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UNIVERSITY OF CALIFORNIA,
IRVINE

# Neural Correlates of Proprioception

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Biomedical Engineering

by

Claire Marie Chaisson

Thesis Committee:
Professor David Reinkensmeyer, Chair
Associate Professor Michelle Digman
Assistant Professor Beth Lopour

2021

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**DEDICATION**

To

Mom and Dad

Thanks for the free housing and food

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## LIST OF ACRONYMS

| | |
|---|---|
| **AJPD** | Active Joint Position Detection |
| **AMEDA** | Active Movement Extent Discrimination Assessment |
| **BP** | Button Press(es) |
| **BNC** | Bayonet Neill-Concelman |
| **BCI** | Brain-Computer Interface |
| **CNS** | Central Nervous System |
| **CNV** | Contingent Negative Variation |
| **CP** | Central Parietal |
| **CPU** | Central Processing Unit |
| **DIP** | Distal Interphalangeal |
| **EEG** | Electroencephalogram |
| **EMG** | Electromyogram |
| **ERD** | Event-Related Desynchronization |
| **ERP** | Event-Related Potential |
| **ERS** | Event-Related Synchronization |
| **ETH MIKE** | ETH Motor Impairment and Kinesthetic Evaluation |
| **FINGER** | Finger Individuating Grasp Exercise Robot |
| **FIR** | Finite Impulse Response |
| **JPR** | Joint Position Reproduction |
| **MEMS-IMU** | Inertial Measurement Unit |
| **MCP** | Metacarpophalangeal |
| **ms or msec** | milliseconds |
| **PIP** | Proximal Interphalangeal |
| **PJPD** | Passive Joint Position Detection |
| **PMDD** | Passive Motion Direction Discrimination |
| **PMDT** | Passive Motion Detection Threshold |
| **RASP** | Rivermead Assessment of Somatosensory Perception |
| **SMR** | Sensorimotor Rhythm |
| **TTDPM** | Threshold to Detection of Passive Motion |
| **TTL** | Transistor-Transistor Logic |
| **USB** | Universal Serial Bus |

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Completing a thesis project is expected to be an involved, time consuming, and challenging task. To say that the COVID-19 pandemic added another degree of difficulty would be an understatement. Finishing my UCI graduate studies remotely from New York, navigating the various restrictions and limitations brought about by the COVID-19 pandemic, and enlisting the service and facilities of NCAN certainly added a different dimension to my project. It was only with the help, encouragement, and support of so many people that I was able to navigate this process and produce this thesis. It is with sincere gratitude, therefore, that I acknowledge those whose help made the completion of this project possible.

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## ABSTRACT OF THE THESIS

Neural Correlates of Proprioception

by

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Master of Science in Biomedical Engineering

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**Background:** Robot-assisted rehabilitation movement training is becoming increasingly popular but produces variable benefits. A recent study showed that the benefits of robotic hand training after stroke decreased if participants could not accurately sense finger movement at baseline. In that study, finger proprioception was measured with a new test called the "Crisscross" test in which participants pushed a button when they thought their index and middle fingers were overlapped as a robot exoskeleton slowly moved their fingers past each other [5]. The goal of this project was to search for a neural correlate of proprioceptive processing during the Crisscross test. Since previous work found that proprioception influences Event Related Desynchronization (ERD) measured before hand movement, we hypothesized that ERD before the button pressing response during the Crisscross test would reflect proprioceptive error. **Methods:** Five healthy participants (4 male, 1 female, aged 22-66) had their right index and middle fingers randomly moved in crossing patterns by a robotic exoskeleton and were asked to press a button with their left hand when they believed their right fingers were perfectly aligned. We measured ERD using EEG electrodes over the motor area contralateral to the button pressing hand. **Results:** The magnitude of the ERD associated with the button press during the Crisscross test was weakly correlated with the size of the proprioceptive error on each trial for four participants. **Conclusions:** Although more evidence is needed, these results suggest the intriguing possibility that ERD may serve as a novel neural correlate of proprioceptive processing.

# I. INTRODUCTION

Imagine yourself walking along Newport Beach. You smell the salt air and feel the sand between your toes. As you walk you hear the sounds of kids playing. You see surfers riding waves to the shore. This is all possible thanks to your five senses….touch, taste, vision, smell and hearing. These five senses allow us to take in information from the outside world, where the brain processes it and we respond. But what if there were more than five senses?

Stand up on your feet and close your eyes. Good. Now stand on one leg while closing your eyes. Your body was able to stand on one leg with your eyes closed in part due to its sense of proprioception. When your eyes were closed you still knew where your legs, hands and fingers were, and you did not fall (hopefully). Why is this?

Broadly speaking, proprioception is our sense of position in space, but to fully understand proprioception it is important to understand how the underlying mechanisms of proprioception work. Instead of taking information from the outside world proprioception takes information from inside the body, using internal sensors. These internal sensors are known as proprioceptors and convey information to the body about, among other things, muscle length, tension and joint angles. Proprioceptors send signals to our brains via the nervous system. Although you just performed a more complex proprioceptive task (standing on one leg with your eyes closed) you can perform a quick and simpler task to test how good your proprioception is. Just close your eyes and touch your finger to your nose. This is an example of being aware of your position in space.

Proprioception helps us perform simple tasks such as getting dressed in the dark, and more complex tasks like attaining yoga poses (the "scorpion" comes to mind). Our sense of proprioception helps us to execute some pretty cool tasks. Dribbling a basketball with our eyes

closed, throwing a ball without looking at the throwing arm, or just simply walking are a few examples that come to mind. It should be evident that this is a sense that we use just as much as the other five, and we would not want to lose it.

People who have lost proprioception or have experienced decreased proprioception suffer from balance issues, lack of coordination, and exhibit clumsy movement. Causes of proprioceptive deficits include brain injuries, stroke, and Parkinson's disease. Previous studies have shown changes in proprioception are also correlated with aging [1] [26]. Proske & Gandevia (2012) showed that proprioception deteriorates with age and concluded that this results in the elderly experiencing an increased risk of falling [28]. Rand (2018) assessed the proprioception of 102 people with chronic stroke using the Thumb Localization Test (TLT) and found that mild to moderate proprioceptive deficits in people with chronic stroke were "negatively associated with motor, functional and daily-use of the affected upper extremity" [10].

Although the behavioral aspects of proprioception have been well studied, and invasive neurophysiological studies have identified brain areas and circuits associated with proprioceptive processing, a non-invasive neural correlate- a signal in brain activity that correlates to proprioceptive ability- has not yet been identified. This leads to the question my thesis seeks to address, is there a signal in the Electroencephalogram (EEG) that corresponds to performance in proprioceptive tasks?

## A. Motivation

Building on previous work, there are two main bases for why finding a neural correlate(s) of finger proprioception would be interesting. First, Rowe et al., (2017) found that baseline finger proprioception, measured with the Crisscross test using FINGER (Finger Individuating Grasp Exercise Robot), predicted how much people benefited from three weeks of Guitar-Hero training with FINGER [5]. Secondly it has been shown that training neural correlates of finger movement with a BCI (brain-computer interface) approach helps people with stroke and unimpaired people move better [23] [39]. If a neural correlate of proprioceptive sensing were known, it is possible that people could train these EEG features with a BCI and improve their proprioceptive sensing (which might help them respond better to robotic finger training).

Identifying a non-invasive neural correlate of proprioceptive ability would provide insight into the brain circuits that process proprioception. If EEG signals related to proprioception could be pinpointed, it would follow that improved treatment methods, potentially using brain-computer interface techniques to train proprioceptive-related brain signals, could be pioneered and applied to a wide range of neurological disorders. If we can understand where proprioceptive signals in the brain originate, we can learn to treat and repair them in people with impaired proprioception. Furthermore, it is thought that training proprioception can benefit individuals in terms of improved joint stability.

Rinderknecht et al., (2018) states that only a few assessments are used clinically- the up-down test, dual joint position test, finger finding and positional mimicry [7]. Clinically used assessments measure joint position sense, force perception and movement sense, among others [11]. These traditional (observer-based) methods for quantifying proprioception have raised concerns about the reliability of these measurements [7] [38].

Individuals that could benefit from proprioceptive training span the spectrum and include children with proprioceptive deficits, adults with decreased motor skills, and athletes. Applying robotic assistance (using a machine to aid in performing a task) to those individuals would allow for streamlined training of proprioception. Individuals with impaired hand function, such as those affected by stroke, could benefit from the use of robots in rehabilitation [15]. Training proprioception has the potential of "healing" those with motor deficits, whereas current treatments often seek to have people learn to adjust to their motor deficiencies. In order to apply robotics in proprioceptive training, proprioception must be properly quantified in a repeatable and uniform manner, hence the motivation for this study. It was with this in mind that this study, employing robotic technology with an electrophysiology recording approach, sought to find a neural correlate of proprioception.

## B. Hypothesis: Signals in the EEG

Potentials in the brain have been identified using an EEG as a testing method. One of the most common is the event-related potential, commonly referred to as an ERP. ERPs occur in response to a stimulus or specific event and are time locked to that event [30]. Sur & Sinha., (2009) explain the different types of ERP waveforms that have been discovered, including the P300, N200 and contingent negative variation (CNV) [30]. The P and N represent positive or negative deflections in the EEG and the number corresponds to the milliseconds before the event [30]. When looking for a neural correlate of proprioception, I would expect to find an ERP. An event (e.g., the crossing of fingers with vision occluded during the Crisscross test) will cause a deflection in the EEG.

Pfurtscheller (2001) concluded that in addition to an ERP, an event-related desynchronization (ERD) or event-related synchronization (ERS) can also occur in the EEG [31].

An ERD represents an amplitude decrease and an ERS represents an amplitude increase in the EEG. Norman et al., (2016) reported that 10 out of 12 participants exhibited an ERD approximately 600-900 ms prior to the start of movement when the participant remained passive, and the robot actively moved the participants fingers [24]. My experiment is similar to the condition in Norman et al., (2016). Therefore, I would expect to see an ERD around 600-900 ms prior to the event (e.g., participant pressing the button when they perceived their fingers were perfectly aligned).

There are different possibilities of where the proprioceptive signal may be seen in the brain and when it will appear in the EEG. ERPs can be observed in any of the frequency ranges of the EEG: delta (0-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (13-30 Hz) or gamma (>30 Hz). When a person is relaxed, they exhibit a decrease in alpha whereas if the person were engaging in a task, their alpha rhythm would increase. For this experiment I would expect to see alpha activity over the sensorimotor cortex, which is referred to as the mu rhythm. McFarland et al., (2000) found that imagery and movement were associated with mu and beta rhythm desynchronization in the sensorimotor area [32]. Furthermore, it was shown that mu rhythm desynchronization was focused over the central-parietal areas (CP3 and CP4) [32]. As the parietal lobe is responsible for processing proprioceptive sensations, it is possible that deflections in the amplitude of the EEG will be seen in the electrodes placed above the parietal lobe. It is also possible that a proprioceptive evoked potential may be seen in the EEG. Studies claim that the motor cortex is involved in proprioception related potentials [29]. As proprioception has a motor component, it is possible that proprioception related activity in the EEG may be seen over the motor cortex. Marini et al., (2019) found there was a higher activation contralateral to the moving limb during a robot-based proprioceptive task in the mu frequency band [18].

Based on the above research, my hypothesis suggests that the strength of the ERD that occurs before the button press on a trial of the Crisscross test will be related to the proprioceptive error on that trial. I would expect to see an ERD in the 8-12 Hz frequency in the left hemisphere 600-900 ms before the proprioceptive task (crisscrossing of index and middle fingers) is performed. I believe that ERD will occur over the somatosensory or motor cortexes (over the parietal or frontal lobes). This may seem like a large area but as proprioception involves sensing and movement, and as the brain is interconnected, I do not think it is out of the realm of possibility to say proprioceptive signals may be seen in more than one region of the brain. However, the occipital and temporal lobes can be ruled out as I do not think proprioceptive signals will be observed there.

## C. Applications and Relevance in Society Today

Knowledge of neural correlates of proprioception could in turn be applied to every facet of life. Examples include rehabilitation therapy, sports medicine, and orthopedic care, as well other civilian and military applications.

FINGER has the potential of being used as a tool to aid in rehabilitation for a variety of motor skill deficiencies. This could include those who have Parkinson's disease, head injuries, experienced a stroke, and other conditions where proprioceptive loss has occurred. Improved proprioception would provide individuals with a better quality of life as their movements would be more fluid, coordinated, and not as spastic, making it easier to perform everyday tasks. Norman et al., (2018) reported that BCI technology with robot assisted movement has been shown to be a promising tool for enhancing motor recovery after stroke [23]. Norman et al., (2018) also found that learning to control person-specific pre-movement SMR (sensorimotor rhythm) features associated with finger extension can improve finger extension ability after stroke for some

individuals [23]. As more than 795,000 individuals in the United States suffer from a stroke each year, this has the potential to benefit many people [40].

Dietz (2002) pointed to the potential of new therapy treatments that could be aimed at utilizing the plasticity of the central nervous system (CNS). This resulted from the growing acceptance of the postulate that certain movement disorders involved both the defective use of afferent input and secondary compensatory processes [25]. Knowing that a neural correlate of proprioception exists and using FINGER as a training modality, it would follow that the plasticity of the CNS could be utilized.

Proprioception training could also be used both as injury prevention and for higher level training. Proper running techniques, pitching form and consistent golf swings could all prevent injury. At the same time athletes could hone their skills, allowing them to reach higher levels of performance. Imagine a golfer being able to square the clubface at impact consistently. Goodbye slice! Even non-athletes could benefit from better proprioception. For example, typing on a keyboard without looking, or playing the piano without looking at the keys. Proprioceptive training even has military applications such as performance imagery [42].

Babies with proprioceptive deficits could also benefit from proprioceptive training. Although babies could not use FINGER as a tool to improve their proprioception, knowing a signal in the EEG would be beneficial in diagnosing a proprioceptive deficit. If an EEG test were performed on a baby and the signal for proprioception was abnormal, the doctor could advise the parent on possible proactive therapy options. Chu (2016) reviewed proprioceptive measures that are available for occupational therapists to use in children with proprioceptive deficits [11]. These proprioceptive tasks, among many others, could be improved with FINGER.

# II. BACKGROUND

## A. Proprioception and Related Areas

### 1. *Proprioception and its History*

There has been some confusion over the exact definition of proprioception and its related term (kinaesthesia). Over the years many papers have sought to clarify and explain the exact definition [8] [14] [28] [29]. Hillier et al., (2015) recognized the difficulty in defining proprioception by citing the variety of tests that were being employed in efforts to measure it [19]. They gave due mention to the difficulty presented by citing its complexity and the multifaceted aspects of kinaesthesia and position sense. They thought it necessary to emphasize these aspects in order that they be quantified and acknowledged to the degree possible and taken into consideration by future research in order to obtain a baseline of standardization regarding the definition and assessment of proprioception [19]. For the purposes of this paper I will provide a brief overview of how the word proprioception came to be. The term proprioception is a combination of the Latin proprius and perception, translating to one's own perception [9]. The study of position movement sensation dates to 1557 when Julius Caesar Scaliger described it as a "sense of locomotion" [42].

