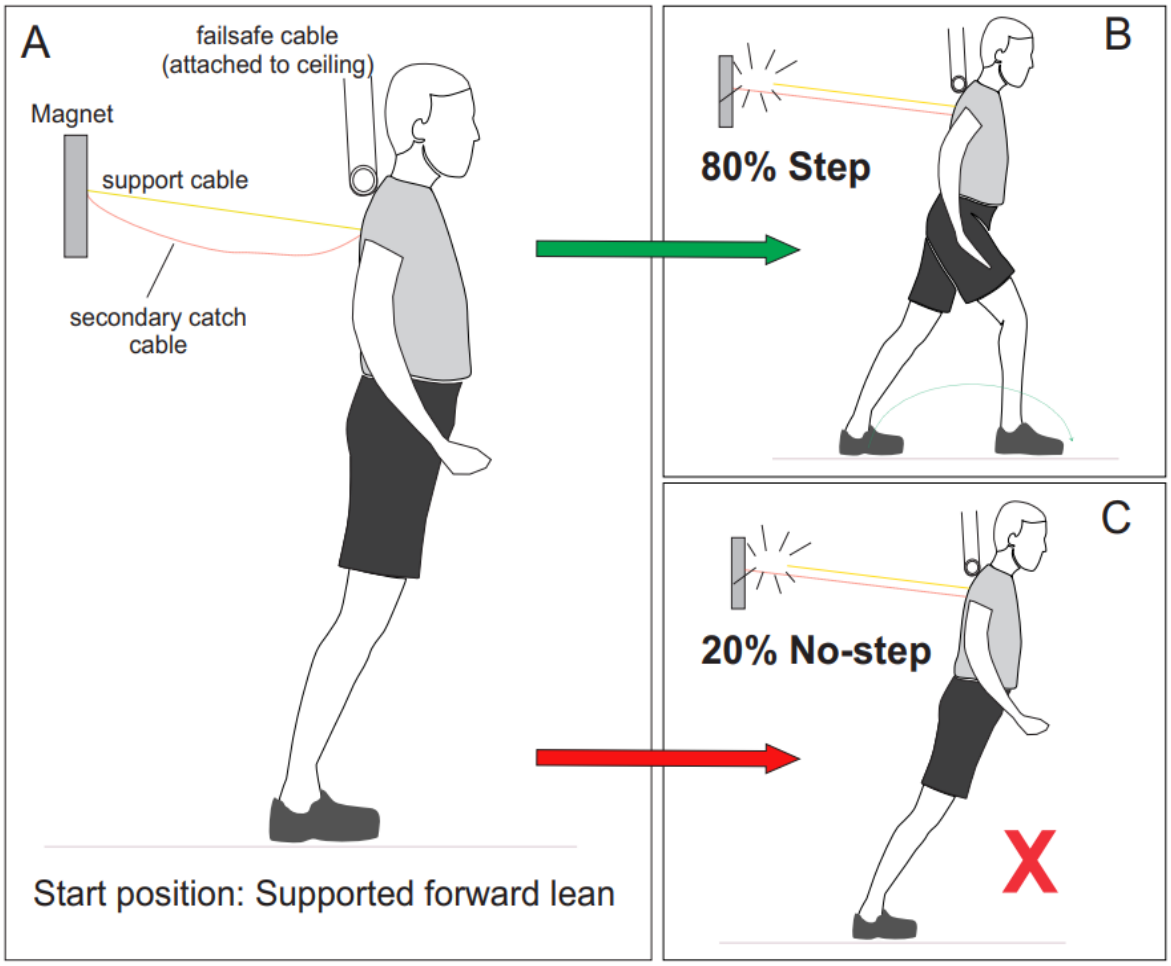
2.2.1 Force Plates

Three force plates (Kistler Instrument Corp., Winterthur, Switzerland) computed vertical ground reaction forces to track stepping responses. Participants were instructed to stand on two

separate force plates with their right and left feet at the start of each trial. The third force plate which detects a forward balance recovery step was in front of the other two plates.

2.2.2 Lean and release system

A custom-made lean and release (L&R) cable system, (**Figure 1**) enforced temporally unpredictable forward perturbations (Rowley et al., 2022). All testing was conducted with the participants standing in a forward lean position at approximately 6°. This position was supported and secured through a body harness and three attachments with cables that served unique purposes. The support cable was held by a magnet attached to the back wall behind the participant that was controlled by a computer program to produce a time-specific release. This release by the support cable represents the postural perturbation. The secondary catch cable was beside the support cable secured to the back wall. This cable catches the participant in a forward lean position for trials where no step but a relaxation into the catch harness was required. The catch cable allowed a forward fall to 10°. The failsafe cable was attached to girders in the ceiling to prevent participants from falling to the ground. To begin each trial, the researcher disengages the magnet thereby causing the participant to fall forward. The direction and amplitude of perturbation was fixed but the onset of perturbation was unpredictable (Bolton & Mansour, 2020).


