

**EFFECT OF NECK MUSCLE VIBRATION ON UPPER LIMB SENSORIMOTOR  
INTEGRATION AND MOTOR PERFORMANCE**

By

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fulfillment of the requirements for the degree of

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## **THESIS EXAMINATION INFORMATION**

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### **Master of Health Science in Kinesiology**

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An oral defense of this thesis took place on July 14, 2022, in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

## ABSTRACT

Upper limb control depends on accurate internal models of the position of the limbs relative to the head and neck. The cerebellum is heavily involved in SMI of neck sensory inputs and motor learning; therefore, it is likely that altered neck sensory input will impact cerebellar processing. However, it is unclear whether acute models of altered afferent input from vibration impacts SMI, somatosensory processing, and proprioception.

Study one used SEPs to investigate the effects of neck muscle vibration on SMI and motor learning while study two used an elbow repositioning task to investigate its effects on upper limb proprioception. Vibration led to differential changes in SEP peaks associated with cerebellar processing and motor skill acquisition, and changes in upper limb accuracy.

This thesis suggests that neck muscle vibration impacts cerebellar processing and motor control, likely due to vibration-induced alterations in body schema leading to neuroplastic adaptations and reduced accuracy.

## KEYWORDS

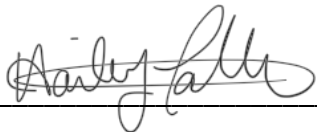
Somatosensory Evoked Potentials (SEPs); Motor acquisition; Sensorimotor Integration; Proprioception; Body Schema

## DECLARATION OF ORIGINALITY

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HAILEY TABBERT

## STATEMENT OF CONTRIBUTIONS

The work described in this thesis was performed at the University of Ontario Institute of Technology (Ontario Tech University) Neurophysiology and Rehabilitation Laboratory in operated by the Research Coordinator Ushani Ambalavanar who assisted with data collections.

I hereby certify that I am the sole author of this thesis. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others.

Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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## LIST OF ABBREVIATIONS

ADHD	Attention Deficit Hyperactivity Disorder
APB	Abductor Pollicis Brevis
ASA	Advanced Source Analysis
ASD	Autism Spectrum Disorder
CBI	Cerebellar Inhibition
CED	Cambridge Electronic Design
CEM	Cervical Extensor Muscles
CNS	Central Nervous System
COR	Cervico-Ocular Reflex
DCML	Dorsal Column Medial Lemniscus
EEG	Electroencephalography
EMG	Electromyography
EPT	Elbow Proprioception Task
FMTT	Force Matching Tracking Task
GABA	Gamma Aminobutyric Acid
HTV	Hand-Transmitted Vibration
IFCN	International Federation of Clinical Neurophysiologists
MVC	Maximal Voluntary Contraction
PNS	Peripheral Nervous System
RPE	Rated Perceived Exertion

SCM	Sternocleidomastoid
SCNP	Subclinical Neck Pain
SEPs	Somatosensory Evoked Potentials
SMI	Sensorimotor Integration
S1	Primary Somatosensory Cortex/Area
TMS	Transcranial Magnetic Stimulation
VA	Ventral Anterior Thalamus
VL	Ventral Lateral Thalamus
VOR	Vestibulo-Ocular Reflex
WBV	Whole Body Vibration

## CHAPTER 1

### INTRODUCTION

## INTRODUCTION TO THE THESIS

When you're in a hurry, you may fail to notice certain objects in your path, like an approaching person, but most of the time you automatically and instinctively avoid them. Control of the body, in avoiding or manipulating objects to reach behavioural goals requires an accurate and constantly updated perception of the body and the space surrounding it. This concept is known as body schema. Body schema is characterized as the cortical representation of the position of the body in space. Broadly, it is the integrated perception of the location, orientation and functional integrity of the body and appendages created by a complex neural network that combines somatosensory and visual information (Holmes and Spence 2004). It includes the shape of each body segment and the body surface, proprioceptive information regarding limb configuration, and the length of each body segment (Maravita, Spence et al. 2003, Haggard and Wolpert 2005). Body schema is integral for spatial orientation and updates constantly during movement permitting proper motor learning and motor control. During movement, proprioceptive and visual feedback are continuously cross-referenced to update body schema and predict future positions (Maravita, Spence et al. 2003). This involves a complex neural network that processes information using the most appropriate reference frame (Medina and Coslett 2010). Body-centered reference frames topographically represent the body in reference to the position of the head and neck while eye-centered reference frames compute the location of body parts using information encoded in the visual cortices (Maravita, Spence et al. 2003, Holmes and Spence 2004). Given that the cortical organization of sensory information from peripheral structures is highly dependent on the position of the head and



neck, proprioceptive input becomes increasingly more important in the absence of visual information.

Proprioception is defined as the conscious and unconscious awareness of the body's position, mediated by proprioceptors in muscle tissue, joints and tendons (Proske and Gandevia 2012, Tuthill and Azim 2018). More specifically, neck muscle proprioception plays a significant role in balance, movement organization and forming accurate body schema (Strimpakos, Sakellari et al. 2006). Muscle spindles are the major proprioceptors of the neck and given the importance of their role it is no surprise that neck muscles have the highest density of proprioceptors in humans (COOPER and Daniel 1963, Richmond and Abrahams 1979, Kulkarni, Chandy et al. 2001). Muscle spindles are activated when high frequency, low amplitude vibration is applied over a muscle belly which is perceived by the central nervous system (CNS) as joint movement and rotation if the vibration frequency exceeds 30Hz (Brown, Engberg et al. 1967, Goodwin, McCloskey et al. 1972, Cordo, Bevan et al. 1995). Consequently, vibration of neck muscles would alter afferent input from peripheral structures as it travels through the neck and to the brain.

The cerebellum is the main site for sensorimotor integration of neck muscle and spine inputs, as well as being primarily responsible for motor learning and online motor control, therefore it is likely that altered afferent input from the neck impacts cerebellar processes that permit proper motor learning and motor control. Previous research has demonstrated that altered afferent input from the neck as a result of joint dysfunction, pain and fatigue impacts

proprioception (Knox and Hodges 2005, Paulus and Brumagne 2008, Guerraz, Caudron et al. 2011, Zabihhosseinian, Holmes et al. 2015, Stanton, Leake et al. 2016), motor control (Guerraz, Blouin et al. 2003, Huysmans, Hoozemans et al. 2010, Zabihhosseinian, Holmes et al. 2017, Zabihhosseinian, Yelder et al. 2019), and motor learning (Daligadu, Haavik et al. 2013, Andrew, Yelder et al. 2018, Baarbé, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2020). Additionally, research has also demonstrated alterations in cortical processing including sensorimotor integration (Andrew, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2020), multisensory integration (Farid, Yelder et al. 2018, Karellas, Yelder et al. 2019) and proprioceptive processing (Paulus and Brumagne 2008, Baarbé, Holmes et al. 2015, Wallwork, Leake et al. 2020). However, it is important to note that pain and fatigue can alter multiple types of feedback through the involvement of spindle inputs, pain afferents and changes in muscle properties (Falla and Farina 2008, Alcaraz-Clariana, García-Luque et al. 2021).

## OBJECTIVE OF THE THESIS

The objective of this thesis was to determine the effect of transient alterations in neck afferent input from muscle vibration on body schema as well as upper limb proprioception, motor control, and motor learning. This was assessed neurophysiologically via differential changes in early and middle-latency somatosensory evoked potentials (SEPs) and behaviourally via changes in performance accuracy using a novel proprioceptive based motor learning task and changes in upper limb proprioception measured using an elbow proprioception task.

## HYPOTHESIS OF THE THESIS

It was hypothesized that neck muscle vibration would lead to neurophysiological and behavioural alterations in proprioception, motor control and motor learning. More specifically, individuals receiving neck muscle vibration would demonstrate poorer motor performance accuracy, increased proprioceptive error, altered motor learning patterns and changes in the associated SEP peak amplitudes compared to controls.

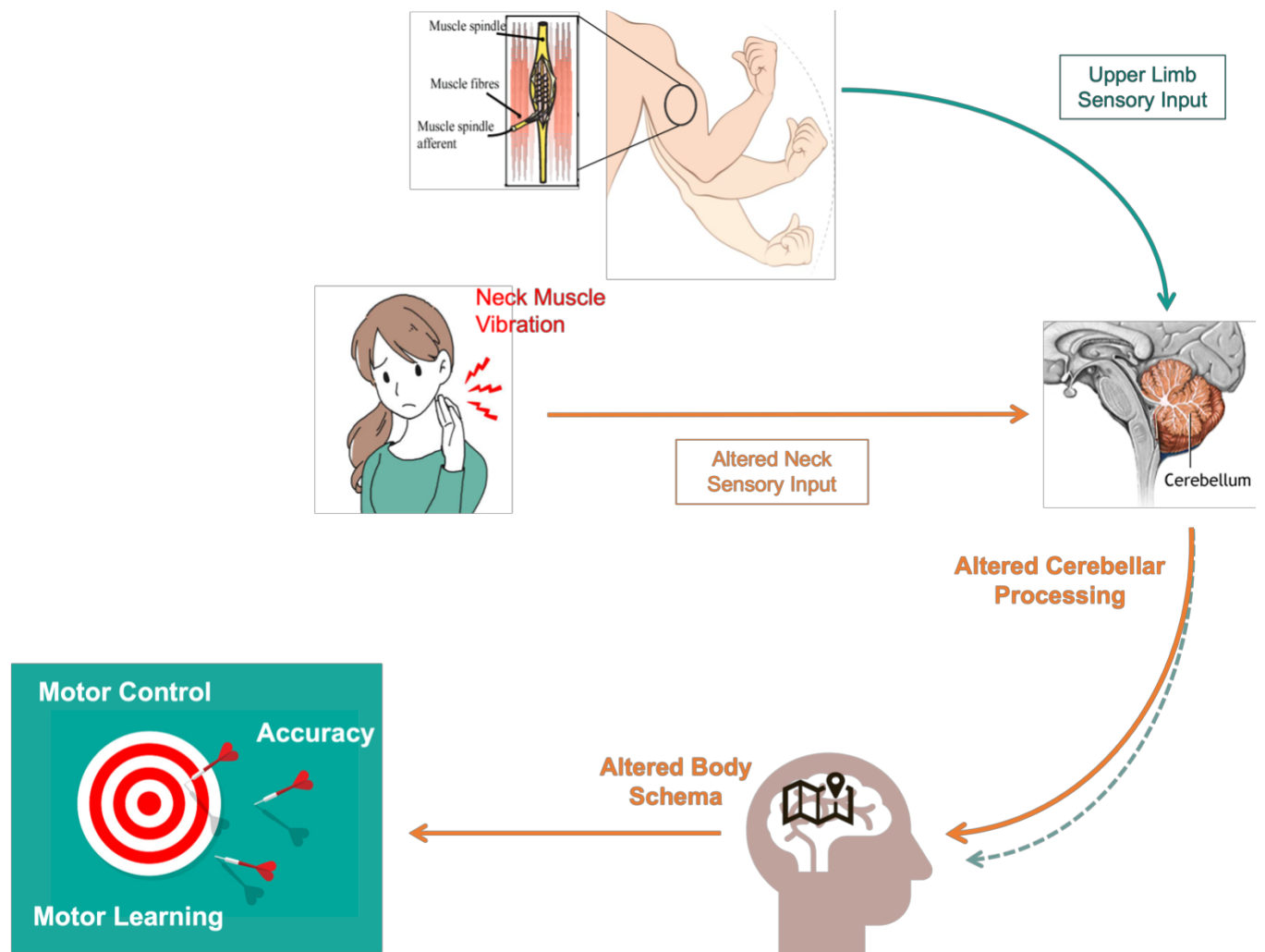


Figure 1, Summary of the thesis introduction illustrating the impact of altered afferent input from the neck on cerebellar processing, body schema and motor control.

## CHAPTER 2

### LITERATURE REVIEW

## Overview

Every day we rely on incoming information from our body to navigate the space around us and react rapidly to new circumstances. Body schema is integral for spatial orientation and accurate motor control and, to that end, is updated constantly during movement involving both central and peripheral processes. During movement, proprioceptive and visual feedback are continuously matched against body schema to predict future positions. In the absence of visual input, proprioceptive input from the muscle spindles become increasingly more important.

The cerebellum is heavily involved in motor control and sensorimotor integration of neck muscle and spine inputs (Manzoni 2005, Felten, O'Banion et al. 2015). Using a feedforward model, the cerebellum receives sensory input from bodily movements and integrates this information into the body schema (Manto, Bower et al. 2012, Daligadu, Haavik et al. 2013). The cerebellum is also actively involved in motor learning. Motor learning tasks induce plasticity of the cerebellar cortex and the motor cortex (Doyon, Song et al. 2002, Doyon, Penhune et al. 2003). Research has demonstrated that loss of cerebellar projections impacts body schema (Picazio, Oliveri et al. 2013). Furthermore, altered afferent input from the neck resulting from joint dysfunction, postural stress, pain, or fatigue has been shown to impact cerebellar processing (Daligadu, Haavik et al. 2013, Andrew, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2020).

Neck muscle vibration has been shown to activate muscle spindles in the neck thereby inducing illusions of movement and joint rotation (Brown, Engberg et al. 1967). Given that the

cerebellum is the main site for sensorimotor integration of the sensory input from this region, as well as being the area primarily responsible for motor learning, it is likely that altered afferent input from the neck will impact how the cerebellum processes this information to create accurate internal models that permit proper motor learning and motor control.

The objective of this thesis was to explore the effects of neck muscle vibration on upper limb sensorimotor integration and motor learning in healthy right-handed participants learning a novel motor task. Specifically, to explore how altering sensory input from the neck impacts body schema, motor acquisition, spatial awareness, and cortical processing. The overall hypothesis of this thesis was that neck muscle vibration would alter afferent input from the neck and lead to alterations in motor acquisition, decreased motor accuracy and alterations in body schema. This thesis will further our understanding of the neurophysiological and behavioural effects of altered neck afferent input on upper limb motor accuracy, sensorimotor integration, and motor acquisition.

## Introduction to Literature Review

This literature review covers the background literature relevant to the topic of this thesis. It begins with an introduction to the functional anatomy of the somatosensory system followed by an overview of the biological processes underlying body schema, proprioception, and motor control.

## Somatosensory System

The somatosensory system supports the perception of sensory information including touch, pressure, vibration, proprioception, pain, temperature, and movement via specialized receptors such as muscle spindles, joint capsules and golgi tendon organs which can be found in muscles, fascia, joints, skin, and viscera (Riemann and Lephart 2002). The process by which these external stimuli are converted to electrical signals and transferred through the central nervous system is referred to as sensory transmission (Hoshiyama and Sheean 1998). The somatosensory system is divided into branches that transmit sensory input to the contralateral cortex: the spinothalamic pathway which transmits pain and temperature information and the dorsal column medial lemniscal (DCML) pathway which transmits touch, pressure, vibration, and proprioception (Riemann and Lephart 2002). For the purposes of this thesis, I will focus on the DCML pathway as this study focuses on proprioception, vibration, and short latency SEPs, all of which are carried and processed in this pathway. The DCML pathway is a three-neuron pathway consisting of a first order, second order and third order neuron that transmit sensory information from the peripheral nervous system to central nervous system. The fasciculus cuneatus portion of this pathway contains long fibres ascending from the upper limbs to the cortex and exists in thoracic (T1-T6) and cervical (C1-C8) segments. The first order neuron is found in the dorsal root ganglia and connects the receptors from the limbs, trunk, neck, and head to the spinal cord. The first order neuron synapses with the second order neuron on nuclei of the lower medulla. For sensory information from the upper limbs, the second order neuron begins at the nucleus cuneatus, for sensory information from the muscle spindles of the head and neck, the second order neuron begins at the lateral cuneate nucleus (COOPER and

Daniel 1963, Lundy-Ekman, Peterson et al. 2018). This difference distinguishes the DCML pathway from the cuneocerebellar pathway. The second order neuron of the DCML ascends the brainstem through the pons and midbrain and terminates on the ventral posterolateral nucleus of the thalamus where it synapses with the third order neuron. Axons from the third order neuron ascend to the postcentral gyrus into the somatosensory areas. The second order neuron of the cuneocerebellar pathway ascends through the inferior cerebellar peduncle and terminates on the medial portion of the cerebellar cortex (COOPER and Daniel 1963, Purves, Augustine et al. 2001, Najarian and Splinter 2012, Lundy-Ekman, Peterson et al. 2018).

## The Neural Construction of Body Schema

The neural representation of the body and the space surrounding it involves a complex network of cortical and subcortical brain areas and is often referred to as the body schema. The body schema is constructed using multisensory representations involving the integration of somatosensory, visual, auditory, and proprioceptive information. Different brain areas work in conjunction to process information in the reference frame appropriate to the body part it concerns (Holmes and Spence 2004). Reference frames can be body-centered or eye-centered. Body centered reference frames represent the body topographically in reference to the position of the head and neck and exist primarily in the primary and secondary somatosensory cortices. Eye-centered reference frames compute the location of body parts using information encoded in the visual cortices. The brain switches between the two frames and seems to use



the most appropriate frame of reference for the information being processed (Childs, Cleland et al. 2008).

Afferent signals from muscle and joint tissues, visual, auditory, vestibular and somatosensory information are integrated in the ventral premotor cortex, representing the space around the arms, hands and face (Graziano, Yap et al. 1994). Somatosensory information projects to the thalamus and then onto the primary somatosensory cortex in Brodmann's areas 1, 2 & 3. The primary somatosensory cortex sends feedback to posterior parietal area 5 to encode the position of the limbs and body movements through integrating proprioceptive and visual information regarding the limbs (Karellas, Yelder et al. 2019). Previous research has demonstrated that the use of virtual limbs (Wallwork, Leake et al. 2020) and tools (Paulus and Brumagne 2008) manipulate the brain's representation of peripersonal space to incorporate their position into body schema indicating that body schema is a multisensory configuration.

### Proprioception – The Ascending Pathways

Proprioception, or the awareness of the position of the body in space, is primarily communicated by mechanoreceptors and proprioceptors in the skin, joints, and muscles. Previous research suggests that muscle spindles are the major proprioceptive sensors (Eklund 1972, Proske and Gandevia 2012). In 1973, Grigg and colleagues demonstrated the importance of muscle spindles as proprioceptors when they discovered that patients with total hip replacements, including removal of all joint and ligamentous components, had intact position

and movement sense post-surgery (GRIGG, FINERMAN et al. 1973). Muscle spindles are the most abundant sense organs in skeletal muscle and function by sensing the change in length of the muscle in which they are located and the velocity of this change (COOPER and Daniel 1963). This is achieved through primary (Ia) afferents and secondary (II) afferents which coil around the non-contractile central portions of intrafusal fibers and sense changes in length and the velocity of this change for a given muscle (COOPER and Daniel 1963, Macefield and Knellwolf 2018). A single spindle receives one large afferent nerve fiber to the primary ending on nuclear bag and chain fibers and one or more smaller afferent nerve fibers to the secondary ending on nuclear chain fibers (COOPER and Daniel 1963). Primary endings have greater dynamic sensitivity to changes in muscle length and movement velocity due an increased diameter and faster conduction velocity (Macefield and Knellwolf 2018). They enter the spinal cord through the dorsal root ganglion and ascend the dorsal column medial lemniscus (DCML) tract to the primary somatosensory cortex (COOPER and Daniel 1963). In contrast, secondary endings have lesser dynamic sensitivity and respond primarily to changes in muscle length. Secondary afferents take an indirect route to the primary somatosensory cortex, have fewer branches and therefore have a much slower conduction velocity in comparison (COOPER and Daniel 1963).

Once the primary and secondary spindle afferents sense deformation in the surrounding tissues, the proprioceptive information is carried up the spinal cord to the brain where it is converted into neural signals (Delhaye, Long et al. 2011). Generally, proprioceptive information is transmitted to the spinal cord where it ascends the DCML tract to the primary somatosensory cortex for processing (O'Sullivan and Schmitz 2007). The cuneocerebellar tract is a high fidelity

branch of the spinocerebellar tract derived mainly from muscle spindle afferents and regulates the transmission of sensory information from the head, neck and upper limbs to the cerebellum (Kandel, Schwartz et al. 2000, Felten, O'Banion et al. 2015). Central axons of the first order neuron in the dorsal column synapse on the lateral cuneate nucleus of the lower medulla to the second order neuron. From here, the axons of the second order neuron project through the ipsilateral inferior cerebellar peduncle and terminate in the medial portion of cerebellar cortex (Felten, O'Banion et al. 2015). Often, proprioception is analyzed behaviourally by measuring the motor performance accuracy of various aiming or repositioning tasks; however, the impact on neural processing can be analyzed neurophysiologically using brain imaging techniques like somatosensory evoked potentials (SEPs) to measure activity in these pathways.

### Motor Control – The Descending Pathways

To perform a motor task, the parietal lobe and anterior frontal lobe communicate information about the current limb position and the motor planning strategy to achieve this task respectively to the primary motor cortex. The primary motor cortex then generates a motor command and sends it through the subcortical basal ganglia loop to ensure fluidity of the intended movement. This information is sent back to the primary motor area through the ventral anterior and ventral lateral (VA/VL) thalamus before descending to medulla and decussating in the medullary pyramids. The efferent information then descends the corticospinal tract to the target effector muscles (Lundy-Ekman, Peterson et al. 2018). The primary motor cortex also sends a collateral projection to the cerebellum about the intended

position, velocity and duration of the movement via the cerebrocerebellar pathway (Knierim 1997 - Present).

As the movement begins to occur, joint receptors and muscle spindles sense a change in joint position, muscle length and the velocity of this change, respectively, and generate an afferent signal to ascend the DCML tract to the primary somatosensory cortex and to the cerebellum via the spinocerebellar pathway (Kandel, Schwartz et al. 2000, Felten, O'Banion et al. 2015). The primary somatosensory cortex processes this information and sends a projection to the cerebellum through the ventral posterolateral nucleus regarding the current position of the target muscle so that it can make the appropriate adjustments. The cerebellum sends an adjusted efferent signal via the cerebrocerebellar pathway to the primary motor cortex and through the spinocerebellar pathways to the reticulospinal and rubrospinal tracts to make movement corrections (Kandel, Schwartz et al. 2000).