Han et al., (2016) does a good job of describing the timeline of how the concept of proprioception came to be. In 1826 Charles Bell described how one nerve conveyed information from the brain to the muscle and another nerve conveyed information from the muscle to the brain [8]. In 1886, Henry Bastian used the word kinaesthesia, a compound of the Greek kinein and aesthesis, which translates to move and sensation [8]. It wasn't until 1906 that Charles Sherrington coined the term proprioception [8]. Sherrington defined proprioception as "the perception of joint and body movement as well as position of the body, or body segments, in space" [8]. Since

Sherrington's landmark paper, researchers and scientists have been studying proprioception and how it relates to body sensing and movement. The definition of proprioception I will use throughout this paper is "the sense through which we perceive the position and movement of our body, including our sense of equilibrium and balance, senses that depend on the notion of force" [41].

### 2. *Proprioceptors*

Proprioceptors convey information to the brain and can be compared to the rods and cones of the eye. Proprioceptors are a type of mechanoreceptor. The types of proprioceptors are Golgi tendon organs, muscle spindles, Pacinian corpuscles and Ruffini end organs. Each of these has its own role when a proprioceptive task is performed. Golgi tendon organs are found in skeletal muscle and sense changes in force. Muscle spindles are found in muscle fibers and respond to the stretch or change in length of the muscle. Pacinian corpuscles and Ruffini end organs are found in the skin and respond to mechanical deformations [33]. Golgi tendon organs, Pacinian corpuscles, and Ruffini end organs are types of joint capsules. These proprioceptors send sensory afferent neurons through the spinal cord to the brain. This process lets us know about our body's position and orientation in space.

Dietz (2002) describes that damage to the peripheral or central nervous system can cause one's proprioception to become impaired which can lead to a movement disorder [25]. Proske & Gandevia., (2012) stated that when the muscles of older people were dissected, it was found that there were fewer intrafusal fibers and primary endings of spindles [28]. These both contribute to our sense of proprioception which may explain why there is a decreased proprioceptive sense with age.

### 3. *Sensorimotor and Somatosensory Systems*

From a young age we are in motion and taking in the outside world. As adults we continue to absorb the information that surrounds us. Whether it is simply walking to the car after work or hiking up Mount Whitney, movement and senses are embedded in our everyday life. Movement occurs when we desire to do something or move. If you want to move your hand, your brain sends a signal through the nerves in your body to your hand. This signal tells the muscles in your hand to contract. When our muscles contract, movement occurs. Our motor and sensory systems work together to help us in our daily lives.

The nervous system can be broken down into the peripheral and central nervous system. Han et al., (2016) maintained that just exactly how each played a role in proprioception had yet to be precisely determined [8]. The central nervous system consists of the brain and spinal cord while the peripheral nervous system consists of the autonomic and somatic nervous systems. The somatic nervous system can be further broken down into afferent (sensory) and efferent (motor) components and is responsible for communicating with sense organs and voluntary muscles [36]. Somatosensory refers to a sensation that occurs in the body such as pressure felt when someone presses their hand on your arm. Merely having senses is not enough, the body needs a way to process the information the senses take in, which is the job of the somatosensory cortex. Soma is Greek for body [34] and combining that with the senses, somatosensory translates to the body's senses. Charles Sherrington noted that one of the main functions of the somatosensory system is proprioception [34]. Additionally, Ingemanson et al., (2017) found that the best predictors of treatment gains could be derived from somatosensory, as opposed to motor measures [17]. This confirms the importance of examining the somatosensory region of the brain. Hillier et al., (2015)

explained that the somatosensory system could include proprioception as one of its components [19].

The sensorimotor system is where motor and sensory information come together and is responsible for maintaining joint homeostasis when the body moves [37]. The somatosensory and motor areas are located next to each other in the brain. A proprioceptive task of the right hand will be represented in the left hemisphere of the brain. The motor cortex in the right hemisphere of the brain represents the motor activity that occurs on the left side of the body. Both the somatosensory and sensorimotor systems play a prominent role in proprioception.

## B. Assessing Proprioception

In clinical and research practices it is crucial to have the same measure of proprioception so a fair comparison can be made. Proprioception can be assessed at different parts of the body including the ankle, knee, wrist and shoulder. Han et al., (2016) and Hillier et al., (2015) conducted reviews on assessing proprioception [8] [19]. I will summarize their findings as they relate to my experiment.

The intricacies of neurophysiological processes prohibit a definitive measure of proprioception. However, a variety of methods have been developed that can be used to monitor proprioceptive acuity [19]. Hillier et al., (2015) described how tests have focused on two aspects of proprioceptive function- the detection of static position and the detection of motion [19]. The three main tests of proprioceptive ability are joint position detection (active/instantaneous position or passive, AJPD or PJPD), passive motion detection threshold (PMDT) and passive motion direction discrimination (PMDD) [19]. Hillier et al., (2015) conducted a review and found the knee was the most commonly measured body part when assessing proprioception. The distal joints

of upper limbs such as the fingers were less commonly measured. Assessing proprioception at the finger follows similar techniques to those used for assessing proprioception at the knee or ankle joint.

Testing proprioception can be active or passive. A machine could move a person's limb (passive movement), or the person can move on their own (active movement). The origin of proprioception assessment techniques dates to the late 1800s with the study of psychophysics [8]. When conducting psychophysical experiments there are three methods used. The first method is the method of adjustment where the participant controls the level of the stimulus by adjusting the level until they feel it reaches the reference stimulus. The second method is the method of limits where the stimulus is at a very low or high level that it cannot be detected by the participant and is slowly adjusted until the participant perceives it. Finally, the third method is the method of constant stimuli where the stimuli is presented in a random order to the participant [8]. Three current testing protocols used in proprioception tests are the threshold to detection of passive motion (TTDPM), joint position reproduction (JPR) and active movement extent discrimination assessment (AMEDA). All are forms of the three classical methods used in psychophysical experiments [8]. When utilizing JPR, a target position is given to the participant and the participant is asked to reproduce the target position. In TTDPM, the stimulus is increased until the participant reports they can perceive it. An example of an AMEDA experiment would involve moving a participant's arm to five different positions. The arm is then moved back to a particular position and the participant is asked to identify what position that is, without feedback.

One widely acknowledged clinical test of finger proprioception is the up or down test. The up or down test is performed by holding a person's index finger while their eyes are closed, and they must determine whether their finger is being moved up or down. However, one pitfall of the

up or down test is it only recognizes proprioceptive loss from gross sensory deficit [4]. A more popular clinical measure of note is the Rivermead Assessment of Somatosensory Perception (RASP). RASP was "generally considered to be a valid and reliable tool but with low precision" [19].

## C. Robotic Methods to Detect Finger Proprioception

### 1. *Overview*

Robotic methods have proven they can successfully quantify proprioception [1] [4] [6] [7]. Robotic methods allow for repeatability in clinical and research settings. The studies mentioned below all use robots in assessing proprioception and have shown similar, if not better, results than traditional assessments. However, using robotic methods in assessing finger proprioception is still a relatively new field and there is room for technological improvement. As a field, rehabilitation is headed towards individualized treatment, where patients have a tailored rehabilitation therapy unique to them. Customizing therapy better helps patients by honing in on their specific needs. Treatment methods for proprioceptive deficits could be improved with the use of robotic devices. Several studies have been conducted to detect proprioception using robotic devices at different locations in the body [3] [12]. This summary focuses on robotic methods used at finger joints as my experiment analyzes finger proprioception.

### 2. *Proprioceptometer*

Wycherley et al., (2005) created a portable and compact device known as the Proprioceptometer for measuring joint position sense in the metacarpophalangeal (MCP) joint of the index finger [4]. The Proprioceptometer allows for individual movement of the index finger, can be used with either the right or left hand, and can be adjusted to different hand sizes. The wrist is velcroed to a platform and the index finger is isolated to allow for full flexion and extension of

the MCP joint [4]. A surface mounted finger silhouette rotates above the index MCP joint indicating the target angle. When a participant is analyzed, the full examination takes only 15 minutes. This not only allows for a fast clinical assessment, but helps the user stay engaged throughout the entire examination. If the device were used in a physical therapy center, it would allow multiple patients to be seen in back-to-back appointments.

### 3. *Robotic Sensory Trainer*

Rinderknecht et al., (2018) used the Robotic Sensory Trainer to measure proprioceptive deficits in hopes to better understand proprioceptive function's involvement in recovering from stroke [7]. Participants placed their arm on two cushions and their index finger on the finger mechanism, securing both with Velcro straps. A touchscreen computer controls finger displacements and provides the user with feedback [7].

### 4. *ETH MIKE (Motor Impairment and Kinesthetic Evaluation)*

Zbytniewska et al., (2019) designed ETH MIKE for the assessment of proprioceptive, motor and sensorimotor hand impairments with the main criteria being that it is easy to learn, quick to set up and easy to individualize patient treatment [6]. The user places one finger in ETH MIKE and rests their hand on the handle of the robot. A tablet provides the user with instructions and can take in patient data which helps streamline the intake process in clinical settings [6]. ETH MIKE can be used with the right or left hand, and can be adjusted to fit different hand sizes [6].

### 5. *FINGER (Finger Individuating Grasp Exercise Robot)*

FINGER has been used in numerous studies and has proven to be an effective tool for experimental use [1] [2] [5] [17] [21] [23] [24]. FINGER consists of two single degree-of-freedom (DOF) 8-bar mechanisms. The mechanisms are on top of each other, one for the index finger and one for the middle finger. To use FINGER, the participant places their index and middle fingers

into the finger cuffs and rests their wrist on the support. The straps around the index and middle fingers can be loosened or tightened to allow for a proper fit for each user. FINGER allows for individuation of the index and middle fingers. FINGER can be utilized in a variety of ways including a sensory test, using a Guitar Hero-like application, and active and passive range of motion tests. This allows for multiple uses with the same robot, which may be beneficial in clinical settings.

#### 6. *Discussion*

Conclusions in the field point to the use of robots becoming more popular than traditional measures to assess proprioception. There is also an increasing interest in studying finger proprioception as opposed to just hand, arm and wrist proprioception. I am convinced the future of rehabilitation therapy involves the use of robots and leans towards individualized treatment. Robots such as FINGER and ETH MIKE are compact and easier to use, which allows the end user to have a better and more personalized session with the robot. As a result of the COVID-19 pandemic, people are opting to limit their contact with others. Therefore, a compact proprioceptive device that can be purchased and used at home may prove to be successful. FINGER can also be incorporated with games such as Guitar Hero making it more appealing for people to improve their motor skills.

## D. Methods of Experiments with FINGER

Being that FINGER was used for my experiment, I will review the methods of other experiments that used FINGER to test finger sensation. Ingemanson et al., (2019) conducted a study where the objective was to analyze the neural basis of finger proprioception deficits after stroke [2]. Passive finger position sense was measured using FINGER. FINGER slowly moved the index and middle fingers of the participant in opposite directions during 12 finger crossing

movements. For each finger crossing movement participants had to press the spacebar on a keyboard when they believed their index and middle fingers were perfectly aligned on top of each other. The data from this study showed that finger proprioception is best measured using a quantitative device, proving FINGER can be used as an accurate method to assess proprioception.

Rowe et al., (2017) examined the therapeutic effects of high and low levels of robotic assistance during finger training using FINGER [5]. Participants used their index, middle or both fingers to play Guitar-Hero for 3 hours a week, for 3 weeks. Rowe et al., (2017) found that baseline proprioception, which was measured using FINGER, predicted how much participants benefited from playing Guitar-Hero [5].

McFarland et al., (2020) and Norman et al., (2018) showed that it is possible to identify features of the EEG that correspond with how well a person moves their fingers [23] [39]. People were then trained to learn how to modulate those features of the EEG using a BCI. As a result of modulating the EEG features (prior to finger movement), people (healthy and unimpaired) showed improvements in finger movement ability [23] [39].

Ingemanson et al., (2015) showed that FINGER can be used as a tool for detecting age-related decline in proprioception [1]. The experiment consisted of a single session with two tasks- an overlap and movement onset task. During the overlap task participants had to press the spacebar when they perceived their index and middle fingers were directly on top of each other. The movement onset task involved the participant pressing the spacebar when they perceived any passive movement in their fingers [1]. In each task, a total of 12 crossover movements occurred over two minutes and were performed on each hand. Each task was performed with and without visual feedback. Ingemanson et al., (2015) showed that hand dominance has no effect on the overlap or movement onset task [1].

The paradigm for this project used an overlap task and was based on Ingemanson et al., (2015) [1]. As Ingemanson et al., (2015) showed that vision makes up for lack of proprioception, one vision run (~12 trials) and ten non-vision runs (~120 trials) were conducted to ensure more trials of a pure proprioceptive task were performed.

# III. METHODS

## A. Systems Setup

The experiment setup can be separated into three systems that all run concurrently. The first system being the FINGER exoskeleton robot, the second a motion tracking MEMS-IMU (inertial measurement unit) (Xsens MTw Awinda) and the third the Electroencephalogram data acquisition system (G.tec GmbH, Austria).

### 1. *System One: FINGER*

System one is FINGER and is used to perform the proprioceptive task. The hardware consists of the host computer, target computer and FINGER. The host computer operates in the Windows environment and has the Crisscross task executable (written in Visual Basic). This is pre-programmed to initiate and stop the finger movements for each trial and to record the key press and robot movements. The host computer is connected via an ethernet cable to the target computer which allows the host and target computer to communicate with each other using TCP/IP protocol (e.g., the host computer sends the Crisscross task executable to the target computer). The target computer is a central processing unit (CPU) that runs the xPC environment and controls and reads signals from the robot actuators.

FINGER is a unit encased in plexiglass, making the hardware of FINGER easy to set up. FINGER uses two identical planar 8-bar mechanisms which curl the index and middle fingers. Finger cups with custom ratcheting straps attach to the participant's right proximal and middle phalanges while their arm rests on the table and wrist lay in the wrist cuff. Two brushless linear motors ("Servo Tube" actuators, Dunkermotoren STA 116-168-S-S03C) independently actuate the 8-bar finger curling mechanisms [21]. The amplifier (Copley Controls ACJ-055-09-S) controls

current to the actuator [21]. Accelerometers (Analog Devices ADXL325EB) are mounted at the end of the actuator rods. More detailed information on FINGER can be found here [21]. Figure 1a shows a picture of FINGER.

The software needed for FINGER includes xPC Target (Mathworks Inc., USA) and the executable in Microsoft Visual Basic that runs the Crisscross task (a custom-made program for FINGER). FINGER can be used passively or actively. For this experiment FINGER actively moved the participants fingers in a crisscross motion while the participant remained passive. Figure 1b shows the joints and phalanges of the fingers used when placed in the FINGER exoskeleton robot. The participant lays their wrist in the black cuff, and their index and middle fingers into the gold and blue cuffs, as shown in Figure 1c. FINGER is mechanically limited (0 to 60 degrees) so as to not cause harm to the user.

Each finger is made up of the phalanges. There is a distal, median and proximal phalanx. The cuffs on the FINGER robot attach to the middle and proximal phalanges. The MCP joint is used in grasping and pinching. The proximal interphalangeal (PIP) joint extends and bends the finger. The distal interphalangeal (DIP) joint connects the distal phalange and the medial phalange.