A
failsafe cable
(attached to ceiling)
Magnet
support cable
secondary catch
cable
Start position: Supported forward lean
B
80% Step
C
20% No-step
X

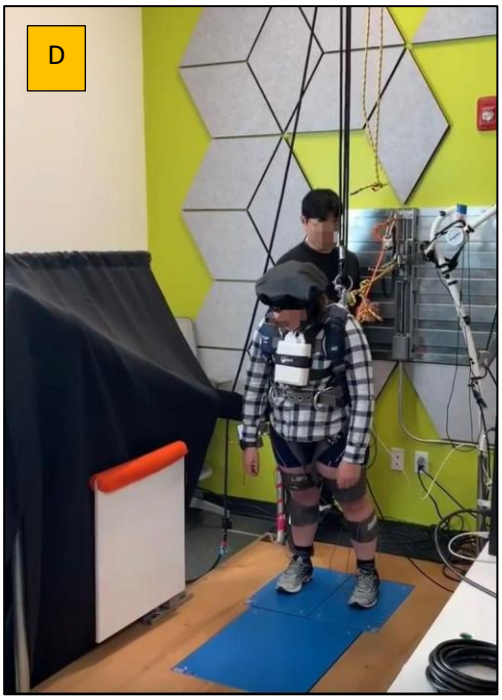

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Figure 1. Lean & release task used to test inhibitory control during a balance recovery step (3). A) Supported lean position before cable release. B) On most trials participants stepped forward to recover balance when released from a support cable. C) On 20% of trials a stop tone instructed participants to suppress a step and relax into a secondary catch cable. A failsafe cable was also attached to prevent any falls to the ground. D) Participant shown in the test apparatus with an fNIRS amplifier strapped to their chest. Force plates measured vertical ground reaction forces to detect stepping responses.

2.2.3 fNIRS

Cortical activation following postural perturbation was recorded by a continuous wave fNIRS system (NIRSport, NIRx Medical Technologies LLC, Berlin, Germany). fNIRS is based on the principle that biological tissues like bone and skin are transparent to near-infrared light, while HbO_2 and HHb molecules in the blood are absorbers in the 700–900 nm spectrum (Severinghaus, 2007) which allows measurement of brain activity. Specifically, the relative HbO_2 and HHb concentrations indirectly reflect neuronal activity (Ferrari et al., 2012). In this study, we entirely focused on the relative HbO_2 that is mainly associated with the inflow of oxygen to the tissues which signifies activation. During tissue activation (excitation of brain areas), oxygen is consumed within the tissue and the tissue reacts by increasing the blood inflow towards the tissue. The fNIRS system included eight red light emitting diode (LED) light sources (760 nm and 850 nm frequency-modulated wavelength) and seven detectors surrounding each light source plus a short separation channel detector. This short separation channel was used to remove extracerebral hemodynamics to better reveal cerebral changes. It aims to remove systemic noise like cardiac cycle and respiration thereby significantly improving the reliability of the signal recorded. Aurora software 1.4.1.1 (NIRx Medical Technologies LLC, Berlin,

Germany) was used to record data at a sampling rate of 10.2Hz. The 16 specialized dual-tip optodes which make up 18 channels as seen in **Figure 2** were placed on an fNIRS cap based on topography with an inter-optode space of 3cm. The cap montage used was specific for the Inferior Frontal Gyrus (IFG) and referenced to the international 10-10 system (montage provided by NIRSite, NIRx Medical Technologies LLC, Berlin, Germany). The right Inferior Frontal Gryrus (right IFG) was defined as an area of interest due to findings in cognitive neuroscience as discussed in the introduction (Aron et al., 2004; Hampshire et al., 2010; Rubia et al., 2003).

Cap sizes (56 or 58 cm) were chosen and positioned on each participant's head by using the Cz position as an anatomical reference. The cap was centered between the nasion and the inion (anteroposterior measurement) and between the preauricular points left and right (mediolateral measurement). The arrangement of probes was fixed on the cap using spring-loaded grommets which held sensors at a consistent pressure on the scalp, optode stabilizers, colored labels, and holders to ensure the same anatomical position of the probes across all participants. The optodes were covered with an opaque black cap as seen in **Figure 1D** to reduce interference from external light. To reduce and eliminate any motion artifacts that would occur if the cap slipped a headband secured the cap in place as chinstraps. The data was recorded using Aurora software (NIRSport, NIRx Medical Technologies LLC, Berlin, Germany), an integrated data acquisition software. At the start of every measurement, the equipment was calibrated to determine light coupling between the sensors and the detectors. During calibration, participants were asked to remain still. The signal quality was verified by an automated signal optimization algorithm before proceeding with data collection. During test sessions, HbO_2 and HHb concentration changes could be viewed in real-time to monitor data quality.