### **Sensorimotor Integration**

As we navigate our environment, the central nervous system integrates incoming sensory information from different parts of the body to produce the proper motor adjustments. Sensorimotor integration (SMI) refers to the cortical processing of afferent information to formulate an appropriate motor response (Wolpert, Ghahramani et al. 1995). Afferent information from the periphery is projected to the sensorimotor cortex to provide necessary information on the current state and position of the body, permitting accurate motor control in ever-changing environments. Effective acquisition and performance of any motor skill depends

on accurate sensorimotor processing. However, due to the plastic nature of the brain there is always a possibility of undesired sensorimotor alterations. Neuroplasticity refers to the ability of the central nervous system to reorganize its structure, function and connections in response to afferent signals (von Bernhardi, Eugénin-von Bernhardi et al. 2017). These changes can outlast the period of afferent input producing long-lasting alterations in neural activity and central functioning (Murphy, Taylor et al. 2003). Increased and decreased neural activity can lead to inhibition or facilitation of subsequent neural signalling (Byl, Merzenich et al. 1997, Baarbé, Yelder et al. 2018). The resulting alterations can be physiologically beneficial or disadvantageous and are referred to as adaptive plasticity and maladaptive plasticity, respectively. SMI substantially influences neuroplastic alterations and therefore, it is important to understand the influence of these changes on motor control and acquisition.

## The Cerebellum

The cerebellum is an area within the hindbrain responsible for many sensorimotor functions and motor learning. It makes up 10% of the brain's total volume but contains over half of the neurons in the brain. The cerebellum is composed of 3 functional divisions which work with other cortical areas to achieve specific cerebellar functions. The cerebrocerebellum is involved in movement planning, motor learning and regulating the coordination of muscle activation (Doyon, Song et al. 2002, Manto, Bower et al. 2012, Sillitoe, Fu et al. 2012). The spinocerebellum is responsible for proprioception and adaptive motor coordination. The high-fidelity cuneocerebellar tract is a branch of the spinocerebellum and regulates the transmission of proprioceptive inputs from the head and neck (Felten, O'Banion et al. 2015). The purpose of

this pathway is to deliver information from peripheral receptors in muscles, tendons, and joints to the cerebellum. This two-neuron pathway is considered high-fidelity as it relays somatotopically arranged information to the cerebellar cortex with little distortion as it travels from neuron to neuron, therefore the information arriving at the cerebellum is very similar to the signal originating at the peripheral receptors (Lundy-Ekman, Peterson et al. 2018). The vestibulocerebellum is responsible for controlling balance and the cervico-ocular (COR) and vestibulo-ocular (VOR) reflexes (Miall, Reckess et al. 2001).

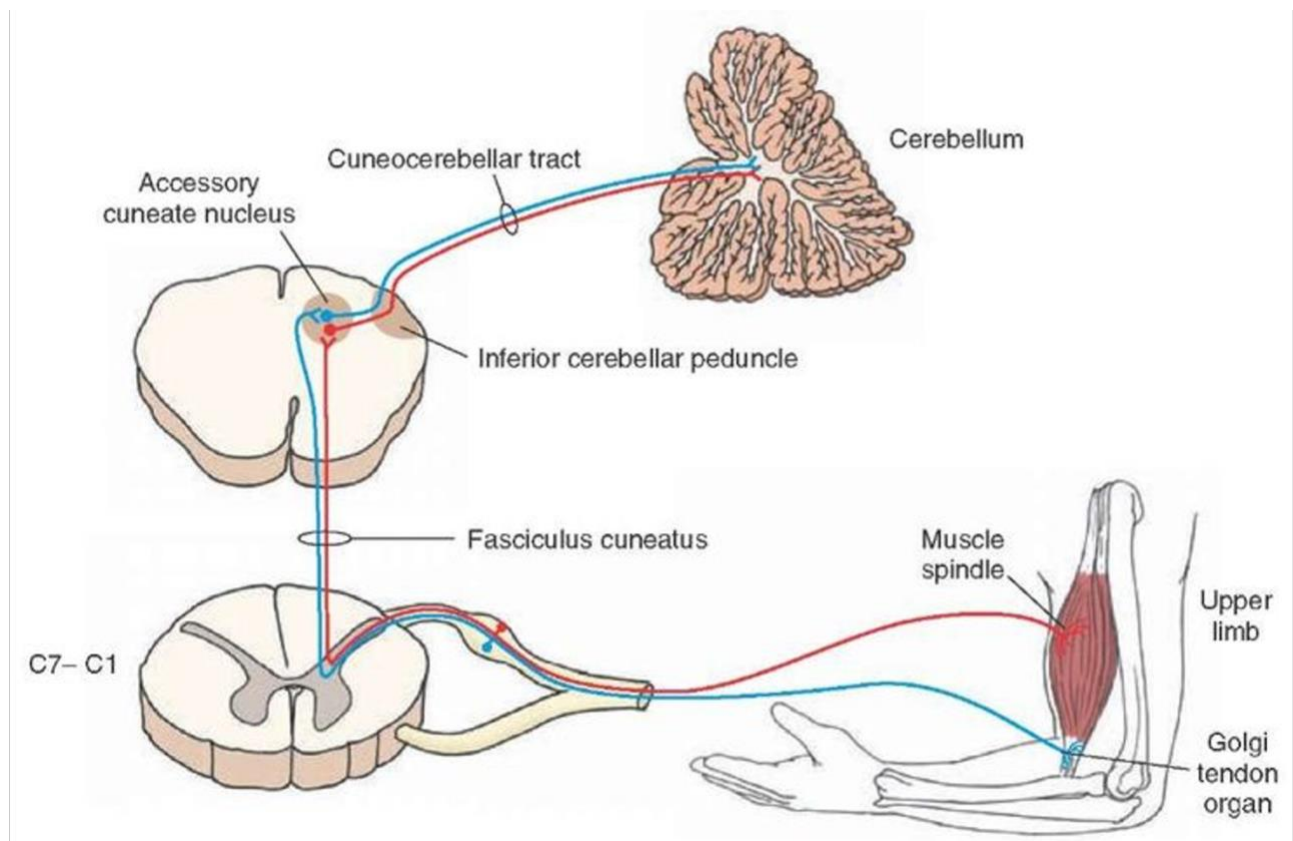


Figure 2. Cuneocerebellar pathway from the upper limb to the cerebellum.

Adapted from: <http://what-when-how.com/neuroscience/the-spinal-cord-organization-of-the-central-nervous-system-part-2/>

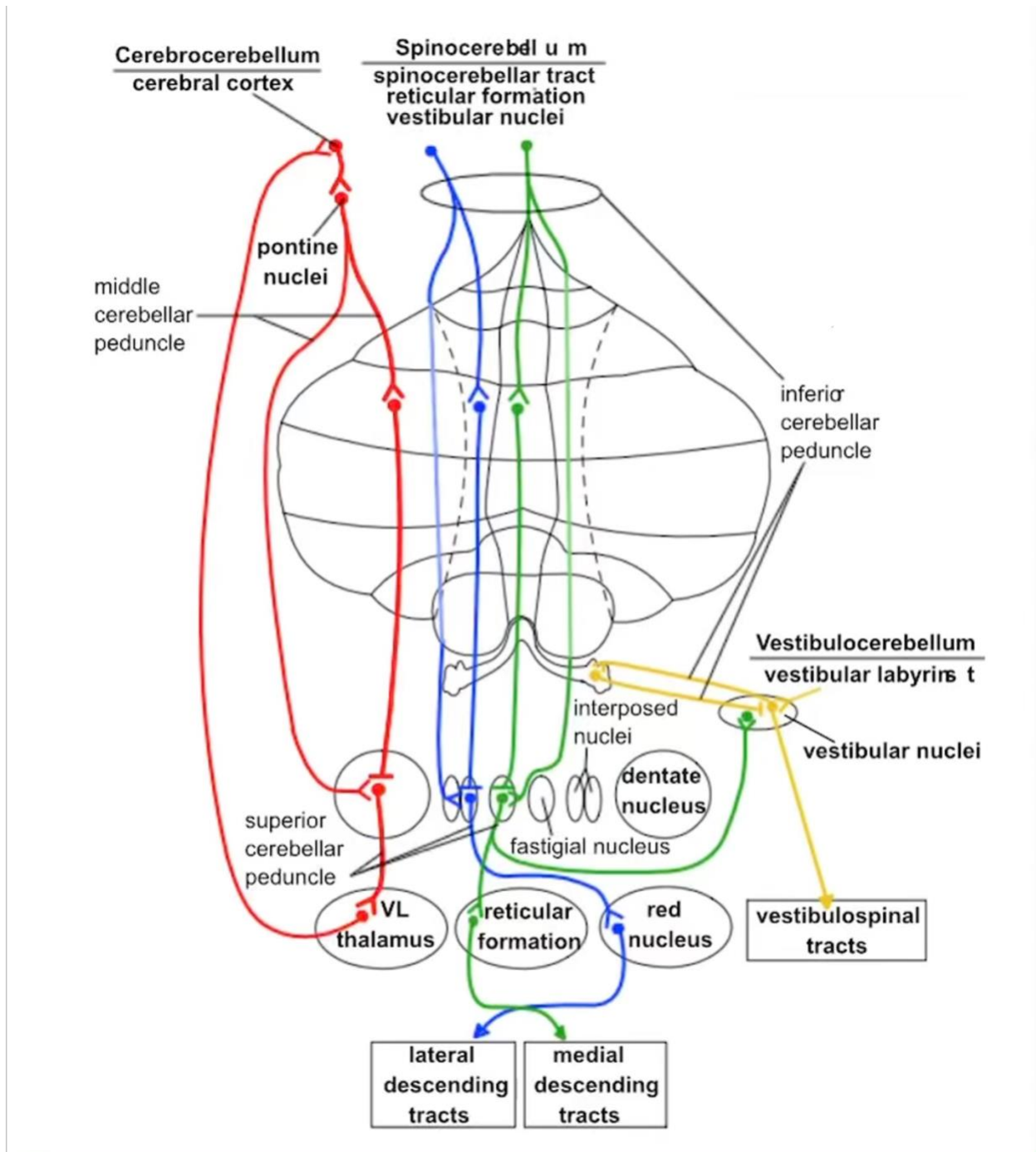


Figure 3. Cerebellar pathways. Cerebrocerebellar tract (red), spinocerebellar tracts (blue and green), and vestibulocerebellar tract (yellow).

Adapted from: (Knierim 1997 - Present).

The cerebellum can be divided into two regions: the cerebellar cortex and deep nuclei. The cerebellar cortex contains many different cell types, all of which provide input to the purkinje cells which facilitate output from the cerebellar cortex via inhibitory projections onto the deep cerebellar nuclei (Shepherd 2004). In the granular layer, mossy fibers synapse with granule cells which send collateral projections called parallel fibers deep into the molecular layer which synapse with purkinje cells (Shepherd 2004). Climbing fibers bypass the granular layer and synapse directly with purkinje cells in the molecular layer (Shepherd 2004). Purkinje cells receive thousands of weak inputs from parallel fibers of granule cells and one extremely strong input from a single climbing fiber. Therefore, almost all spikes generated by parallel fiber inputs result in tonic inhibition of cerebellar nucleus targets while spikes generated by climbing fiber inputs initiate changes in strength of the parallel fiber inputs (Shepherd 2004, Popa, Hewitt et al. 2013). The deep cerebellar nuclei are composed of the fastigial, interposed, dentate, and vestibular nuclei. Each play specific roles in accordance with the functional division they are associated with and constitute as the sole source of output for the cerebellum. The cerebellar deep nuclei receive collateral projections from mossy fibers, climbing fibers and purkinje cells of the cerebellar cortex (Shepherd 2004). Mossy fibers and climbing fibers make excitatory synapses with the deep cerebellar nuclei through the involvement of glutamate while purkinje cells utilize Gamma Aminobutyric Acid (GABA) to make inhibitory connections to the inferior olivary nucleus (Shepherd 2004). Therefore, the nucleo-olivary projection provides inhibitory feedback to match the excitatory input from climbing fibers and mossy fibers to the deep cerebellar nuclei.



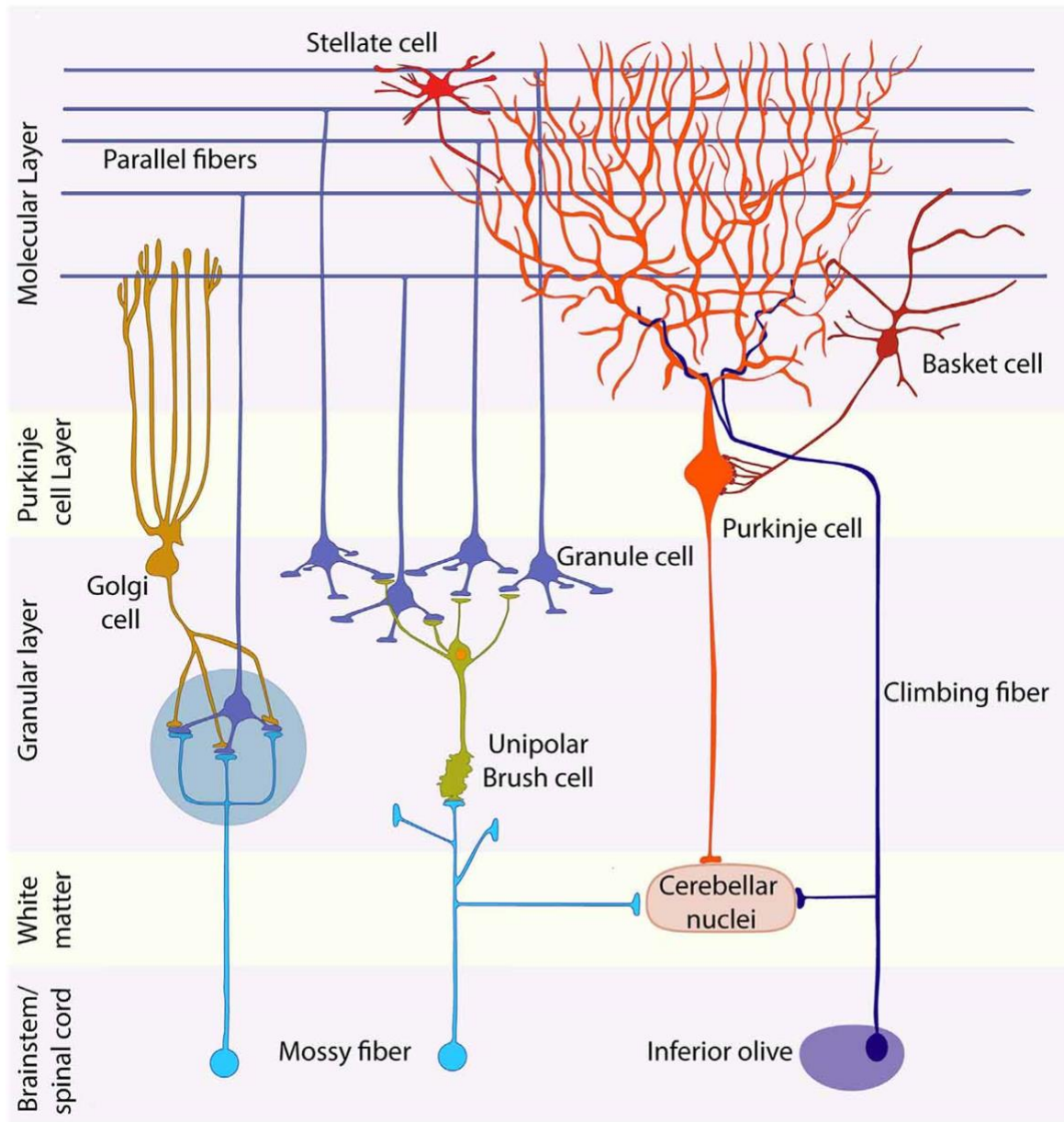


Figure 4. Cellular organization of the cerebellum.

Adapted from (Consalez, Goldowitz et al. 2021).

To carry out its functions, the cerebellum integrates sensory input before modulating output through purkinje cells (Popa, Hewitt et al. 2013). This allows for the learning of smooth, continuous movements and the formation of an accurate body schema. The cerebellum plays

an important role in the construction of body schema. Previous research using Transcranial Magnetic Stimulation (TMS) to inhibit the cerebellum demonstrates that a loss of cerebellar projections has negative impacts on body schema and the ability to perform a mental rotation task (Picazio, Oliveri et al. 2013). In addition, the cerebellum transfers sensory input to aid in reorganization and plasticity of cortico-striatal networks when learning new tasks and regulating movement through adaptive motor coordination (Doyon, Song et al. 2002, Doyon, Penhune et al. 2003). It also plays a role in oculomotor control by regulating reflexive and voluntary eye movements including the vestibulo-ocular reflex (VOR) and cervico-ocular reflex (COR) which permit target fixation by stabilizing the eyes in response to vestibular stimulation and stabilizing the eyes during head and trunk movements respectively (de Vries, Ischebeck et al. 2016). It is through these functions that the cerebellum provides a mechanism for adapting our movements and position to maintain a consistently updated and accurate body schema in reference to changing visual information as we navigate our environment (Miall, Reckess et al. 2001). It is considered fundamental in the neural integration of the eye and hand during visually guided tracking tasks (Miall, Imamizu et al. 2000, Miall, Reckess et al. 2001). Research has shown that cerebellar dysfunction results in decreased motor accuracy during visually guided tracking tasks and coordinated eye and hand movements (Miall, Imamizu et al. 2000), supporting its involvement in hand-eye coordination and sensorimotor integration.

## **Motor Learning and Acquisition**

The process of improving novel motor skills through practice, with lasting improvements in skill capabilities, is referred to as motor learning or motor acquisition (Doyon, Song et al.

2002). Motor acquisition consists of two phases of learning: early learning and late learning. Fitts & Posner's model of motor learning breaks down these two phases into 3 distinct stages termed the cognitive, associative, and autonomous stages. The cognitive stage is considered an acquisition stage with a high degree of error and extremely rapid improvements in performance (Fitts and Posner 1967). This is followed by the associative stage, also known as the retention stage which demonstrates continued improvements in performance, increased consistency and fewer errors (Fitts and Posner 1967). Both the cognitive and associative stages are considered early learning. Lastly, the autonomous stage, also known as the transfer stage is when performance of the motor skill become automatic, adaptable, and free of errors (Fitts and Posner 1967). Acquisition of a motor skill is typically measured by reduced reaction times and increased accuracy. Retention of this skill is assessed 24-48 hours following acquisition (Doyon and Ungerleider 2002).

During the transition from early to late learning, there is a shift in cortical activation from the cerebellum to the cortico-striatal networks (Doyon, Owen et al. 1996, Doyon, Song et al. 2002, Doyon, Penhune et al. 2003). Functional MRI studies reveal an experience-dependent shift during motor sequence learning of the serial reaction time task. During the early stages of motor learning, the cerebellar cortex and cerebellar deep nuclei showed increased activation compared to other areas (Doyon, Song et al. 2002). During the late stage of motor learning activation of the cerebellar cortex and deep nuclei was significantly reduced while activation in cortico-striatal networks was greatly increased (Doyon, Song et al. 2002). Other researchers have found that this shift in cortical activation is also dependent on the context of learning

(motor sequence learning vs. motor adaptation). It was found that the cortico-striatal networks and cortico-cerebellar systems contribute differently to motor sequence learning and motor adaptation, respectively, and that this is most apparent during the retention phase (Doyon, Penhune et al. 2003).

Research done using animal models demonstrated that early motor learning induced plasticity at inhibitory granule-purkinje synapses within the cerebellar cortex (Mauk 1997). Further improvements in performance induced plasticity at excitatory mossy fiber synapses in the deep cerebellar nuclei (Mauk 1997). During periods of early learning cerebellar disinhibition occurs to permit appropriate error correction and motor adaptation as movements occur. As we transition to the later stage of motor learning, cerebellar inhibition occurs as fewer errors are occurring and the need for motor adaptation is minimal. This is supported by other animal studies which demonstrate an increase in the amplitude of cerebellar activity in the fastigial, interposed, and dentate nuclei that decreased with extended practice when the animal began producing smooth movements with minimal error (Bloedel, Bracha et al. 1997).

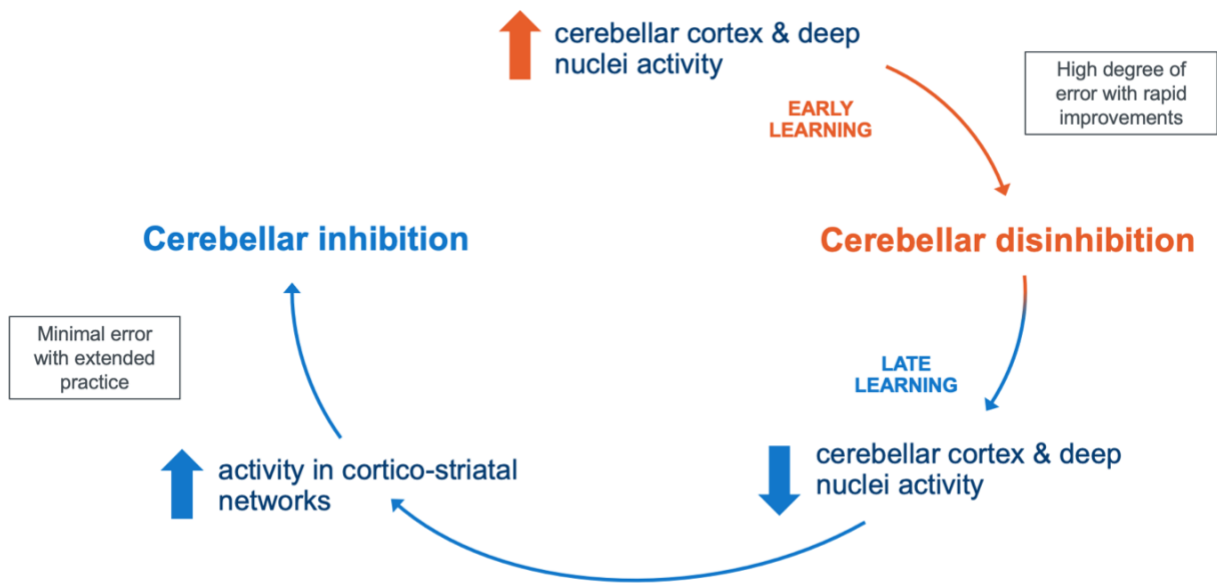


Figure 5. Experience dependent changes in cortical activation through the early and late stages of motor acquisition.