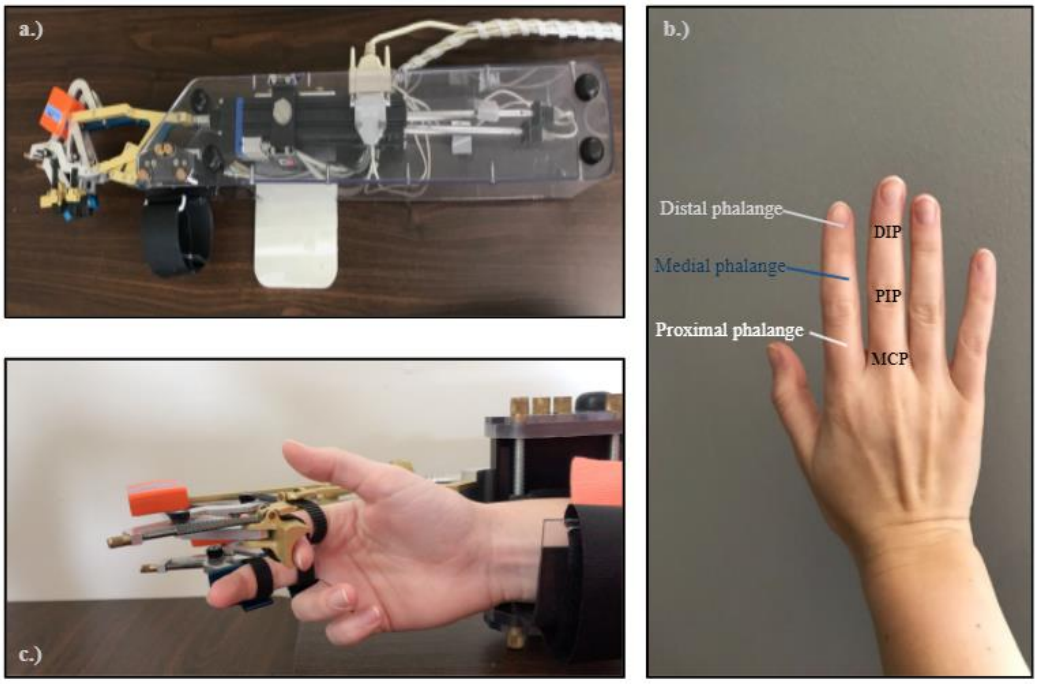



**Figure 1: Finger Placement in FINGER**

1a.) Finger Individuating Grasp Exercise Robot with Xsens sensors placed on the index and middle finger mechanisms. 1b.) Locations of finger joints and phalanges. 1c.) A person using FINGER from a side view. The participant places their right wrist on the wrist cuff and their proximal and medial phalanges of their index and middle fingers into the finger cuffs. The wrist and finger cuffs can be loosened or tightened.

### 2. *System Two: Motion Tracking*

The Xsens MTw Awinda sensors were used to record the button presses the participant made on the laptop and to send timestamps to the EEG system. Xsens is portable and easy to use and install. The corresponding software is MT Manager which is used to enable the sensors to visualize and record sensor data [20].

The MTw Awinda system is a wireless human motion tracker system which includes multiple sensors for complete body measurements. For this experiment three sensors (2" x 1.25" x .5") were used. The sensors are wireless MEMS-IMU sensors that have an accelerometer, gyroscope and magnetometer [20]. The docking station is a base unit where the sensors are

charged and the motion tracking information received. Additionally, the Xsens base unit allows a 3.3V transistor-transistor logic (TTL) pulse via a Bayonet Neill-Concelman (BNC) connector to be sent out when the recording is started. This allows the Xsens and EEG data streams to be aligned. The docking station is also connected (via USB) to a computer (Windows Operating System) that runs the MT manager software. The participant presses the spacebar on the laptop when they feel their index and middle fingers on their right hand are perfectly aligned. This is the proprioceptive task and going forward will be referred to as the button press.

The button press is recorded via a sensor on the spacebar. The index and middle finger movements are captured via sensors on FINGER. Figure 2 shows the sensors on the spacebar and on the middle and index finger mechanisms of FINGER. As FINGER moves, the position of the participant's fingers is recorded. When the participant presses the spacebar, it can be matched to the two sensors on FINGER.

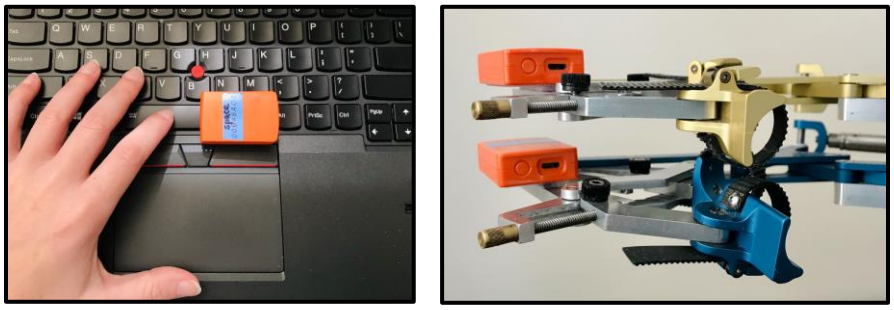


**Figure 2: Xsens Sensor Placements**
The participant uses their left hand to press the spacebar on the computer and the sensor picks up the exact timing of the button press. The sensors on FINGER (as well as FINGER) record the position of the participant's fingers.

### 3. *System Three: EEG Data Acquisition*

System three is the EEG Data Acquisition system. There are two USB bio signal amplifiers from g.tec Medical Engineering (GmbH, Austria). EEG is recorded with a reference and ground on the mastoid bone, located behind each earlobe. The gUSB amplifies and digitizes weak EEG

signals. The amplifier also receives a digital synchronization pulse from the Xsens at an isolated digital I/O port. This is recorded in sync with the EEG data. The electrodes (made of tin) non-invasively measure electrical activity in the brain. There were 32 (34 including reference and ground) electrodes pre-set in an elastic cap according to the International 10-20 System in a modified montage. Electrodes cover the motor and somatosensory areas where proprioceptive evoked potentials and ERD have been observed in other studies. The electrodes in the cap are connected to the amplifier via ribbon cables as shown in Figure 3. Conductive electrode gel (Electro-gel) is applied to the skin at each electrode site to reduce impedance at the skin-electrode interface.

The software for the data acquisition program is BCI2000 [13] [16] [22]. BCI2000 is an open-Source software designed for data acquisition, stimulus presentation, and brain monitoring applications [35]. More information can be found at [35] where BCI2000 is available to download.

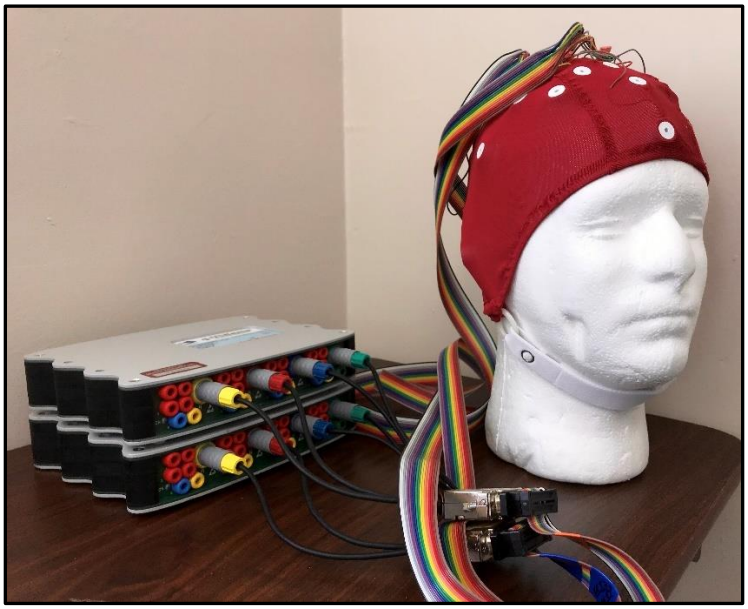


**Figure 3: EEG Setup**
The cap with electrodes is worn by the participant and is connected to two amplifiers. The electrodes are pre-set in the cap which allows for easy donning and doffing of the cap.

### 4. *Setup Overview*

This section describes how the three systems are connected. First, FINGER is connected to the target computer which in turn is connected via ethernet to the host computer in the *xPC Target* environment. The host computer is the computer the participant interacts with during the experiment. Next, Xsens sensors are placed on FINGER and the spacebar of the host computer to allow the motion of FINGER and the participant's pressing of the spacebar to be recorded. The sensors are wireless and send information to the Xsens base unit via Wi-Fi (wireless fidelity). The base unit is connected via BNC to the amplifiers and via USB to the computer that acquires the EEG. The amplifiers are connected via USB to this computer as well. The BCI2000 and MT manager on this computer continuously record and save EEG and Xsens data streams and display them on the screen. This allows monitoring of the sensors and EEG throughout the entire experiment. This computer is kept out of sight of the participant to prevent any distractions. Figure 4 displays the wiring of the experimental setup, while Figure 5 displays the actual lab setup.

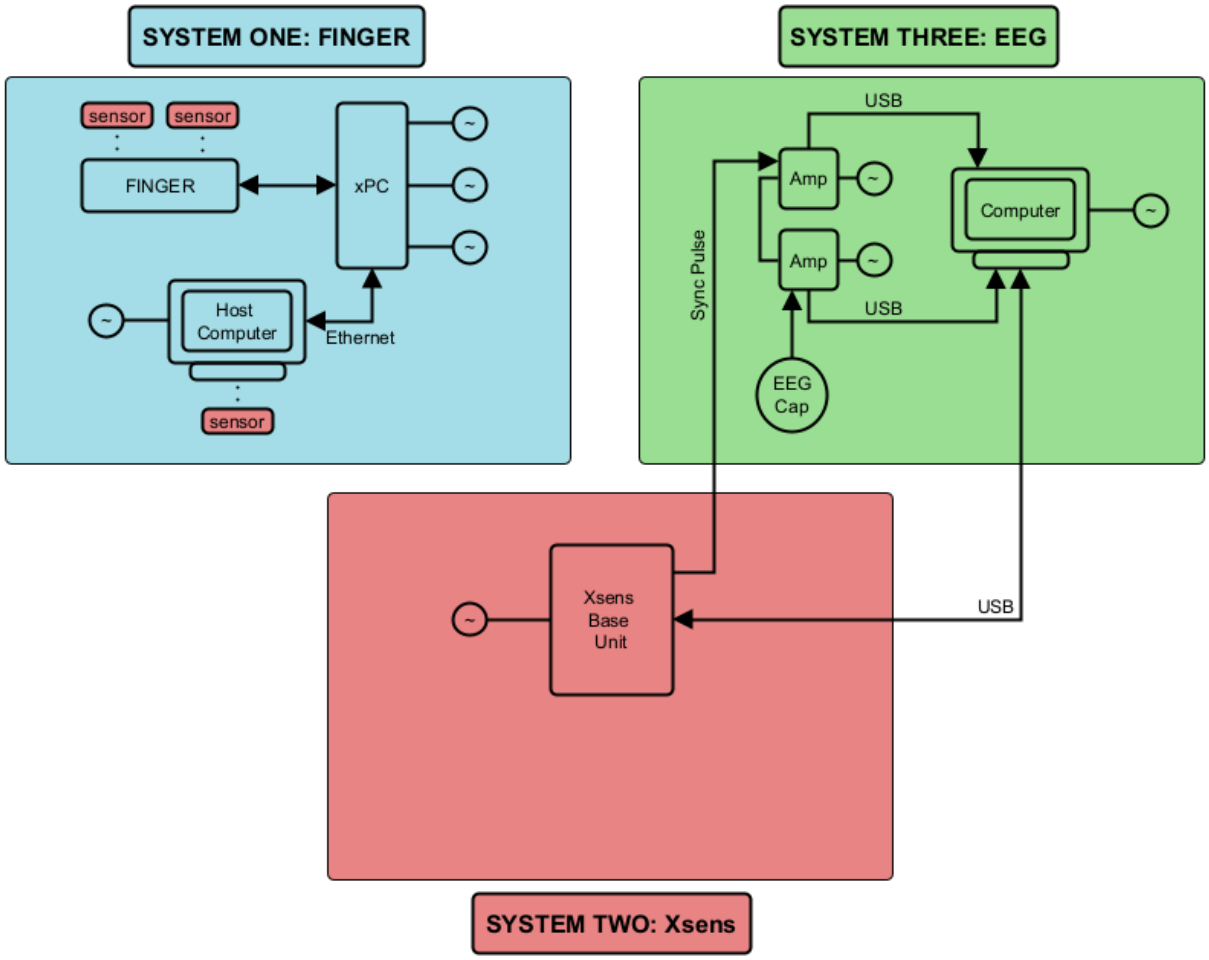



**Figure 4: Block Diagram of Experiment Setup**

There are two sensors on FINGER. FINGER is connected to a target and host computer. There is a sensor on the host computer's keyboard. The Xsens base unit and amplifiers are connected to a second computer.



**Figure 5: Experiment Layout**
The participants sat in the black chair with an EEG cap on their head. The chair could be adjusted up or down for comfort. The participants placed their right hand in FINGER and their left hand on the laptop. The experimenter sat in the green chair and monitored the Xsens and EEG data in real time.

## B. Paradigm

### 1. *Participants*

Five healthy people (1 female and 4 males [mean = 38.2, standard deviation = 15.1]) participated in the experiment and ranged in age from 22 to 66 years old. Participants are referred to as letters A-E. All participants were asked their age, gender and hand dominance. They were also asked if they had taken any medication in the last 24 hours that might affect their cognitive processes. All participants answered no to this question and all participants were right hand dominant. This information was collected via a run sheet which is shown in the Appendix. Due to COVID-19 related safety regulations, participants were only allowed to participate if they had been fully vaccinated. Masks were worn at all times and all equipment was thoroughly cleaned and sanitized after each participant. The protocol was approved by the Albany Stratton Veteran Affairs Institutional Review Board. All participants gave signed informed consent.

### 2. *Experimental Design*

The proprioceptive task performed was the Crisscross task using FINGER. The Crisscross task involves the crossing of the right index and middle fingers. When participants believed their fingers were perfectly aligned in FINGER, they would have to press the spacebar with their left hand. The experiment consisted of a single session where participants sat in front of a laptop (host computer) and used FINGER. The participants were instructed to place their left hand on the spacebar of the laptop. The participants' right middle and index fingers were placed in FINGER and secured via finger cuffs. A cushion was provided to the participants who requested one for their right elbow. FINGER actively moved the participants' middle and index fingers in a crisscross motion. For every crisscross motion there was one moment in time where the participants' fingers were aligned (directly on top of each other). As soon as the participants believed (sensed) their fingers were aligned they were instructed to press the spacebar with their left hand.

Only the right hand was used in FINGER as Ingemanson et al., (2015) determined that hand dominance did not have an affect during an overlap task using FINGER [1]. Participants underwent 11 runs (1 vision run and 10 non-vision runs). The vision run (7-11 trials) allowed participants to watch their fingers in FINGER, ensuring they fully understood the task. Once it was confirmed that participants understood the task, they underwent 10 non-vision runs. In the non-vision runs the participants view of their hand in FINGER was blocked by a shelf frame draped with a black cloth (to make this is a purely proprioceptive design). During the non-vision runs each participant was asked to fixate on the computer screen. Each non-vision run was ~1.5 min long (2 min max) and consisted of 5-11 trials, depending on the length of the random interstimulus interval (0-3 sec).

Although it was planned for each participant to have one session consisting of 11 runs, participant A had 8 runs due to the robot crashing, which is why there are varying numbers of runs as illustrated in Table 1. EEG setup took approximately 30 minutes and the time to complete the actual experiment varied from 30-60 minutes, as some participants requested breaks in between runs.