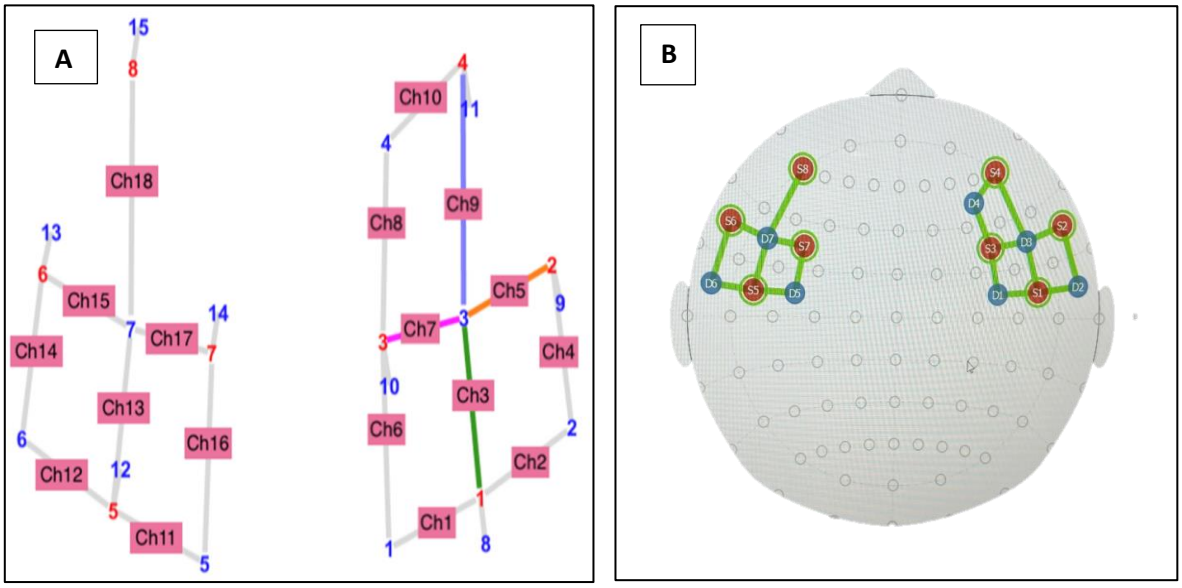

Figure 2. The 18-channel probe layout. A) Specific channel numbers. B) Their location on the head showing the light sources (red), detectors (blue) and the respective channels (green).

2.3 Experimental protocol

At each test session's start, practice trials were conducted to familiarize the participants with the test requirements. Task instructions were read to participants directly from a sheet to keep all instructions consistent. The practiced tasks were 1) rapid balance recovery step following a cable release (STEP); 2) relaxing into a catch harness following a cable release with a high-pitched tone (STOP); 3) randomized presentation of both conditions i.e., the main study task. The participants were instructed to lean as far forward as the cable allows at approximately 6° with both feet approximately hip-width apart, keeping both feet in contact with the force plates and still relaxing. To make sure that the participants stepped back into the set position; their feet were outlined with a chalk marker. This was done to prevent inter-trial/participant start position disparity.

The main trials began with a baseline period (30 seconds of data collection in which the participants were instructed to lean forward and remain still) to bring the hemodynamic status close to a resting state as possible. Immediately after this period, the balance recovery stepping task followed. The cable release functioned as a go cue to which participants stepped forward as quickly as possible. In some trials, a high-pitched stop tone (200ms sinewave, frequency 500Hz) was played, to which participants suppressed the urge to step and relaxed into the catch harness. These tones were presented in a randomized manner using a set of fixed delays (0 – 60 ms) to make the delays challenging but also manageable. After each step (STEP) or relaxation into the harness (STOP), the participants were instructed to hold their positioning for three seconds. This was done to capture the hemodynamic response. After this brief pause, the participant stepped back into the start position, the magnet was reattached, and then the forward lean to start the next trial. Each trial was five seconds with a five to ten second break between trials to reset the participant in the start position (i.e., supported forward lean). Testing was conducted in blocks of 50 trials with standing or seating breaks in between each block for a total of 200 trials. The participants could step with either leg, but they were instructed to maintain the chosen leg throughout the testing session. They were also instructed not to talk during an active trial. Testing sessions lasted for about two hours and 30 minutes.

The STEP condition occurred on 80% of trials while the STOP condition occurred on 20% of trials at random. This specific ratio was selected to automate the stepping response to a perturbation. The infrequent STOP condition was intended to expose the involvement of inhibition in a reactive balance recovery context.

2.4 Force plate analysis

The force plate determined stopping success for the L&R task. The vertical ground reaction force under the stepping leg was used to determine whether a step was taken or not. This gave a direct measurement of the decision to take a step or suppress a step. A response error was defined as in the STEP trial, no stepping or stepping outside the force plates. While a response error on the STOP trials was classified as lift-off (moment when vertical force was zero) from the force plate under the stepping leg or an actual step.

According to a recent study, (Rowley et al., 2022) the average stopping success relative to 40 stop trials/participant was calculated from lift-off values in the STOP trials. In the standard stop signal task, the goal is to achieve a successful stop % of close to 50% and ideally between 25-75% (Verbruggen et al., 2019). This stop success range indicates sufficient task difficulty to allow estimation of the covert stopping process.

2.5 fNIRS signal processing

The fNIRS data processing was completed using the open-source Homer3 toolbox in MATLAB (R2002a, The MathWorks Inc, Natick, Massachusetts, USA). The processing stream created was based on guidelines for the analysis of fNIRS data (Lorenzo et al., 2019). The following were the steps executed: (1) the raw intensity data were converted to optical density (OD) data (*hmR_Intensity2OD*), (2) channels that showed very high or low optical intensity were excluded for an active channel from further analysis (*hmR_PruneChannels*), (3) Motion artifacts were detected with *hmR_MotionArtifactByChannel* (tMotion: 0.5, tMask: 1.0, STDEVthresh: 20, AMPthresh: 0.5) and (4) motion correction *hmR_MotionCorrectSpline* (p: 0.99). Then, (5) Band-pass filtered *hmR_BandpassFilt:Bandpass_Filter_OpticalDensity* (hpf: 0.01, lpf: 0.5), and 6)

Optical density data were converted to Hb concentration changes using *hmR_OD2Conc* (ppf: 1.0 1.0). (7) Finally, the *hmR_GLM* function was applied to use short separation channels to remove physiological noise from the hemodynamic response (trange: 2.0 10.0; glmSolveMethod: 1, idxBasis: 1, paramsBasis: 1.0 1.0, rhoSD_ssThresh: 15.0, flagNuisanceRMethod: 1, driftOrder: 0, c_vector: 0). The resulting hemodynamic response was exported as a txt file for subsequent analysis in a customized LabVIEW program (National Instruments, TX, USA). This program determined the averaged hemodynamic response function amplitude over a set period of (1-6 seconds) following cable release/post perturbation. The HbO_2 response was combined into a group average for all participants and for each region of interest (right or left hemisphere) to contrast STEP versus STOP conditions in the 14 channels outlined in **Figure 4**. A total of four channels were removed due to noise (channels 9 and 18) and to have equal channels/areas for hemispheric contrast (channels 8 and 10). The channels were renamed channels 1 to 14 after this elimination.