## Force Tracking

Acquisition of novel motor tasks has been shown to generate quantifiable changes in cortical activity. Following the acquisition of a visuomotor tracking task, researchers found hemispheric and lateralized activation in cortical areas responsible for proprioception and movement planning (Brown, Caligiuri et al. 2004). Other research demonstrates that acquisition of dynamic force matching tasks leads to changes in functional connectivity of cortico-cerebellar networks (Mehrkanoon, Boonstra et al. 2016, Dal Maso, Desormeau et al. 2018) and increased corticomotor excitability (Pearce and Kidgell 2009). Increased excitability in descending cortico-motor networks was also shown following the acquisition of dynamic and static visuomotor tracking tasks (Pearce and Kidgell 2010). While force matching and

visuomotor tracking are widely used to evaluate improvements in motor performance associated with motor learning, only one study has examined the associated cortical changes in the activity of neural correlates involved in sensorimotor integration. Using a power grip visuomotor tracking task, researchers demonstrated that there was substantial attenuation of the N30 SEP peak during periods of force generation compared to force relaxation and rest (Wasaka, Kida et al. 2012) (see next section for an explanation of SEPs). One interpretation of greater N30 peak attenuation during force generation is that increased activity in motor areas strongly modulates information processed in the primary somatosensory area. Differences in N30 peak amplitudes between force generation and force relaxation could also be attributed to the demand for somatosensory feedback to control grip movement. In either case, this study suggests that there are implications for neuronal changes in the cortical networks involved in motor learning and somatosensory processing during the acquisition of a force matching task. Furthermore, the above studies support that novel force tracking tasks can be used to evaluate sensorimotor integration. Pilot research comparing differences in early SEP peaks between force tracking and motor tracing tasks suggests that force tracking is more heavily reliant on proprioception than classic visuomotor tracing tasks used in previous studies. Therefore, for the purposes of this study a novel force tracking task will be used to evaluate the impact of experimentally altered neck sensory input on motor learning and sensorimotor integration.

### **Somatosensory Evoked Potentials (SEPs)**

Evoked potentials refer to cortical activity as a direct result of the external stimulation of peripheral nerve pathways, which is commonly achieved using electrical stimulation of

peripheral nerves and measuring the resulting cortical response (Passmore, Murphy et al. 2014). Somatosensory evoked potentials (SEPs) refer to cortical activity occurring as a direct result of external somatosensory stimulation via peripheral nerve pathways in the arms via the ulnar or median nerves, or the legs via the tibial or peroneal nerves. This is commonly achieved using electrical stimulation of somatosensory receptors in skin, muscle or directly over the peripheral nerve of interest but can also be achieved through physiological stimulation in the same manner (Passmore, Murphy et al. 2014). The stimulus elicits an action potential in the peripheral nerve that is transmitted to the cortex, where the resulting electrical activity is measured over the scalp using surface electrodes. This generates a complex waveform which is averaged over multiple stimulations and then analyzed in terms of peaks and troughs present at different time points relative to the stimulus. Each SEP peak represents the arrival of the action potential at various cortical and subcortical areas and is referred to based on the number of milliseconds it occurs after stimulation. The peaks and troughs are measured in two ways: amplitudes in microvolts ( $\mu\text{V}$ ) and latencies in milliseconds (ms). The amplitude of a SEP peak represents activity of the cortical area it is associated with, and the latency of a SEP peak represents the time in milliseconds it takes for the information to be transmitted from the peripheral nerve to a given cortical area. Therefore, any fluctuations in amplitude represent alterations in cortical activity and any fluctuations in latency represent alterations in neural transmission. Clinically, increases or decreases in peak latencies or peak amplitudes can be used as indicators of neurological dysfunction (Cruccu, Aminoff et al. 2008). This technique provides an objective and direct means of assessing the integrity of the sensory pathways of the nervous

system and is frequently used to examine how the peripheral nervous system (PNS) and central nervous system (CNS) work together to transmit and process sensory information.

The International Federation of Clinical Neurophysiologists (IFCN) uses two labelling conventions: polarity and latency (Cruccu, Aminoff et al. 2008). Each SEP peak and trough are named based on their deviation direction or polarity and their latency. Peaks, or upward deflections represent a negative polarity and are given the prefix “N” while troughs, or downward deflections represent a positive polarity and are given the prefix “P”. The number that follows represents the number of milliseconds it takes post-stimulus for the deflection to appear in a healthy population. For example, the N18 peak represents an upward deflection occurring 18ms after stimulus and the P25 represents a downward deflection occurring 25ms after stimulus. Factors including height, age and neurological disorders can affect waveform latencies (Nuwer, Aminoff et al. 1994).



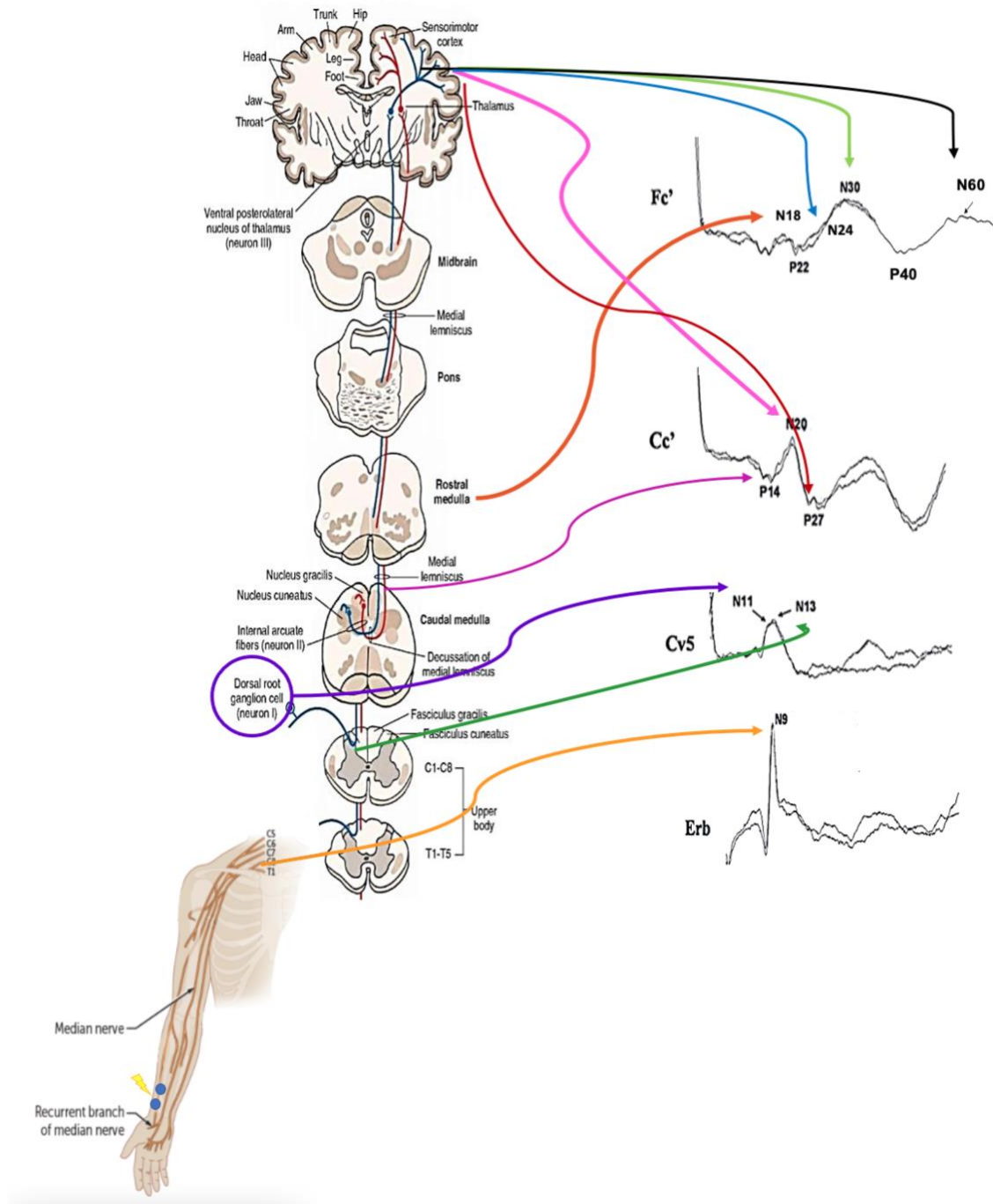


Figure. Median nerve SEPs pathway with neural generators and the associated SEP peaks.

Adapted from (Zabihhosseini, Yelder et al. 2021).

## Early SEP Peak Neural Generators

Each SEP peak is generated by a neural generator or the area of the sensory pathway that produces the positive or negative potentials (Passmore, Murphy et al. 2014). Ionic currents influencing the flow of ions across cell membranes of active cortical areas result in potential voltage differences (Valeriani, Restuccia et al. 1998). In accordance with IFCN guidelines, this study will compare peak amplitudes of the following SEP components: the peripheral N9, the cervical N11 and N13, the far-field N18, the parietal P14, N20 and P25, the frontal N24 and N30 and the fronto-central N60.

### N9 SEP Peak

The N9 peak is located in the peripheral nerve pathway in the brachial plexus. It is recorded at Erb's point, over the brachial plexus near the clavicle and the posterior border of the clavicular head of the sternocleidomastoid muscle (Crucchi, Aminoff et al. 2008). The reference electrode for this peak is typically placed on the ipsilateral earlobe but can also be placed over the contralateral clavicle or the scalp. The N9 amplitude is a control measure ensuring that afferent nerve volley is stable between trials so that any changes in subsequent SEP peaks can be attributed to changes in neural activity or cortical processing and not changes in posture which could impact which peripheral nerve fascicles are stimulated. The IFCN guidelines require the N9 amplitude to be within  $\pm 20\%$  when comparing pre and post changes in subsequent SEP peak amplitudes (Crucchi, Aminoff et al. 2008).

### N11 SEP Peak

The N11 peak is recorded over the 5<sup>th</sup> cervical spinous process and represents the afferent volley arriving at the cervical cord (Nuwer, Aminoff et al. 1994). The reference electrode for the N11 peak is placed over the trachea on the anterior neck (Nuwer, Aminoff et al. 1994, Cruccu, Aminoff et al. 2008). It is believed that the N11 peak reflects the ascending volley in the dorsal column fibers within the dorsal root at the cervical level as they travel to the cuneate nucleus (Mauguiere, Allison et al. 1999). This is supported by a study in patients with nerve root avulsions who demonstrate absent N11 & N13 peaks (Synek and Cowan 1982).

### N13 SEP Peak

The N13 peak is recorded over the same site as the N11, at the spinous process of the 5<sup>th</sup> cervical vertebrae (Nuwer, Aminoff et al. 1994, Passmore, Murphy et al. 2014) and is generated at the first synaptic relay of the spinothalamic tract (Cruccu, Aminoff et al. 2008). This peak originates from the postsynaptic potential of interneurons within the dorsal horn and mid-cervical cord and reflects activity in the neurons of the dorsal horn (Cruccu, Aminoff et al. 2008). Previous research shows that patients with dorsal column lesions do not demonstrate a peak at N13 (Sonoo 2000). A peak at N13 with no peaks of further latency would indicate that the afferent volley is reaching the spinal cord just before the medulla with no cerebral activity (Nuwer, Daube et al. 1993, Cruccu, Aminoff et al. 2008, Passmore, Murphy et al. 2014). Typically, the N13 peak is preceded by a positive P9 deflection or a compound N9/P9 deflection reflecting generation of the dorsal root volley (Mauguiere, Allison et al. 1999).

## N18 SEP Peak

The N18 peak originates in the inferior olive and dorsal column medial lemniscus nuclei of the lower medulla and the midbrain – pontine region (Sonoo 2000). This peak is recorded over the contralateral frontal cephalic site and reflects activity in the neural correlates that have inputs to the cerebellum and has been used to measure alterations in cerebellar activity (Sonoo, Genba et al. 1992, Cruccu, Aminoff et al. 2008, Passmore, Murphy et al. 2014). It was originally thought that the N18 peak originated in the thalamus but was later disproven when researchers found the N18 peak was preserved in patients with thalamic lesions (Desmedt and Cheron 1981, Desmedt and Ozaki 1991, Urasaki, Tokimura et al. 1992, Noël, Ozaki et al. 1996). The N18 peak is a long-lasting scalp negative deflection which is preceded by the positive P14 (Noël, Ozaki et al. 1996). The IFCN guidelines recommend the use of a non-cephalic reference for this peak as a cephalic reference may have a nullifying effect on the N18 peak (Nuwer, Aminoff et al. 1994). Typically, this peak is referenced using an ipsilateral earlobe electrode (Nuwer, Aminoff et al. 1994, Valeriani, Restuccia et al. 1998).

## P14 SEP Peak

The positive P14 peak originates in the lower brainstem around the cervico-medullary junction and is recorded from the contralateral frontal cephalic site (Noël, Ozaki et al. 1996). It is generated by the afferent volley in the medial lemniscus above the foramen magnum but below the cortex (Cruccu, Aminoff et al. 2008). This is supported by a study which demonstrated absent P14 peaks in brain dead patients and in those with cervico-medullary lesions (Mauguière, Courjon et al. 1983, Wagner 1991). The IFCN recommends using the

ipsilateral earlobe non-cephalic reference site for this peak (Nuwer, Aminoff et al. 1994, Valeriani, Restuccia et al. 1998).

#### N20 SEP Peak

The N20 peak is recorded 2cm posterior to the contralateral central scalp site and originates in Brodmann's area 3b of the primary somatosensory cortex, specifically in the posterior bank of the Rolandic fissure (Desmedt and Ozaki 1991, Passmore, Murphy et al. 2014). This peak reflects the earliest cortical processing in the primary somatosensory cortex and indicates activity of the bipolar neurons in Brodmann's area 3b (Nuwer, Aminoff et al. 1994). A non-cephalic reference site is recommended by the IFCN for this peak (Nuwer, Aminoff et al. 1994, Valeriani, Restuccia et al. 1998, Mauguire, Allison et al. 1999)

#### P22 SEP Peak

The positive P22 peak is recorded over the contralateral frontal cephalic site using a non-cephalic reference (Nuwer, Aminoff et al. 1994, Valeriani, Restuccia et al. 1998). Though occurring close in latency, this peak is independent of the N20 peak and is generated in the primary motor cortex (Noël, Ozaki et al. 1996). Studies in patients with precentral lesions found an absence of the P22 peak indicating a precentral neural generator for this peak (Mauguière, Desmedt et al. 1983). The independence of the P22 peak is supported by studies in patients with parietal lesions who demonstrated absent N20 peaks with preserved P22 and N30 peaks (Mauguière, Desmedt et al. 1983).

## N24 SEP Peak

The N24 peak is recorded from the contralateral frontal cephalic site, along with the negative N18 and N30 as well as the positive P22 peaks (Nuwer, Aminoff et al. 1994). This peak can be difficult to isolate as it appears on the ascending slope of the N30 peak, also known as the P22-N30 complex (Nuwer, Aminoff et al. 1994). Previous research has shown that increasing the stimulation rate of the peripheral nerve leads to attenuation of the N30 peak, producing a clear and easily identifiable N24 peak without reducing its amplitude (Haavik and Murphy 2011, Passmore, Murphy et al. 2014). The N24 peak is generated close to the N20 peak, near the wall of the central sulcus in the pathway linking the cerebellum and primary somatosensory cortex and reflects cerebellar processing (Waberski, Buchner et al. 1999, Passmore, Murphy et al. 2014). This is supported by testing patients with cerebellar lesions who demonstrate a significant reduction or complete absence of the N24 peak (Restuccia, Valeriani et al. 2001).

## P25 SEP Peak

The positive P25 peak is recorded 2cm posterior to the contralateral central scalp site with a non-cephalic earlobe reference (Nuwer, Aminoff et al. 1994, Valeriani, Restuccia et al. 1998). This peak originates from a group of neurons within Brodmann's area 1 of the primary somatosensory cortex (Taylor and Murphy 2007) and represents neural processing of somatosensory information from cutaneous inputs (Allison, McCarthy et al. 1992).

### N30 SEP Peak

The N30 peak originates at the frontal lobe and posterior wall of the central sulcus and is related to activity within complex connections linking the thalamus, basal ganglia, premotor, motor and prefrontal cortices (Passmore, Murphy et al. 2014, Macerollo, Brown et al. 2018). This peak has multiple neural generators. Previous research has linked activity in the basal ganglia as well as the supplementary motor area to the N30 component (Pierantozzi, Mazzone et al. 1999, Pierantozzi, Sabato et al. 2000). This is supported by studies in patients with supplementary motor area lesions who demonstrated an absent N30 peak and in those with Parkinson's disease who have a significantly reduced N30 peak (Rossini, Babiloni et al. 1989, Pierantozzi, Sabato et al. 2000)

### N60 SEP Peak

It is known that both short and middle latency SEPs originate from processing in the somatosensory area (Allison, McCarthy et al. 1992). However, while short latency peaks have been extensively studied, few have investigated the middle latency peaks recorded between 40-100ms. The middle latency N60 peak has a fronto-central origin. Previous intracortical readings in drug resistant epileptic patients suggest that middle latency SEPs originate in the premotor cortex and supplementary motor area (Barba, Valeriani et al. 2005). However, studies using cortical surface recordings have found that the secondary somatosensory area, the lower parietal lobe and the upper bank of the sylvian fissure are have the highest activity following electrical stimulation of the median nerve (Mima, Ikeda et al. 1997). This is supported by other intracortical studies demonstrating the presence of a biphasic peak between 60-90ms recorded

from intracortical electrodes in the secondary somatosensory area and concurrent activation of dipolar neurons in this region between 60-120ms following median nerve stimulation (Mauguiere, Merlet et al. 1997, Frot and Mauguière 1999).

### Effects of Altered Afferent Input from the Neck

The cortical organization of sensory information from the upper limb is highly dependent on head and neck position (Paulus and Brumagne 2008). Neck muscle proprioception plays a significant role in balance, movement organization and forming accurate body schema (Strimpakos, Sakellari et al. 2006). To compute the position of the upper limbs, the CNS references incoming sensory information against the position of the head and neck. Given this, alterations in sensory inputs due to pain, prolonged postures, muscle vibration or changing the orientation of the head alter the body schema and may impact motor accuracy. Previous research has demonstrated that chronic neck pain and subclinical neck pain (SCNP) alter afferent input from the neck and impact many cortical processes including proprioception (Paulus and Brumagne 2008, Baarbé, Holmes et al. 2015, Stanton, Leake et al. 2016, Wallwork, Leake et al. 2020), sensorimotor integration (Elsig, Luomajoki et al. 2014, Andrew, Yelder et al. 2018), cerebellar processing (Daligadu, Haavik et al. 2013, Baarbé, Yelder et al. 2018), motor learning (Baarbé, Yelder et al. 2018) and multisensory integration (Farid, Yelder et al. 2018, Karellas, Yelder et al. 2019). Cervical extensor fatigue has also been shown to alter afferent input from the neck leading to impaired proprioception (Zabihhosseinian, Holmes et al. 2015), altered sensorimotor integration and reduced motor accuracy of the upper limb and that these effects were greater in the absence of visual information of the target (Zabihhosseinian, Yelder



et al. 2019). The cerebellum plays a major role in sensorimotor integration and altered afferent input has been shown to impact cerebellar processing. Previous research has demonstrated that individuals with subclinical neck pain experience alterations in selective early sensorimotor integration processes demonstrated by a marked increase in the N24 SEP peak in this group (Andrew, Yelder et al. 2018).

Changing the orientation of the head has also been used to altered afferent input from the neck. Research shows that head rotation and lateral flexion impair upper limb accuracy during simple drawing (Guerraz, Blouin et al. 2003), aiming (Popov, Smetanin et al. 1989, Fookson, Smetanin et al. 1994) and elbow repositioning tasks (Guerraz, Caudron et al. 2011). Additionally, neck muscle vibration can be used to alter afferent input from the neck and other parts of the body. Muscle vibration has been shown to alter whole-body orientation (Paulus and Brumagne 2008, Wannaprom, Treleaven et al. 2018), limb position sense (Goodwin, McCloskey et al. 1972, Knox, Cordo et al. 2006) and upper limb accuracy (Pettorossi, Panichi et al. 2015).

## Muscle Spindles & Vibration

Previous research demonstrates that the spindles of cervical spine muscles are the major proprioceptors of the neck (Richmond and Abrahams 1979, Treleaven 2017). Furthermore, cervical muscles have the highest density of proprioceptors in the human body (Kulkarni, Chandy et al. 2001, Peng, Yang et al. 2021). The most influential finding in support of

muscle spindle involvement in proprioception is the illusion of limb movement and position elicited by cervical muscle vibration (Eklund 1972, Goodwin, McCloskey et al. 1972).

High frequency, low amplitude vibration over a muscle belly excites the muscle spindles and associated afferent nerves of that muscle which is perceived by the central nervous system as joint rotation and movement (Brown, Engberg et al. 1967, Goodwin, McCloskey et al. 1972). Muscle spindles are the most susceptible proprioceptors to experimental manipulation via vibration. It was found that primary (Ia) afferents were highly sensitive to high frequency, low amplitude vibration while secondary afferents and golgi tendon organs remained insensitive to vibration regardless of frequency. (Brown, Engberg et al. 1967). However, golgi tendon organs were sensitive to changes in amplitude, where high amplitude vibration increased activation and low amplitude vibration had no effect (Brown, Engberg et al. 1967). Seminal literature demonstrates that limb position sense (Goodwin, McCloskey et al. 1972), perceived length of body parts (Lackner 1988), and whole body orientation (Paulus and Brumagne 2008) can be distorted by altering muscle spindle input using vibration. However, the vibration rate must exceed 30Hz to trigger an illusion (Cordo, Bevan et al. 1995). Previous research demonstrates that vibration of the left or right sternocleidomastoid (SCM) and contralateral splenius muscles, at a frequency of 59-64Hz, was sufficient to induce illusions of head rotation and alter elbow position sense (Knox, Cordo et al. 2006). This is supported by subsequent research showing that 60Hz vibration of the SCM for 10 minutes was sufficient to increase tracking position error above controls. A dose response relationship exists between vibration frequency and effect duration where higher frequencies yield longer lasting effects. Previous work has demonstrated

that at a frequency of 60Hz, positional error remained elevated for up to 22 hours, at 80Hz effects persisted for up to 3 days and up to 5 days when frequencies were increased to 100Hz (Pettorossi, Panichi et al. 2015).

Workers in several occupational settings encounter vibration and can be exposed to occupational vibration on a daily basis. Vibration exposure can be presented by handheld power tools referred to as hand-transmitted vibration (HTV) or from operating vehicles or operating tools that vibrate at low-frequencies and high amplitudes such as jack hammers, referred to as whole body vibration (WBV) (Krajnak 2018). Occupational vibration exposure has been associated with an increased risk of musculoskeletal pain in the back, neck, hips and upper extremities (Krajnak 2018). Therefore, understanding the neurophysiological effects of vibration could help provide valuable insights to occupational practices with regard to work-rest ratios and limiting exposure.

