SENSORY INTEGRATION IN BALANCE PERCEPTION IN POST-STROKE INDIVIDUALS

An Undergraduate Thesis

by

Hannah Odom

Approved by:

Dr. Michael Borich, DPT, PhD

Dr. Lena Ting, PhD

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CHAPTER 1. ABSTRACT

Stroke leads to somatosensory perceptual deficits that impair whole-body motion (WBM) as well as deficits in overall balance. Literature suggests that impaired perception during WBM may result in decreased overall balance ability, but the underlying neural mechanism between the two is unknown. Investigating the role of cortical sensory processing may help inform a connection between impaired balance and impaired WBM perception after stroke. We hypothesized that reception of sensory information in somatosensory cortex is impaired after stroke, which disrupts balance and WBM perception. We elicited somatosensory evoked potentials (SEPs) to measure cortical sensory processing and compared between controls and participants with stroke in both sitting and standing conditions. We also conducted tests of perceptual ability and overall balance ability and compared performance in those tasks to latency and amplitude of SEPs. Results showed that latency is delayed on the paretic side of participants with stroke, but not between the left and right side of controls. SEP amplitude was larger on the paretic side than the non-paretic side in participants with stroke but showed no side differences for control. Amplitude of SEPs were larger in sitting than in standing across all conditions and sides. However, delayed and weakened cortical sensory processing did not correlate with impaired overall balance or perceptual abilities, indicating that cortical sensory processing is most likely not the link between the two after stroke.

CHAPTER 2. INTRODUCTION

Stroke is the leading cause of disability after injury in the United States (GBD Stroke Collaborators, 2019). A stroke occurs when disruption of blood flow to the brain causes tissue damage, and the widespread impact of stroke can result in devastating physiological, psychological, and perceptual deficits (GBD Stroke Collaborators, 2019). A prominent effect of stroke is impaired balance, with those who experience impaired balance after stroke having a higher rate of falls, creating both devastating physical effects as well as psychological impairments that inhibit their overall confidence in doing daily tasks (Tyson, 2006). On top of balance issues after stroke, many individuals experience sensory deficits as well. These can include impaired perception of sensory modalities such as proprioception, or one’s ability to perceive body position or movement (Doyle, 2010). Much is unknown about how decreased sensory perceptions could lead to impaired balance in individuals post-stroke. Existing research on sensory function in balance post-stroke focuses on coarse clinical assessment tools investigating at single joints or movements, which have limited translation widely non-applicable to functional behaviors like maintaining balance (Bolognini, 2016). Without research addressing sensory integration in balance when doing tasks involving whole-body motion, we cannot understand the neural mechanisms of balance deficits after stroke. Furthermore, given the heterogeneity of stroke, we must consider that perhaps cortical sensory processing is the unifying factor between balance and WBM perception impairments post-stroke.

We addressed these unknowns by creating a whole-body balance experiment that combined measuring whole-body motion perception with neurophysiology data. These neurophysiology data were collected through somatosensory-evoked potentials (SEP), which are cortical responses evoked by a peripheral electrical stimulus to a nerve (Smith, 2014). Analyzing the latency and amplitude of these SEP peaks via an electroencephalogram (EEG), which measures electrical activity from the scalp, can give valuable information as to the timing of initial sensory arrival and strength of that signal (Smith, 2014). We collected SEP data in both sitting and standing positions with consistently paced perturbations for three minutes each. These data gave us information regarding the latency and amplitude of initial processing in somatosensory cortex, which we compared between healthy older adults and individuals with stroke as well as between the paretic and non-paretic legs of the individual with stroke. These comparisons between participants with stroke and controls gave insight into potential stroke-related changes in cortical sensory processing, which contribute to post-stroke deficits in balance and perception of WBM. We then collected data focusing on perception of whole-body motion during balance perturbations. Participants experienced a pair of support surface perturbations to standing balance in either the same or different directions and were asked to label them as "same" or "different." This task gave us information about their threshold of whole-body motion as well as measured their neural and mechanical responses to a perturbation using the EEG and motion data accrued during the task.

Combined SEP data and whole-body motion perception data may contribute to developing a neural mechanism that could inform impairments in whole body motion perception and balance after stroke. Enhanced understanding of sensory mechanisms post-stroke may shift current rehabilitation approaches to focus on both sensory and motor deficits and help develop novel interventions to improve balance and lead to decreased falls and increased confidence. We can potentially alleviate many of the balance deficits that patients with stroke face by informing future therapies and in turn, make them feel more equipped to live out daily tasks with confidence and lack of fear of falling due to balance impairments.

CHAPTER 3. LITERATURE REVIEW

Stroke presents a serious public health and personal health issue to millions of Americans, affecting over 12 million Americans alone in 2019 (GBD Stroke Collaborators, 2019). The widespread impact of stroke can result in devastating physiological, psychological, and perceptual effects. The most common type of stroke is an ischemic stroke, or a stroke caused by a blockage of a vein or artery, followed by intracerebral hemorrhage and subarachnoid hemorrhage type strokes, or strokes caused by an open bleed in the brain (GBD Stroke Collaborators, 2019). Additionally, stroke, often associated with age, with rates increasing in adults younger than 70, shows a startling trend for other risk factors such as high BMI, blood pressure, and other comorbidities (GBD Stroke Collaborators, 2019). With higher rates of stroke occurring in younger adults than ever seen before, this requires more resources to treat patients with stroke, resulting in a large public health burden that reached upwards of $53 billion dollars in 2018 in treating patients post-stroke (CDC, 2018**).** Given the physical and mental resources needed to treat those who have experienced stroke, stroke clearly poses a massive public health issue that needs to be addressed with more effective and specific therapies.

Stroke has lasting effects of stroke on the body that are often detrimental, especially on the motor and sensory systems. From a body composition standpoint, patients experience significant decreases in their overall muscle mass and bone density, which increases the deficits in the paretic side of the patients with stroke (Celik, 2008). These weaknesses on the paretic side of the body often lead to disuse, decreased independence, and other issues affecting daily life, which ultimately lead to increased sensorimotor dysfunction. On top of the physical damage, stroke often leaves individuals who survive with severe psychological issues as well. These issues can include depression, anxiety, pseudobulbar affect, or sudden episodes of laughing and crying, and mood and emotion swings due to the cognitive impairment they experience (Chohan, 2019). However, the largest, most devastating impact of stroke presents as the tangible neurological changes in the brain post-stroke. In the motor system, these neurological changes that result in long-lasting muscular changes can transform the body all the way down to the motor unit (Arene, 2009). Additionally, changes in motor processing in the brain result in changes in muscular function that create difficulties for rehabilitation for patients (Chohan, 2019).

However, one of the most prominent sensorimotor impairments from stroke comes in the form of balance deficits. Balance disability is common in patients with stroke, with more severe strokes often resulting in more debilitating deficits in balance (Tyson, 2006). Balance deficits lead to increased falls, which can result in serious injury or death depending on the circumstances. Additionally, balance issues are difficult psychologically – for many patients with stroke, being self-sufficient in activities such as grocery shopping, socializing, and traveling can already be difficult. With a constant fear of falling, many patients with stroke do not have the confidence to live independent, fear-free lives, which makes research into the impact of stroke on balance so important. Balance deficits often occur due to the leg on the paretic side, which often has decreased muscle mass, mobility, and increased weakness (Tyson, 2006). Because of this, many patients with stroke have difficulty maintaining balance while walking due to shifting weight between their paretic and non-paretic sides. Although self-perception of balance often matches balance evaluations from professionals, these balance deficits can be very dangerous for those with stroke (Kassberg, 2021).