2.7 Statistical Analysis

The average HbO_2 response was determined over a five second window spanning 1-6 seconds post-perturbation. To address the main research question, channels on the right and left hemisphere were group averaged and a two-way, repeated measures ANOVA was conducted using SPSS (version 25.0; SPSS Inc.) with two levels of condition (STEP, STOP) and two levels of hemisphere (right, left). Follow-up analyses were conducted on individual channels using two-tailed, paired t-tests with the application of Bonferroni correction to account for multiple comparisons (corrected alpha threshold = 0.05/14 = 0.0036). As an exploratory analysis, we investigated the correlation between performance on the reactive balance task and brain activity. Successful stopping ability in the balance recovery task was measured as stop %. The HbO_2

response was represented as a z-score, which was created by taking the average HbO_2 response in the STOP trials minus STEP trials and dividing this difference by standard deviation from STEP trials. In this manner, normalized HbO_2 response was used as a marker of brain activation to determine if IFG activity was correlated with stopping success using a Pearson r correlation.

3.0 RESULTS

3.1 Cortical activity

A change in cortical activity in the IFG elicited by a balance recovery step was measured. The average HbO_2 changes were contrasted between STEP and STOP trials, 1-6 seconds post perturbation. Two-way, repeated measures ANOVA revealed no significant interaction ($F_{1, 20}$ = 1.212, p = 0.284) between the factors of hemisphere and task condition and no significant main effect for hemisphere ($F_{1, 20}$ = 0.282, p = 0.601). However, there was a significant main effect for task condition where STOP trials produced a greater response compared to STEP trials ($F_{1, 20}$ = 31.617, p < 0.001), shown in **Figure 3.** Follow-up analysis for each of the individual channels showed a significant increase for STOP relative to STEP trials for three channels on the right hemisphere (channels 1, 5, and 6) and three channels on the left hemisphere (channels 8, 13, and 14) as seen in **Figure 4**.