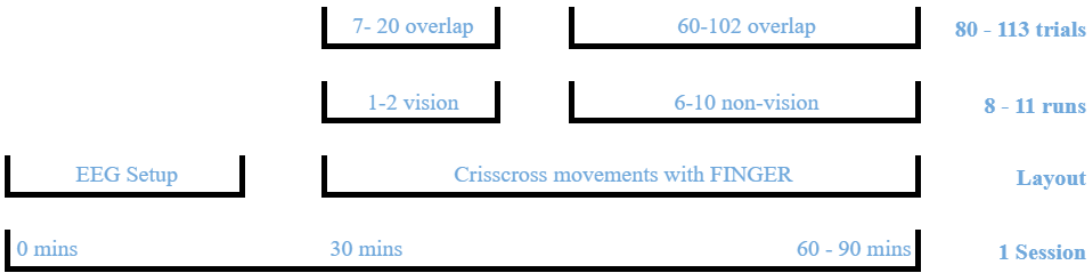



**Table 1: Session Layout**

One session lasted approximately 1-1.5 hours depending on the length of the interstimulus interval and if the participant asked for a break. EEG and FINGER setup lasted ~30 minutes and the 11 runs lasted ~30 minutes. The 11 runs consisted of 1 vision run and 10 non-vision runs. Each run lasted approximately 2 minutes and consisted of 5-11 overlap movements. Participants underwent a minimum of 7 overlap movements with vision and a minimum of 60 overlap movements with vision occluded.

### 3. *FINGER Crisscross Task*

This experiment was based on Ingemanson et al., (2015) and so I will summarize their methods. FINGER was designed to move the fingers at a MCP angular velocity of 0.24 radians per second [1]. The position in space where the fingers were directly aligned varied for each crisscross movement [1]. FINGER performed symmetric and asymmetric movements. Symmetric movements were defined as the index and middle fingers producing mirroring movements. Asymmetric movements were defined as when one finger moved in a larger range than the other finger, thus producing different finger velocity paths [1]. A pause of 0-3 seconds came after each crisscross movement, this produced a random pattern so the participant could not guess the timing.

### 4. *EEG Data Acquisition*

Non-invasive scalp EEG was acquired with reference to the mastoid bone, using two g.usb amps, BCI2000 software and a 32 channel EEG electrode cap. The electrodes were pre-set in the EEG cap as shown in Figure 3. The cap was placed on the participant's head and aligned based on the circumference of their head. The participant's nasion-to-inion distance and circumference of the head was then measured. If the participant's nasion-to-inion distance was 50 cm, then electrode Fpz was placed at 10% of this distance from the nasion (5 cm from nasion in this example). The electrode montage used was a modified set of 32 channels from the International 10-20 EEG system, shown in Figure 6.

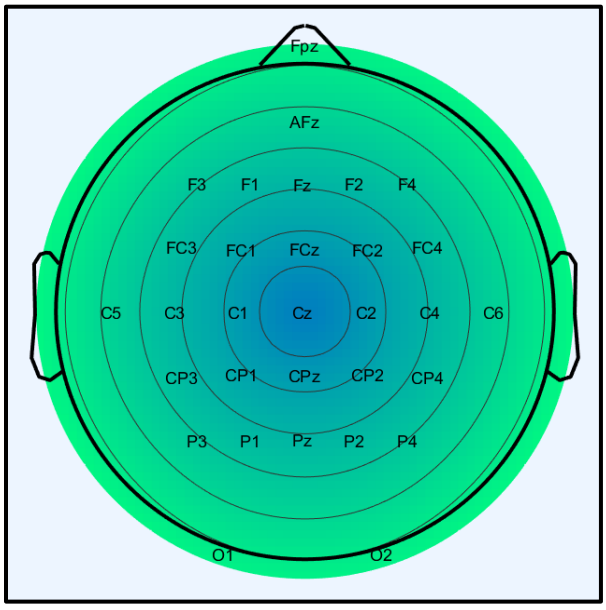



**Figure 6: EEG Montage**

The electrode names correspond to the region of the brain it is measuring (P = parietal, C = central, F = frontal and O = occipital). It is expected that during the Crisscross task of the right hand, proprioceptive signals will be seen contralaterally. These signals are expected to appear in electrodes C1, C3 and C5.

EEG signals can be noisy, meaning there can be interference with the underlying neural mechanisms being analyzed. By checking the impedance of each electrode the amount of noise can be reduced. The impedances were checked by running BCI2000 in an impedance checking

mode which displayed the impedance values for each electrode. The ideal impedance values for scalp electrodes are less than 40 ohms, which was achieved for most electrodes. If the impedance value for an electrode was greater than 40-60 ohms, the electrode was re-gelled to ensure a clean signal. Once all impedances were below 40 ohms the experiment was commenced.

To test if the EEG was acquiring neural signals correctly, the participant was asked to clench their teeth, blink and open and close their eyes. During these tests corresponding effects were reflected in the EEG in real time. When the participant clenched their teeth, it showed EMG noise across all electrodes; when they blinked, it showed an ocular artifact across the frontal electrodes; when they opened and closed their eyes, alpha (8-14 Hz) activity appeared across all electrodes. These tests indicated the EEG was set up correctly. Artifacts are picked up by the EEG but are not signals from the brain. Artifacts can be of electrical (line noise), cardiological, muscular or ocular origin. The EEG was continuously monitored throughout the experiment to ensure impedances were low and signals were clean. This guaranteed that if an electrode suddenly became disconnected it could be corrected without excessive loss of data.

The sampling rate for EEG acquisition was 256 Hz. The amplifiers received an isolated TTL digital input from the Xsens base unit. The EEG recording was started first and soon after the Xsens recording was initiated. BCI2000 was monitored to ensure the Xsens TTL pulse was received in the EEG data stream. The crisscross application was started last, and was started and stopped for each run. The Xsens and EEG were left recording continuously throughout the experiment.

### 5. *Xsens Data Acquisition*

The Xsens sensors measured acceleration, orientation and magnetic forces in 3 dimensions (x, y, z) at a sampling rate of 100 Hz. These measurements were saved and displayed as continuous

signals in real time. The Xsens measurements and EEG signals were shown next to each other on the same computer allowing for easy monitoring for the duration of the experiment.

# IV. ANALYSIS

## A. Overview

The aim of this experiment was to find a change in the EEG that correlated with the errors in the proprioceptive task. The data was analyzed by aligning the files from FINGER and Xsens with the EEG. The demographics of the 5 participants (A-E) who completed the experiment are shown in Table 2.

| Participant | Gender | Age | Handedness | Runs | Vision Trials | Non-Vision Trials |
|---|---|---|---|---|---|---|
| **A** | Male | 22 | Right | 2 vision, 6 non-vision | 20 | 60 |
| **B** | Male | 40 | Right | 1 vision, 10 non-vision | 7 | 96 |
| **C** | Female | 66 | Right | 1 vision, 10 non-vision | 11 | 102 |
| **D** | Male | 34 | Right | 1 vision, 10 non-vision | 11 | 100 |
| **E** | Male | 29 | Right | 1 vision, 10 non-vision | 11 | 100 |

**Table 2: Participant Demographics**
Four participants underwent 11 runs (1 vision and 10 non-vision)
and one participant underwent 8 runs (2 vision and 6 non-vision).

Participant A had two vision runs and three non-vision runs before requesting a break. Upon resuming, the robot application froze and only three more non-vision runs were able to be conducted. The remaining participants underwent one vision run and ten non-vision runs. Participant B was the only participant to wear gauze on his fingers, as he felt it was more comfortable in the finger cuffs. Participant A was the only participant to wear noise cancelling headphones. Participants B-E did not wear noise cancelling headphones as they caused too much noise to appear in the EEG.

There was one condition (non-vision) used in the experiment which consisted of 10 runs. The experiment started with one vision run to ensure the participant understood the task. Both the vision and non-vision runs were programmed to produce a maximum of 12 trials per run. One

trial consisted of one crossing of the index and middle fingers. Table 3 shows the number of trials each participant made during each run. The varying number of trials per run are the result of the interstimulus interval.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| **Vision Run 1** | 11 | 7 | 11 | 11 | 11 |
| **Vision Run 2** | 9 | | | | |
| **Non-vision Run 1** | 11 | 11 | 11 | 9 | 11 |
| **Non-vision Run 2** | 11 | 11 | 11 | 9 | 9 |
| **Non-vision Run 3** | 9 | 11 | 9 | 11 | 7 |
| **Non-vision Run 4** | 11 | 11 | 9 | 9 | 9 |
| **Non-vision Run 5** | 9 | 11 | 9 | 7 | 11 |
| **Non-vision Run 6** | 9 | 9 | 9 | 11 | 11 |
| **Non-vision Run 7** | | 5 | 11 | 11 | 11 |
| **Non-vision Run 8** | | 9 | 11 | 11 | 11 |
| **Non-vision Run 9** | | 9 | 11 | 11 | 11 |
| **Non-vision Run 10** | | 9 | 11 | 11 | 9 |
| **Total** | **80** | **103** | **113** | **111** | **111** |

**Table 3: Number of Trials per Participant**
This table shows the number of trials each participant made during each run. One trial corresponds to one crossing of the index and middle fingers.

Since previous studies compared one non-vision and one vision run, it was decided to include the vision run in the analysis for preliminary checks and comparison with these previous studies [1].

## B. FINGER Data Analysis

The Crisscross task for FINGER outputs the finger trajectories and the button presses. The sampling rate of FINGER was 1,000 Hz. Figure 7 shows the data (position and button presses) for participant B. The red curve represents the movement of the index finger and the blue curve represents the movement of the middle finger. When the red and blue curves intersect it represents the exact moment the participant's fingers were perfectly aligned (crossover point). The vertical

lines represent the point when the participant believed their fingers were perfectly aligned (moment of the button press). The position values on FINGER varied from 0 to .902 and can be converted to degrees. A position value of 0 corresponds to 0 degrees and a position value of .902 corresponds to 54.12 degrees.

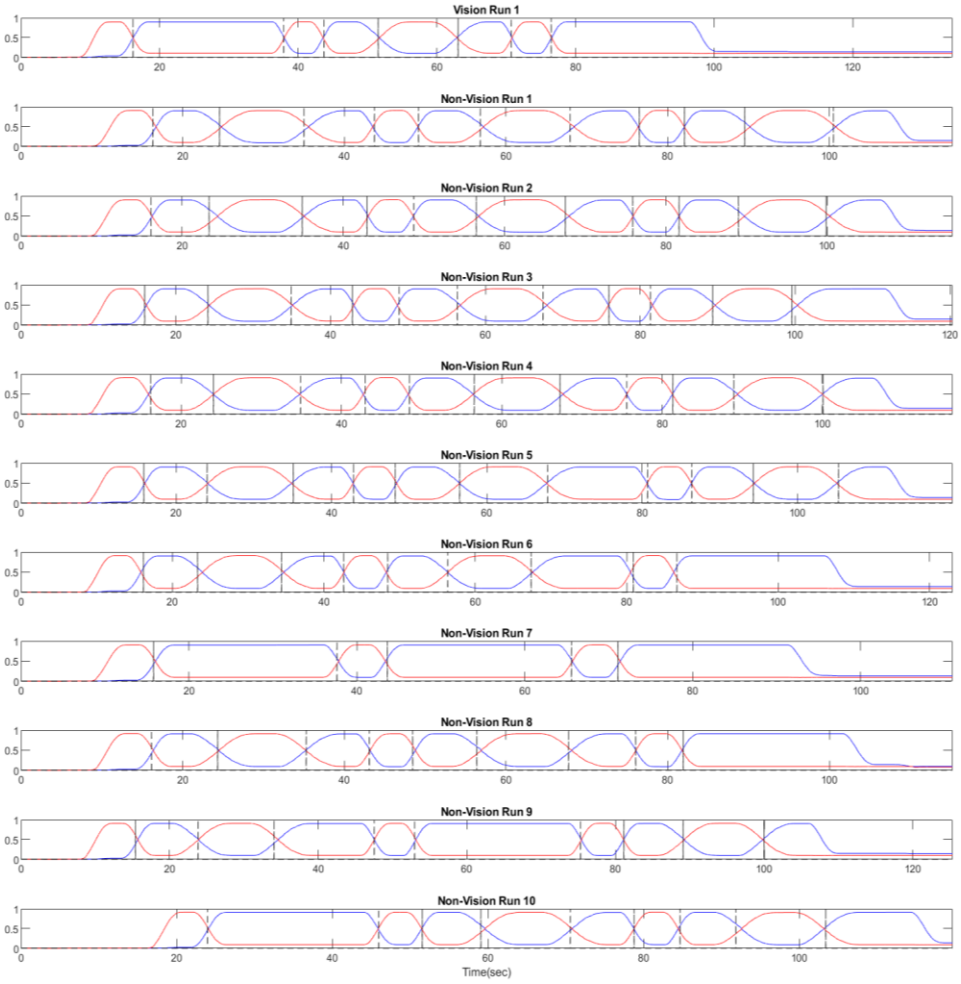



**Figure 7: Position and Button Presses for Participant B**
The position values from FINGER for one run with vision and ten runs without vision for participant B. The other participants have similar results.

The trajectories from FINGER are used to detect the crossover points for each trial. The button presses are used to calculate the errors for each trial. Some experiments analyze error in time, but for this experiment error in space (position error) was analyzed.

Position error can be categorized into two types- temporal and spatial error. When measuring position error in the temporal domain (Type A: Temporal Position Errors), it can be categorized as positive or negative depending on the sign of the reaction time. If the sign is positive it is referred to as an anticipatory error and if the sign is negative it is referred to as a delayed error. When measuring position error in the spatial domain (Type B: Finger Specific Spatial Errors), it can be categorized as positive or negative depending on whether the index or middle finger was further extended. The breakdown of the classification of errors for this experiment is shown in Figure 8. The main difference between Type A and Type B error is Type A error is irrespective of relative position and Type B error is irrespective of time. This type of error analysis is a new contribution to the paradigm.