A significant amount of research has focused on the motor components behind stroke, with limited emphasis on sensory components. Sensorimotor integration in primary somatosensory cortex, primary motor cortex, and posterior parietal cortex are often changed after stroke, suggesting that they may play a role in the neural changes that impact motor and sensory function (Edwards, 2019). However, many experts treat sensorimotor integration as a purely motor issue, when recent research suggesting sensorimotor integration often gets disrupted during stroke (Edwards, 2019). Overall, it is known that without restoration of sensory integration, motor recovery cannot occur (Bolognini, 2016). An extensive literature review on sensorimotor integration found that although individual sensory tasks can be targeted with specific interventions, few studies investigate sensory integration during functional whole-body behaviors (Bolognini, 2016).

One of the most challenging aspects of understanding balance impairments in stroke is that balance requires continuous interactions between both sensory inputs and motor outputs. Balance requires a complete integration of sensory information such as proprioception, tactile, vision, and auditory forms (Bong, 2020). It is well established that the somatosensory input to balance is controlled by the dorsal medial lemniscus pathway (Kim, 2020). This pathway delivers information regarding cutaneous touch, vibration, and most importantly for balance, proprioception (Kim, 2020). Proprioception is defined as one's ability to sense limbs during stationary positions as well as during movement (Kim, 2020). Proprioception deficits occur in 34-64% of patients after stroke, so when one cannot fully sense body motion due to neural disruption, this can result in balance impairments (Kim, 2020). Despite the presence of some research on stroke's impact on sensory processing, the coarseness of methods investigating cortical sensory processing in balance result in unknown mechanisms and results that cannot be generalized to the full body. Existing studies on proprioception normally focus on assessing sensory ability at specific joints in a controlled setting often not applicable to real-world tasks (Han, 2016). Since balance requires sensory integration across multiple joints, current assessment tools may not be indicative of balance impairments overall.

Aside from deficits in a patient's ability to maintain their balance, patients also may display deficits in perception of whole-body motion when standing balance is perturbed. By perturbing their balance in different directions, one can measure the threshold of their perceptual abilities and potentially measure their sensory deficits. The paradigm created in Bong et al. allows for a study of whole-body perception of balance, not just on a specific body part or in a specific direction, through calculating a perceptual threshold. More importantly, they found that perceptual deficits go hand in hand with impaired balance in patients with Parkinson's disease, which given the prevalence of impaired balance after stroke, shows that this metric may give valuable information regarding balance deficits after stroke (Bong, 2020). This study occurred in patients with Parkinson's disease, which is known to also have balance and somatosensory perceptual deficits (Bong, 2020). Because of the balance deficits present in both Parkinson's disease and stroke, this paradigm becomes a valuable way to test whether the same effects occur in patients with stroke. If we couple this paradigm with a method investigating more of the neural mechanisms, we can narrow down our pursuit of how sensory changes are involved in balance deficits after stroke.

Despite existing knowledge regarding the impact of sensory deficits and their contribution to balance, the mechanisms behind how stroke disrupts this sensorimotor integration are not fully established. Some have suggested that affected sensory input might be the key to connecting balance deficits in stroke; however, the literature lacks significant knowledge regarding the impact of cortical sensory processing on balance after stroke (Kim, 2020). One potential way to investigate the sensory changes after stroke is through a somatosensory evoked potential (SEP). A SEP is a response evoked by sensory stimulation of a peripheral nerve (Smith, 2014). Sensory information is received at the point of stimulation through somatosensation and then integrated up through the brain. This can be measured using electroencephalography (EEG) and analyzing the amplitude and latency of various peaks in the EEG wave (Smith, 2014). The latency of the peak informs how fast information is being processed throughout the brain, while the amplitude of the peak gives information about the strength of the signal between the stimulated nerve and its somatosensory cortex. Prior research on SEPs in lower limb showed that they involve inputs from both the peripheral and central nervous system, which suggests integration of input from both systems contributing to cortical sensory processing in lower limbs (Morita, 1998). Previous findings show that deficits in cortical sensory processing measured through SEP were an accurate prognostic tool for recovery of ambulatory function after stroke (Hwang, 2016). Even after the acute phase, impaired somatosensory functioning measured through SEPs negatively affected balance and ambulatory abilities in patients with stroke (Kim, 2020). Lower limb SEPs collected in the supine position indicated that balance issues may be due to an inability to filter out irrelevant sensory information after stroke (Peters, 2018). More research has been conducted on upper-limb SEPs than on lower-limb SEPs, but both may provide valuable information about the sensory integration of information after stroke through measurements of peak amplitude and latency. Measuring lower-limb SEPs at the tibial nerve and analyzing latency and amplitude of the peak are shown to correlate with pre-established clinical measures of balance such as timed up and go, step test, and functional reach test, suggesting that they accurately demonstrate motor impairments after stroke

(Hwang, 2016). Therefore, SEPs can be a useful tool for measuring the strength and timing of sensory integration, especially after stroke as a way to evaluate how sensory integration has changed. Despite this valuable knowledge, the majority of SEP research occurs in supine position, which is not necessarily relevant to whole-body balance perception after stroke. This is why evaluating SEPs during standing could be more beneficial for investigating balance perception after stroke. Given limited research on tibial nerve SEPs in post-stroke individuals, further research can inform potential balance deficits after stroke (Peters, 2018).

However, it is unknown whether cortical sensory processing may be the connection between perceptual deficits and balance deficits post-stroke. We aimed to investigate the role of cortical sensory processing in balance and WBM perceptual deficits. We hypothesized that cortical sensory processing measured with SEPs is impaired after stroke and may offer an overarching neural mechanism connecting balance impairment and perceptual deficits in WBM after stroke. Participants, both healthy older adults and adults who have experienced stroke, performed a two-option discrimination test after perturbing balance where they chose whether two successive perturbations occur in the same or different direction. This tested perception of WBM during balance perturbation in a whole-body setting as they were standing for these tests. We collected SEPs of participants in both standing and sitting settings, allowing for direct measuring of cortical sensory processing at certain important electrode sites. We predicted that cortical sensory processing would be impaired after stroke. We also predicted that impaired cortical sensory processing will correlate with impaired overall balance as well as impaired perception during WBM, which may suggest a connection between the two deficits after stroke. This research will fill in gaps in current knowledge in the aforementioned literature and inform future therapies that will increase quality of life for the millions of people affected by stroke.

CHAPTER 4. METHODOLOGY

Rationale

To investigate the relationship between impaired balance and impaired perception during WBM, one must combine WBM perceptual data, balance data, and neurological data such as SEPs. In addition, it is important to establish a clinical baseline of balance ability using clinical balance tests such as the beam task and the miniBEST test. Therefore, all of the testing conducted allows us to compare impaired cortical sensory processing with impaired perception and clinical balance deficits to better understand the neural pathways behind balance deficits in post-stroke individuals.

Participant Selection

Participants were over the age of 50. 18 individuals with stroke and 8 individuals without a stroke completed a single experimental session. The projected sample size is 20 participants in each group (stroke, controls). Control participants were included if they were adults over the age of 50 who have not experienced a stroke or any other major neurological deficits. Stroke participants were included if they experienced an ischemic stroke that is their first recorded stroke. The stroke must be unilateral, or on one side of the brain, and chronic, or at least six months after the initial stroke. Participants with stroke were excluded from the study if they had severe visual or language deficits. Both NOA and participants with stroke were included if they could communicate verbally with the researchers, walk up to 10 steps at a time, and stand unassisted for up to 15 minutes.