## Conclusion to Literature Review

It is clear from the existing literature that upper limb control depends on accurate internal models of the position of the limbs in reference to the head and neck. It is also clear that upper limb proprioception is dependent on accurate sensory inputs and accurate cortical processing. However, the bulk of body schema research is directed at understanding the psychological effects of altered body schema. Understanding the underlying neurological changes that occur is important not only for research, but also to inform the psychological side of the discussion and generate both real world and clinical applications. Currently, most of the

neurological body schema research investigates peripheral mechanisms without neurophysiological measures. Some have evaluated proprioception (Paulus and Brumagne 2008, Guerraz, Caudron et al. 2011, Wallwork, Leake et al. 2020), upper limb aiming accuracy (Guerraz, Blouin et al. 2003, Huysmans, Hoozemans et al. 2010), and joint position sense (Knox and Hodges 2005, Knox, Cordo et al. 2006). However, there is very little research investigating the central adaptations associated with these behavioural measures. In other words, what is happening in the brain when these errors are occurring?

Some researchers have looked to fill this gap by investigating this through the lens of neck pain and fatigue. Previous research demonstrates that both SCNP & cervical fatigue generate behavioural alterations in motor learning and motor control associated with neurophysiological changes measured using somatosensory evoked potentials (SEPs) and transcranial magnetic stimulation (TMS) (Daligadu, Haavik et al. 2013, Zabihhosseinian, Holmes et al. 2015, Andrew, Yelder et al. 2018, Baarbé, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2019). Both neck pain and fatigue lead to altered afferent input from the neck and researchers have speculated that alterations seen in these groups are the result of an altered body schema. However, it is important to note that both neck pain and fatigue have the potential to alter multiple types of afferent feedback through the involvement of muscle spindles, pain afferents and other receptor types. Individuals with SCNP may also have varying pain levels, range of motion and altered biomechanics. Fatigue can also induce pain or discomfort and the effects are extremely short lived with individuals recovering within 5 minutes of fatigue protocol (Zabihhosseinian, Holmes et al. 2015). Muscle vibration allows the

specific targeting of the Ia afferents that carry the proprioceptive information used to construct body schema and provide the opportunity to induce longer-lasting effects on afferent feedback without causing pain or discomfort. This enables us to experimentally alter a specific type of afferent input (muscle spindle feedback) without the additional unwanted effects of pain, and enables us to determine whether altered afferent input from neck muscle spindles has a true impact on cortical processing and motor control, as has been suggested by past studies (Andrew, Yelder et al. 2018, Baarbé, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2020).

## CHAPTER 3

## MANUSCRIPTS

Manuscript 1

**Title: Effect of Neck Muscle Vibration on Somatosensory Evoked Potentials and Motor Learning of a force-based tracking task**

## Manuscript 1

Title: Effect of Neck Muscle Vibration on Somatosensory Evoked Potentials and Motor Learning of a Forced-based Tracking Task

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**Keywords:** Somatosensory evoked potentials, electroencephalography, motor acquisition, sensorimotor integration, cervical muscle vibration



## Abstract

**Background:** Neck joint dysfunction impacts motor learning, proprioception, and cortical processing, due to altered afferent input from the neck. It is unclear whether transient alterations in neck sensory input from muscle vibration impacts body schema as well as the neural mechanisms associated with sensorimotor integration (SMI) and somatosensory processing following the acquisition of a proprioceptive-based task. The purpose of this research is to determine the effects of neck muscle vibration on SMI and motor learning using Somatosensory Evoked Potentials (SEPs) and a novel force tracking motor learning task.

**Methods:** 25 right-handed, healthy participants (12 Female) aged  $22.08 \pm 2.73$  had electrical stimulation at 2.47Hz and 4.98Hz over the right-median nerve to elicit short and middle latency SEPs. 1000 sweeps were recorded and averaged using a 64-lead EEG cap pre- and post-acquisition of a force matching tracking task (FMTT). Following the pre-acquisition phase, controls (CONT) (n=13, 6F) received 10 minutes of rest and the vibration group (VIB) (n=12, 6F) received 10 minutes of 60Hz vibration on the right sternocleidomastoid (SCM) and left cervical extensors (CEM). During this time, all participants wore occluding goggles to eliminate visual feedback. Task performance was measured 24 hours later to assess retention. Repeated measures ANOVAs compared SEP amplitudes and performance accuracy normalized to baseline.

**Results: SEPs:** Significant time by group interactions occurred for the *N18 SEP Peak* ( $F_{(1, 23)} = 6.475, p = 0.018, \eta_p^2 = 0.220$ ): where the amplitude increased by 58.74% in CONT and

decreased by 21.77% in VIB and the *N24 SEP Peak* ( $F_{(1, 23)} = 5.787, p = 0.025, \eta_p^2 = 0.201$ ):

decreased by 14.05% in CONT and increased by 16.31% in VIB.

*Motor Performance:* Relative to baseline performance, there was a significant effect of time post-acquisition ( $F_{(1, 23)} = 52.812, p < 0.001, \eta_p^2 = 0.697$ ) with a 12.3% improved for CONT and 14.22% for VIB. At retention, both groups showed improvement relative to baseline ( $F_{(1, 23)} = 35.546, p < 0.001, \eta_p^2 = 0.607$ ) with CONT retaining their post-acquisition improvement (12.72%), while VIB showed a slight decrease in performance relative to post-acquisition (13.72%), however the time by group interaction was not significant.

**Discussion:** Group-dependant changes in SEP peaks associated with cerebellar processing (N18 and N24) occurred post motor acquisition. Improvements in motor performance that persisted at retention combined with a decreased N24 peak suggests that motor learning resulted in significant changes in cerebellar-somatosensory (S1) pathways in CONT. Initial improvements followed by a small reduction at retention combined with an increase in the N24 peak in VIB suggests differences in cerebellar-S1 processing. This suggest that neck muscle vibration altered proprioceptive inputs used to construct body schema, generating alterations in cerebellar processing, motor learning and motor control.

## Introduction

While rushing, individuals may fail to notice certain objects in their path, but most of the time they automatically and instinctively avoid them. This is the body schema at work. In order to constantly guide and monitor movements of the body, the brain constructs an internal map of the body's position in reference to other body parts and the objects surrounding it. Control of the body in avoiding or manipulating objects to reach behavioural goals requires an accurate and constantly updated perception of the body in space and time (Holmes and Spence 2004). This concept is known as body schema. Body schema is integral for spatial orientation and updates constantly during movement involving both central and peripheral processes. It includes the shape of each body segment and the body surface, proprioceptive information regarding limb configuration, and the length of each body segment (Maravita, Spence et al. 2003, Holmes and Spence 2004, Haggard and Wolpert 2005).

The central nervous system (CNS) monitors and modifies the body schema based on proprioceptive feedback and previous body movements, relying on both feedforward and feedback models resulting from the coordination of visual information, proprioceptive feedback, and the predicted consequences of a given movement (Head, Rivers et al. 1920, Blakemore, Frith et al. 2001, Nixon and Passingham 2001, Haggard and Wolpert 2005). An accurate body schema is crucial for executing accurate movements and plays an important role in motor acquisition (Doyon, Penhune et al. 2003). Motor acquisition refers to the process of improving novel motor skills through practice with lasting improvements in skill capabilities (Doyon, Song et al. 2002). During the early stages of motor learning the cerebellar cortex and

deep nuclei are highly active followed by a significant reduction in cerebellar activity in the late stage of motor learning (Doyon, Song et al. 2002, Doyon, Penhune et al. 2003). The cerebellum plays an important role in sensorimotor integration by modulating sensory inputs that generate and adjust motor responses based on the expected sensory output (Manzoni 2005). This directly influences the activity in neural pathways between the cerebellum and sensorimotor cortex which can be quantified using somatosensory evoked potentials (Waberski, Buchner et al. 1999, Passmore, Murphy et al. 2014, Britton, Frey et al. 2016).

Sensorimotor integration refers to the ability of the CNS to integrate sensory information from the environment with motor output to generate the appropriate motor response (Abbruzzese and Berardelli 2003). Many experimental paradigms have used short latency somatosensory evoked potentials (SEPs) to examine alterations in sensorimotor integration using motor acquisition tasks. Previous research has demonstrated differential SEP changes following the acquisition of a complex motor pursuit task in neck pain participants compared to controls (Andrew, Yelder et al. 2018). Another study done using a neck pain population found differential changes in the N24 peak following the acquisition of a simple typing task, indicating that individuals with neck pain have altered cerebellar processing (Daligadu, Haavik et al. 2013). Changes in head orientation via passive head or neck movement and cervical muscle fatigue have also been shown to alter upper limb proprioception and motor accuracy (Guerraz, Blouin et al. 2003, Knox and Hodges 2005, Guerraz, Caudron et al. 2011, Zabihhosseinian, Holmes et al. 2015, Zabihhosseinian, Yelder et al. 2019). Additionally, previous research demonstrates that cervical muscle vibration influences proprioception and

motor accuracy of the elbow and forearm (Knox, Cordo et al. 2006, Pettorossi, Panichi et al. 2015).

Neck muscles have the highest density of proprioceptors in the human body (COOPER and Daniel 1963, Kulkarni, Chandy et al. 2001, Peng, Yang et al. 2021) with the muscle spindles being the major proprioceptors (Richmond and Abrahams 1979). Therefore, alterations in sensory feedback caused by neck pain (Paulus and Brumagne 2008), fatigue (Zabihhosseinian, Holmes et al. 2015) or vibration (Goodwin, McCloskey et al. 1972) can influence the information sent to the CNS leading to impaired upper limb accuracy (Huysmans, Hoozemans et al. 2010, Guerraz, Caudron et al. 2011), proprioception (Eklund 1972, Lackner 1988, Knox, Cordo et al. 2006, Paulus and Brumagne 2008, Zabihhosseinian, Holmes et al. 2015, Stanton, Leake et al. 2016), and motor learning (Daligadu, Haavik et al. 2013, Andrew, Yelder et al. 2018). Altered afferent input from the neck, as a result of neck joint dysfunction, postural stress, pain or fatigue, is a complex phenomenon often involving multiple receptor types. Many researchers have examined the effects of this phenomenon through the lens of recurrent or chronic neck pain and cervical muscle fatigue. However, both neck pain and fatigue have the potential to alter multiple types of sensory feedback through the involvement of muscle spindles, pain afferents and changes in muscle properties (Falla and Farina 2008, Alcaraz-Clariana, García-Luque et al. 2021). Additionally, the effects of fatigue can be short lived with recovery occurring within 5 minutes of the fatigue protocol (Schieppati, Nardone et al. 2003). It is important to take a step back and examine the effects of altered afferent input from neck muscles in the absence of these confounding factors in order to understand the role played by neck muscle

spindles in upper limb SMI. High frequency, low amplitude vibration over a muscle belly excites the primary (Ia) afferents of muscle spindles and provides long-lasting effects without causing pain or discomfort (Brown, Engberg et al. 1967, Cordo, Bevan et al. 1995, Pettorossi, Panichi et al. 2015). This is perceived by the CNS as joint rotation and movement, thereby inducing illusions of movement when vibration frequencies exceeded 30Hz (Goodwin, McCloskey et al. 1972, Cordo, Bevan et al. 1995). Therefore, muscle vibration can be used to specifically target Ia afferents to experimentally alter afferent input and examine the direct impacts on cortical processing and motor control.

While the effects of altered afferent input have been examined in neck pain and muscle fatigue populations, there is a gap in the research involving the effects of neck muscle vibration on motor learning and sensorimotor integration. The purpose of this study was to determine the effects of neck muscle vibration on the motor acquisition of a novel proprioceptive-based force matching tracking task (FMTT) and early and middle-latency SEP peaks associated with somatosensory processing, sensorimotor integration, and motor learning. It was hypothesized that neck muscle vibration would lead to alterations in motor acquisition and motor accuracy of the upper limb determined by differential changes in force tracking performance and the associated SEP peak amplitudes. Furthermore, it was hypothesized that participants in the vibration group would demonstrate poorer force tracking accuracy and altered motor learning patterns when compared to controls.

## Methods

### **Participants**

25 right-handed participants, 13 males and 12 females were recruited for this study and randomly allocated to the vibration (n=12, 6 Females) or control (n=13, 6 Females) group. Inclusion criteria for the study required all participants to be between the ages of 18 and 35 years old and to be right hand dominant, determined by a score of above 40 on the Edinburgh handedness inventory. Participants must be healthy individuals, meaning they cannot have neck pain indicated by a score of less than 5 on the Neck Disability Index (Vernon 2008). Exclusion criteria included left hand dominance, due to possible differences in neural processing (reference Luc Holland et al. and others) and those with any conditions that may alter electroencephalography (EEG) suitability such as multiple sclerosis, epilepsy, seizure disorders, recurrent neck pain, autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD). This research was reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board and received ethical approval [REB #16520].

### **SEP Stimulation Protocol**

The right median nerve was stimulated at the wrist using conductive adhesive hydrogel EMG electrodes. The anode was placed proximally and electrodes were fixed on the skin over the median nerve 2-3cm proximal to the distal crease of the wrist to ensure there was no movement during the recording (Nuwer, Aminoff et al. 1994). Constant wave pulses of 0.2ms were provided and intensity was adjusted to produce a visible twitch in the abductor pollicis brevis (APB) muscle. To ensure familiarity with the stimulus, motor thresholding was performed

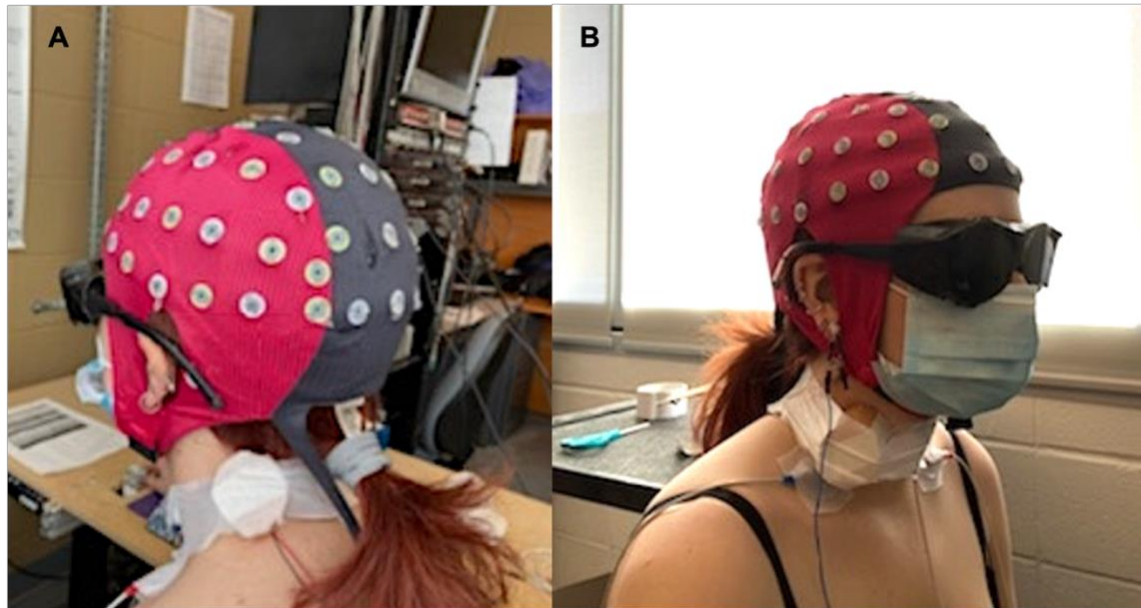
for each participant. The motor threshold was defined as the lowest intensity which elicited contraction of the APB muscle. SEP stimulation was done at 2 frequencies to allow for the clear identification of SEP peaks. The median nerve was stimulated at a frequency of 2.47Hz to enable optimal recordings of the N30 peak, followed by a stimulation frequency of 4.98Hz to produce a clear N24 peak through attenuation of the N30 peak (Haavik and Murphy 2011). Peripheral SEP peaks were recording using electromyography (EMG) electrodes on Erb's point over the brachial plexus and over the spinous process of the 5<sup>th</sup> cervical vertebrae with reference electrodes placed on the anterior tracheal cartilage, the contralateral clavicle and an earlobe reference clip (Nuwer, Aminoff et al. 1994). Cortical SEP peaks were recording using a 64 lead ANT Neuro Waveguard Electroencephalography (EEG) cap. The cap was fitted for each participant using the internationally standardized 10-20 system in accordance with IFCN guidelines (Nuwer, Aminoff et al. 1994). Each cortical electrode was filled with conductive gel to reduce impedance and improve signal acquisition.

### **Cervical Muscle Vibration**

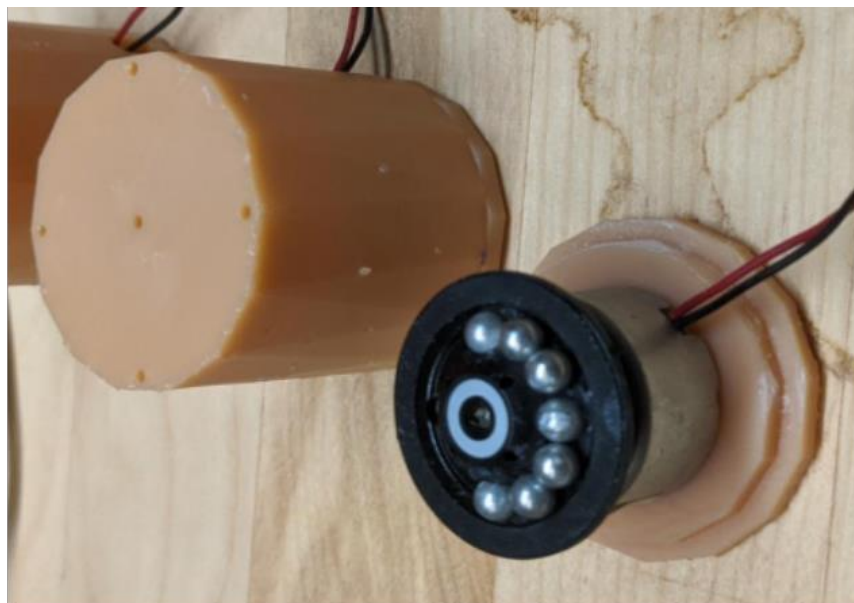
Cervical muscle vibration was applied using two small custom DC-motor vibrators measuring 4cm in diameter. High frequency, low amplitude vibration was applied to the right sternocleidomastoid (SCM) and left cervical extensor muscles (CEM) at a frequency of 60Hz for 10 minutes. The vibrator heads were placed antero-laterally, 2cm from the midline and 5cm below the mastoid for the SCM and 2-3cm lateral to the C5 spinous process for the CEM (Pettorossi, Panichi et al. 2015). The vibrators were firmly affixed to the neck using hypafix tape to ensure sufficient contact was maintained. Participants were fitted with blackout goggles for



the duration of the vibration protocol to eliminate visual feedback. Participants in both groups were asked “*In terms of the position or direction of your head and neck, how do you feel?*” to determine if participants experienced movement illusions. This question was introduced at the start of the vibration protocol and was asked again at the end.



*Figure 3. Depiction of vibration set up affixed using hypafix tape. A: shows position of the left CEM vibrator. B: shows the position of the right SCM vibrator.*



*Figure 6. Custom built vibrators in 3d printed scaffolding.*

### **Force Matching Tracking Task**

Participants were seated in a chair with their right arm fixed to an adjustable table housing a small 50 kg force transducer that fit comfortably against their right thumb. A computer monitor was placed 2 meters in front of them displaying visual information regarding the task. Prior to beginning the task, the transducer was calibrated to eliminate any inherent noise. An average of 3-5 maximal voluntary contractions (MVCs) of the APB muscle were taken to calibrate the target line to the strength of each individual participant. The force matching tracking task (FMTT) required participants to push against the force transducer using their right thumb to match a series of white-dotted square sinusoidal waves calibrated to their thumb strength. A set of red error bars were situated 5% above and below the white-dotted target line, as a guide for participants. Pressing harder would direct the trace line upwards, while pressing lightly would direct the trace line downwards. Targets were presented on the monitor as one trial with two 10-second-long force traces. Target lines and tracking performance were displayed in real-time using a custom made LABVIEW software program (National Instruments, Austin, TX, USA). Prior to beginning the task, participants were given one familiarization trial. The FMTT consisted of 5 phases, each containing 4 blocks with 12 trials. The phases included a pre-acquisition phase, 3 acquisition phases, a post-acquisition phase and a retention phase. Phases of the task were delivered in sequence while the blocks within each phase were randomized for each participant. Each trial lasted 22 seconds in duration with a total of 72 trials across all phases. Preliminary EMG findings suggest that this task does not induce fatigue, however, participants were given breaks as requested.

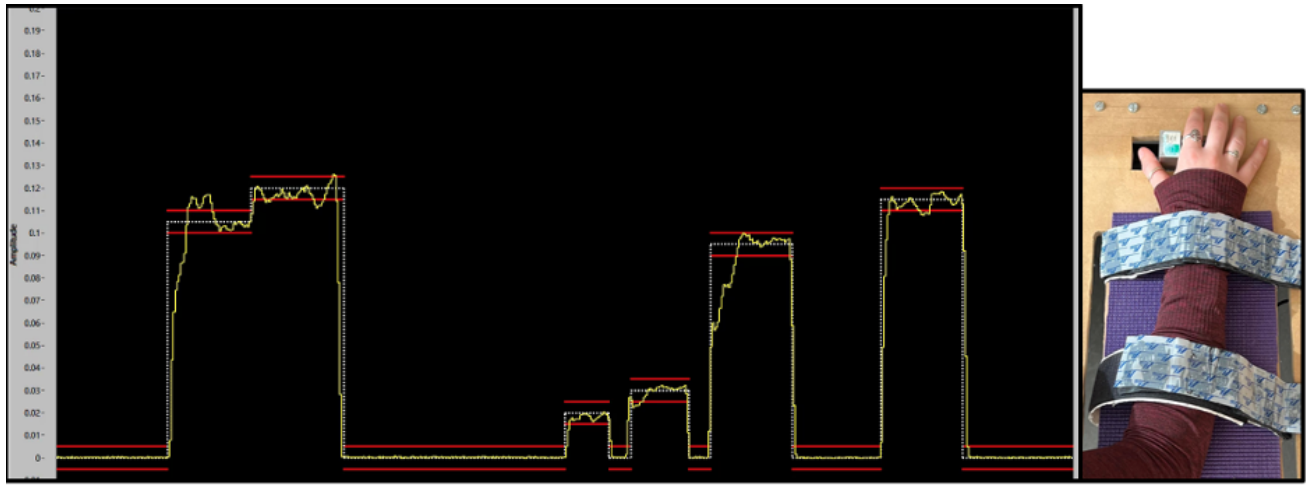


Figure 7. Depiction of FMTT program. Yellow line indicates participant's force output while the white-dotted line reflects the target line. Red lines reflect boundary guidelines. Right image shows the position of participant's right thumb on the force transducer.