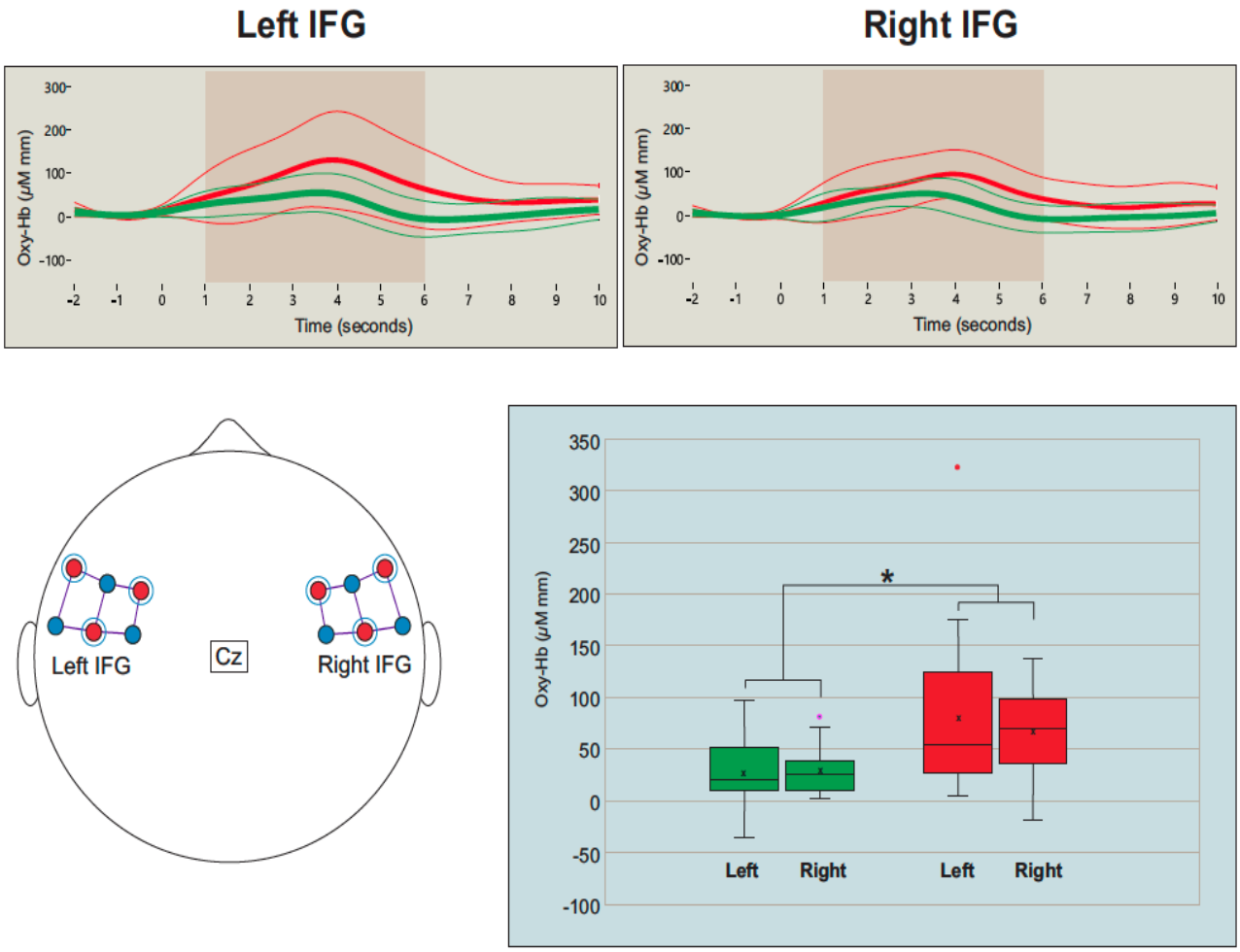

Figure 3. *Top.* Group average HbO_2 time series data for each hemisphere. The shaded region represents the time window used for averaging and standard deviation bars are presented as thin lines. *Bottom Left.* Specific channel numbers and their location on the head. *Bottom Right.* Boxplot depicting average HbO_2 response for each hemisphere (grouped as a region of interest) and for each condition: Step (green) or Stop (red). The significant main effect for condition where Stop trials produced a greater response compared to Step trials is indicated with an asterisk.

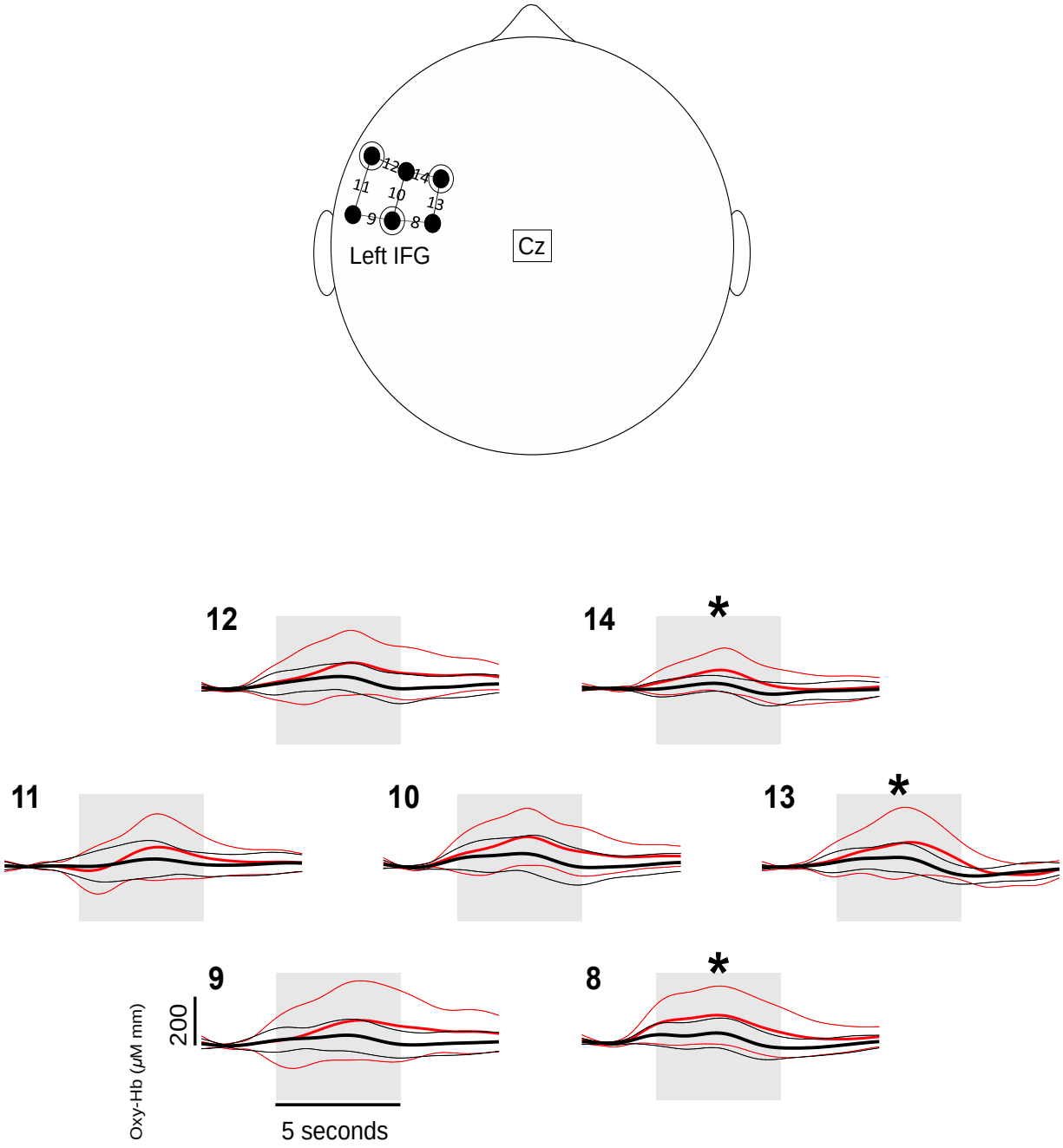

Figure 4A. Average HbO_2 response for channels on the left hemisphere; Step (black) or Stop (red). The asterisk indicates a significant increase for Stop trials ($p < 0.0036$).