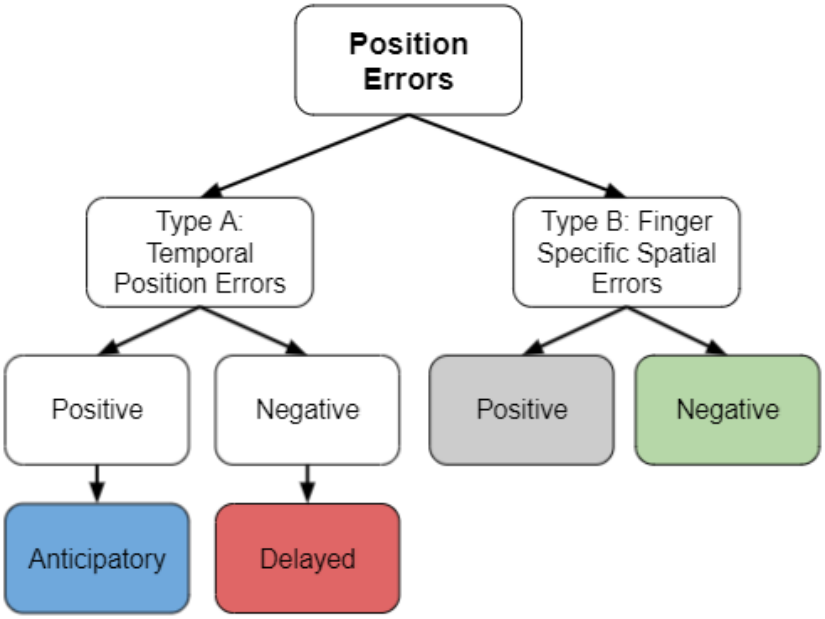
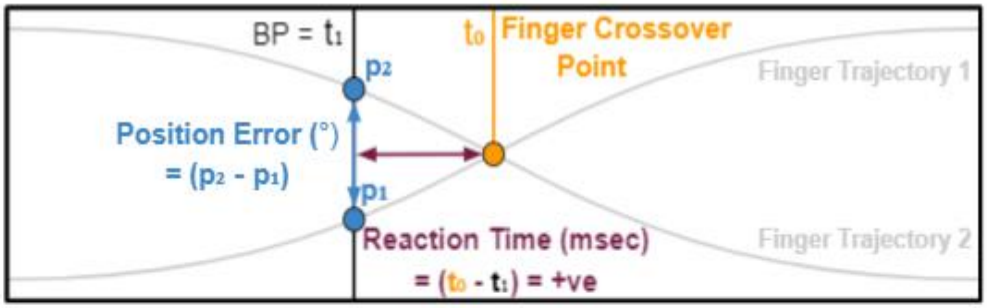



**Figure 8: Error Classification**

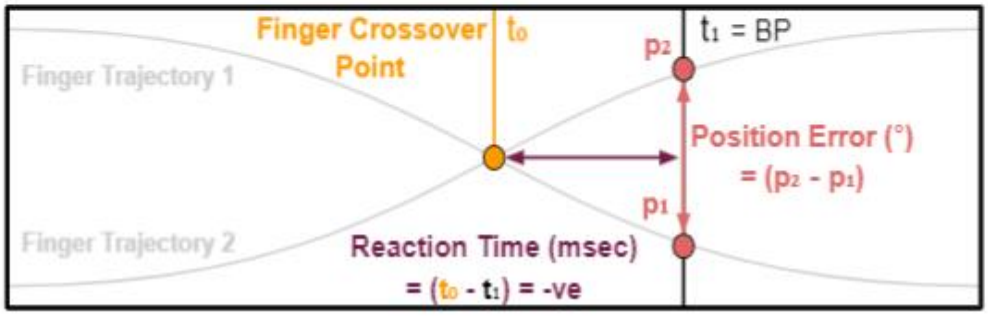
Type A: Temporal Position Errors can be positive or negative based on the sign of the reaction time. Positive temporal position errors are referred to as anticipatory and negative temporal errors are referred to as delayed. Type B: Finger Specific Spatial Errors can be positive or negative based on how far each finger is extended. The colors (red, blue, green, gray) correspond to the graphs in the Results section. Blue represents an anticipatory error and red represents a delayed error. Gray indicates a positive spatial error and green indicates a negative spatial error.

### 1. *Error Type A: Temporal Position Errors (Anticipatory and Delayed)*

It was possible that the participant pressed the button too early (before their fingers were crossed) or too late (after their fingers had crossed). This can be seen in Figure 9 where the vertical lines appear both before (anticipatory) and after (delayed) the crossing of the gray curves. The sign for Type A errors is obtained from the corresponding reaction time of that trial. For example, if reaction time ($t_0$ - $t_1$) is positive, position error ($p_2$ -$p_1$) is also positive and is considered an anticipatory error as illustrated in Figure 9a. If reaction time is negative, position error is negative and counted as a delayed error as shown in Figure 9b.




**a.) Anticipatory Error:** Button Press occurs *before* the actual finger crossover




**b.) Delayed Error:** Button Press occurs *after* the actual finger crossover

**Figure 9: Anticipatory and Delayed Errors**

9a.) An anticipatory error is when the participant's reaction time was positive. 9b.) A delayed error is when the participant's reaction time was negative. $t_1$ represents when the participant pressed the button and t0 represents the actual crossover point of the fingers. Finger Trajectory 1 represents the index finger and Finger Trajectory 2 represents the middle finger. Reaction Time is calculated by subtracting when the participant pressed the spacebar from the actual finger crossover point (measured in msec). Position error is calculated by subtracting Finger Trajectory 1 ($p_1$) from Finger Trajectory 2 ($p_2$) (measured in degrees).

### 2. *Error Type B: Finger Specific Spatial Errors (Positive and Negative)*

Type B error is calculated based on the distance between the index and middle fingers when the participant pressed the spacebar with their left hand. If the index finger was further extended than the middle finger it was classified as a positive spatial error. For example, if $p_1$ is more extended than $p_2$ the resulting position error would be positive, as shown in Figure 10a. If the middle finger is more extended than the index finger it is classified as a negative spatial error. For example, if $p_2$ is more extended than $p_1$, the resulting position error will be negative, as shown in Figure 10b. Type B spatial errors are measured in degrees and time is ignored.

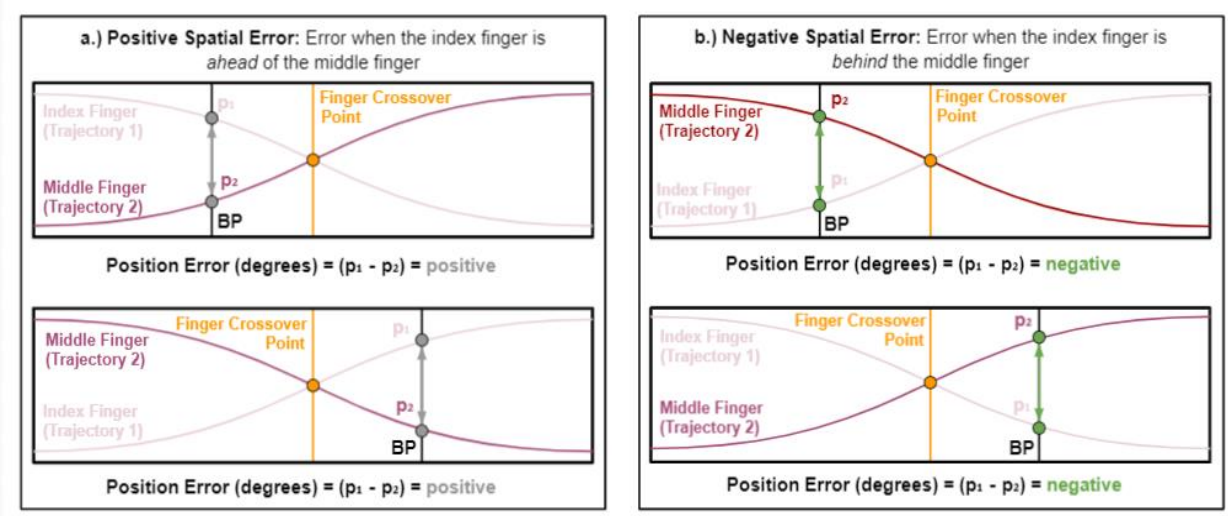



**Figure 10: Positive and Negative Spatial Errors**

10a.) The vertical line labeled 'BP' represents when the participant pressed the spacebar. The orange line represents the actual finger crossover point. Positive spatial error is the difference between the index and middle finger ($p_1$ - $p_2$), shown in gray. 10b.) Negative spatial error, shown in green, is when the middle finger was further extended than the index finger.

## C. Xsens Data Analysis

Xsens sensors on FINGER captured the position of the index and middle fingers as well as the time the spacebar was pressed by the participant, in order to align the button presses with EEG. Figure 11 shows the Xsens data from one non-vision run for Participant B. The red line represents

the index finger moving and the blue line represents the middle finger. The intersection of the red and blue lines indicates the moment when the participant's fingers were perfectly aligned. As a proprioceptive task was performed, participants may have pressed the spacebar before or after the actual crossing of their fingers, which is reflected by the black lines. The trajectories from Xsens were mainly used to distinguish the relevant button presses from spacebar presses captured at other times during the experiment.

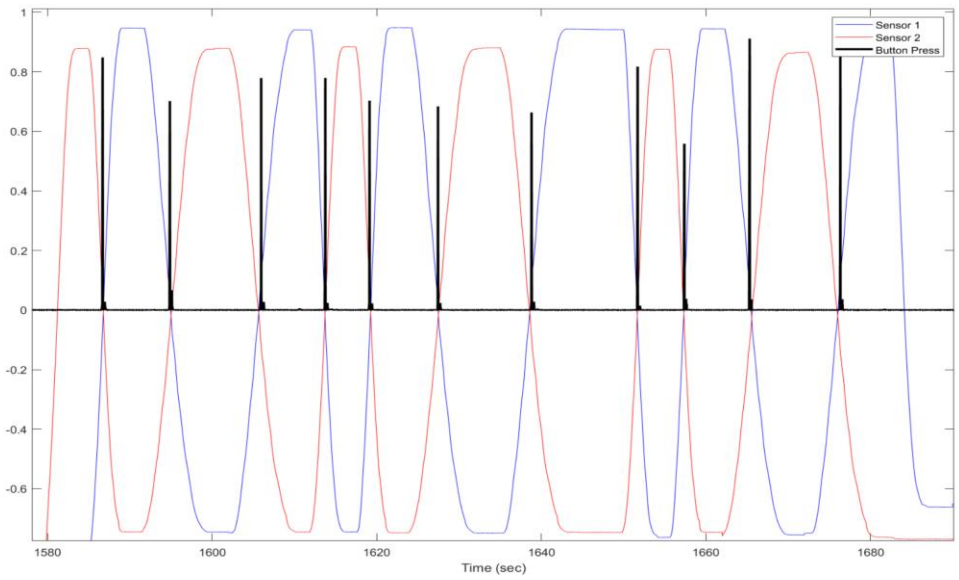



**Figure 11: Xsens Non-Vision Run for Participant B**
Xsens captured the button press of the left hand on the keyboard (black vertical line) and the movement of the index (red curve) and middle (blue curve) fingers of the right hand. The Xsens files are noisier than FINGER files but is good to have them as a cross-reference.

The first button press of each run was marked manually in the Xsens data file. These were then aligned with the corresponding first button press in the FINGER run files. After the Xsens and FINGER files were aligned, all button presses in each run could be automatically extracted. The time points that marked the button press were transferred to the EEG data files. Aligning the Xsens and EEG allowed the event information (button presses) in the EEG to be marked and for the EEG to be segmented into epochs (smaller time periods). Separating EEG into epochs allowed

the data to be analyzed for a neural correlate of proprioception and for the relationship of the index and middle finger position errors on a trial basis to be analyzed.

## D. EEG Data Analysis

### 1. *Synchronization of EEG and Button Presses*

When Xsens started recording a digital signal was sent to BCI2000 where it was saved as a state (Digital Input 1). This event appeared in the EEG data collected by BCI2000 and was monitored in real time using watches in BCI2000. The time points before the event were removed allowing Xsens and EEG to be aligned at 0 seconds. The alignment of EEG and Xsens data allowed the button presses captured by the Xsens sensors to be marked at the same time point in the EEG. If the Xsens trigger was not saved, it would not be known when the button presses occurred in the EEG.

### 2. *EEG Pre-Processing*

EEG data was collected at 256 Hz. Prior to data collection, bad channels (high impedances) were fixed on the EEG. All channels were in normal range (low impedances) before conducting the experiment. After the experiment the data was pre-processed to account for different artifacts including ocular, muscular and electrical. The data was checked for any bad channels and analyzed offline in MATLAB (Mathworks Inc.) with customized programs and EEGLAB toolbox [27]. As the right hand was being tested, the left cortical channels in the motor and somatosensory area were of most interest (as they correspond to the right hand). The data was high and low pass filtered at 0.2 and 50 Hz. This eliminated possible electrical line noise (60Hz) from FINGER and the room where data was collected. It also removed very low frequency noise (< 0.2 Hz). The data was then re-referenced using a common average reference. Finite Impulse Response (FIR)

filters (zero-phase) were used for temporal filtering. Lastly, data epochs were extracted and baseline (-2000 to -1700 msec) normalization was applied.

### 3. *EEG Epoching*

Button presses were imported into EEGLAB as events. These events were categorized as 1, 2, 3 and 4. One represented anticipatory error, two represented delayed error, three represented positive spatial error and four represented negative spatial error. These events were used to segment the EEG data into epochs (periods) as shown in Figure 12. The epochs were -2 to 2 seconds with respect to the button press. This means that across all EEG channels, each trial was able to be analyzed 2 seconds prior and 2 seconds after the participant pressed the button.

When looking at proprioceptive activity in the brain it is important to look at the time leading up to the proprioceptive event. Norman et al., (2016) found that "ERD was observed approximately 600-900 ms before the start of movement when the participant remained passive and the robot moved the participants' fingers" [24]. As mentioned in my hypothesis, this task was similar to my experiment so data was analyzed for an ERD 600-900 ms prior to button press.

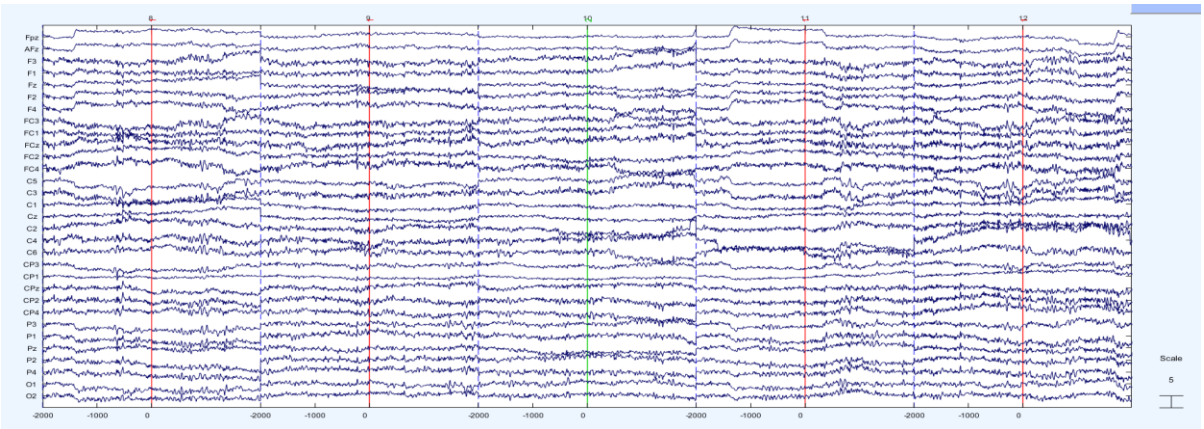


**Figure 12: EEG Epochs for Participant B**

The above figure shows the data epochs for participant B. The y-axis represents the electrode channels in the EEG cap. The x-axis represents time. The red vertical lines represent an anticipatory error and the green vertical lines represent a delayed error.

### 4. *Time Domain Analysis*

Time domain analysis is referred to as ERP (event-related potential) analysis. After epochs are extracted, they are stacked and their average is taken and plotted, this is known as ERP analysis. This process is illustrated in Figures 21 and 22, which shows the EEG signal represented in the time domain stacked as trial epochs. The average or ERP can be represented as a signal which is depicted by the blue line in Figures 21 and 22.