### Experimental Procedure

The pre-post experimental procedure is outlined in **FIGURE 6**. Participants completed baseline dual SEP recordings as outlined above. If needed, participants were allowed 2-minute rest following the SEP protocol. Participants then completed the pre-acquisition phases of the force tacking task consisting of 12 trials. Participants in the vibration group received 10 minutes of cervical muscle vibration while controls received 10 minutes of rest. To mitigate possible bias, all participants were fitted with the vibration set-up however, vibrators were only turned on for those in the vibration group. Following vibration or rest, the participants then completed the 3 acquisition and post phases of the FMTT followed by the post-intervention dual SEP recordings. 24-48 hours later, participants returned to complete the retention phase of the FMTT.



Figure 8. Flow of experimental procedures from baseline to retention for both groups.

## Data Processing

SEP peaks were recorded at a sampling frequency of 2048Hz using Cambridge Electronic Design (CED) software. The peripheral N9, N11 and N13 SEP peaks were analyzed using Signal Software while the cortical N18, N20, N24, P25, N30 and N60 SEP peaks were analyzed using Advanced Source Analysis (ASA lab) Software. Cortical SEP data was band-pass filtered with a low cut-off 0.2Hz and a high cut-off of 1000Hz and all eye blinks were filtered out using artefact events. Artefact detection parameters were set at a minimum of  $-100\mu\text{v}$  and a maximum of  $+100\mu\text{v}$  to filter out any artefacts missed by the band-pass filter. Amplitudes were measured at the peak of interest in accordance with IFCN guidelines (Nuwer, Aminoff et al. 1994). Latencies were recorded from the onset of stimulation to the maximal peak or depression for each SEP component. Changes in SEP amplitudes from pre-intervention to post-intervention were reported as a percentage increase or decrease from baseline for each group.

FMTT data were recorded and analyzed using a customized LabVIEW data analysis program. A 0.5 second moving average was conducted to smooth the force trace data prior to analysis. Tracking accuracy was measured as absolute percent error calculated as the difference

between the participant's trace line and the presented target line. The formula for absolute error is as follows:

$$\text{Absolute \% Error} = \left( \left( \frac{\text{Force traceline}}{\text{target line}} \right) * 100 \right) - 100$$

Absolute percent error was calculated for each block of the baseline, post-acquisition, and retention phases separately. Data were normalized to baseline by dividing the phase average by the baseline average for each phase and then averaged for each group.

### Statistical Analysis

All statistical analyses were performed using SPSS version 26 (Armonk, New York, USA). Normalized SEP peak data were analyzed using a two-way repeated measures multivariate analysis of variance (ANOVA) with group (control vs vibration) as a factor, and time (pre/post) as the repeated measure. 2 x 3 mixed methods repeated measures ANOVA was used to compare the mean difference in performance accuracy with between subject and within subject factors as group (control vs. vibration) and time (pre-acquisition, post-acquisition, and retention) as the repeated measure. Pre-planned simple contrasts to baseline were included in both repeated measures ANOVAs. Pearson's correlations were used to investigate the relationship between SEP peak amplitudes and performance accuracy post-acquisition to examine differences in sensorimotor integration between groups. *All correlations were computed at the significance level ( $\alpha = 0.05$ ) using a two-tailed test.* Statistical significance was set as  $p \leq 0.05$  for all statistical tests. The Shapiro-Wilk's test was used to test for a normal distribution for all datasets. If violated, log transformations were applied to ensure data were

normally distributed. Mauchly's test of sphericity was used to test sphericity for the performance accuracy data. Greenhouse-Geisser corrections were reported for performance accuracy data that violated Mauchly's test of sphericity. Partial eta squared values are reported with 0.2 equal to small, 0.5 equal to medium and 0.8 equal to large effect sizes for ANOVAs (Cohen 1995). The Benjamini-Hochberg test was used to correct for multiple comparisons that are independent of each other as each SEP peak has its own set of neural generators. This correction controls for the likelihood of type I error or false discovery rate by ranking the individual p-value from smallest to largest and is then compared to the Benjamini-Hochberg critical value (McDonald 2009). With this correction, datasets are considered statistically significant if the adjusted p-value is smaller than the chosen family-wise error rate. The false discovery rate was set at 0.2 in an excel spreadsheet created to test for Benjamini-Hochberg (McDonald 2009). P-values provided in the results section are the unadjusted p-values as recommended (McDonald 2009), however statistical significance for SEP peak data was determined by the Benjamini-Hochberg test.

## Results

Movement illusions were reported as perceived movement of the head or neck in the absence of an actual movement occurring. Of the 12 participants in the vibration group, 11 reported movement illusions. Of the 11 who experienced illusions, 5 reported feeling neck extension, 1 reported feeling neck flexion, 2 reported feeling right rotation, 2 reported feeling left rotation and 1 reported feeling left lateral flexion. No illusions were reported in controls.

Table 1. Frequency of reported movement illusions in vibration group.

Reported Illusion	Frequency	Percentage
Neck Extension	5	0.42
Neck Flexion	1	0.08
Right Rotation	2	0.17
Left Rotation	2	0.17
Left Lateral Flexion	1	0.08
No Illusion	1	0.08

Values represent frequency of movement illusions reported by participants in the vibration group (n=12) and the percentage of the group that experienced each illusion.

#### *SEP Peak Amplitudes*

All participants met the N9 criteria of a change within  $\pm 20\%$ , therefore all SEP data was included in analysis. There was no effect of time ( $F_{(1, 23)} = 0.012, p = 0.915, \eta_p^2 = 0.001$ ) or time by group interaction ( $F_{(1, 23)} = 2.585, p = 0.121, \eta_p^2 = 0.101$ ). Consistency of the N9 SEP peak pre to post is critical to ensure subsequent changes in spinal and cortical SEP peaks are the result of changes in neural activity following motor learning and experimental manipulation.

Table 2. Proportional change in SEP peak amplitudes following motor acquisition and experimental manipulation for both groups.

	Group	
	Control	Vibration
<i>Proportional Change in SEP Peak Amplitudes</i>		
N9 Peak Amplitude	0.97 ± 0.10	1.03 ± 0.10
N11 Peak Amplitude	1.18 ± 0.79	0.96 ± 0.33
N13 Peak Amplitude	1.03 ± 0.31	1.06 ± 0.45
N18 Peak Amplitude	* $p \leq 0.05$ 1.59 ± 1.07	0.78 ± 0.22
N20 Peak Amplitude	1.02 ± 0.29	1.21 ± 0.41
N24 Peak Amplitude	* $p \leq 0.05$ 0.86 ± 0.28	1.16 ± 0.35
P25 Peak Amplitude	1.09 ± 0.24 *	1.19 ± 0.39 *
N30 Peak Amplitude	1.07 ± 0.14 *	1.11 ± 0.28 *
N60 Peak Amplitude	0.90 ± 0.35	1.00 ± 0.23

Values are group means ± SD for participants in control (n=13) and vibration (n=12) groups. \* $p \leq 0.05$  denotes significant differences in the respective SEP peak amplitude between groups (reported as proportional change from baseline to post). SEP data that had a significant effect of time is marked with an asterisk (\*) where  $p \leq 0.05$ .

**N18 SEP Peak:** There was a significant time by group interaction ( $F_{(1, 23)} = 6.475$ ,  $p = 0.018$ ,  $\eta_p^2 = 0.220$ ) where the amplitude increased by 58.74% in controls and decreased by 21.77% in vibration.

**N24 SEP Peak:** There was a significant time by group interaction ( $F_{(1, 23)} = 5.787$ ,  $p = 0.025$ ,  $\eta_p^2 = 0.201$ ) where the SEP peak amplitude decreased by 14.05% in controls and increased by 16.31% in vibration.



*P25 SEP Peak:* There was a significant effect of time ( $F_{(1, 23)} = 4.556$ ,  $p = 0.044$ ,  $\eta_p^2 = 0.165$ ) with the SEP peak amplitude increasing for both groups, by 9% in controls and 18.55% in vibration and no time by group interaction.

*N30 SEP Peak:* There was a significant effect of time ( $F_{(1, 23)} = 4.403$ ,  $p = 0.047$ ,  $\eta_p^2 = 0.161$ ) which increased for both groups, by 7.38% in controls and 10.96% in vibration, with no time by group interactions.

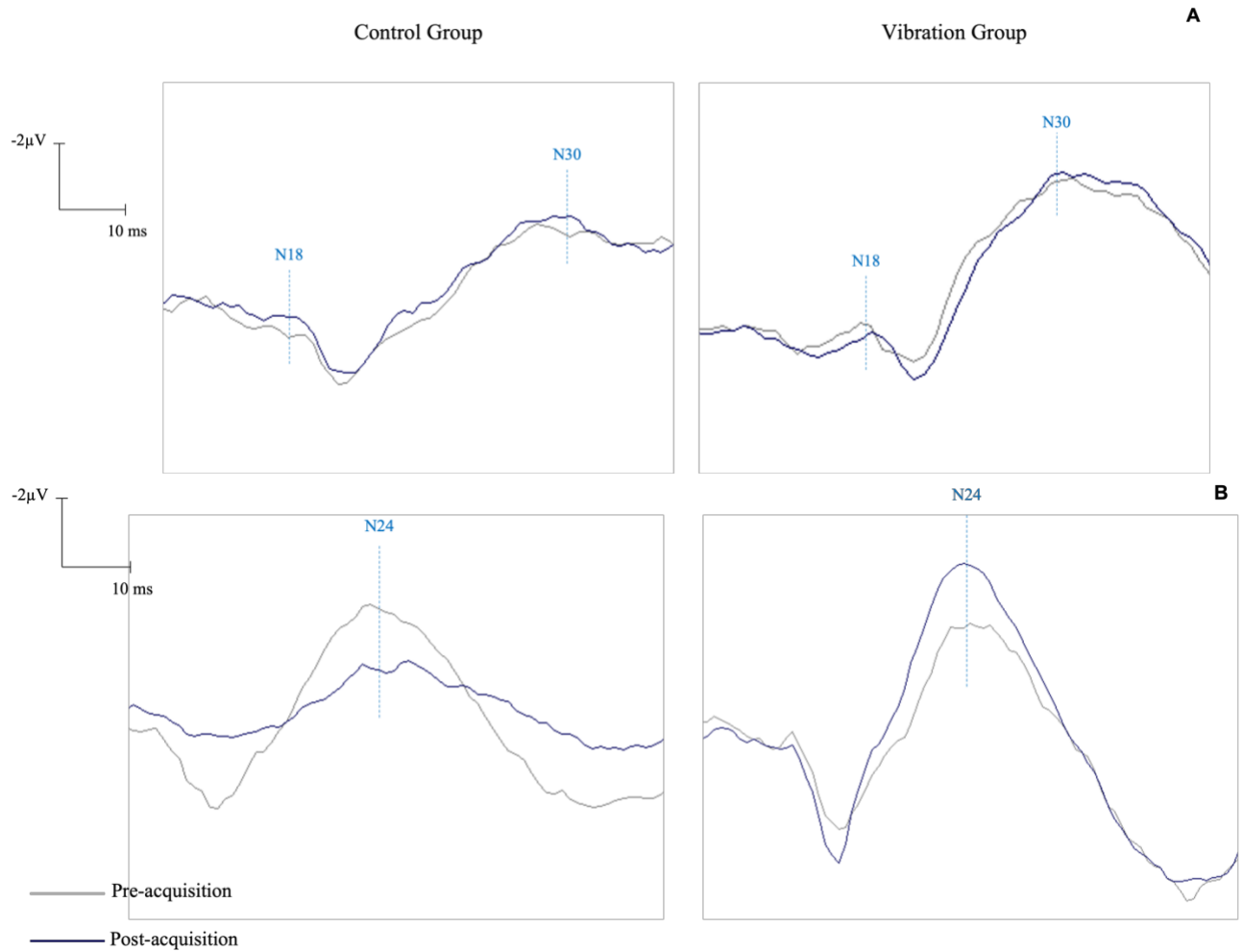


Figure 9. Representative datasets from control (left) and vibration (right) groups showing raw SEP peaks at baseline and post-acquisition. Pre-acquisition SEP peaks are in grey while post-acquisition SEPs are in dark blue. A: N18 and N30 SEP peak amplitudes recorded at a stimulation frequency of 2.47 Hz. B: N24 SEP peak amplitude recorded at a frequency of 4.98 Hz.

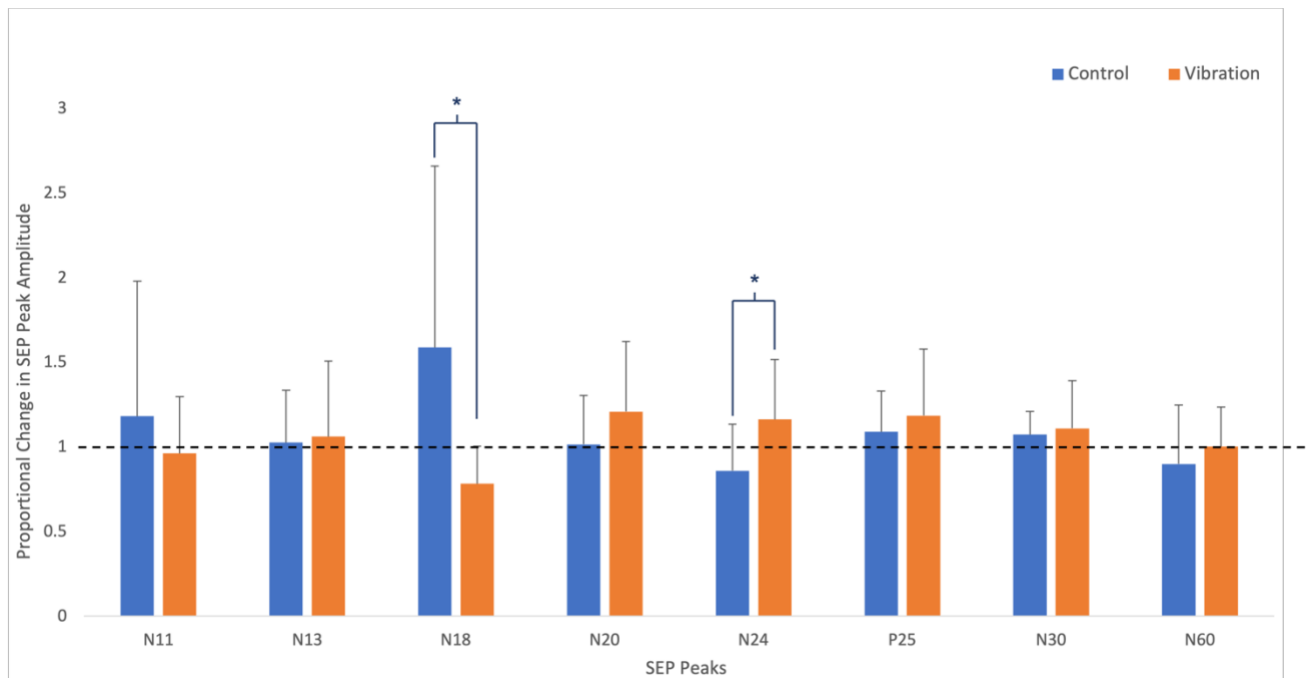


Figure 10. Proportional change in average SEP peak amplitudes following motor acquisition of FMTT for controls (blue) and vibration (orange). Error bars represent SD. The black dotted line represents the normalized baseline amplitude. (\*  $P \leq 0.05$ )

### Motor Performance Accuracy

There was a significant effect of time when comparing performance accuracy where both groups improved relative to baseline performance ( $F_{(1, 23)} = 38.878$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.628$ ). When comparing pre-acquisition to post acquisition both groups demonstrated significant improvements in performance ( $F_{(1, 23)} = 52.812$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.697$ ) where controls improved by 12.3% and vibration improved by 14.22%. At retention, both groups improved relative to baseline ( $F_{(1, 23)} = 35.546$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.607$ ) where controls improved by 12.72% and vibration improved by 13.72%.

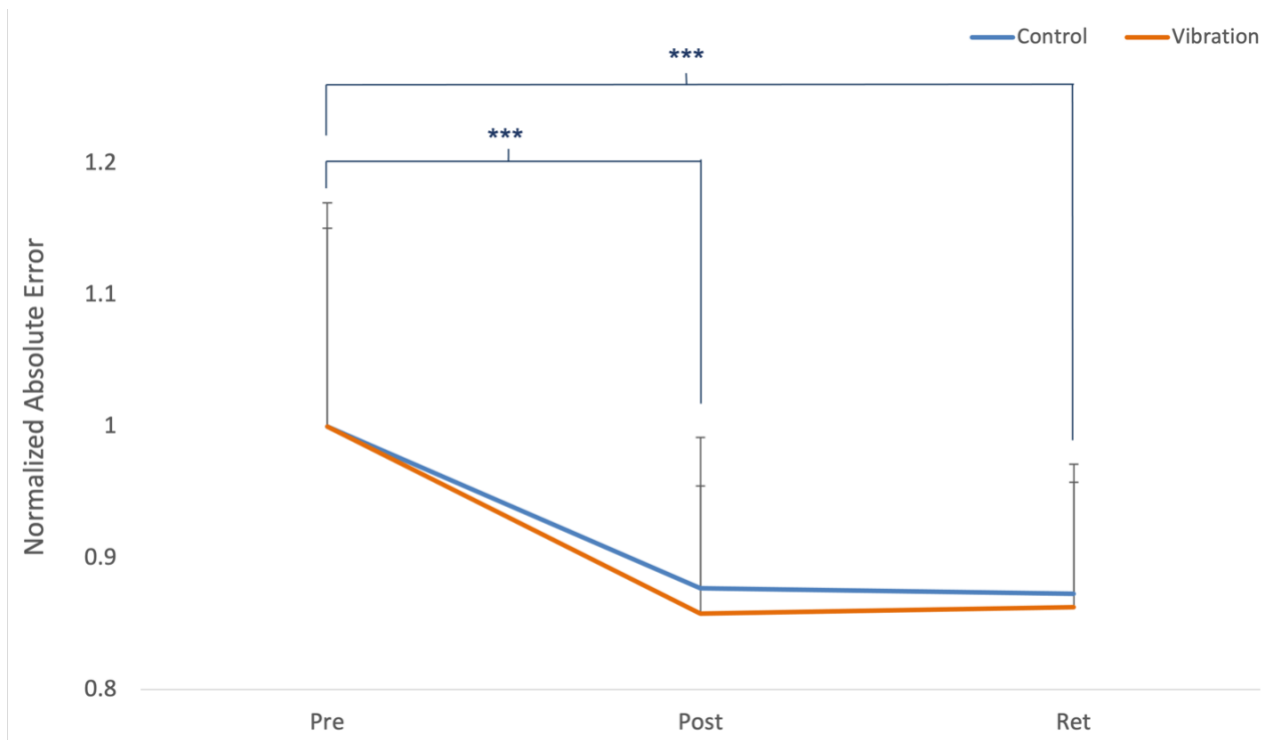


Figure 11. Normalized absolute error during the pre-acquisition, post-acquisition, and retention phases of FMTT. Error bars represent SD. (\*\*\*)  $P \leq 0.001$ .

Table 3. Normalized and absolute motor performance accuracy data for both groups.

	Time		
	Pre-acquisition	Post-acquisition	Retention
<i>Normalized Motor Performance Accuracy</i>			
Absolute error control (%)	1 ± 0.150	0.877 ± 0.115 *	0.872 ± 0.099 *
Absolute error vibration (%)	1 ± 0.170	0.858 ± 0.097 *	0.863 ± 0.095 *
<i>Absolute Motor Performance Accuracy</i>			
Absolute error control (%)	0.679 ± 0.150	0.595 ± 0.115	0.592 ± 0.099
Absolute error vibration (%)	0.673 ± 0.170	0.577 ± 0.097	0.581 ± 0.095

Values are group means ± SD for participants in control (n=13) and vibration (n=12) groups. For normalized data a significant effect of time is marked with an asterisk (\*) where  $p \leq 0.05$ . Absolute performance data shows group averages not normalized to baseline.

### Pearson's Correlations

**N11 SEP Peak & FMTT:** There was a positive correlation between the N11 SEP peak amplitude and performance accuracy in the vibration group (Figure 12.B) following motor acquisition ( $r = 0.610$ ,  $p = 0.035$ ). There was no correlation in controls ( $r = -0.367$ ,  $p = 0.217$ ).

**P25 SEP Peak & FMTT:** There was a negative correlation between the P25 SEP peak amplitude and performance accuracy in the control group (Figure 13.A) following motor acquisition ( $r = -0.556$ ,  $p = 0.048$ ). No correlation was observed in the vibration group ( $r = 0.348$ ,  $p = 0.267$ ).

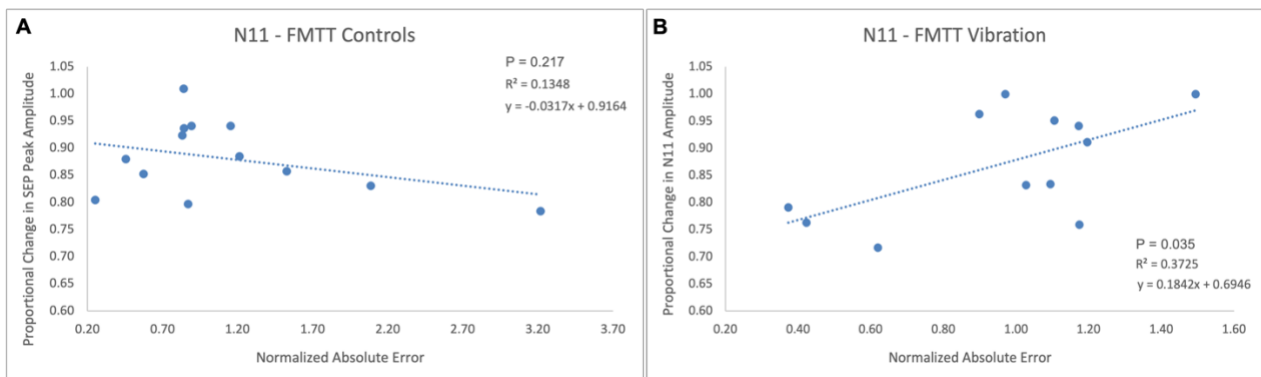


Figure 12. Correlation plot comparing normalized absolute error (x-axis) to proportional change in N11 SEP peak amplitude (y-axis) in the A: control group and B: vibration group. P-value, correlation coefficient (R<sup>2</sup>), and equation shown in right corner.