Participant Number	Age	Gender	Chronicity (months)	Paretic side	miniBEST score	Beam Walking Score (feet)
S01	69	Male	215	right	26	5.03
S02	57	Male	64	right	24	10.25
S03	50	Female	77	left	22	3
S04	68	Female	12	right	22	5.92
S05	59	Male	8	left	20	7.89
S06	50	Male	41	left	11	1.25
S07	55	Male	79	left	24	9.5
S08	57	Female	26	right	23	5.25
S09	73	Male	61	left	10	0
S10	63	Male	6	left	20	5.5
S11	51	Male	16	left	21	5.46
S12	55	Male	65	left	15	4.3
S13	60	Male	12	right	27	10.125
S14	57	Female	11	left	19	5.4

S15	55	Male	28	left	9	0
S16	67	Male	28	left	8	0
S17	76	Male	23	left	26	9.33
S18	57	Male	31	left	24	10.17
Averages	**60.3125**		**47.5625**		**19.23529412**	**5.188529412**

Table 1: Table of participant information including age, gender, chronicity of (time since) stroke, left vs right side lesion, miniBEST score, and perceptual threshold score on the standing paretic side.

Clinical Balance Tests

After participants arrived at the lab, they underwent clinical measures of balance. Balance ability was assessed using a narrowing beam walking test (Figure 1) and the miniBEST test. For the narrowing beam-walking task, participants were instructed to walk down a beam of decreasing width with crossed arms and a tandem walking stance, or one foot in front of the other without shuffling (Sawers and Hafner, 2018). The length at which they first stepped off was recorded and repeated for a total of six trials that were then averaged to a final beam walking score. Participants completed the mini-BEST test, which is a widely validated clinical measure of balance (Marques et al, 2016). This test assigned a score of 0-2 on a number of balance tasks that measure dynamic movement, postural control, and sensory awareness (Marques et al, 2016).

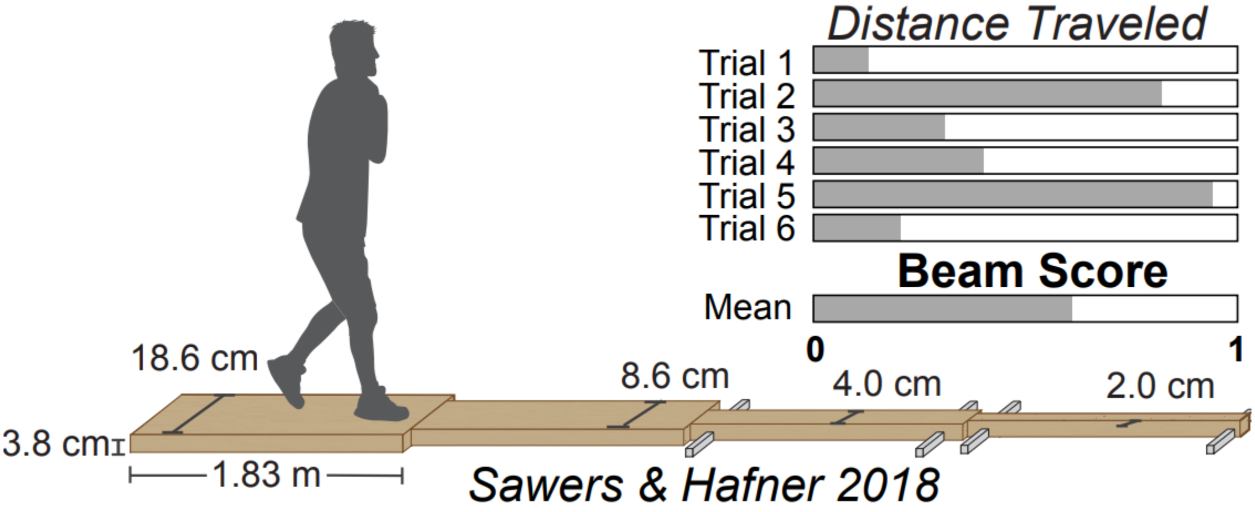


Figure 1: Narrowing beam-walking task. Participant walks with arms crossed across chest in a tandem style walk. Beam narrows as participant advances. The point at which participant uncrosses arms or steps off is measured and recorded.

Participant Setup

Participants were first put into a harness to ensure safety during the perception task. Participants were outfitted with a "backpack" to hold wires that will later be put on. Participants were outfitted with electromyography (EMG) equipment to measure muscle activity in accordance with brain activity during the task. Areas of placement for the EMG were shaved, exfoliated, and wiped down with an alcohol wipe to diminish interference. EMG leads were applied on the appropriate muscles and connected to the "backpack" via the appropriate wires. Participants were marked with 33 reflective markers. These markers interact with the VICON camera system to allow for real time motion to be recorded during perturbations. Markers were placed on the head, shoulders, hips, legs, and mainly feet as much of the study is concerned with the lower leg and feet as a measure of balance. A ground electrode was also placed on the lower leg. Participants were fitted with a 64-lead electroencephalography (EEG) cap (ActiCHamp, actiCAP, Brain Products GmbH) (sampling frequency 1000Hz, impedance <5kQ, frequency range: 0.01-1000Hz, 0.5uV/bit resolution). Head size was measured to determine cap size and fitted with the appropriate leads. The cap was placed and secured on the participant's head. Electrode gel was applied to the leads to conduct and ensure proper scalp electricity recording.

WBM Balance Perception Task

Participants transitioned into the whole-body motion (WBM) balance perception task (Figure 2). Participants stood on the perturbation platform barefoot with arms crossed across the chest, eyes closed, and headphones playing white noise to reduce any outside auditory and visual feedback. Participants stood about shoulder width apart, a stance that was then marked with tape to ensure consistent stance throughout. They experienced two perturbations in the background direction. About 5 seconds after the first perturbation, a second perturbation was delivered that deviated in a pseudo-random direction either to the left or right at a specific angle that changed to find the threshold (Bong et al, 2020). Participants then provided a verbal response of whether perturbations were in the “same” or “different” direction. Over time, different degrees of difference between the perturbations were tested to determine a perceptual threshold, or angle at which the participant correctly discriminated the direction on half of the trials. The participants underwent 30 trials of perturbations in each direction to determine this perceptual threshold, which gives valuable information when comparing the non-paretic and paretic sides of individuals with stroke. Perceptual thresholds were calculated for both the left and right sides, allowing comparison between the two that was analyzed against cortical sensory processing results.