### 5. *Time Frequency Domain Analysis*

ERD stands for event-related desynchronization and is time locked to the event (button pressing). The areas of most interest are the sensorimotor and somatosensory areas on the contralateral side of the brain (left hemisphere) and correspond to electrodes C5, C3, C1, CP1 and CP3. It is expected that ERD will be seen over the sensorimotor area contralateral to the hand performing the crisscross task in the frequency range of 8-12 Hz.

Single trial analysis was performed to see if there was a change in ERD based on the proprioceptive error associated with each trial. It was hypothesized that low proprioception error would show a larger ERD (large reduction in power in the alpha band) and that high proprioception error would show a smaller ERD. The time domain was converted to alpha frequencies for each time point. An epoch of [-2 sec 2 sec] was taken and split into two time windows, a baseline and sensing window. During the baseline window [-2000 msec -1700 msec] little activity was occurring and as a result, alpha was expected to be high. During the sensing window [-1500msec -1000msec] it was expected that a change in the EEG might occur (prior to the button press). In the baseline and sensing window of the EEG spectral power in the alpha region was analyzed. How the ERD correlates with proprioceptive error was also analyzed.

The alpha and mean of each window were taken which provided two sets of numbers for each window. The numbers represented the spectral power for each window and were compared to each other to determine if there was a correlation. A positive correlation occurred if one vector increased as the other vector increased. Conversely, a negative correlation occurred if one vector decreased as the other vector decreased. The color blue in the topography of Figure 23 represents a negative correlation.

## E. Statistical Analysis

A non-parametric test was used to analyze the collected data. A non-parametric test was used as all of the data was not normally distributed. The type of non-parametric test used was the Mann-Whitney U test. The Mann-Whitney U tests the null hypothesis that two distributions have equal medians. A one-tailed test was used at a 5% significance level. All of the plots in the Results section were analyzed using the Mann-Whitney U test and were performed across all participants.

# V. RESULTS

## A. Assessment of Proprioception Errors

Position error was analyzed based on the sign of reaction time (Type A) and on how far each finger was extended (Type B). Type A errors (anticipatory and delayed) represent how long (in msec) the participant's fingers had to go or went until their fingers crossed. If the button press occurred before the actual finger crossover, it was classified as an anticipatory error. If the button press occurred after the actual finger crossover, it was classified as a delayed error. Type B errors (positive and negative) represent how far the participants fingers (in degrees) were away from each other when the button was pressed. If the index finger is further extended than the middle finger when the spacebar was pressed, it was classified as positive spatial error. If the middle finger is further extended than the index finger when the spacebar was pressed, it was classified as negative spatial error. For each type (A and B) of error, the count and extent were analyzed. The count of error represents the number of errors across participants and the extent represents the position error in degrees.

### 1. *Error Type A: Anticipatory and Delayed Errors*

The count of error for 1 non-vision run, 1 vision run (~12 trials each) and all non-vision runs was analyzed across participants, shown in Figures 13, 14 and 15 respectively. The top and bottom left distributions in Figure 13 show anticipatory errors were made 0-20 degrees and 0-900 msec before the participants fingers crossed. Delayed errors were made 0-30 degrees and ~0-600 msec after the participants fingers crossed. The top and bottom right distributions in Figure 13 are shown in absolute error to demonstrate that errors get lost when sign (positive or negative) is not considered. For example, the left and right graphs of Figure 13 show different distributions when the absolute error is taken.

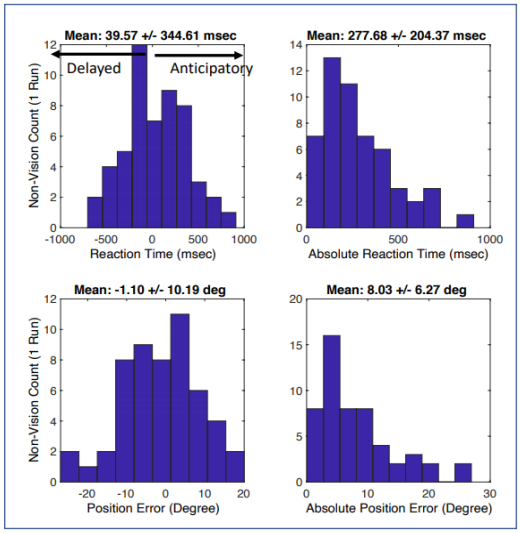



**Figure 13: Distribution of Count Errors for 1 Non-Vision Run**
The top left distribution shows the count of error for 1 non-vision run in reaction time (msec). The top right distribution shows the absolute reaction time (msec), with absolute meaning the sign is ignored. The bottom left distribution shows the count of error in position error (degrees). The bottom right graph shows the absolute position error (degrees).

Equal amounts of anticipatory and delayed errors (in degrees) were made during 1 vision run when the sign (positive and negative) was taken into consideration as shown in the bottom left graph of Figure 14. The majority of anticipatory and delayed errors were made ~0-250 msec before and after the button press, as shown in the top left graph of Figure 14. When sign is again taken out of consideration, the distribution of reaction and position error changes, as shown in the absolute error graphs in the top and bottom right distributions of Figure 14.

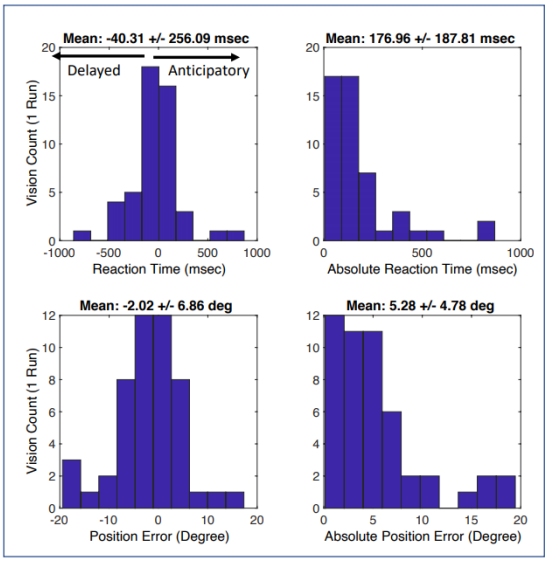



**Figure 14: Distribution of Count Errors for 1 Vision Run**
The top right distribution shows the absolute reaction time (msec). The top left distribution shows the reaction time (msec). The bottom left distribution shows the position error (degrees). The bottom right graph shows the absolute position error (degrees).

Ingemanson et al., (2015) compared one non-vision run to one vision run [1]. The results shown in Figures 13 and 14 are consistent with their findings. Ingemanson et al., (2015) found that the signed average overlap errors for the young, middle and old age group was -3.2 $\pm$ 2.9 degrees, -0.01 $\pm$ 3.9 degrees and 2.6 $\pm$ 6.3 degrees [1]. Although this experiment did not break groups by age, the results are consistent as the signed average overlap error was -2.02 $\pm$ 6.86 degrees for the vision run and -1.10 $\pm$ 10.19 degrees for the non-vision run.

When absolute reaction time and position error are analyzed, it shows a distribution skewed to the left, as shown in Figure 15b. However, when reaction time and position error are analyzed (maintaining positive and negative values), the distributions become less skewed to the left, as shown in Figure 15a. The top graph of Figure 15a (reaction time in msec) shows a normal distribution indicating that participants were more likely to make smaller reaction time errors

(<310.43 msec) than they were to make larger reaction time errors (>310.43 msec). When analyzing the position error for all non-vision runs, the distribution is skewed to the right, as shown in the bottom graph of Figure 15a. When analyzing 1 non-vision run, participants had larger errors in msec, showing that over the course of 10 runs, it is possible to improve one's sense of position.

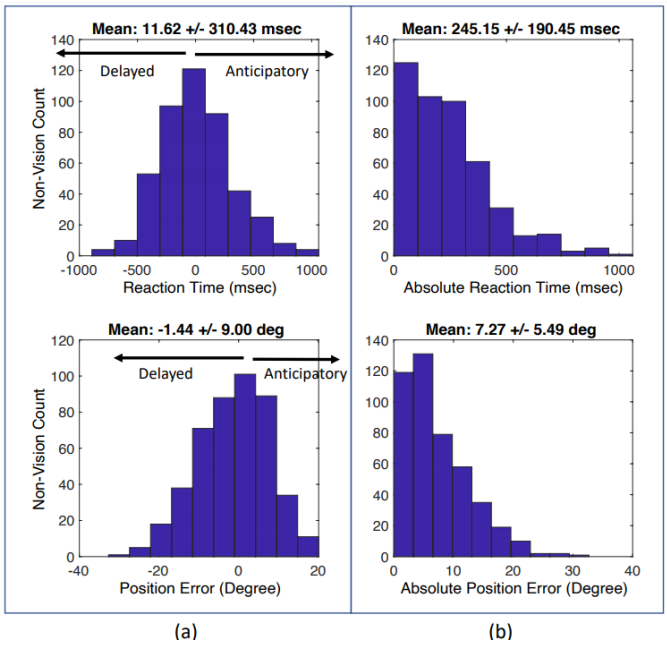



**Figure 15: Distribution of Count Errors for all Non-Vision Runs**

15a.) The top distribution shows the reaction time (msec) and the bottom distribution shows the position error (degrees). 15b.) The top distribution shows the absolute reaction time (msec) and the bottom distribution shows the absolute position error (degrees).

After the distributions of count errors for Type A were calculated across 1 non-vision run, 1 vision run and across all non-vision runs bar graphs were created. Error was analyzed based on the extent (error in degrees) and compared to the count error. Figure 16 shows the anticipatory and delayed errors for all non-vision runs. On average participants made slightly more delayed errors than anticipated errors in position error count as shown in Figure 16a. Additionally, on average all participants made more delayed errors than anticipated errors when measured in degrees, as shown in Figure 16b. On average anticipatory errors were 6 degrees and the delayed

errors were 7.5 degrees. Both graphs in Figure 16 have p-values > 0.5, indicating that the average across all non-vision runs across all participants was not significant.

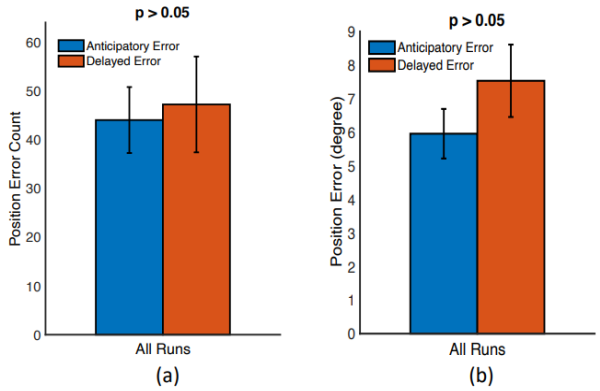



**Figure 16: Anticipatory and Delayed Errors for all Non-Vision Runs**
16a.) Anticipatory and delayed error in position error count. 16b.) Position error in degrees for anticipatory and delayed error. Both graphs are not significant (p>0.5).

Figure 17 shows the extent and count errors for 6 non-vision runs and 1 vision run across all participants. As participant A only completed 6 non-vision runs, data was analyzed for the first 6 non-vision runs to allow for consistency across all participants. For the 6 non-vision runs and 1 vision run, when analyzing the error count, none of the runs were significant (p>0.5) as shown in the top graphs of Figure 17. When analyzing the error extent across 6 non-vision runs and 1 vision run, none of the runs were significant (p>0.5) as shown in the bottom graphs of Figure 17. For 1 vision run, the participants made more delayed errors than anticipatory errors, in both error count and extent. On run 1 of the non-vision runs participants also made more delayed errors than anticipated errors for both count and extent. When analyzing across 6 non-vision runs, the participants made more delayed errors than anticipatory errors in terms of extent. None of these results were significant (p>.05), meaning that if the error was anticipatory or delayed had no effect.

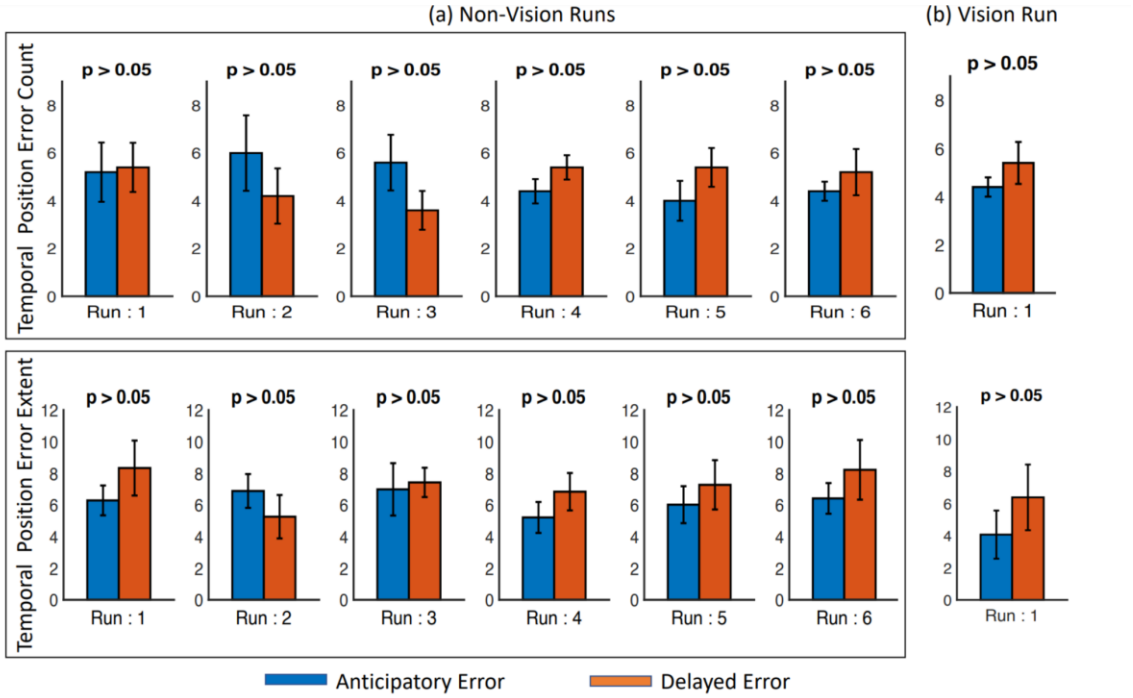



**Figure 17: Extent and Count of Anticipatory and Delayed Errors**

17a.) The error count and extent for anticipatory and delayed errors for 6 non-vision runs. 17b.) The error count and extent for anticipatory and delayed errors for 1 vision run.

### 2. *Error Type B: Spatial Error*

Finger specific spatial error (Type B) was analyzed across participants and was categorized into positive and negative errors. A positive spatial error was defined as the index finger being further extended than the middle finger when the button was pressed and a negative spatial error was defined as the middle finger being further extended than the index finger when the button was pressed. It is important to remember that finger specific spatial error is irrespective of time (when the button was pressed).

As the count of error for 1 non-vision run, 1 vision run (~12 trials each) and all non-vision runs was analyzed across participants for Type A errors, the same procedure was done for Type B errors. For the purpose of this thesis, I will not include any of the distributions for Type B errors and will only discuss the bar graphs.

When analyzing spatial error count across all non-vision runs, participants made more positive than negative spatial errors, as shown in Figure 18a. In other words, this means that participants made more errors when their index finger was further extended than their middle finger. These results were significant ($p<0.05$) indicating that future studies with a larger dataset should be analyzed. When analyzing spatial error in degrees slightly more positive spatial errors were made than negative spatial errors as shown in Figure 18b. These results were not significant ($p>0.5$).