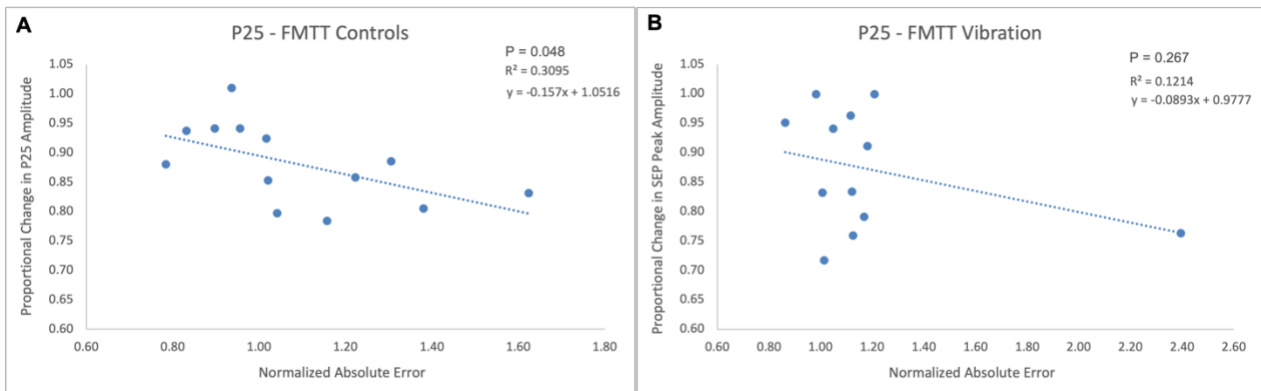


Figure 13. Correlation plot comparing normalized absolute error (x-axis) to proportional change in P25 SEP peak amplitude (y-axis) in the A: control group and B: vibration group. P-value, correlation coefficient (R<sup>2</sup>), and equation shown in top right corner.

## Discussion

This study is the first work to assess the impact of vibration on a proprioceptive based motor learning paradigm in conjunction with neurophysiological adaptations in the form of SEP peaks. The results indicate that neck muscle vibration led to differential changes in SEP peaks associated with cerebellar processing (N18 and N24), somatosensory processing (P25) and sensorimotor integration (N30). Both groups demonstrated significant improvements in motor performance following acquisition of the novel motor learning task dependent on force modulation. The differential correlations between performance accuracy and SEP peak amplitudes between groups for certain SEP peaks suggests underlying differences in somatosensory processing post-acquisition that may be the result of vibration induced alterations in body schema. The neurophysiological differences between groups indicate that neck muscle vibration was sufficient generate alterations in cerebellar processing of proprioceptive inputs used to construct body schema.

### *Neurophysiological Findings*

#### *N18 SEP Peak*

The N18 Peak originates in the inferior olive, dorsal column medial lemniscus (DCML) nuclei of the lower medulla and the midbrain-pontine region and reflects inhibitory activity at the level of the dorsal column nuclei, possibly due to the collaterals from the cuneate nucleus (Sonoo, Genba et al. 1992, Sonoo 2000). A novel finding from this study indicated that those in the vibration group had a reduction in N18 amplitude following motor acquisition, reflecting reduced inhibition of olivary-cerebellar inputs or selective filtering of cerebellar inputs at the

level of the inferior olive. This was likely necessary to continuously refine motor output to the right thumb, potentially due to alterations in proprioceptive inputs from vibration. Changes in inferior olive activity are associated with the performance of well learned movements and inferior olive activity is known to increase during motor acts contributing to online motor control and motor learning (Gilbert and Thach 1977). This suggests that those in the vibration group had a greater reliance on proprioceptive input when learning the motor acquisition task compared to controls. Previous work demonstrates that vibration activates primary afferents of muscle spindles (Brown, Engberg et al. 1967, Knox, Cordo et al. 2006, Pettorossi, Panichi et al. 2015). The transmission of sensory information from the neck, head and upper limb is regulated by the cuneocerebellar tract, specifically the lateral cuneate nucleus located in the dorsolateral medulla at the level of the inferior olive (Felten, O'Banion et al. 2015). The cuneate nuclei topographically relay precise proprioceptive information through complex feedback-regulated sensorimotor cerebellar connections to other areas of the cerebral cortex (Noël, Ozaki et al. 1996, Sonoo 2000). Therefore, changes in N18 amplitude could reflect alterations in cerebellar SMI and unconscious proprioception. The observed reduction in N18 amplitude is likely the result of vibration induced alterations in proprioceptive inputs.

Previous work utilizing similar methodology saw an increased N18 amplitude in controls following the acquisition of a novel force matching task (Ambalavanar 2021). This coincides with the results from the current study which show that controls had an increase in N18 amplitude post-acquisition. This is likely due to increased inhibitory input from the inferior olive to the cerebellum to minimize errors (Miall and Wolpert 1996). An increased N18 amplitude

may suggest greater inhibitory inputs along the olivary-cerebellar network to accurately produce and modulate forces during motor acquisition. This aligns with past work which illustrates an increased N18 amplitude following the acquisition of an upper limb motor tracing task (O'Brien, Andrew et al. 2020).

#### *P25 SEP Peak*

The P25 peak reflects activity in Brodmann's area 1 of the primary somatosensory cortex and is associated with somatosensory processing of cutaneous inputs (Allison, McCarthy et al. 1992, Mauguiere, Allison et al. 1999). The increase in P25 amplitude seen in both groups suggests greater activity in S1 following acquisition of the FMTT. This coincides with past work which illustrated an increased P25 following the acquisition of a motor pursuit task which was more heavily reliant on visuomotor integration compared to the current FMTT (Andrew, Yelder et al. 2018).

#### *N24 SEP Peak*

The N24 peak is generated near the wall of the central sulcus in the pathway linking the cerebellum and primary somatosensory cortex (S1) (Cruccu, Aminoff et al. 2008, Passmore, Murphy et al. 2014). Therefore, changes in this peak reflect alterations in cerebellar processing (Haavik and Murphy 2011). The large decrease in N24 peak amplitude seen in controls is likely related to decreased cerebellar nuclei activity and decreased cerebellar processing subsequent to learning. During the early stages of motor acquisition, the cerebellar deep nuclei and cortico-cerebellar networks are highly active in order to contribute to motor adaptation and error



correction as a skill is learned (Doyon, Owen et al. 1996, Doyon, Song et al. 2002, Doyon and Ungerleider 2002). Although the deep nuclei contribute to the motor sequences used to execute a motor task, long term representations of this sequence are stored elsewhere in the brain resulting in an experience dependent shift in cortical activation from cerebellar cortex and deep nuclei when a skill is first established to cortico-striatal networks with extended practice (Doyon, Song et al. 2002, Doyon, Penhune et al. 2003). A decreased N24 amplitude following motor learning is indicative of reaching the later stages of consolidated learning and forming a greater reliance on a well-formed internal schema.

The novel finding in the current study was that the vibration group appeared to have altered cerebellar processing as demonstrated by an increased N24 peak amplitude following motor learning. An increase in N24 amplitude reflects increased cerebellar deep nuclei activity as well as increased cerebellar to S1 processing and is indicative of a lack of disinhibition, or greater cerebellar inhibition in response to motor training. While this is the first study to report quantifiable changes in cerebellar activity following vibration, others have utilized similar methodology to investigate N24 peak changes as a result of neck fatigue, pain and joint dysfunction. Previous work has shown a similar increase in N24 amplitude in response to motor learning in groups that experience altered afferent input from the neck including SCNP and fatigue (Andrew, Yelder et al. 2018, Zabihhosseinian, Yelder et al. 2021). The results from the current study suggest those in the vibration group were unable to reach the later stage of consolidated learning in a similar manner to controls.

### *N30 SEP Peak*

The N30 peak is related to activity within the complex connections linking the thalamus, premotor, motor, and prefrontal cortex and basal ganglia, which are all involved in SMI (Mauguiere, Allison et al. 1999, Passmore, Murphy et al. 2014, Macerollo, Brown et al. 2018). Both groups demonstrated similar increases in N30 peak amplitude post-acquisition, suggesting increased activity in the neural correlates involved with SMI necessary for precise motor control and force modulation required during the FMTT.

### *Motor Performance Accuracy*

Motor learning can be assessed behaviourally by measuring improvements in performance accuracy after acquisition of a novel motor skill (Fitts and Posner 1967, Schmidt and Lee 1988). Consolidation of this skill is measured as continued improvement or maintenance of the skill 24 to 48 hours following acquisition (Doyon and Ungerleider 2002). The increase in motor accuracy from baseline to post-acquisition in addition to a continued increase in accuracy at retention is indicative that motor learning has occurred in controls. The initial increase in motor accuracy post-acquisition seen in the vibration group suggests those in this group were able to learn the task, however, the reduction in accuracy when comparing post-acquisition to retention suggests those in the vibration group did not retain the task like controls. While this is the first study to report changes in motor learning patterns following vibration, previous work has shown increased tracking position error of the upper limb following cervical vibration (Knox, Cordo et al. 2006, Pettorossi, Panichi et al. 2015). Similar alterations in motor learning were observed in SCNPs populations following acquisition of a

simple typing task (Baarbé, Yelder et al. 2018) and acquisition of a motor pursuit task (Andrew, Yelder et al. 2018). The lack of group differences in the current study may be due to challenge point framework where vibration group had to work harder to learn the task, overriding the impact of vibration-induced alterations in body schema (Guadagnoli and Lee 2004). Previous research has shown an inverted-U relationship between task difficulty and motor learning where the second highest difficulty was most effective for skill acquisition while learning was delayed at the least and most difficult levels (Akizuki and Ohashi 2015).

#### *Correlations Between SEP Peaks and Performance Accuracy*

The positive correlation between N11 amplitude and performance accuracy indicates greater absolute error coincides with greater N11 amplitude in the vibration group. This relationship was not observed in controls. The N11 peak represents the ascending peripheral volley arriving at the spinal cord (Nuwer, Aminoff et al. 1994). Greater N11 amplitudes in those with greater absolute error may suggest an increased reliance on proprioceptive inputs and somatosensory processing at the level of the spinal cord to permit accurate force modulation of the APB muscle.

The negative correlation between P25 amplitude and performance accuracy seen in controls indicates higher absolute error was associated with lower P25 amplitudes. Lower P25 amplitudes in participants with higher absolute error could suggest a lower reliance on

Brodmann's area 1 or sensory gating of cortical networks associated with somatosensory processing (Seki and Fetz 2012). This relationship was not observed in the vibration group.

### Limitations

A limitation of this study is that this sample consisted of university students ranging in age from 18-30 therefore these results may not be generalizable to older adults or young children. Additionally, there was a period of delay during the FMTT protocols to allow for set-up and removal of the vibrators. Due to the discontinuous nature of the experiment, the time delay may have impacted task difficulty. However, because both groups were fitted with the vibration set up any delays between trials throughout the duration of the FMTT were similar across groups.

### Conclusion

This work is the first to assess the effects of vibration on the neurophysiological mechanisms involved in the motor acquisition of a proprioceptive based force matching tracking task. Alterations in cerebellar processing and motor learning were observed in the vibration group. Those in the vibration group exhibited significantly reduced N18 peak amplitudes and significantly increased N24 peak amplitudes post-acquisition suggesting reduced inhibition at the level of the cuneate nucleus or possibly the inferior olive following motor training resulting in altered cerebellar SMI and increased processing at S1. This may reflect a greater reliance on proprioceptive feedback and is likely due to vibration induced alterations in proprioceptive inputs used to construct body schema. Although both groups

demonstrated significant improvements in performance, trends at retention suggest controls retained their post-acquisition improvements while the vibration group showed a slight decrease in performance relative to post-acquisition, however the time by group interaction was not significant. Future work should assess retention at longer intervals to determine if the neurophysiological adaptations observed in the vibration group translate to more profound changes in motor performance and motor skill consolidation. In conclusion, this work demonstrates that neck muscle vibration induces alterations in cortical processing in the neural correlates associated with learning a proprioceptive-based motor paradigm.

## Preface to Manuscript 2

The differences in SEP peaks associated with cerebellar processing (N18) as a result of neck muscle vibration indicate changes in the processing of unconscious proprioceptive inputs compared to controls. Altered proprioceptive processing may lead to changes in upper limb proprioception and motor control. Manuscript 2 will investigate if neck muscle vibration also impacts upper limb proprioception.

Manuscript 2

**Title: Effect of Neck Muscle Vibration on Upper Limb Proprioception**

## Manuscript 2

Title: Effect of Neck Muscle Vibration on Upper Limb Proprioception

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**Keywords:** Proprioception, cervical muscle vibration, upper limb accuracy



## Abstract

**Background:** Upper limb control depends on accurate internal models of the position of the limbs in reference to the head and neck, as well as accurate sensory inputs and accurate cortical processing. It is known that neck joint dysfunction, pain, and fatigue impact proprioception due to altered afferent input from the neck. However, it is unclear whether transient alterations in neck sensory input from muscle vibration impacts body schema as well as upper limb proprioception in the absence of visual feedback. The purpose of this research is to determine the effects of neck muscle vibration on upper limb proprioception using a novel elbow proprioception task (EPT).

**Methods:** 26 right-handed, healthy participants (12 Female) aged  $22.21 \pm 2.64$  performed an elbow repositioning task consisting of 3 target angles between 80-90 degrees, 90-100 degrees and 100-110 degrees. Participants were instructed to replicate each target as accurately as possible. Controls (n=13, 6F) received 10 minutes of rest and the vibration group (n=13, 6F) received 10 minutes of 60Hz vibration on the right sternocleidomastoid (SCM) and left cervical extensors (CEM). Participants wore occluding goggles for the duration of the experiment to eliminate visual feedback. Task performance was reassessed immediately following the experimental manipulation. Repeated measures ANOVAs compared proprioceptive error normalized to baseline.

**Results:** Significant time by group interactions occurred for target 1: 80-90 degrees ( $F_{1,24} = 25.330, p < 0.001, \eta_p^2 = 0.513$ ) where accuracy increased by 26.08% for controls and decreased

by 134.27% for vibration, target 2: 90-100 degrees ( $F_{1,24} = 16.157$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.402$ ) where controls improved by 20.39% and vibration group worsened by 109.54%, and target 3: 100-110 degrees ( $F_{1,24} = 21.923$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.447$ ) where controls improved by 37.11% and vibration worsened by 54.39%. There was a significant effect of time for all targets where controls improved from baseline while error increased in the vibration group ( $F_{1,24} = 9.711$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.570$ )

**Discussion:** Group-dependant changes in performance accuracy were observed following vibration protocols. Improvements in elbow repositioning accuracy across all targets indicate accurate proprioceptive processing occurred in controls. By contrast, decreased accuracy across all target angles following vibration indicates altered proprioceptive processing occurred in the vibration group. This suggests that vibration altered proprioceptive inputs used to construct body schema leading to inaccurate joint position sense and the observed behavioural changes in elbow repositioning accuracy.

## Introduction

The cortical organization of sensory information from the upper limb is highly dependent on head and neck position (Paulus and Brumagne 2008). Neck muscle proprioception plays a significant role in balance, movement organization and forming accurate body schema (Strimpakos, Sakellari et al. 2006). To compute the position of the upper limbs, the central nervous system (CNS) references incoming sensory information against the position of the head and neck. Proprioception is defined as the conscious and unconscious awareness of the body's position, mediated by proprioceptors in muscle tissue, joints and tendons (Proske and Gandevia 2012, Tuthill and Azim 2018). Previous research demonstrates that muscle spindles are the major proprioceptors of the neck (Richmond and Abrahams 1979) and that neck muscles have the highest density of proprioceptors in humans (COOPER and Daniel 1963, Kulkarni, Chandy et al. 2001). Body schema is the cortical perception of the location, orientation and functional integrity of the body and its appendages in space (Holmes and Spence 2004). It is cortically constructed through the integration of somatosensory and visual information involving a complex network of cortical areas that process this information using the most appropriate reference frame (Holmes and Spence 2004, Medina and Coslett 2010). Body-centered reference frames provide a topographical representation of the body in reference to the position of the head and neck, and exist primarily in the primary and secondary somatosensory cortices (Maravita, Spence et al. 2003, Medina and Coslett 2010). Eye-centered reference frames compute the location of body parts using information encoded in the visual cortices (Holmes and Spence 2004). In the absence of visual information, proprioceptive information from muscle spindles becomes increasingly more important. Given this, alterations

in sensory inputs due to pain, prolonged postures, joint dysfunction, and head orientation can alter body schema and may impact motor accuracy.

Previous research has demonstrated that chronic neck pain and subclinical neck pain (SCNP) alter afferent input from the neck and impact many cortical processes including proprioception (Paulus and Brumagne 2008, Baarbé, Holmes et al. 2015, Stanton, Leake et al. 2016, Wallwork, Leake et al. 2020), sensorimotor integration (Elsig, Luomajoki et al. 2014, Andrew, Yelder et al. 2018) and multisensory integration (Farid, Yelder et al. 2018, Karellas, Yelder et al. 2019). When comparing the effects of SCNP on head, shoulder, trunk and whole body positions during active and passive movement of the right shoulder, researchers found significant differences in head movements between groups suggesting inconsistencies in reference frame selection (Paulus and Brumagne 2008). This indicates altered cervical proprioception and suggests that individuals with SCNP demonstrate altered proprioceptive processing, possibly due to re-weighting of sensory information. Cervical extensor muscle fatigue leads to impaired upper limb proprioception (Zabihhosseinian, Holmes et al. 2015), altered sensorimotor integration and reduced motor accuracy of the upper limb (Zabihhosseinian, Yelder et al. 2019). These effects were greater in the absence of visual information of the target (Zabihhosseinian, Yelder et al. 2019). Head orientation also influences upper limb proprioception, demonstrated by deviations in reproduced hand drawings while the head was tilted in either direction (Guerraz, Blouin et al. 2003). Head rotation in either direction has also been shown to generate increased joint position error of the upper limb indicating an impact on upper limb proprioception (Knox and Hodges 2005). Once again, proprioceptive

dysfunction was exacerbated in the absence of visual feedback (Knox and Hodges 2005, Guerraz, Caudron et al. 2011).

High frequency, low amplitude vibration over a muscle belly excites muscle spindles and the associated primary (Ia) afferents (Brown, Engberg et al. 1967). This is perceived by the CNS as joint rotation and movement thereby generating illusions of movement if the vibration frequency exceeds 30Hz (Goodwin, McCloskey et al. 1972, Cordo, Bevan et al. 1995). This is supported by research done by Knox and Hodges, who found that vibration of the left or right sternocleidomastoid (SCM) and contralateral splenius at a rate between 59-64Hz was sufficient to induce illusions of head rotation (Knox, Cordo et al. 2006). Other research demonstrates that 10 minutes of SCM vibration at rates between 5Hz-100Hz was sufficient to increase upper limb position tracking error above controls, with rates above 60Hz generating prolonged error up to 22 hours following vibration (Pettorossi, Panichi et al. 2015).

It is clear from the literature that upper limb control depends on accurate internal models of the position of the limbs in reference to the head and neck, and upper limb proprioception depends on accurate sensory inputs and accurate cortical processing. While it is known that altered afferent input from the neck as a result of joint dysfunction, postural stress, pain and fatigue impacts proprioception, it is unclear whether transient alterations in neck sensory input from muscle vibration impacts body schema as well as proprioception and motor control. The purpose of this research is to determine the effects of cervical vibration on upper limb proprioception using a novel elbow proprioception task (EPT).

## Methods

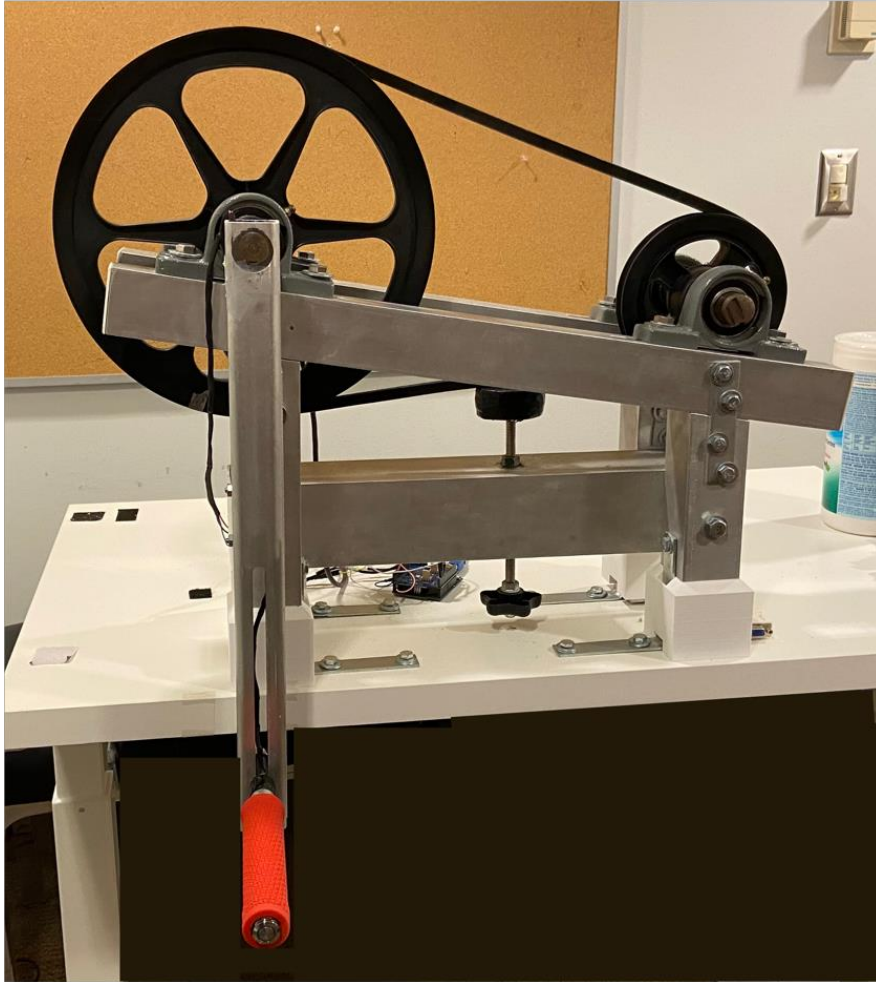
### **Participants**

26 right-handed participants, 14 males and 12 females were recruited for this study and randomly allocated to the vibration (n=13, 6 Females) or control (n=13, 6 Females) group. Inclusion criteria for the study required all participants to be between the ages of 18 and 35 years old and to be right hand dominant, determined by a score of above 40 on the Edinburgh handedness inventory. Participants must be healthy individuals, meaning they cannot have neck pain indicated by a score of less than 5 on the Neck Disability Index (Vernon 2008). Exclusion criteria included left hand dominance and those with any neurological or neuromuscular disorders including multiple sclerosis, epilepsy, seizure disorders, recurrent neck pain, autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD). This research was reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board and received ethical approval [REB #16520].