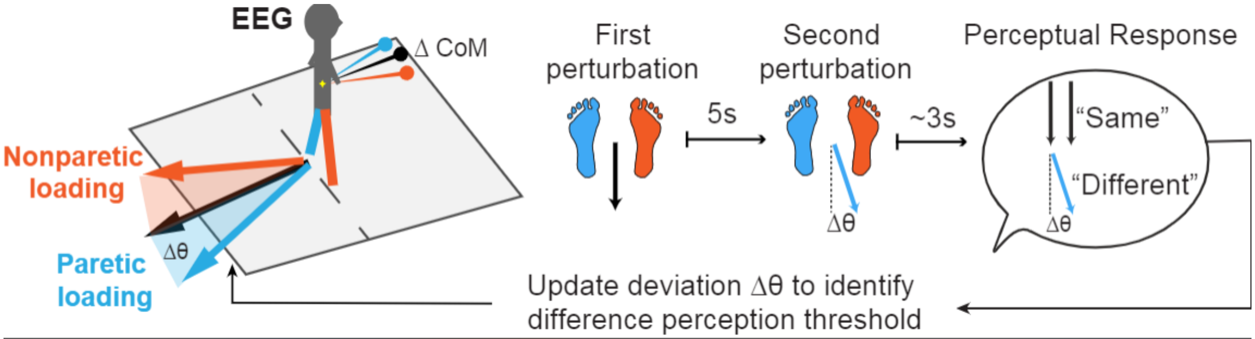
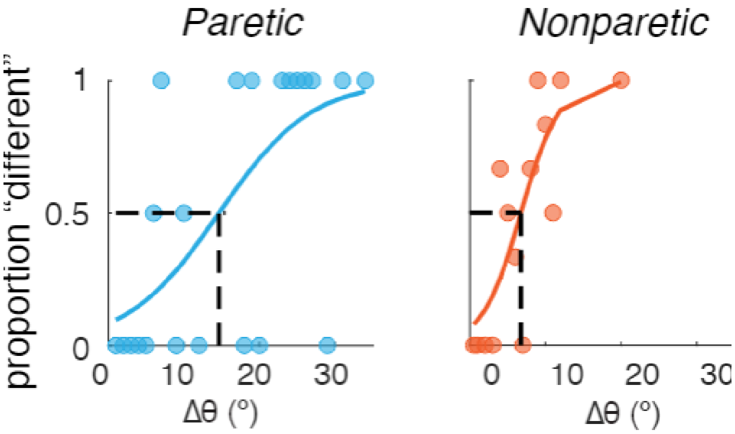


Figure 2: Perceptual balance perturbation task. Participant is perturbed twice with varying degrees of difference between perturbations. Participant gives “same” or “different” verbal response. Perception threshold to which a participant can distinguish is determined.



* *Dashed line denotes threshold*

Figure 3: Example psychometric curve generated for paretic vs non-paretic side. Perceptual threshold indicated by dashed line.

SEP Stimulation Task

A bar electrode was placed posterior to the medial malleolus over the tibial nerve. Participant report of perception of the stimulus was used to confirm correct placement of electrode location (Palmer, 2019). Electric stimulation using a monophasic pulse was delivered using a constant current stimulator (DS7A, Digitimer Ltd.), increasing in amplitude of stimulation until an M-wave was obtained in the form of a muscle twitch in the flexor hallucis longus, indicating that supra-threshold stimuli level was obtained (Palmer, 2019). Stimuli were consecutively delivered once per second for three minutes total using a 200-microsecond wide pulse under four separate conditions: left foot sitting, left foot standing, right foot sitting, and right foot standing. EEG data was continuously recorded during this time.

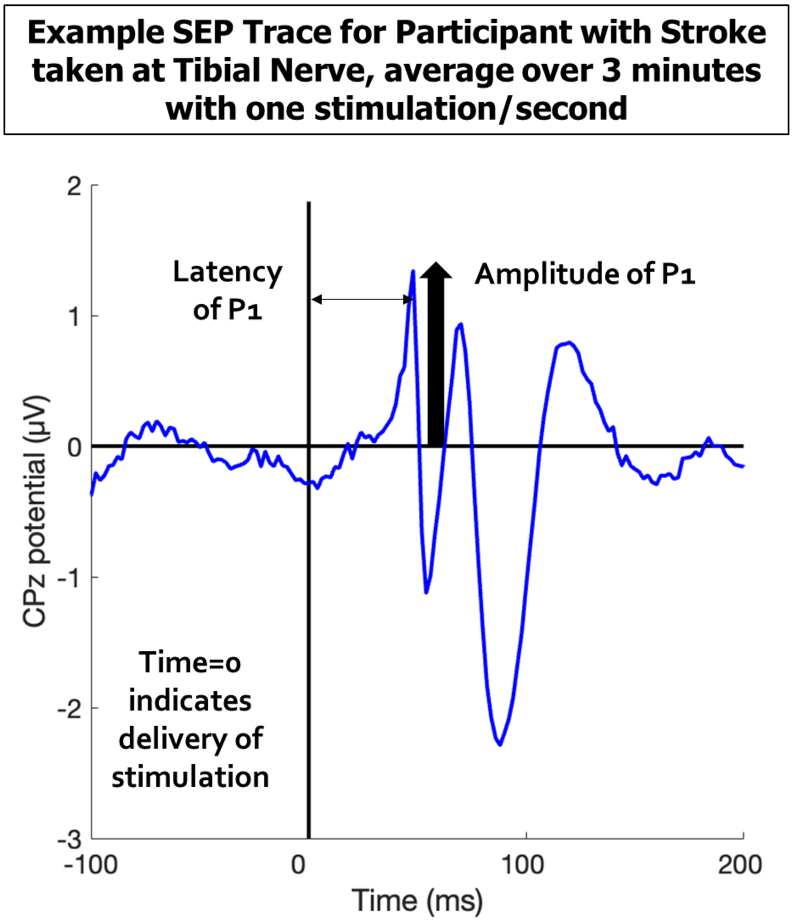


Figure 4: Sample SEP trace showing latency and amplitude.

Data Analysis

Raw EEG Data was run through standard pre-processing features using EEGLAB (Palmer,2021). Continuous data was imported and filtered with a high pass filter of 1 Hz**.** Bad channels were removed and interpolated, and the average was referenced. Line noise was then removed using the Cleanline plugin in EEGLAB, and events were epoched from -200 to 400 milliseconds relative to the delivery of the peripheral nerve stimulus (Palmer, 2021). Adaptive Mixture ICA (AMICA) was then used to remove any eye blinks, muscle twitches, and any other non-brain sources. Remaining brain sources were back projected to channel space for analysis (Palmer, 2021).

For data from the WBM perception task, perceptual thresholds were calculated. For each side, the correctness of participant responses was fit to a logistic function and used to calculate a perceptual threshold, or the angle at which participants were equally likely to respond with “same” or “different.” (Figure 3).

After this, the primary peaks for analysis of SEPs were defined from the Cz electrode. These peaks were quantified at a certain millisecond value after stimulus onset. The first positive peak was defined as P1 and analyzed for amplitude and latency using MATLAB (Peters et al, 2018). The first positive peak was generally defined as the P1 peak around 50 milliseconds. Prior literature suggests that when stimulating at the tibial nerve posterior to medial malleolus that the first positive peak is the best indicator of cortical sensory processing (Tzvetanov, 2005). Confirmation of peaks were done manually by parsing through data points and using MATLAB to determine specific x (latency) and y (amplitude) values. Trials were averaged within each condition, after which a peak was extracted to determine the average peak amplitude and latency for each of the four conditions per participant. Subjects S03, S10, S11, S12, S15, S19, and S20 were excluded from processing of SEPs due to insufficient or missing data due to comfortability or inability to elicit an SEP on both the paretic and non-paretic side.