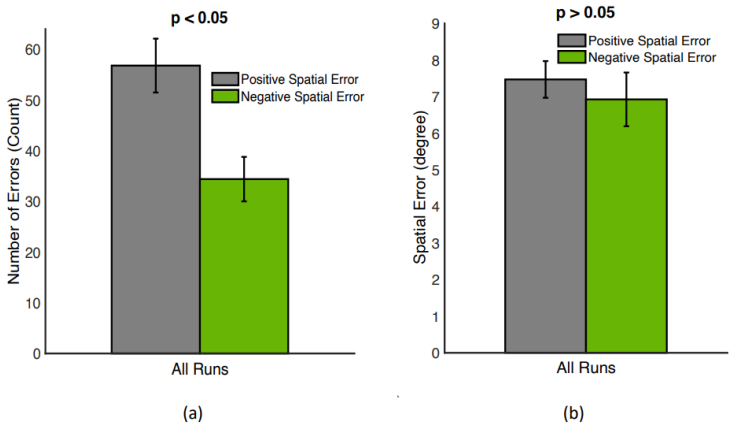



**Figure 18: Positive and Negative Spatial Errors for all Non-Vision Runs**
18a.) Positive and negative spatial count errors across all participants for all non-vision runs. 18b.) Positive and negative spatial errors (in degrees) across all participants for all non-vision runs.

Next the extent and count of spatial errors was calculated and compared across 6 non-vision runs and 1 vision run. The extent didn't show much change across 6 non-vision runs but the count showed a nice progressive change over time as more runs, and hence more trials, were completed. As participants completed more non-vision runs (therefore had more practice), more positive spatial errors were made as shown in the top graph of Figure 19a. By run 4 of the non-vision runs, the results become significant and by run 6 of the non-vision runs, the results are similar to when the participant had vision of their fingers. In other words, by the 6th run of non-

vision participants were making the same number of positive and negative errors as they did when they had vision of their hand. Non-Vision Runs 1-3 were not significant ($p>.05$) and Non-Vision Runs 4-6 were significant ($p < .05$). As the Non-Vision Runs 4-6 were significant, this means the statistical result did not occur by chance.

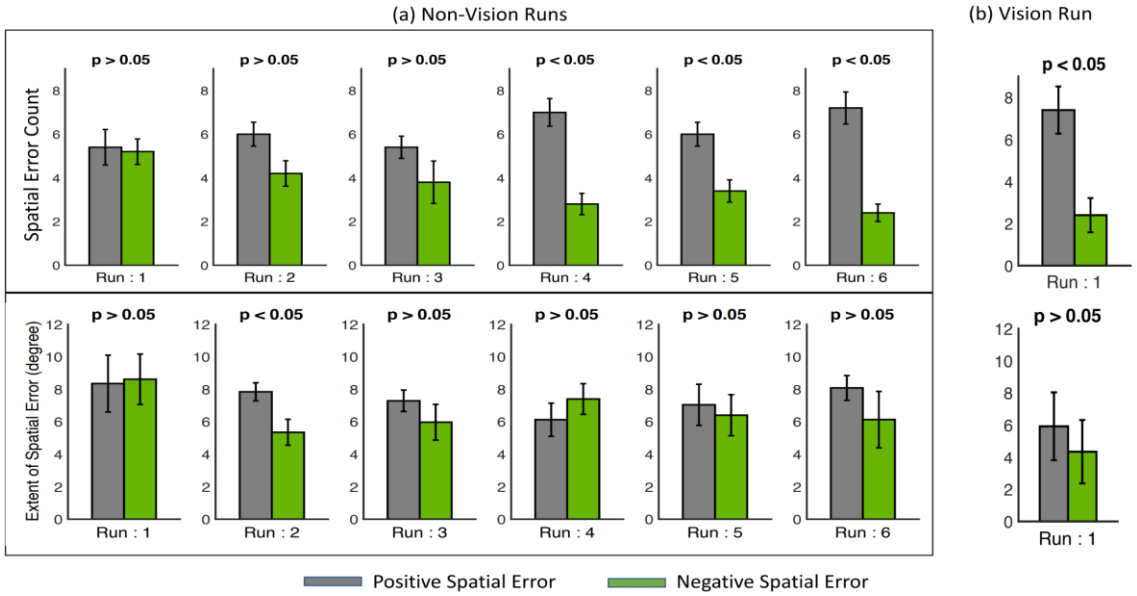



**Figure 19: Extent and Count of Positive and Negative Spatial Errors**
19a.) Positive spatial error is shown in gray and negative spatial error is shown in green. The top graph shows the count error for 6 non-vision runs. The bottom graph shows the extent of error for 6 non-vision runs across all participants. 19b.) The top graph shows the count error for 1 vision run and the bottom graph shows the extent error for 1 vision run.

## B. EEG: Cortical Response to Proprioception

### 1. *Time Domain*

EEG data was first analyzed by looking at ERP across participants in the time domain for both Type A and Type B errors. Type B errors (positive and negative spatial errors) showed the most promising results and hence were included in this thesis. Channels C3 and C5 were analyzed because the right hand was performing the proprioceptive task and a spike in the EEG would appear in the left hemisphere of the brain (around C3 and C5). Channels C4 and C6 are in the

same location as C3 and C5, but located on the right hemisphere of the brain and were included for comparison purposes. Figure 20 shows the epochs [-2 sec 2 sec] for channels C3, C5, C4 and C6 for participant B for positive spatial error. The epochs are stacked and aligned with the button presses at 0 msec. This allows all trials to be shown in one plot which in turn allows for trial responses to be compared with each other. The x-axis indicates time and the y-axis represents each trial number. The epochs are stacked based on the trial sequence (the order of how the trials were collected). The colors correspond to numbers which in turn represent the amplitude of the signal. The color blue represents a reduction in amplitude and the color red represents an increase in amplitude.

The graphs of C3 and C5 in Figure 20 show the signal is blue right before the button press for the first 15 trials and as time goes on (as more trials are collected), the color shifts to yellow for the remaining 15 trials. In other words, during the first 15 trials a strong reduction in amplitude was seen in C3 and C5 and during the last 15 trials there was no change in amplitude. Looking at this data across time (blue line under C3 and C5 in Figure 20) shows a decreased amplitude right before the button press and an increased amplitude right after the button press. This is similar to the ERD that was expected to be seen. Participant B was the only participant to exhibit this phenomenon. C4 and C6 in Figure 20 represent two electrodes in the right hemisphere and show an increase in amplitude right before the button press and a decreased amplitude right after the button press. This phenomenon is opposite of what was seen in the left hemisphere of the brain.

C3 and C5 show a decrease in amplitude approximately 500 ms prior to the button press for the first 20 trials. Approximately 250 ms after the button press in C3 and C5 there is a decrease in amplitude for the first ~10 trials but an increase in amplitude for the remaining trials. This corresponds to the results shown in Figure 22.

Electrodes on the left hemisphere of the brain had a trend of decreasing amplitude prior to the event (crossing of fingers). This phenomenon was limited to the contralateral side of the brain where the proprioceptive task was being performed. Electrodes C4 and C6 do not exhibit this phenomenon. This is because the right hand was in FINGER and therefore the response was seen in the left hemisphere of the brain. The channels on the right side of the head showed an increasing amplitude after the event.

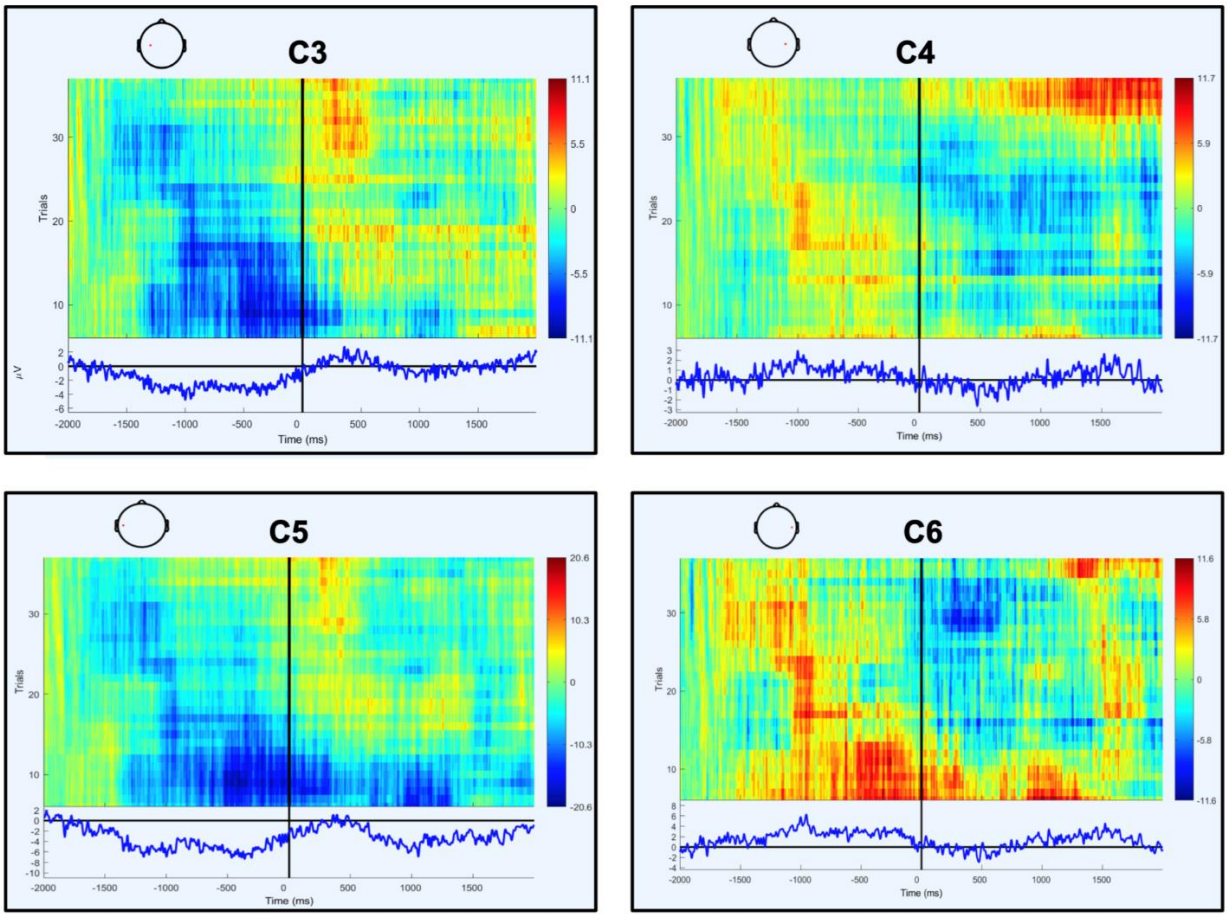



**Figure 20: Positive Spatial Errors for Participant B**

The black line represents when the participant pressed the spacebar. The left two panels show two electrodes (C3 and C5) in the left hemisphere. These electrodes are located over the somatosensory cortex. Each horizontal line represents the electrical activity of a single trial. These trials are stacked on top of each other producing an ERP image. The red color corresponds to positive amplitude values and the blue color corresponds to negative amplitude values. The blue line below the ERP image represents the average of the single trial activity. The right two panels show two electrodes (C4 and C6) in the right hemisphere. This figure was obtained using EEGLAB.

Figure 21 shows the epochs for C3, C5, C4 and C6 for negative spatial error. Trials 25-40 show a strong amplitude increase ~1000 ms after the button press in electrodes C3 and C5. Conversely, in electrodes C4 and C6 a strong reduction in amplitude occurred ~1000 ms after the button press. It is interesting to note that C4 and C6 closely mirror C3 and C5, but instead of amplitude increases after the button press amplitude decreases occurred.

The two graphs on the right of Figure 21 represent the right hemisphere of the brain. The plots on the right show an increase in amplitude prior to the event instead of a decrease which seen in the left panel. This shows that the phenomenon is limited to the left motor area.

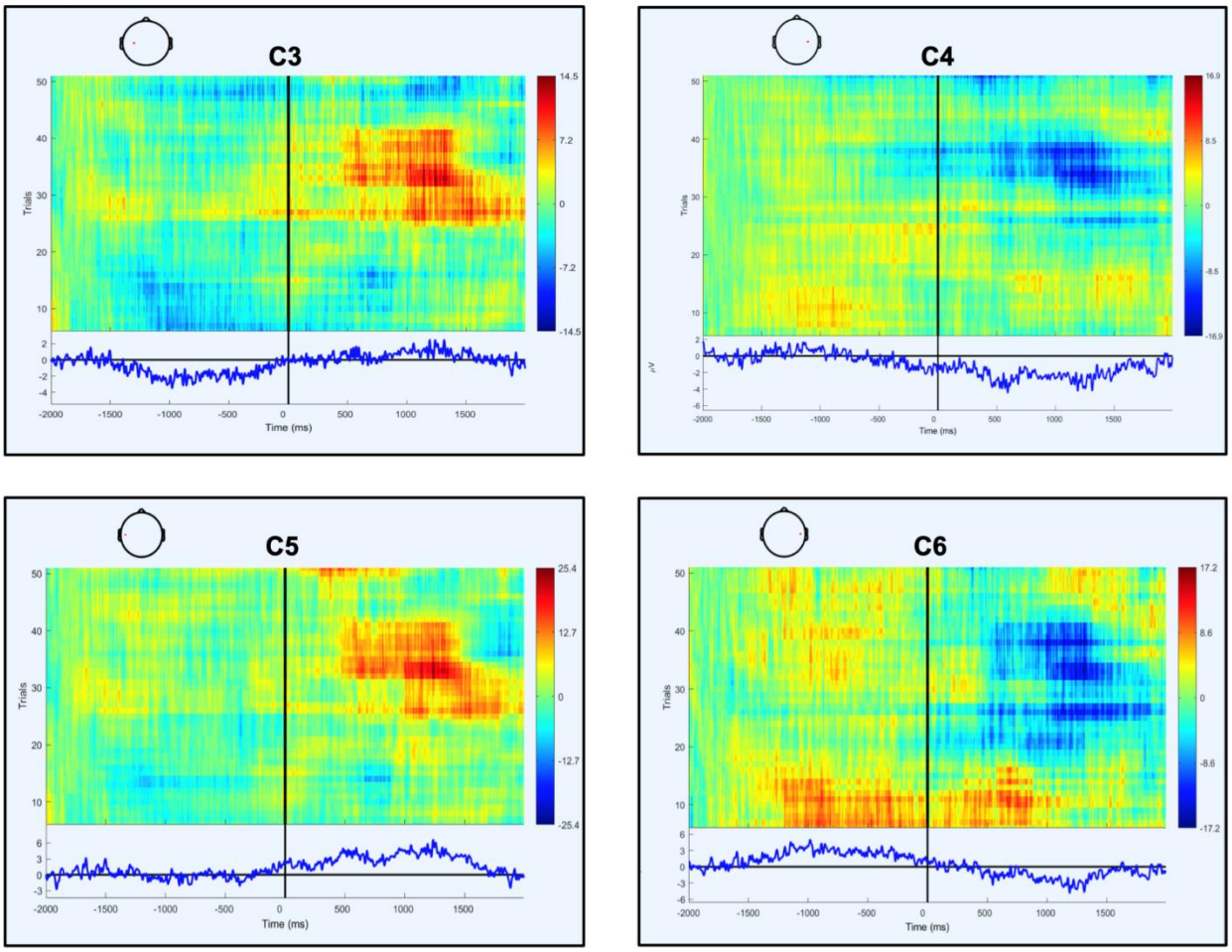



**Figure 21: Negative Spatial Errors for Participant B**

The above figure was obtained using EEGLAB. The x-axis represents time in milliseconds and the y-axis represents the number of trials. The color scale represents positive and negative values, with red being a positive spike in the EEG and blue being a negative spike in the EEG. The left two panels show electrodes C3 and C5 (in the left hemisphere) and the right two panels show electrodes C4 and C5 (in the right hemisphere).