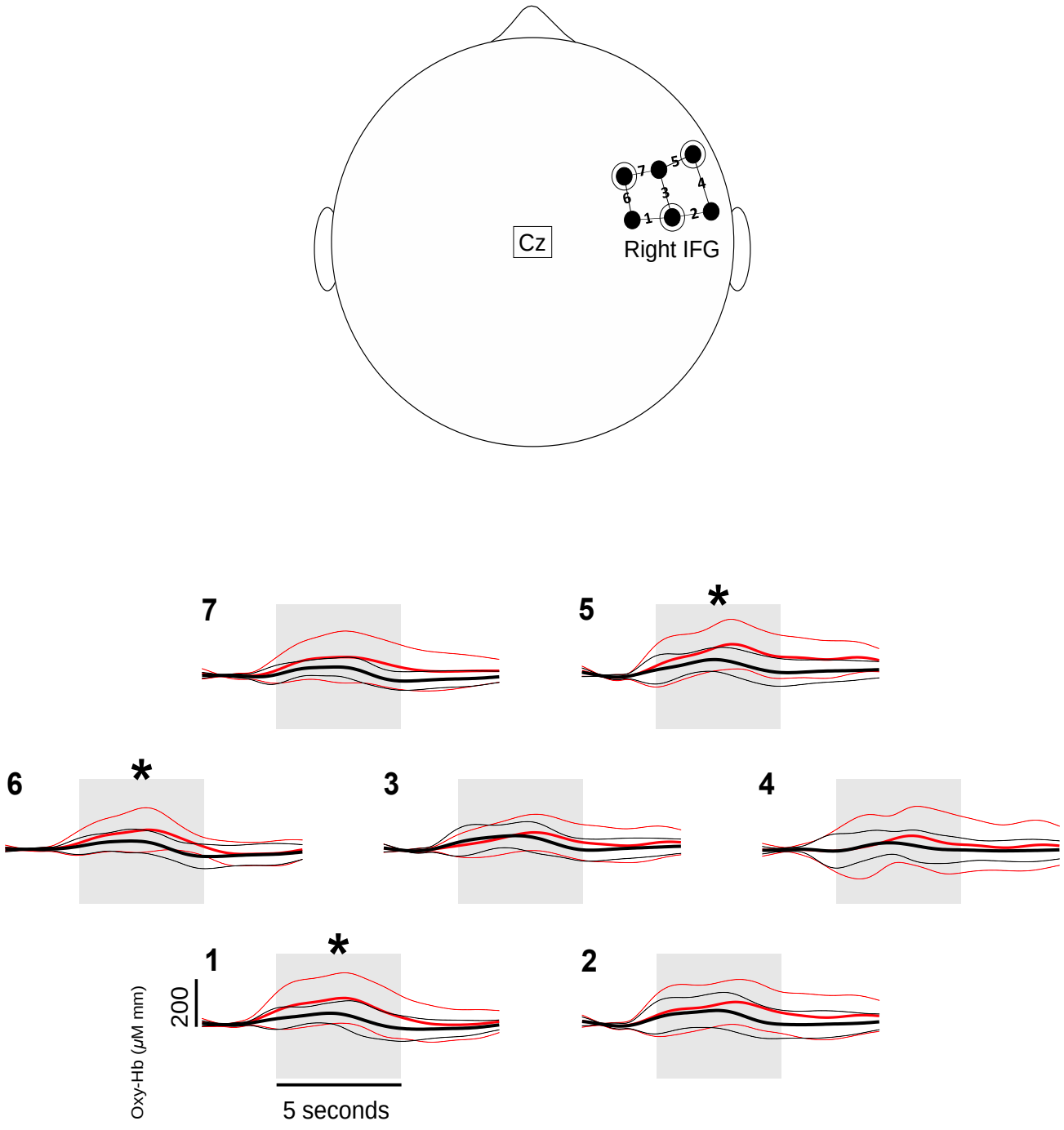

Figure 4B. Average HbO_2 response for channels on the right hemisphere; Step (black) or Stop (red). The asterisk indicates a significant increase for Stop trials ($p < 0.0036$).

3.2 Behavioral performance

There were four left steppers out of the 21 participants. **Table 1** depicts the stop success rates for all participants with an overall average of 31%. The average Go reaction time for stepping responses on STEP trials was 327.9 +/- 52.6 ms. None of the participants exhibited outright Go omissions when they were released from the support cable. **Figure 5** plots the relationship between the HbO_2 normalized change in the right IFG and stopping success for all 21 participants. The exploratory analysis between step suppression and brain activation revealed no significant correlation between the normalized HbO_2 response and stop success R_{21}= -0.152; p = 0.511.

Subjects	% Success
1	65
2	50
3	42
4	45
5	30
6	38
7	35
8	8
9	35
10	18
11	22
12	25
13	88
14	18
15	5
16	10
17	12
18	54
19	18
20	25
21	5
AVG	30.8571429

Table 1. The % success rate of all 21 participants based on lift off from the force plate.