Statistical Analysis

Once SEP peaks were defined and quantified, we conducted a three-way ANOVA test in RStudio. We compared the latency and amplitude of SEPs for the paretic vs non-paretic sides of the participants with stroke in both sitting and standing. We also compared both right and left values between healthy older adults and adults with stroke in both sitting and standing. The results of the three-way ANOVA test determined whether there was a statistically significant difference between sitting vs standing conditions, left vs right sides, and paretic vs non-paretic sides between the healthy older adults and the individuals with stroke.

Correlations were established between the amplitude of the SEP and the intensity of the stimulation at the tibial nerve. Pearson correlation coefficients were established in Microsoft Excel (Statology, 2020). We compared the left sitting, left standing, right sitting, and right standing amplitudes against their respective stimulation intensities.

Next, correlations were established between SEP values and measures of balance and perception during WBM. SEP latency and amplitude were measured from the paretic standing condition as clinical balance and perceptual testing were also done in a standing condition. Separate correlations were performed for each combination of SEP parameter (amplitude, latency) and ability (balance, perceptual threshold). Correlations were established in Microsoft Excel using a Pearson correlation coefficient (Statology, 2020). These tested whether there is a relationship between impaired ability and impaired cortical sensory processing.

CHAPTER 5. RESULTS

SEP Latency and Amplitude in Participants with Stroke vs HOA:

In healthy older adults (HOAs), P1 latency showed no significant difference between left and right sides (p=0.8597). In contrast, in participants with stroke, there was a significant difference between P1 latency between the paretic and non-paretic side, with the paretic latency being significantly larger than the non-paretic side (p=0.0014). (Figure 5)

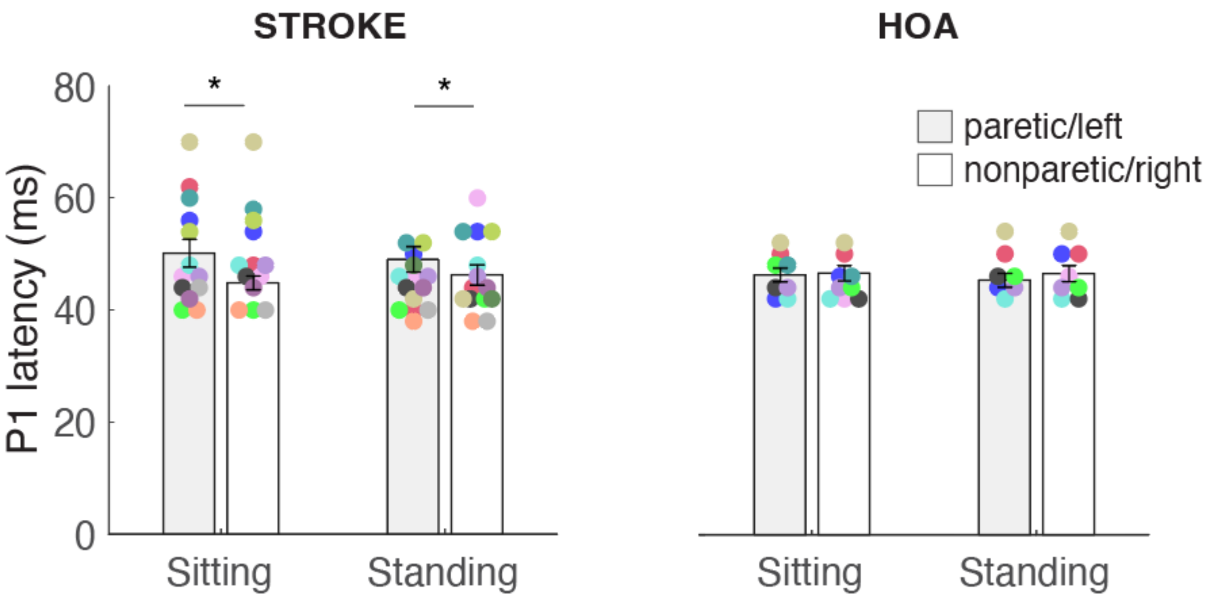


Figure 5: Latency of the P1 between paretic and nonparetic side and left vs right side in participants with stroke and control.

In HOAs, there was no significant difference between the left and right side amplitude. In contrast, in participants with stroke, the paretic side was significantly larger than the non-paretic side (p=0.007) (Figure 6). In both control and participants with stroke, amplitude in the sitting condition was significantly larger than amplitude in the standing condition (p=0.0004). The mean and standard deviation in the paretic sitting condition were 1.60 and 1.06 respectively, while the mean and standard deviation for the nonparetic sitting condition were 1.12 and 0.80 respectively. P1 amplitude on the paretic side was larger in sitting than in standing (p=0.07). Controls also demonstrated this trend on the left side between sitting and standing (Stance X Group: p= 0.75). This would indicate that regardless of group or side, P1 amplitude was larger in sitting than in standing.

There was no correlation between increased amplitude of SEP and higher stimulation intensity at the tibial nerve for the paretic sitting condition (p=0.42), the paretic standing condition (p=0.28), the non-paretic sitting condition (p=0.83), and the non-paretic standing condition (p=0.96).

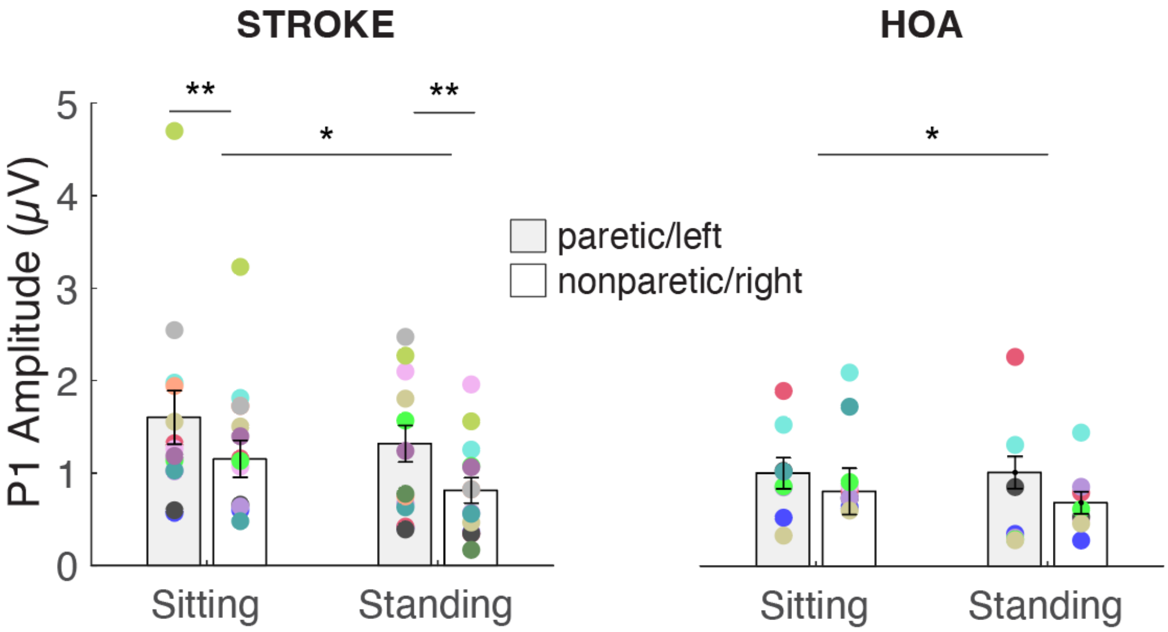


Figure 6: Amplitude of the P1 between paretic and nonparetic side and left vs right side in participants with stroke and control.