When comparing positive spatial error (Figure 20) to negative spatial error (Figure 21) the EEG is very different depending on whether crisscross error was positive or negative. This would indicate that there is a neural correlate of proprioception, however this was only seen for one participant out of five and warrants further research.

### 2. *Time Frequency Domain*

EEG data was acquired in the time domain and converted to the frequency domain via Fourier Transforms for all 5 participants. The frequency response of single trials was analyzed. In order to analyze the relationship of the degree of error to the ERD response, the frequency response across the entire length of data was extracted using instantaneous frequency (Hilbert Transform). This frequency response was alpha band activity in the 8-12 Hz range. The change in power in the alpha band associated with ERD was correlated with the finger crossing error measured on each trial. Less alpha reduction was associated with higher error. Figure 22 shows the correlation and p-values across all five participants.

The mean alpha response was taken for each trial in each channel during a time period that was expected to reflect ERD (-1400 to -700 msec before the button press). The baseline mean alpha response (-2000 to -1700 msec before the button press) was subtracted from the mean alpha response per trial per channel. The difference was then tested for correlation at 0.05 significance with the absolute proprioception error (in degree). These values were plotted on topography. The left column of Figure 22 shows this topography and represents a visualization of what occurs in each electrode over both the left and right hemispheres. The correlation coefficients shown via topography in the left column allow the EEG channels that correlate with proprioceptive error to be analyzed. The color blue represents a negative correlation. Negative correlations are seen in the contralateral hemisphere and positive correlations are seen in the ipsilateral hemisphere of participants B, C, D and E over the sensorimotor areas. This shows the potential for a correlation between EEG and proprioceptive error; however, it is hard to say with certainty as more participants and trials need to be analyzed.

The negative log of the significance at 0.05 was also plotted on a second topography, as shown in the right column of Figure 22. The cutoff value for significance p-value is -log(0.05) = 2.99.

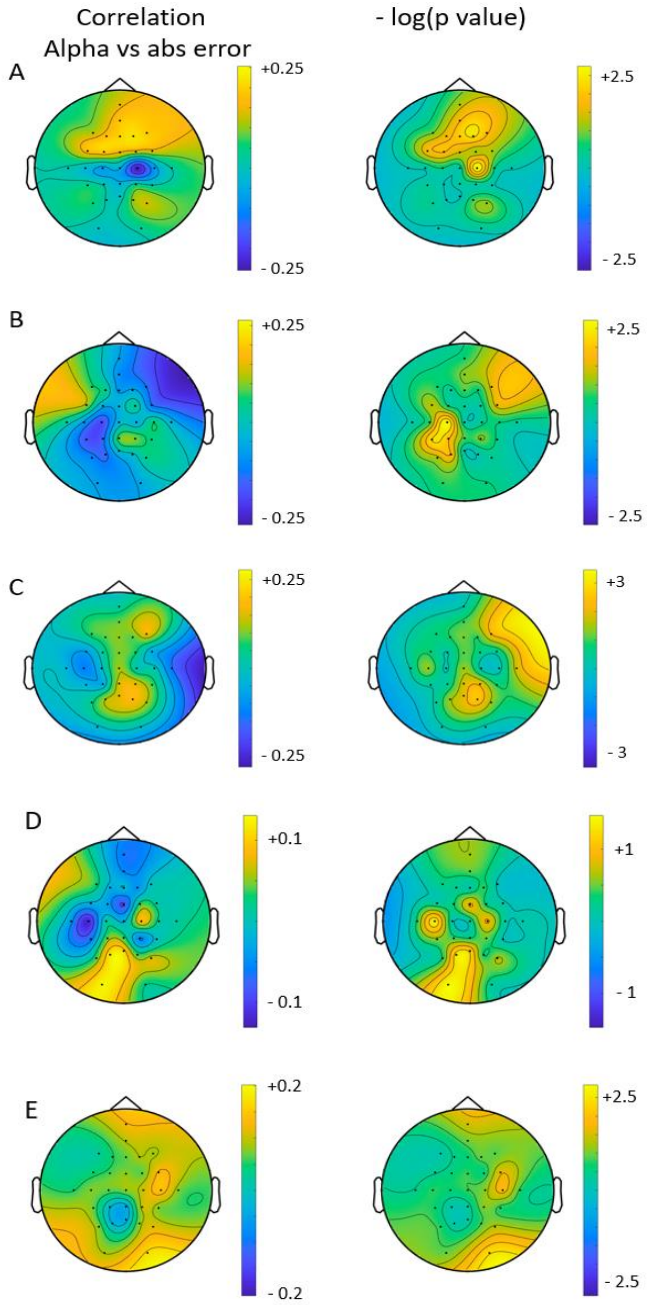



**Figure 22: Correlation of ERD and Proprioceptive Errors**

This graph shows the correlation of the change in power in the alpha band associated with ERD with absolute finger proprioceptive error across all five participants (left column) and the p-values associated with each correlation (right column). Power in the alpha band was extracted for all trials per channel per participant, comparing a time window just before the button press to a baseline time window. In the left column, the blue represents a negative correlation between change in alpha power and proprioceptive error. For example, if alpha in a window of interest is high then the proprioceptive error would be low. The yellow represents a positive correlation between the change in alpha power and proprioceptive error. The right column represents the p-values for each correlation.

Referring to my hypothesis, the strength of the ERD that occurs before the button press on a trial of the crisscross test will be related to the proprioceptive error on that trial, because ERD is known to be influenced by proprioception [24]. Norman et al., (2016) reported that 10 out of 12 participants exhibited ERD during passive participant/active robot movements [24]. Based on this premise, the change of ERD from baseline (ERD in sensing window - baseline) should also be larger. This means that the difference (ERD in sensing window - baseline) plotted in Figure 22 would be large for smaller proprioception errors, hence negatively correlated. Although a trend is apparent in Figure 22, some of the p-values for the correlations do not reach significance. This could be due to the small number of trials analyzed and or due to the fact that the data was analyzed on a single trial basis.

# VI. DISCUSSION

## A. Assessment of Proprioception Errors

### 1. *Error Type A: Anticipatory and Delayed Errors*

The maximum difference between the participant's index and middle fingers was 60 degrees. This distribution of errors is as expected and was observed in Ingemanson et al., (2015) where they had found the signed average overlap errors to be -3.2 $\pm$ 2.9 degrees (mean $\pm$ SD) for the young group, -0.01 $\pm$ 3.9 degrees for the middle-aged group and 2.6 $\pm$ 6.3 degrees for the older group [1]. The mean of anticipatory and delayed errors in reaction time was 39.57 $\pm$ 344.61 msec for a single run of non-vision and -40.31 $\pm$ 256.09 msec for a single run of vision. These are quite opposite for one run, however the data for anticipatory vs delayed errors was not significant.

### 2. *Error Type B: Spatial Error*

When the positive and negative spatial errors of the 6 non-vision runs are compared to the 1 vision run, they are similar. It is possible that in the vision run, participants learned the position they thought represented zero error (based on their angled view of their fingers). As participants completed more non-vision runs, it is possible that they reproduced the position they believed to be zero error as seen in the vision run. It is thought that participants will perform the best on the vision run, as they have vision of their fingers during the proprioceptive task. At run 6 of the non-vision run, participants made similar positive and negative spatial errors to the one vision run. This suggests that participants were adapting to the task, and possibly improving their proprioception, over time. As the crisscross task portion of the experiment only lasted approximately 30 minutes, these results are quite compelling. If this experiment were repeated with multiple sessions, it would be interesting to see if the learning would increase over time or level out. If participants can learn to improve their proprioceptive sense in 30 minutes using FINGER, people with

proprioceptive losses could possibly benefit even more from a longer and more intense training regimen. This is a preliminary result and using a larger data set could confirm that improving proprioception can be done by performing the Crisscross task using FINGER.

Another conclusion that can be drawn from the spatial error results is that participants were making more positive spatial errors than negative spatial errors. This means that participants made more errors when their index finger was further extended than their middle finger. This could mean that there are different proprioceptive pathways for each finger. As the index finger is the most used finger (in everyday life), I would not expect more errors to be made when the index finger was ahead. Since the index finger is commonly used, I would expect it to have the best proprioception of all the fingers.

Six runs were compared as one participant only had 6 non-vision runs. The error type changed over the course of 6 non-vision runs, having similar results from run 6 of non-vision to run 1 of vision. For the type of error, the first three runs of non-vision were not significant but runs 4-6 were significant showing the potential for people to improve their proprioception with practice. The extent of error (in degrees) did not change throughout the 6 non-vision runs, showing that the angle at which participants made the error did not change over time.

## B. EEG: Cortical Response to Proprioception

### 1. *Time Domain*

Results showed upward trends in the electrical activity of the left hemisphere of the brain, contralateral to the hand involved in the proprioceptive task. The upward trends were centralized to the motor and somatosensory areas. This is what was expected. The next task to explore would be why this phenomenon only occurred in one participant. It is possible that participant B

exhibited a contingent negative variation (CNV), which occurs in anticipation of an event. Collecting data from more people would allow us to see if this phenomenon occurs in other people as well.

### 2. *Time Frequency Domain*

The results show negative correlations between the size of the ERD over the left hemisphere and the finger proprioception error in four out of the five participants. Although not all of the correlations reached significance, these early results are promising.

When looking at single trials for analysis, the data is very noisy. The data needs extensive denoising or numerous trials to see a trend. For single trials, it is harder to find a cleaner association between EEG data and the signal someone is looking for. The p-values in Figure 22 show that some correlations are reaching significance but have not yet reached full significance ($p < .05$). This could be due to the noise between trials, the interstimulus interval or the fact that there were not enough trials or participants analyzed.

## C. Limitations

After the first participant, it was decided not to use noise cancelling headphones as they introduced a lot of noise in the EEG. This was because the headphones went over the ground and reference electrodes of the EEG that were placed on the mastoid bones. Noise cancelling headphones would ideally eliminate the artifact (cortical noise due to sound processing) that the robot noise would introduce in the EEG data. However, as the use of headphones was inadvertently affecting the EEG even more, it was decided to leave them out. The noise of FINGER does not assist in the judgement of proprioception, so it should not introduce any bias in the analysis. For further projects, it may prove beneficial to use a different reference and ground

location. Four participants had 1 vision and 10 non-vision runs while one participant had 2 vision runs and 6 non-vision runs. This made it difficult to compare 10 non-vision runs across all participants as not all participants underwent 10 non-vision runs.

Usually with EEG data numerous trials are averaged across participants so a frequency response can be seen. This study analyzed the EEG of five participants on a single trial basis. This produced approximately 500 trials which made it difficult to see a strong frequency response. As EEG is nonstationary, single trial data is very noisy which further complicates seeing a neural correlate of proprioception in the EEG. In addition, there has not been a lot of prior research pertaining to neural correlates of proprioception which made it difficult to choose a baseline time window. Future studies would require more in-depth analysis on the baseline to use.

# VII. CONCLUSION

## A. Conclusions

In conclusion, the results show hints of a novel neural correlate of proprioception. The magnitude of the ERD associated with the button press during the Crisscross test was weakly correlated with the size of the proprioceptive error on each trial for four participants. As data was analyzed on a single trial basis, repeating the experiment with more trials may show a stronger ERD response. Although more evidence is needed, these results suggest the intriguing possibility that ERD may serve as a novel neural correlate of proprioceptive processing. When analyzing data in the time domain, one participant exhibited an amplitude decrease prior to the button press in the left hemisphere. This amplitude decrease could be a result of anticipation for the button press.

A new type of error analysis (positive and negative spatial error) was introduced. It was found that by the sixth non-vision run participants made the same count errors as on run 1 of the vision run, suggesting short-term adaptation of proprioceptive ability. Over the course of the non-vision runs, it appeared participants were learning and, hence improving their proprioception. The error assessment from the FINGER data showed preliminary evidence that proprioception errors can change, perhaps towards improvement, over the course of 6 non-vision runs (~60 - 70 trials). This result was not something that was originally set out to be studied but was an interesting observation and is something that warrants future study.

## B. Future

In the future, this experiment could be adjusted based on the preliminary results I have shown. For example, the experiment can be done with participants performing all non-vision runs

and no vision run. The methods could also be modified so participants perform 1 vision run followed by10 non-vision runs and 1 vision run. Having a vision run at the end of the experiment would make for a good comparison with the vision run at the beginning. As the spatial count error changed over the course of six non-vision runs, the above suggestions to the paradigm may offer more insight into why the spatial count error changed as more non-vision runs were performed. Additionally, as the EEG data was analyzed on a single trial basis, more denoising of the data could be performed in the future. This may help to show a stronger alpha versus absolute error correlation. Lastly, this experiment could be replicated using a larger population such as 30 participants. This will allow the learning effects across non-vision runs to be seen on a larger scale. Studying a larger population would also allow for more trials to be collected which will allow the ERD in single trial analysis results to be analyzed with more statistical power.

There are many theories on the role proprioception plays within the body, but no concrete evidence has been found. Dietz 2002 stated that for complex behaviors, "afferent input related to load and hip-joint position probably has an important role in the proprioceptive contribution to the activation pattern of the leg muscles [25]." This is further reason to look for signals in the EEG, which might help explain the anatomical relationship of proprioception and the body.

Hillier et al., (2015) recommends collaborations between neurophysiologists and clinicians when studying proprioception [19]. Looking at proprioceptive signals from breadth before depth could provide a wider view of knowledge.

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# IX. APPENDIX

**Run Sheet: Example**

| Basic Information | Cap Information | Storage Information |
|---|---|---|
| **Subject:** X | **Circumference:** 58 cm | **BCI2000 File Name:** X.dat |
| **Date:** 3-3-2021 | **Nasion to Inion:** 36 cm | **Xsens File Name:** X.mtb |
| **Gender:** Female | **Cap Color:** Blue | **Session Number:** one |
| **Age:** 33 | | **Experimenters:** TS & ZE |
| **Handedness:** Right | | |
| **Consent Form:** Yes | | |

| | |
|---|---|
| **Start BCI2000 time:** 9:30 am | **Start Xsens time:** 9:31 am |
| **Stop BCI2000 time:** 10:01 am | **Stop Xsens time:** 10:00 am |

| Run | Time | Notes |
|---|---|---|
| **X1** | 9:32 am | vision |
| **X2** | 9:35 am | no vision |
| **X3** | 9:37 am | no vision |
| **X4** | 9:39 am | no vision |
| **X5** | 9:40 am | no vision |
| **X6** | 9:43 am | no vision |
| **X7** | 9:45 am | no vision |
| **X8** | 9:46 am | no vision |
| **X9** | 9:49 am | no vision |
| **X10** | 9:52 am | no vision |
| **X11** | 9:56 am | no vision |

| |
|---|
| **Other:** |