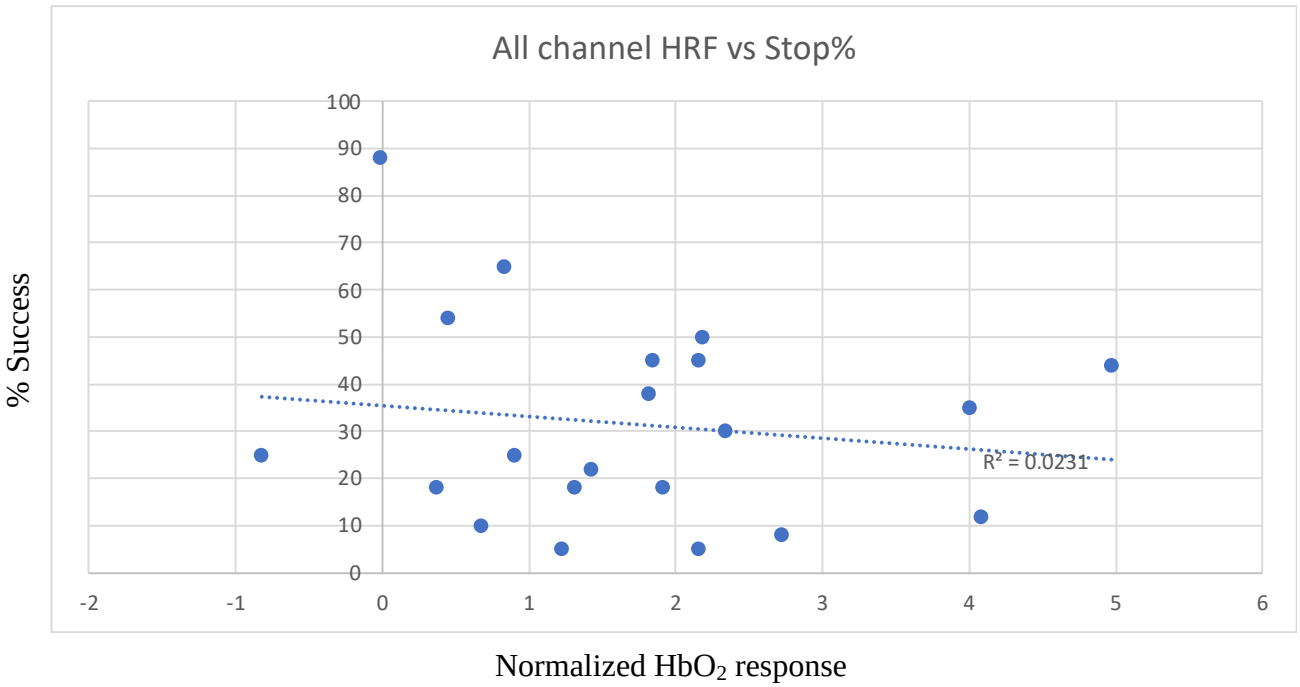

Figure 5. The scatterplot shows no correlation between z-score normalized changes in HbO_2 or 'HRF' (Hemodynamic Response Function). This displays the normalized step vs. stop response and % stopping success for all participants.

4.0 DISCUSSION

This study outlined a novel method for assessing response inhibition in an upright postural context where rapid stepping reactions are required. The purpose of the study was to determine if suppressing an automatic balance recovery step would elicit increased PFC activity, specifically in a prefrontal region (IFG) known to play a key role in response inhibition. A balance recovery task was created to temporally impose unpredictable perturbation by releasing participants from a supported forward lean. The task required participants to step 80% of the time and stop (20%) occasionally. This stopping requirement that was imposed in a highly

automatic context enabled the potential exposure of the neural mechanism(s) for response inhibition using fNIRS. Unlike fMRI, fNIRS can be used outside a scanner to test brain activity while participants perform gait and posture tasks and fNIRS is also known for its robustness against motion artifacts. Therefore, fNIRS was desirable in this study as it involved an explosive balance recovery step.

Response inhibition has typically been researched using focal hand reaction tasks performed by seated participants. This approach combined with neuroimaging has revealed a neural stopping network, which includes the right Inferior Frontal Gyrus (right IFG) as a key node in this network (Aron et al., 2014; Swann et al., 2009). Consistent with our hypothesis, the present results showed a larger hemodynamic response measured in the IFG when stopping. It is important to note that in the Mihara study (2008), they never contrasted a step versus a stop. In their study, participants were forced to use a fixed support reaction due to their specific testing device (i.e., a raised platform with a small surface area that prevent a step) and by instruction to remain in stance. Consequently, if participants always needed to avoiding stepping, one would predict that this would result in pronounced prefrontal activity to suppress a natural urge to step in response to a loss of balance. What this means, is the pronounced prefrontal response in Mihara's work may be due to the constraint on stepping and their conclusion may have been influenced by their study design. The significant difference in this present study is the inclusion of a step condition for comparison to see a clear difference in brain activation. Overall, present results support the idea that executive brain networks are active when suppressing a balance recovery step and this is suggestive of one of the potential ways in which effective inhibitory control could contribute to fall prevention (i.e., by suppressing an unwanted step reaction when a situation calls for it).

In previous cognitive neuroscience findings, the right IFG is particularly activated during inhibitory control (Aron et al., 2004; Hampshire et al., 2010; Rubia et al., 2003; Schaum et al., 2021). But contrary to our expectations, there was no right IFG preference in the effects observed in this study. Rather, we found no difference in increased activation when comparing hemispheres. In as much as most studies support that response inhibition is right lateralized, studies like that of Swick et al. (2008) found a different observation. They found a clear performance deficit in patients with damage to their left PFC (with right PFC intact) suggesting a contribution from the left hemisphere to inhibitory control. They explained that the contribution of the left PFC is more than minor, since the spared right PFC was not enough to compensate for the effect of the left PFC. This is consistent with results from Boecker (2007), where these authors found activation in the left PFC as well as the right (although still with a slight right hemisphere bias). Collectively, these findings indicate that successful motor inhibition is not exclusively under the control of the right hemisphere. In another study looking at age-related changes in response inhibition (Heilbronner & Münte, 2013), the authors presented a critical idea that bilateral prefrontal activity during response inhibition task may reflect compensation by older adults. The idea here is that older adults have a lower capacity and consequently would need to recruit additional resources to keep up with task demands. Although the present study doesn't compare age groups, the relevant point is that our task may be particularly challenging and it's this heightened challenge that may similarly require additional neural resources. This notion of a high task difficulty is supported by the low success rate across participants where the average success rate for suppressing a step after the tone was only about 30%. Therefore, the bilateral IFG activity may reflect the need to bring on more brain resources to handle a challenging task. This would seem unsurprising when one considers that (a) these reactions are

triggered by a postural perturbation, which tends to evoke faster and more viscerally arousing responses (Bolton, 2015), and (b) the balance recovery step involves higher coordination demands (e.g., coordination between step and support leg while also managing trunk muscle activation).