SEPs vs Balance and Perception during WBM:

Beam Walking

There was no correlation between the latency or amplitude of the P1 in the paretic standing condition and the beam walking score with outliers removed (p=0.88, p = 0.16, respectively) (Figure 7). This indicates that there is no correlation between delayed and weakened cortical sensory processing and impaired overall balance.

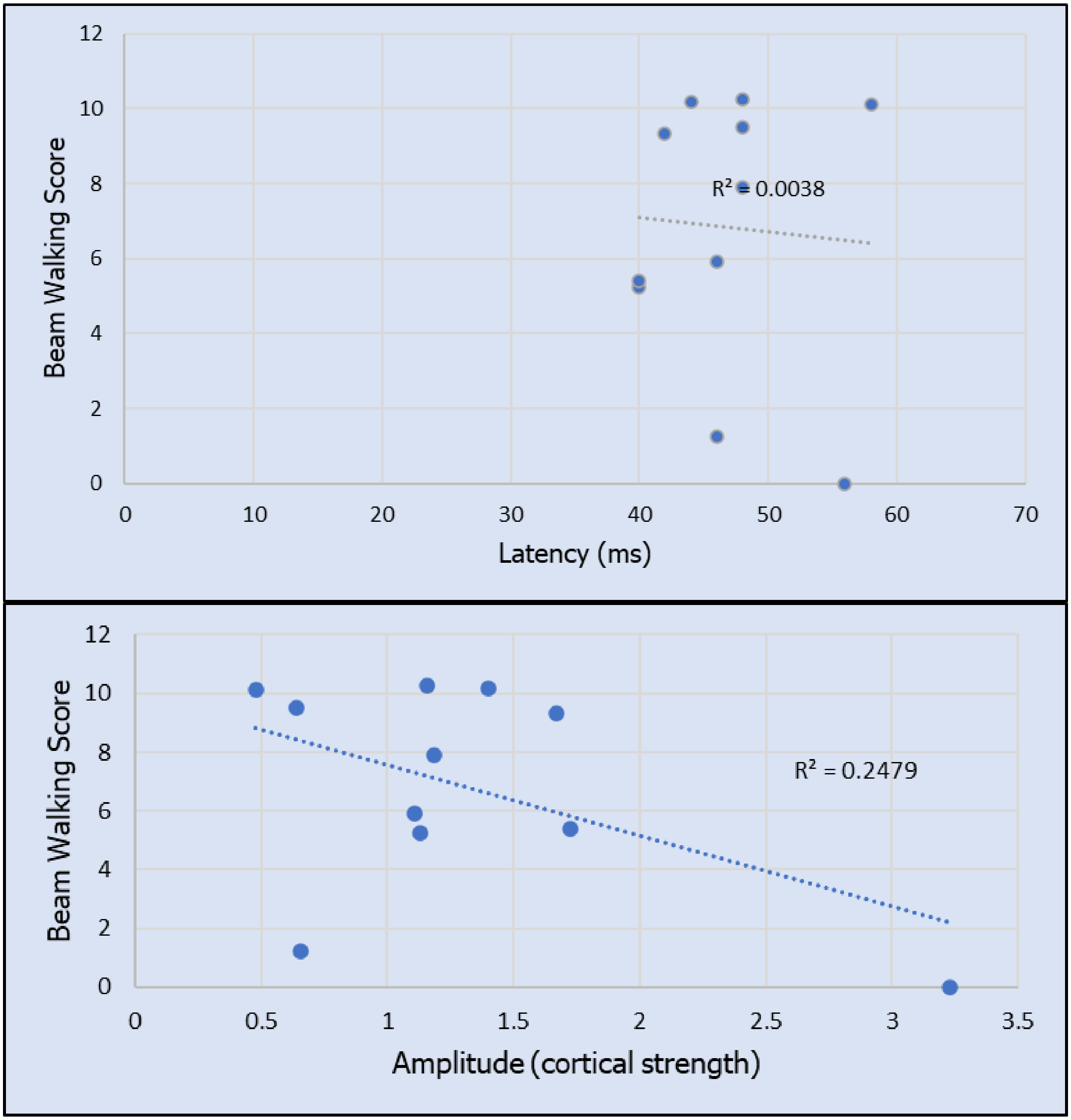


Figure 7: Latency and amplitude as correlated with beam walking score (feet).

miniBEST

There was no correlation between the latency of the P1 in the paretic standing condition and the miniBEST score (p=0.62) (Figure 8). However, there was a correlation between the amplitude of the P1 in the paretic standing condition and the miniBEST score (p=0.03) (Figure 8). But this correlation is due to an outlier. After removal of the outlier, there was no correlation between amplitude and miniBEST score (p=0.20). This indicates that there is no correlation between cortical sensory processing strength and performance on the miniBEST test.