### **Elbow Proprioception Task (EPT)**

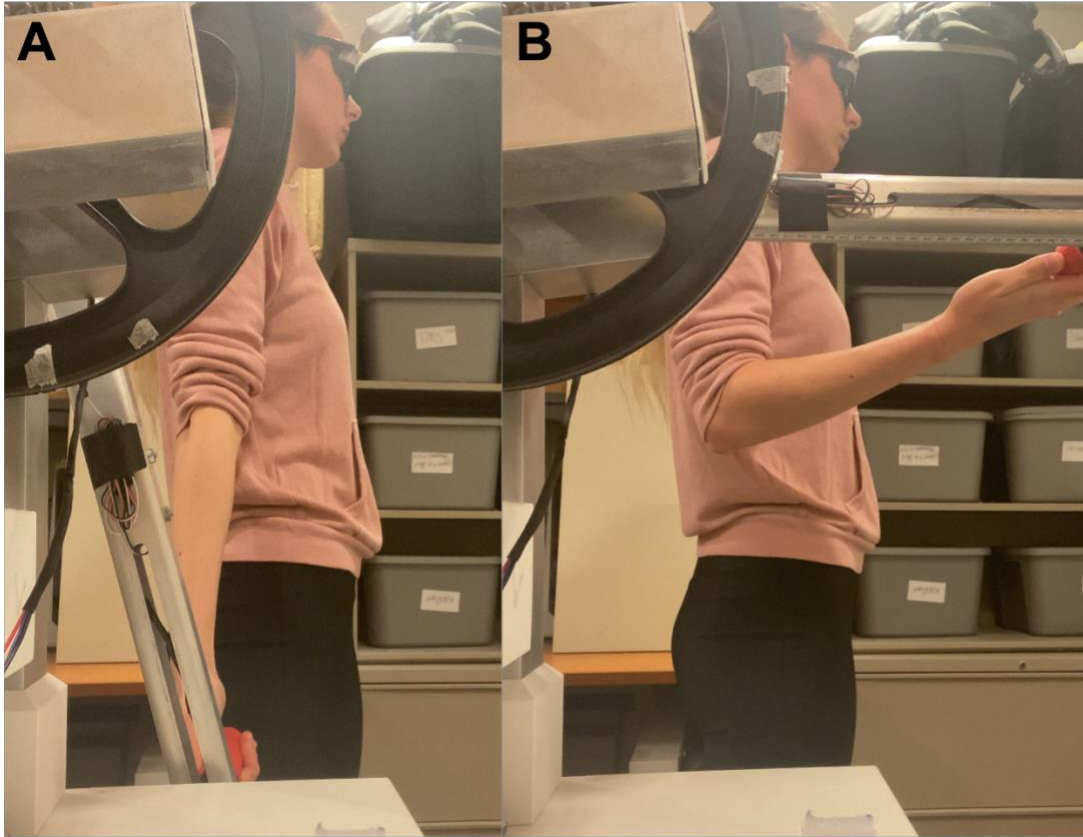
The elbow proprioception device was composed of a mechanical goniometer containing a handle housing a small button. This device was fixed to an adjustable table so that the handle fit comfortably in the palm of each participant's right hand while standing in anatomical position with the elbow in extension. Prior to beginning the protocol, participants were fitted with occluding goggles to eliminate visual feedback for the duration of the study. Participants were given 3-5 familiarization trials to ensure participants are comfortable with the device and

the movement. Participants were instructed to reproduce a given target angle by flexing the elbow. To set the target angle, the researcher passively flexed the participant's elbow to the appropriate target angle and maintained this position for 5 seconds before returning them to a neutral position (0°). Participants were then given 3 trials to reproduce the target angle as accurately as possible. The task consisted of 3 blocks, block 1 had a target angle between 80-90 degrees, block 2 was between 90-100 degrees and block 3 was between 100-110 degrees. Between blocks, participants performed 2 full ranges of motion, moving from elbow extension to elbow flexion to reduce thixotropic contributions transferring between targets. Participants rated their perceived exertion using the Borg's Rated Perceived Exertion (RPE) scale at baseline and at the end of each block. Preliminary testing has shown that participants did not experience fatigue from this task. Additionally, pilot testing revealed that there are very minimal learning effects as the average error remained similar across blocks.



*Figure 14. Elbow repositioning task device mounted to height adjustable table. Height adjustable handle (red) houses small button that activates angle reader.*





*Figure 15. Depiction of elbow repositioning task. A: participant shown in starting position at elbow extension. B: participant's final position of elbow flexion.*

### **Cervical Muscle Vibration**

Cervical muscle vibration was applied using small custom DC-motor vibrators measuring 4cm in diameter. High frequency, low amplitude vibration was applied to the right sternocleidomastoid (SCM) and left cervical extensor muscles (CEM) at a frequency of 60Hz for 10 minutes. The vibrator heads were placed 6 cm inferior and 2 cm anterior to the mastoid process for the SCM and 2 - 3 cm lateral to the spinous process of the 5<sup>th</sup> cervical vertebrae for the CEM (Pettorossi, Panichi et al. 2015). The vibrators were firmly affixed to the neck using hypafix tape to ensure sufficient contact was maintained. Participants were fitted with blackout goggles for the duration of the vibration to eliminate visual feedback during the protocol.

Participants in both groups were asked *“In terms of the position or direction of your head and neck, how do you feel?”* to determine if participants experienced movement illusions. This question was introduced at the start of the vibration protocol and was asked again at the end.

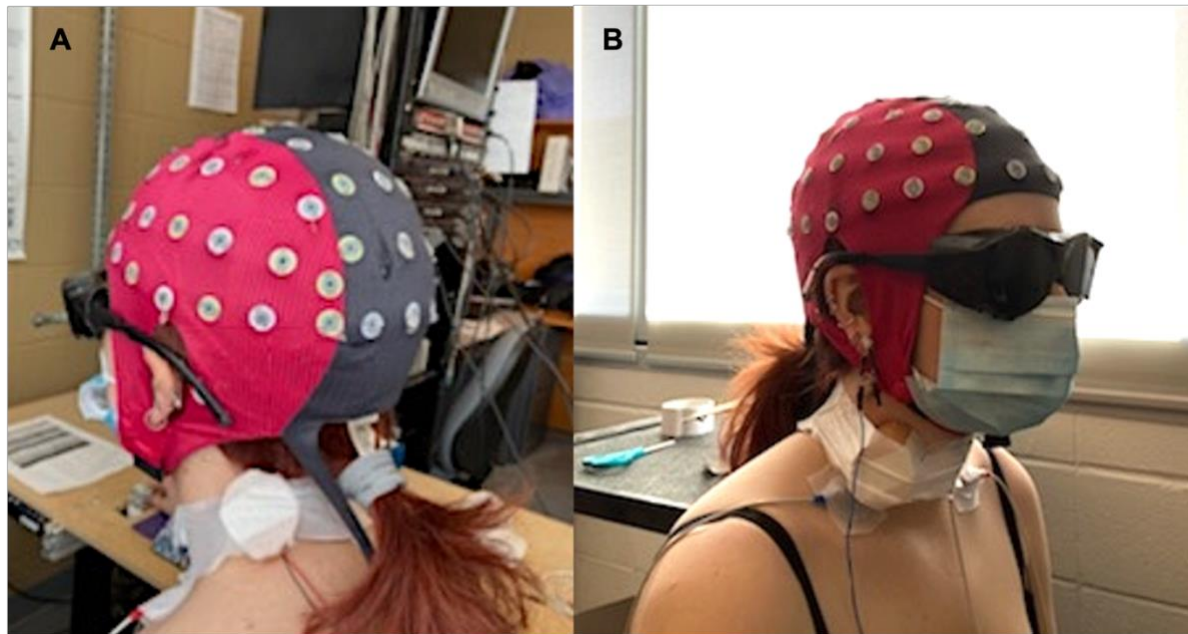


Figure 16. vibration protocol set up affixed with hypafix tape. A: shows the position of the left CEM vibrator. B: shows position of the right SCM vibrator.

### **Experimental Procedure**

The experimental flow is outlined in figure 16 below. Participants completed baseline EPT as outlined above. Following proprioceptive measures, participants in the vibration group received 10 minutes of cervical muscle vibration while controls received 10 minutes of rest. To mitigate possible bias, all participants were fitted with the vibration setup as described above however, vibrators were only turned on for those in the vibration group. Following vibration or rest, the participants completed post-intervention EPT.

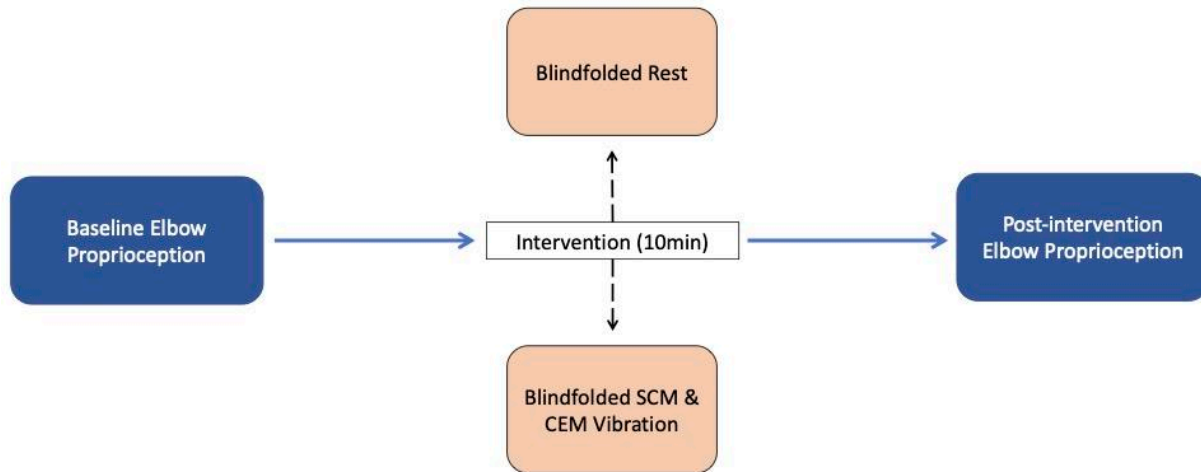


Figure 17. Experimental flow from baseline to post measures for both groups.

## Data Processing

Performance accuracy was measured as absolute percent error calculated as the average difference between the participant's reproduced angles and the target angle. Precision was measured as variable error calculated as the difference between the each of the participant's reproduced angles. The calculation for absolute error and variable error are as follows:

$$Absolute \% Error = \left( \frac{\sum_{error} (\text{reproduced angle} - \text{target angle})}{\# \text{ of trials}} \right) * 100$$

$$Variable Error = \sqrt{\left( \frac{\sum (\text{error} - \text{constant error})^2}{\# \text{ of trials}} \right)} * 100$$

Absolute percent error and variable percent error were calculated at baseline and post-intervention for each target angle (T1 = 80°-90°, T2 = 90°-100°, and T3 = 100°-110°) and normalized to baseline by dividing the post value by the baseline value before being averaged for each group.

### Statistical Analysis

All statistical analyses were performed using SPSS version 26 (Armonk, New York, USA). Normalized absolute error was analyzed using a 2 x 2 two-way repeated measures multivariate analysis of variance (ANOVA) with group as a factor and time (pre/post) as the repeated measure. Pre-planned simple contrasts to baseline were included in the repeated measures ANOVA. Statistical significance was set as  $p \leq 0.05$  for the statistical tests. The Shapiro-Wilk's test was used to test for a normal distribution for all datasets. If violated, log transformations were applied to ensure data were normally distributed. Partial eta squared values are reported with 0.2 equal to small, 0.5 equal to medium and 0.8 equal to large effect sizes for ANOVAs (Cohen 1995).

## Results

Movement illusions were reported as perceived movement of the head or neck in the absence of an actual movement occurring. Of the 13 participants in the vibration group, 12 reported movement illusions. Of the 12 who experienced illusions, 5 reported feeling neck extension, 1 reported feeling neck flexion, 2 reported feeling right rotation, 3 reported feeling left rotation and 1 reported feeling left lateral flexion. No illusions were reported in the control group.

Table 4. Frequency of reported movement illusions in vibration group.

Reported Illusion	Frequency	Percentage
Neck Extension	5	0.38
Neck Flexion	1	0.08
Right Rotation	2	0.15
Left Rotation	3	0.23
Left Lateral Flexion	1	0.08
No Illusion	1	0.08

Values represent frequency of movement illusions reported by participants in the vibration group (n=13) and the percentage of the group that experienced each illusion.

Overall, there was a time by group interaction ( $F_{1,24} = 15.747, p < 0.001, \eta_p^2 = 0.682$ ) as well as a significant effect of time ( $F_{1,24} = 9.711, p < 0.001, \eta_p^2 = 0.570$ ) where absolute error decreased in controls and increased in vibration. This remained consistent across all target angles. There was also a significant time by group interaction ( $F_{1,24} = 13.134, p < 0.001, \eta_p^2 = 0.642$ ) as well as a significant effect of time ( $F_{1,24} = 9.629, p < 0.001, \eta_p^2 = 0.568$ ) where variable error decreased in controls and increased in the vibration group. The results of this study are summed up in table 5.

Table 5, Normalized and absolute elbow proprioception accuracy data for both groups.

		Time	
		Pre	Post
<i>Normalized Elbow Repositioning Accuracy</i>			
<i>Target 1: 80°- 90°</i>			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.74 ± 0.49 ***
Absolute error vibration (%)		1 ± 0	2.34 ± 1.23 ***
Variable error controls (%)	** $p \leq 0.01$	1 ± 0	0.79 ± 0.49 **
Variable error vibration (%)		1 ± 0	2.09 ± 1.80 **
<i>Target 2: 90°- 100°</i>			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.79 ± 0.62 ***
Absolute error vibration (%)		1 ± 0	2.09 ± 1.49 ***
Variable error controls (%)	** $p \leq 0.01$	1 ± 0	0.86 ± 1.06 **
Variable error vibration (%)		1 ± 0	2.19 ± 3.14 **
<i>Target 3: 100°- 110°</i>			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.63 ± 0.44 *
Absolute error vibration (%)		1 ± 0	1.54 ± 0.75 *
Variable error controls (%)	** $p \leq 0.01$	1 ± 0	0.64 ± 0.51
Variable error vibration (%)		1 ± 0	1.36 ± 0.86
<i>Absolute Elbow Repositioning Accuracy</i>			
<i>Target 1: 80°- 90°</i>			
Absolute error controls (%)		4.13 ± 1.71	3.05 ± 1.35
Absolute error vibration (%)		2.89 ± 1.59	6.79 ± 3.04
Variable error controls (%)		6.42 ± 3.21	5.11 ± 2.53
Variable error vibration (%)		4.96 ± 3.18	10.40 ± 5.66
<i>Target 2: 90°- 100°</i>			
Absolute error controls (%)		3.37 ± 1.82	2.68 ± 1.32
Absolute error vibration (%)		2.52 ± 1.53	5.27 ± 1.24
Variable error controls (%)		5.18 ± 2.86	4.44 ± 2.59
Variable error vibration (%)		3.72 ± 2.85	8.15 ± 3.55
<i>Target 3: 100°- 110°</i>			
Absolute error controls (%)		3.45 ± 1.38	2.17 ± 1.02
Absolute error vibration (%)		2.78 ± 1.63	4.28 ± 1.43
Variable error controls (%)		5.42 ± 2.37	3.45 ± 1.76
Variable error vibration (%)		4.85 ± 3.31	6.61 ± 3.01

Values are group means ± SD for participants in control (n=13) and vibration (n=13) groups. For normalized data significant time by group interactions are marked with respective  $p$ -values (\*\*\* $p \leq 0.001$ ) and (\*\* $p \leq 0.01$ ). An asterisk (\*) denotes a significant effect of time where (\*\*\* $p \leq 0.001$ ), (\*\* $p \leq 0.01$ ) and (\* $p \leq 0.05$ ). Absolute repositioning accuracy data shows group averages not normalized to baseline.

### Target 1: 80-90 Degrees

There was a significant time by group interaction ( $F_{1,24} = 25.330, p < 0.001, \eta_p^2 = 0.513$ ) as well as a significant effect of time ( $F_{1,24} = 16.414, p < 0.001, \eta_p^2 = 0.406$ ), where accuracy increased by  $26.08\% \pm 0.488$  for controls and decreased by  $134.27\% \pm 1.23$  for vibration (Figure 18). There was also a significant time by group interaction ( $F_{1,24} = 10.510, p = 0.003, \eta_p^2 = 0.305$ ) as well as a significant effect of time ( $F_{1,24} = 7.917, p = 0.01, \eta_p^2 = 0.248$ ) in variable error, where precision increased by  $20.43\% \pm 0.49$  in controls and decreased by  $109.55\% \pm 1.80$  in the vibration group (Figure 19).

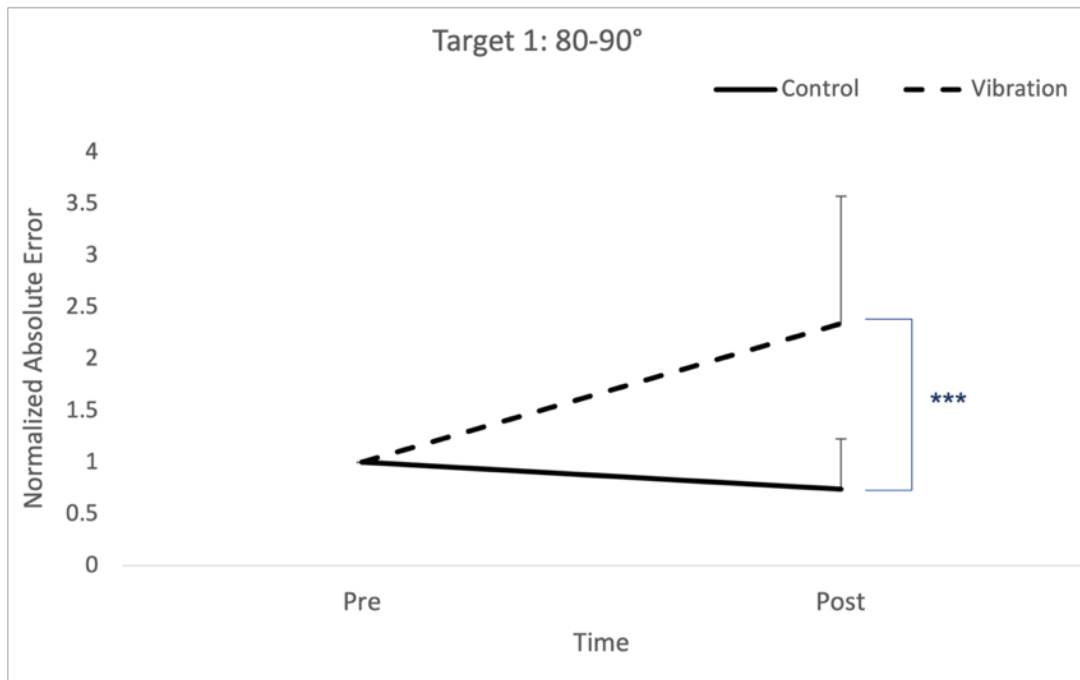


Figure 18, Normalized mean absolute error for target angle 1: 80-90 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*\*\*)  $P \leq 0.001$ .

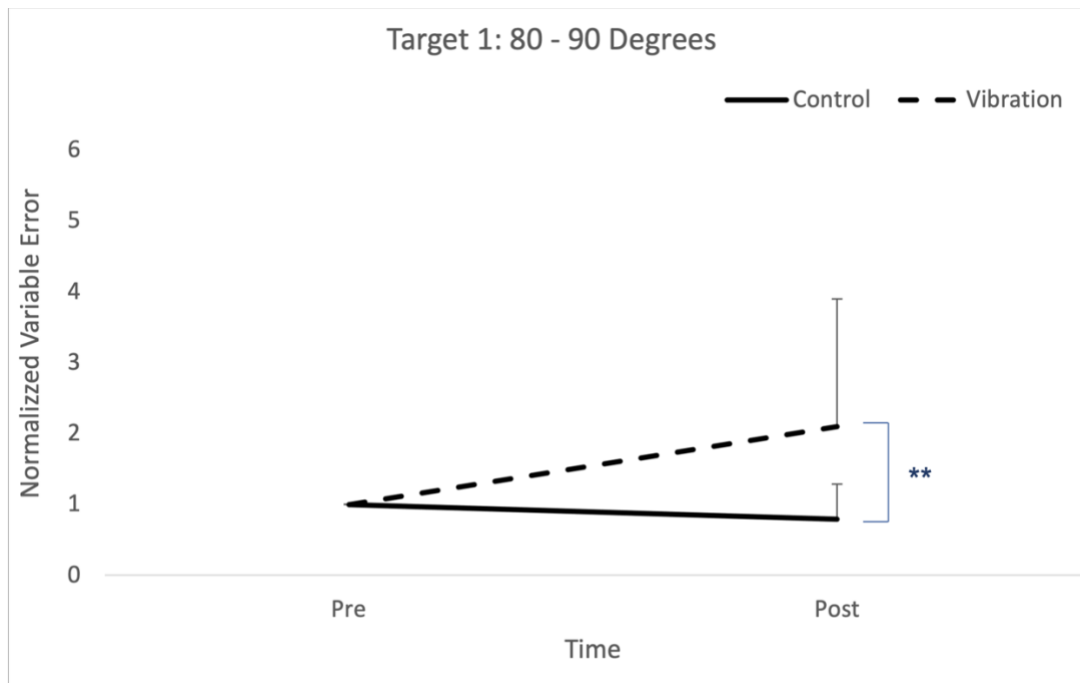


Figure 19, Normalized mean variable error for target angle 1: 80-90 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*\*  $P \leq 0.01$ ).