The contribution of the right IFG in predicting inhibitory performance at a behavioral level was explored and this was examined by determining the relationship between normalized HbO_2 changes and % stopping success. No significant correlation was seen between the two measures suggesting that the increased IFG response may not directly relate to stop success. This would seem to argue against the fact that our hemodynamic response relates directly to a stop command. Consistent with our findings, in an earlier study (Boecker et al., 2007), they found no difference in prefrontal activation for successful versus failed stops using fNIRS in a seated response inhibition task. The proposed reason for this result is that even on failed stop attempts these same stopping networks would be active. This is predicted by the horse-race model whereby two independent processes are engaged during the standard stop signal task – one to generate an action, and a separate, active braking process – and the winner of this race determines whether a response is emitted or not. Furthermore, the observed higher brain signal on stop trials may actually reflect detection of an infrequent/oddball stimulus that lead to motor slowing and cognitive distraction (Wessel & Aron, 2017). This increased brain activity may have been a reaction to the infrequent tone stimulus which was met with either a successful or a failed stop/relaxation into the harness. Wessel and Aron (2017) proposed that unexpected events recruit the fronto-basal-ganglia network for stopping which includes specific frontal nodes that are also recruited to rapidly stop action. What this means for the present study is that a global shutdown of motor output may be automatically triggered by an unexpected perceptual event (i.e., an

infrequent tone) and this could indirectly act to suppress a step. Future study designs may need to account for tasks that actually demand action suppression versus a condition that is an infrequent surprise but without behavioral requirement.

4.1 Limitations and Methodological Considerations

It is important to note that the present study has several limitations. The first limitation deals with our specific method for testing reactive balance and how applicable it is to actual balance control and falls in everyday life. As stated earlier, this study required participants to either recover balance with a rapid step or suppress action altogether by relaxing into a catch harness. In avoiding a fall in real life (i.e., where we don't have a catch harness) we would either need to take a step, or to activate muscles in the trunk and legs (feet-in-place strategy) to resist falling forward (Maki & McIlroy, 1997). This involves a switch or change of support instead of just response inhibition (stop). Our rationale for using this approach was to clearly dissociate a 'Go' signal from a 'Stop' command with the goal of exposing cortical activation involved in total action suppression (note: this approach is consistent with traditional cognitive neuroscience studies that investigate response inhibition with 'all-or-none' keystrokes). Nevertheless, in a study by Boecker et al. (2007) they found that changing a response versus outright inhibition produced a similar increase in prefrontal activity. Their study would therefore support the idea that complete suppression of a balance recovery step would have the same neural demands as switching to a failed inhibition reaction. In subsequent versions of this study, scenarios where feet-in-place balance reactions are used would be introduced instead of complete response suppression. In such a scenario, our prediction would be the brain activity would again be higher when using a feet-in-place strategy instead of allowing a step.

Beyond the applicability of our task design to real life falls, the current study has potential limitations in how we measured task performance and brain activity. For example, our measure of successful versus failed stops relied entirely on lift off from the force plates. In the standard stop signal task (on which this specific balance task is based), the goal is to achieve a successful stop success rate of close to 50% and ideally between 25-75% (Note: This specific success range is based on recent consensus guidelines (Verbruggen, et al. 2019) by experts in the field to aid researchers working with the 'Stop Signal Task' – i.e., the gold standard for response inhibition assessment). Our results showed that only 11 out of 21 participants (52%) achieved stop success rates (25-75% success). While this low stop success rate reflects how challenging this task can be, it may also reflect methodological issues regarding how we measured response inhibition – i.e., lift off from the force plate. Lift off from a force plate is a very "all or none" measure that leaves no room for nuance and because of this, there was a failure to capture more subtle tendencies to step such as postural shifts, or partial unloading of the step limb without actually lifting off the ground. This could be alleviated in future studies by measuring other indications of steps or stops (e.g., the degree of weight shifting). Another potential methodological consideration is the fact that the hemodynamic response is relatively slow as it takes a few seconds to develop whereas the balance task is extremely fast (reactions in milliseconds). At the very least this complicates directly matching brain activity with task success/failure.

4.2 Conclusion

In conclusion, this study presents a novel method of assessing response inhibition in an upright postural context using fNIRS where rapid stepping reactions are required. It demonstrates a way in which higher brain processes may help us prevent falls in complex

environments where behavioral flexibility is necessary highlighting the prospective value of this measure as an early marker of the risk of falling given the link between performances in inhibition test and falls (Anstey et al., 2009; Mirelman et al., 2012; Nagamatsu et al., 2011). Future studies would need to explore if the present inhibitory mechanisms are deficient in an older population which may suggest subtle changes in the PFC necessary for inhibition or a generalized cognitive decline which would mean an exposure to a higher risk of fall. Furthermore, in clinical settings, a modified version of this test could be used as a behavioral measure alone or with neural imaging to identify brain networks engaged in suppressing inappropriate postural responses (Hannah & Aron, 2021).

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