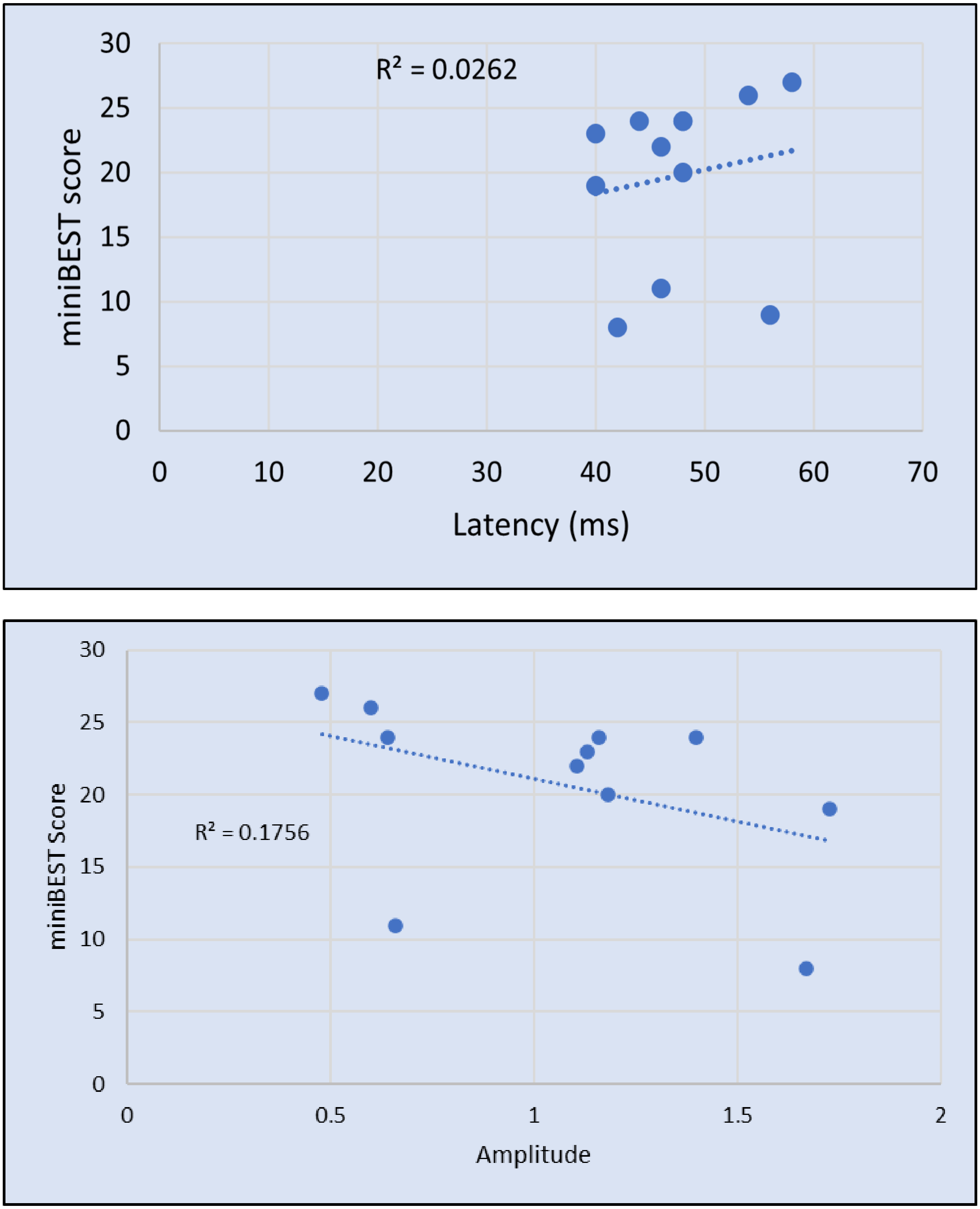


Figure 8: Latency and amplitude correlated with miniBEST score.

Perceptual Threshold

There was no correlation between the latency of the P1 in the paretic standing condition and the perceptual threshold on the paretic side of participants with stroke (p=0.14) (Figure 9). There was a significant correlation between the amplitude of the P1 in the paretic standing condition and the paretic side perceptual threshold (p=0.02) (Figure 9). However, there was an outlier perceptual threshold with a value of 50 degrees that skewed the data. After removing the outlier, there was no correlation between the amplitude of the P1 in standing paretic condition and paretic perceptual threshold (p=0.20).

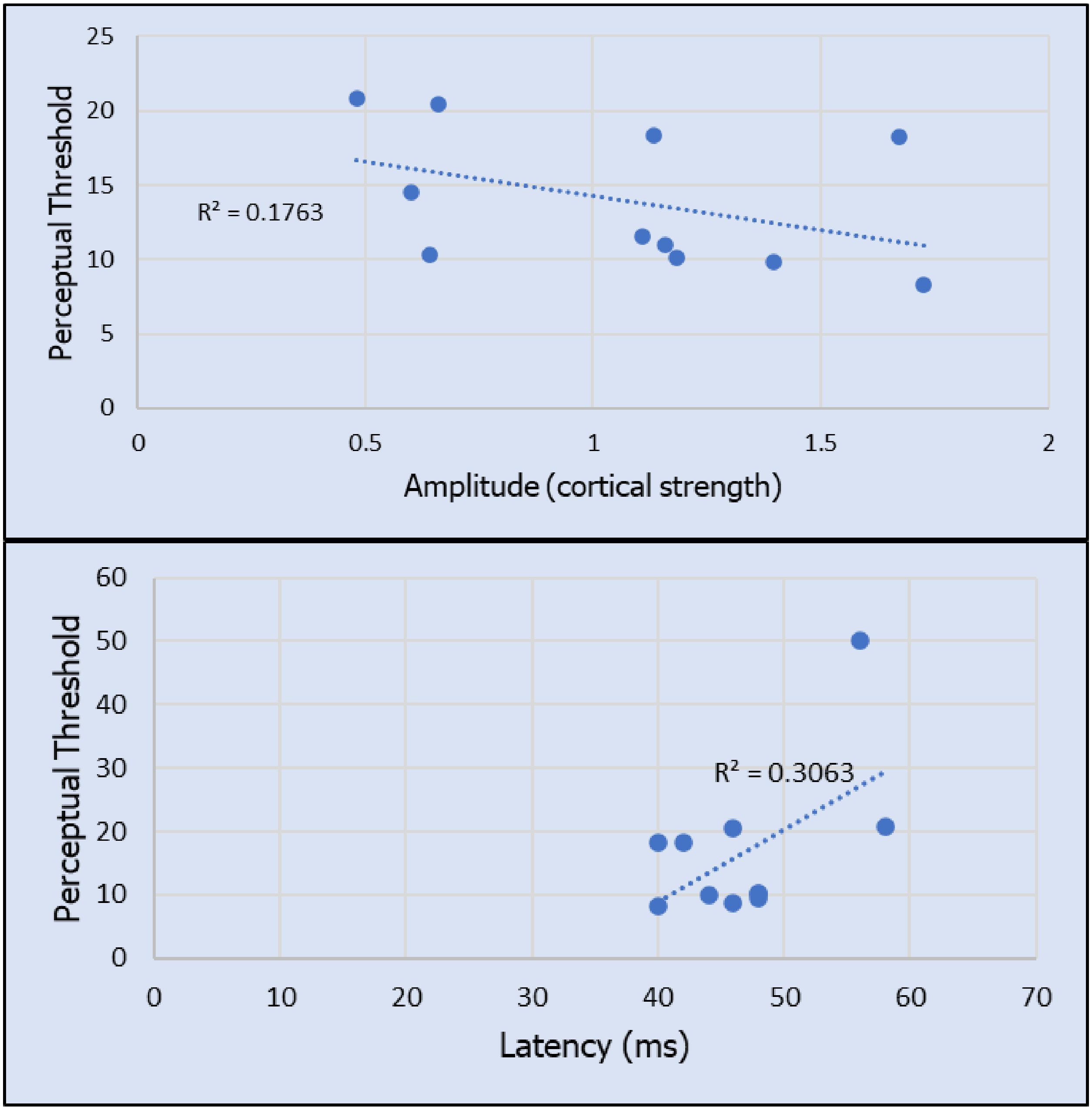


Figure 9: Amplitude and latency of the paretic side in standing as correlated with perceptual threshold (degrees) with outlier removed.

CHAPTER 6. DISCUSSION

Slowed latency of the P1 on the paretic side indicated that cortical sensory processing was delayed on the paretic side of individuals with stroke. This confirmed our hypothesis. This delayed reception of that information to somatosensory cortex thus delays its integration with other information during balance. Similar results were found in patients with stroke by stimulating SEPs at the shoulder, where increased latencies were also observed (Roosink, 2011). However, slowed cortical sensory processing on the paretic vs non-paretic side does not appear to explain impaired balance or impaired perception during WBM.

Amplitude of the P1 was significantly larger on the paretic side as compared to the non-paretic side as well as the healthy older adults in both sitting and standing conditions. This contradicts our hypothesis with the opposite result. This would indicate that cortical sensory processing produces a stronger signal on the paretic side of participants with stroke. This result begged the question of why this may have occurred, which is why we investigated whether there is a correlation between the amplitude of the SEP and the intensity at which the tibial nerve was stimulated during data collection. However, there was no correlation between amplitude of the P1 response and the intensity at which the tibial nerve was stimulated for both sitting and standing conditions on both the paretic and non-paretic sides. This indicates that the significantly increased amplitude of the P1 is not due to a methodological error. However, it remains unknown why the paretic side of individuals with stroke would have stronger cortical processing, not weaker. Investigating this result could give rise to future experiments. Research on rats with chronic stroke indicated almost completely diminished depolarization ability within somatosensory cortex, which contradicts results found here (Sweetnam, 2013). The increase in cortical processing strength observed in this study could be due to rearranged cortical mapping in somatosensory cortex that often occurs after stroke. By the chronic phase of stroke, surviving neurons often recruit from other healthy areas and cross normal boundaries of which neurons process sensory stimuli from other areas (Winship, 2009). This results in potential recruitment of neurons from the non-paretic side, which combined with remaining neurons on the paretic side, could result in both confirmation of reception of sensory signals in cortex as well as stronger cortical sensory processing on the paretic side.

Amplitude of the P1 was larger in sitting than standing in both stroke and control across all groups. This indicates that the strength of cortical sensory processing is stronger during sitting than standing for these stimulations. Investigating why this occurs may give more information regarding the role of cortical sensory processing during standing balance, especially if there is weaker cortical sensory processing during standing in whole-body motion. Sensory gating may occur more during standing position, resulting in decreased cortical sensory processing from decreased ability to filter out irrelevant sensory information. This may be due to observed asymmetry of cortical processing in patients with stroke during standing as compared to sitting, making it more difficult to maintain balance and making cortical sensory processing more asymmetric, which may be dangerous given paretic deficits (Wang, 2021).

For both latency and amplitude, there was no significant difference between the left and right side of healthy older adults. This indicates that differences seen between the paretic and non-paretic side in stroke are not due to differences due to side of body that would appear in any participant, not just a participant with stroke.

There was no significant correlation between measures of perceptual ability and cortical sensory processing. This suggests that reduced perceptual abilities during WBM cannot be explained by reduced cortical sensory processing. While impaired cortical sensory processing may have small effects on a case-by-case basis, it cannot explain differences in perceptual abilities during WBM in individuals who have had a stroke. Similarly, impaired balance predominantly did not correlate with impaired cortical sensory processing. This would suggest that overall, cortical sensory processing cannot explain reductions in overall balance ability. Balance requires integration from multiple sensory and motor areas, so logically, deficits in one of those singular areas may not be enough to impact overall balance abilities (Bong, 2020). Lack of correlation would correspond with previous findings on perception's necessary integration of sensory and motor information given that SEPs measure sensory processing (Bong, 2020). Because of the multiple factors, cortical sensory processing deficits alone cannot explain balance deficits. However, the miniBEST test measures many aspects of balance despite being an overall combined score. Certain types of balance that require the ability to stay balanced on one foot may correlate more with cortical sensory processing as these involve consistent feedback from the foot. However, tests within the miniBEST that require balance during WBM may not be correlated as much given the lack of correlation initially measured between cortical sensory processing and perception during WBM. This would be an area to study further to find if there are any more specific correlations with cortical processing and aspects of the miniBEST.

Given the overall lack of relationship between cortical sensory processing and impaired balance and perceptual ability, impaired cortical sensory processing is most likely not the neural connection between those deficits in individuals after stroke. Because of this, research must be directed to other areas involved in balance and perception during WBM that may be the link between the two. Cortical sensory processing is certainly involved in perceptual ability, but perception requires input from various modalities - the vestibular system, sensory information from body parts, feedback from the motor system. Prior research suggests that perception requires functioning feed-forward and feedback control from the motor system, which may involve cortical sensory processing, but more closely involves command of motor systems (Bolognini, 2016). Given that SEPs only measure cortical sensory processing of somatosensory information, they may not capture the sensorimotor complexity required for perception. Because of this, expanding research to other neural correlates may be more worthwhile. Prior research shows that the connection between sensorimotor and cerebellar networks may be damaged after brain injury, and investigating neural correlates of this pathway may result in more definitive results regarding neural correlates of perception and balance (Joubran, 2022).

Limitations:

There are various limitations to consider within this study, mainly the environment. These balance perturbations and measured SEPs occurred in a controlled setting, and although participants were not notified before perturbations, they did know that perturbations would eventually occur. For people with stroke who are living their daily lives, they often cannot anticipate potential falls and disruptions to balance. Additionally, disruptions to balance are not always backwards in a horizontal plane - they often involve curbs, stairs, and uneven surfaces. So, while these findings accurately display changes to sensory stimuli processing in a controlled setting, they may change in regard to balance during everyday life. However, the findings from this study can still help in discovering neural mechanisms that change after stroke in regard to response to balance perturbation and falls.

Another limitation of this study involves the use of somatosensory evoked potentials. Somatosensory-evoked potentials measure the amplitude and latency of neural signaling due to sensory stimuli and are essentially representative of the reception of sensory information. However, they are a very basic measurement and do not encompass all of the neural mechanisms involved in perception of WBM. Although they are useful, they are not all-encompassing of data necessary to construct a neural mechanism and would need to be combined with additional data to understand changes after stroke to balance. Perhaps perceptual deficits may be due to deficits in integration from primary motor cortex, posterior parietal cortex, and primary somatosensory cortex (Edwards, 2019). Inability to integrate information from all three of these areas would impair perceptual deficits, and study of the relationship between these areas may lead to a clearer neural mechanism to explain these perceptual deficits.

The physical conditions of patients also made collection of somatosensory evoked potentials difficult. Many participants, both with and without stroke, have physical conditions that limit SEP collection. For many, the process of eliciting an SEP can be uncomfortable, especially if one has heightened sensitivity in the feet. For others, conditions such as edema can make it physically difficult to reach the nerve used to elicit SEPs. And for some participants with stroke, feeling is limited or nonexistent in sensory modalities on the paretic side of the body, so SEPs cannot be elicited. So, for some participants, SEPs were only collected on one side or not at all.

Future Directions

Despite the lack of correlation between impaired cortical sensory processing and impaired balance and perception of WBM, comparing this data on a case-by-case level may provide novel insights into severe impairment. While there may not be a consistent relationship, severe impairment in sensory cortical processing may impair ability for overall balance as one cannot receive information from the feet. This could be an interesting place for a case study of particularly impaired individuals.

Amplitude of the SEP could be a fascinating place for potential further study. Amplitude was larger on the paretic side than the non-paretic side, which is the opposite of expected results. It is important to address why this may occur after stroke as well as how this may impact ability to function after stroke. Additionally, given that amplitude is larger in sitting than standing, it may be worthwhile to investigate the strength of cortical sensory processing differences in stance and gait. This may help create more specific therapies to address deficits after stroke in sitting in a different way than standing.

Additionally, the lack of correlation between cortical processing impairment and balance and WBM perception impairments indicates that cortical sensory processing may not be the connection between impaired balance and impaired WBM perception. This indicates that one of the many other processes involved during processing and integrating sensory information may be the key linking the two and begs further research.

These results provide excellent starting points from which research can expand. The main future goal would be to use this data, in conjunction with other data, to construct a neural mechanism of how balance is affected after stroke. Combining clinical, EEG, SEP, and perceptual threshold data can further this pursuit of a neural mechanism. However, this data would best serve to be combined with additional imaging data such as functional magnetic resonance imaging (fMRI) to create a complete picture of potential areas of disruption of proprioceptive abilities in post-stroke individuals. This can use larger data, such as fMRI, or even more specific data, such as working towards discovering why individuals with stroke experience deficits in amplitude and latency of SEPs as observed in this data.

Further understanding of disrupted pathways involved in balance and WBM perception will allow for more effective therapeutics for individuals with stroke. With more knowledge of what brain regions are affected and how they are damaged, neurologists and physical therapists can tailor interventions to individual patient deficits that they can identify through increased knowledge of how these proprioceptive deficits occur. Individuals with stroke, with these improved treatments, will have better outcomes, experience less falls and injuries, and live better qualities of life.

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