### Target 2: 90-100 Degrees

There was a significant time by group interaction ( $F_{1,24} = 16.157, p < 0.001, \eta_p^2 = 0.402$ ) as well as a significant effect of time ( $F_{1,24} = 13.444, p = 0.001, \eta_p^2 = 0.359$ ), where accuracy increased by  $20.39\% \pm 0.619$  for controls and decreased by  $109.54\% \pm 1.495$  for vibration (Figure 20). For variable error there was a significant time by group interaction ( $F_{1,24} = 9.280, p = 0.006, \eta_p^2 = 0.279$ ) as well as a significant effect of time ( $F_{1,24} = 10.443, p = 0.004, \eta_p^2 = 0.303$ ), where precision increased by  $14.22\% \pm 1.06$  in controls and decreased by  $119\% \pm 3.14$  in the vibration group (Figure 21).



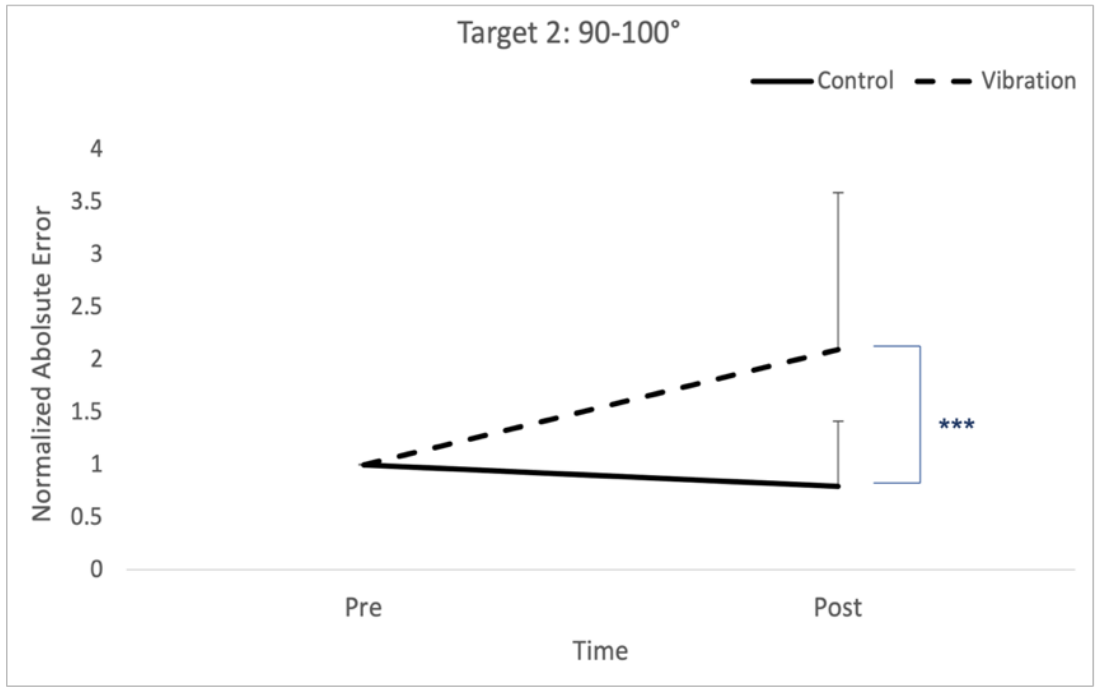


Figure 20, Normalized mean absolute error for target angle 2: 90-100 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*\*\*)  $P \leq 0.001$ .

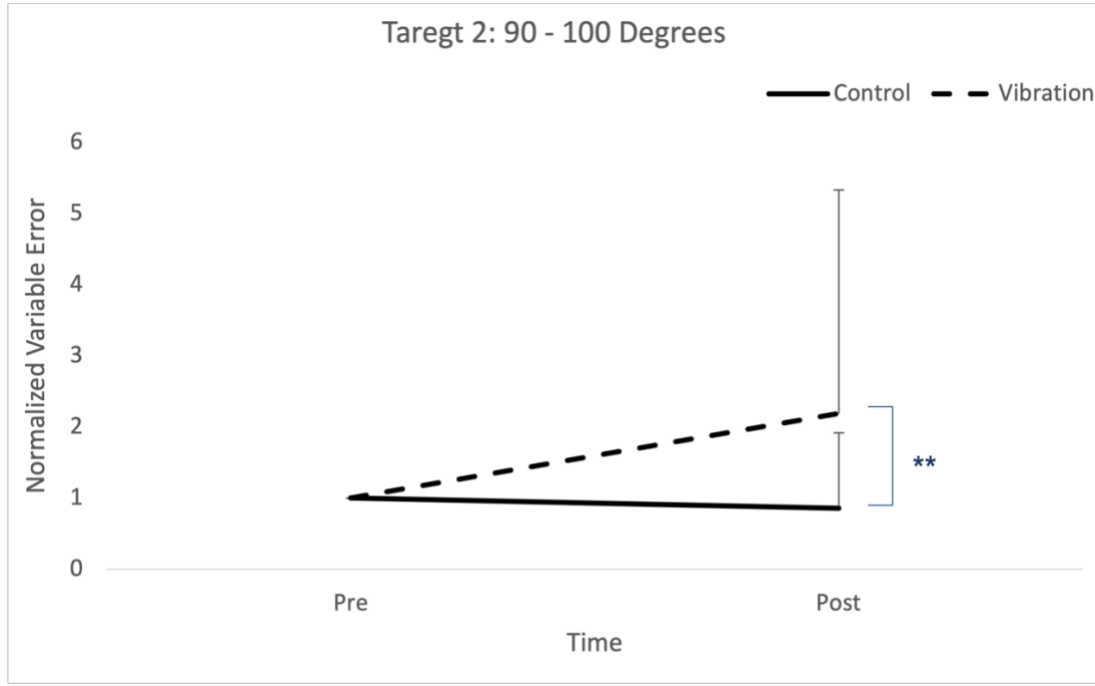


Figure 21, Normalized mean variable error for target angle 2: 90-100 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*\*  $P \leq 0.01$ ).

### Target 3: 100-110 Degrees

There was a significant time by group interaction ( $F_{1,24} = 21.923, p < 0.001, \eta_p^2 = 0.447$ ) as well as a significant effect of time ( $F_{1,24} = 5.753, p = 0.025, \eta_p^2 = 0.193$ ), where accuracy increased by  $37.11\% \pm 0.444$  for controls and decreased by  $54.39\% \pm 0.755$  for vibration (Figure 22). For variable error, there was a significant time by group interaction ( $F_{1,24} = 12.226, p = 0.002, \eta_p^2 = 0.337$ ), where precision increased by  $36.26\% \pm 0.502$  in controls and decreased by  $36.31\% \pm 0.86$  in the vibration group (Figure 23).

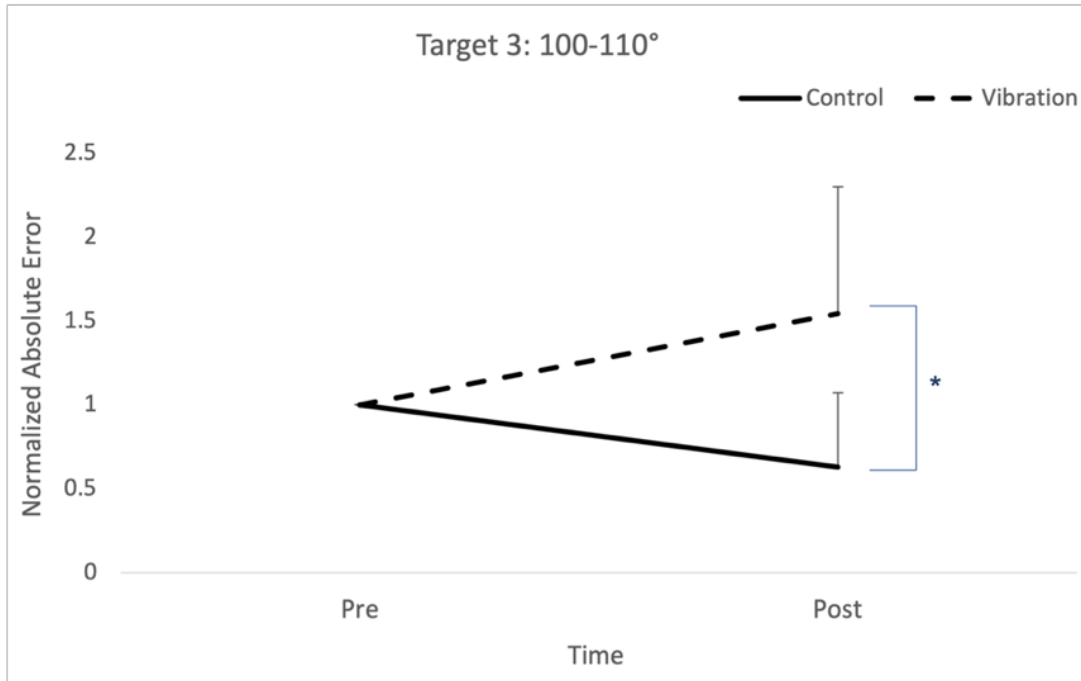


Figure 22, Normalized mean absolute error for target angle 3: 100-110 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*  $P \leq 0.05$ ).

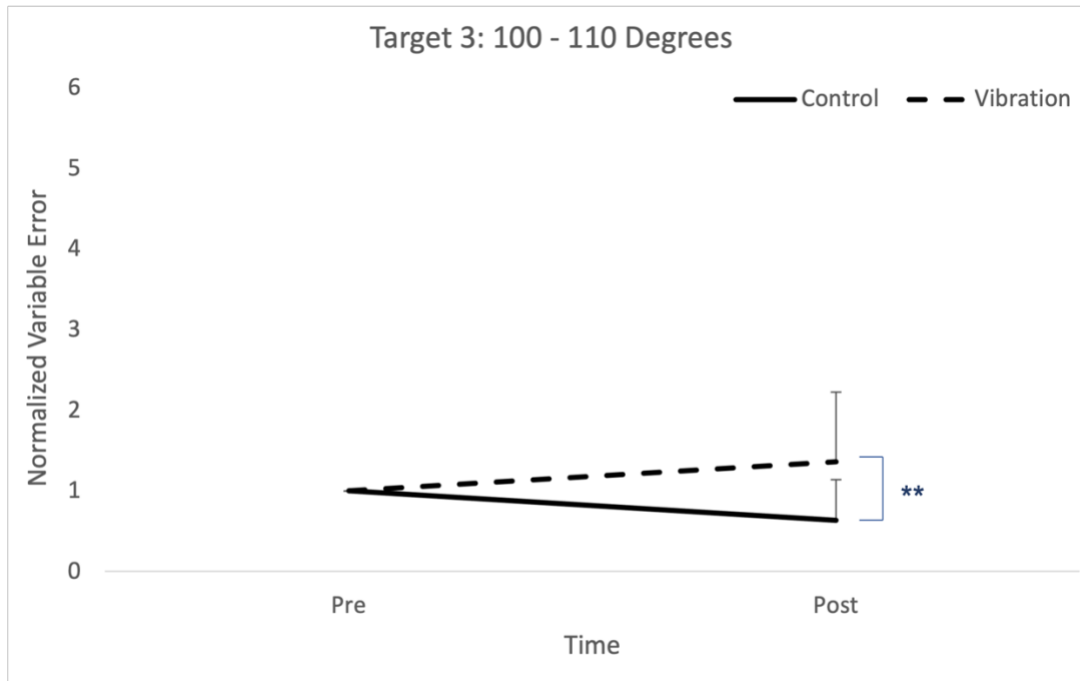


Figure 23, Normalized mean variable error for target angle 3: 100-110 degrees. Post measures have been normalized to baseline scores. Control scores are represented with the solid line while vibration scores are in the dashed line. Error bars represent SD. (\*\*  $P \leq 0.01$ ).

## Discussion

Behavioural assessments of upper limb proprioception revealed differential changes in repositioning accuracy of the right elbow following vibration of the right SCM and contralateral CEM. In general, the control group showed significant improvements in performance while the vibration group demonstrated reductions in performance at post-measures. Improvements in accuracy from baseline to post were observed in controls consistently across all presented target angles. In the vibration group, there was a significant reduction in performance accuracy after neck muscle vibration. The behavioural differences between groups indicate that neck muscle vibration generated alterations in upper limb proprioception and motor control.

### *Repositioning Accuracy*

These results of this experiment illustrate vibration-induced alterations in upper limb proprioception. At target angles between 80-90 degrees and 90-100 degrees, repositioning error increased two-fold in the vibration group. By contrast, controls demonstrated 26.08% and 20.39% reductions in error respectively. Previous research supports this finding showing reduced error when the head was in a neutral position (control condition) while those who had their head rotated in either direction or flexed forward exhibited significantly increased joint position sense error (Knox and Hodges 2005). This is further supported by previous research in SCNP populations which saw altered proprioceptive processing and joint position sense in an SCNP group compared to controls (Huysmans, Hoozemans et al. 2010, Baarbé, Holmes et al. 2015). At target angles between 100-110 degrees, repositioning error continued to increase in the vibration group while error decreased in controls. This coincides with previous work showing increased tracking error of the upper limb following SCM vibration (Knox, Cordo et al. 2006, Pettorossi, Panichi et al. 2015) as well as decreased motor accuracy of an upper limb motor sequence task following vibration of the biceps tendon (Cordo, Bevan et al. 1995). Additionally, similar results were found in fatigue studies, reporting impaired upper limb proprioception following CEM fatigue protocols compared to controls (Lee, Liao et al. 2003, Zabihhosseinian, Holmes et al. 2015).

These results also demonstrate significant reductions in precision as a result of vibration. While accuracy refers to the distance between a measurement and the correct value of the quantity being measured, precision measures the variability of the measurements in

reference to one another (Stallings and Gillmore 1971, Freund and Williams 1991). At targets between 80-90 degrees and 90-100 degrees, there was a two-fold increase in variable error in the vibration group. By contrast, the control group exhibited 20.43% and 14.22% reductions in variable error respectively. At target angles between 100-110 degrees, variable error increased by 36.31% in the vibration group and decreased by 36.26% in controls. This suggests that vibration not only impacts accuracy of the upper limb, as measured by changes in absolute error, but also precision as measured by changes in variable error. Similar results have been shown in previous work, which reported significant increases in variable error those with non-specific neck pain when examining position sense acuity and tracking position error of the upper limb (Huysmans, Hoozemans et al. 2010). These results provide strong evidence that neck muscle vibration negatively impacts precision and accuracy of the upper limb as the vibration group was consistently further from the target and exhibited higher variability in the reproduced angles when compared to controls.

While repositioning error was higher in the vibration group relative controls, both groups had the lowest degree of error when the target was between 100-110 degrees. This is likely the result of greater soft tissue approximation between the structures of the anterior upper arm and forearm as elbow flexion approaches its end range of motion. This is supported by previous studies that reported improvements in joint position sense as the target angle approached end range (Lönn, Crenshaw et al. 2000, Janwantanakul, Magarey et al. 2001), which can be attributed to increased stimulation of capsuloligamentous mechanoreceptors in the end ranges of motion due to deformation of their parent tissues (Grigg 1976, Salo and Tatton 1993).

### *Vibratory Effects on the Central Nervous System*

The CNS is dependent on accurate perceptions of the position of the head and neck to permit proper sensory processing and motor control via spindle inputs from cervical musculature. Transmission of sensory information from the head, neck and upper limbs is regulated by the cuneocerebellar tract, which transmits this information to cerebellar networks responsible for unconscious proprioceptive processing (Felten, O'Banion et al. 2015). The cuneate nuclei are responsible for the proprioceptive component of the cuneocerebellar tract by topographically relaying precise proprioceptive information to the cerebral cortex through complex feedback-regulated cerebellar connections (Noël, Ozaki et al. 1996). The first study in this thesis showed that individuals in the vibration group exhibited altered cerebellar processing and cerebellar inhibition (CBI) patterns determined by changes in SEP peaks associated with cerebellar processing (N18 and N24). Therefore, differences in proprioceptive accuracy are likely related to altered cerebellar processing in the vibration group.

The cerebellum also provides a mechanism for adapting our movements and position to maintain a consistently updated and accurate body schema in reference to changing visual information as we navigate our environment (Miall, Reckess et al. 2001). It is considered fundamental in the neural integration of the eye and hand during visually guided tracking tasks (Miall, Imamizu et al. 2000, Miall, Reckess et al. 2001). To maintain an updated body schema, several brain areas work in conjunction with the cerebellum to integrate visual and somatosensory information (Maravita, Spence et al. 2003, Holmes and Spence 2004). Without visual feedback, the cerebellum is unable to cross-reference incoming muscle spindle inputs

from the neck and upper limb. To accurately correct movement errors, an efference copy is sent from the primary motor cortex to the cerebellum consisting of information on the intended position, velocity and acceleration of the movement (Kandel, Schwartz et al. 2000, Lundy-Ekman, Peterson et al. 2018). The efference copy includes the expected consequences of the intended movement, including the expected sensory feedback. However, if there is a mismatch between the expected sensory feedback and the incoming inputs from muscle spindles, the cerebellum is unable to accurately modify descending motor commands. It is possible that a lack of visual information in conjunction with inaccurate proprioceptive inputs influenced the ability of the cerebellum to properly integrate ascending sensory information with descending motor output leading to impaired feedforward and feedback control. It is also feasible that alterations in body schema occurred as a result of the CNS processing inaccurate somatosensory input from muscle spindles as if it was accurate. Therefore, the observed changes in upper limb proprioception are likely due the result of the CNS receiving misinformation while updating body schema, leading to inaccurate motor output and increased repositioning error.

## Limitations

Due to the nature of this device, there was likely some degree of shoulder proprioceptor contribution as participants moved from elbow extension to elbow flexion. However, this contribution was very minimal as the table height, handle height and lateral position of the device were adjusted to each participant to mitigate involvement of the shoulder joint.

Additionally, due to the nature of this sample, these results may not be generalizable to young children and older adults.

## Conclusion

This work is the first to investigate changes in upper limb proprioception across varying target angles following SCM and contralateral CEM vibration. Group-dependant changes in performance accuracy were observed following vibration protocols. Increased repositioning error was observed in the vibration group at targets of 80-90 degrees, 90-100 degrees and 100-110 degrees while controls exhibited improvements at all target angles, suggesting that those in the vibration group experienced alterations in proprioceptive processing and motor control. This could be reflective of altered body schema in this group due to vibration induced changes in proprioceptive input. Future work should investigate whether this relationship persists during upper limb precision tasks. Postural instability may have contributed to the results in upper limb accuracy as participants were blindfolded while standing for the duration of the study. Future work could examine the effects of neck muscle vibration on postural sway and determine the impact of postural sway on upper limb control. Additionally, future directions could examine the effects of vibration on upper limb kinematics with and without visual input to determine if transient alterations in afferent input can be corrected through visual feedback.



## CHAPTER 4

## SUMMARY

## THESIS SUMMARY

This thesis contributes important knowledge on the effects of transient alterations in neck afferent input on motor learning, proprioception and motor control and the role it plays in adaptive or maladaptive plasticity in response to learning novel motor skills. The experiments in this thesis investigated the effects of neck muscle vibration on motor learning, sensorimotor integration, upper limb proprioception and motor control.

In manuscript one, experimental alterations in afferent input via sternocleidomastoid (SCM) and contralateral cervical extensor muscle (CEM) vibration completed prior to acquisition of a novel force matching tracking task (FMTT) led to differential changes in SEP peaks associated with cerebellar processing and altered motor learning outcomes. The N18 SEP peak amplitude increased for controls and decreased for vibration post motor learning suggesting alterations in cortico-cerebellar inhibition and proprioceptive processing in the vibration group. The N24 SEP peak amplitude decreased in controls and increased for vibration following motor acquisition suggesting a lack of cerebellar disinhibition and altered motor learning at a neural level in the vibration group. These differences indicate that the cerebellum and associated cerebellar networks are selectively affected by SCM and CEM vibration. While motor learning occurred in both groups, as demonstrated by decreased absolute error post-acquisition, trends at retention suggest that controls were continuing to improve while accuracy was beginning to diminish in the vibration group. This provides strong evidence that transient alterations in afferent input at the level of the neck directly influence the ability of the central nervous

system (CNS) to accurately process proprioceptive inputs used to construct body schema required to learn a novel motor skill.

Manuscript two built on the results on manuscript one by examining the impact of SCM and contralateral CEM vibration on upper limb proprioception by comparing performance accuracy of an elbow repositioning task prior to and immediately following vibration protocol. Differential differences in group performance were observed across three presented target angles between 80-90 degrees, 90-100 degrees and 100-110 degrees where the vibration group consistently exhibited greater error at post-measures while controls showed improvements in motor accuracy. Motor performance was best for both groups when the presented target angle was between 100-110 degrees, likely the result of increased stimulation of capsuloligamentous mechanoreceptors in the end ranges of motion. These results are evidence that transient alterations in neck sensory input impair upper limb proprioception and motor control. This is likely due to the CNS receiving misinformation when updating body schema and is related to altered cerebellar processing of unconscious proprioception via the cuneocerebellar tract observed in this group.

Additionally, there are implications of employing a seated posture during the motor learning paradigm in manuscript one and a standing posture during the proprioception task in manuscript to that may be relevant to the results of this thesis. It is possible that there are differences in the re-weighting of sensory information in a seated posture compared to standing. The weight given to each sensory input during multisensory integration depends on

many factors, but evidence suggests that sensory information is integrated in the most statistically optimal fashion (Ernst and Banks 2002, Ernst and Bühlhoff 2004). Work using an adaptation of the maximum-likelihood estimation investigated the relationship between visual and haptic feedback in the weighing of sensory inputs and reported that visual feedback dominates when variance associated with visual estimation is lower than the variance associated with haptic estimation (Ernst and Banks 2002). Therefore, it is possible that the weight assigned to neck proprioceptive inputs is greater during standing postures when compared to seated postures. This is supported by the results from this thesis which demonstrated significantly greater changes in upper limb control while participants were in standing postures compared to the changes observed in seated postures employed in manuscript 1.

## GENERAL CONCLUSION

The findings of this thesis suggest that SCM and contralateral CEM vibration negatively impacts the ability of the CNS to accurately process somatosensory information to learn a novel motor skill. Changes in cerebellar processing are likely due to transient alterations in afferent input as it travels from the upper limb through the neck and to the CNS as determined by differential changes in short latency SEP peak amplitudes demonstrating alterations in unconscious proprioceptive processing and a lack of cerebellar disinhibition in response to motor learning. Coupled with changes in proprioception and motor accuracy, these results indicate the neck muscle vibration significantly impairs the ability of the CNS to compute the position of the upper limb. In conclusion, transient alterations in neck sensory input directly

impact the ability of the CNS to construct an updated and accurate body schema required for proper motor control and motor learning.

## PRACTICAL SIGNIFICANCE AND FUTURE DIRECTIONS

Understanding in which types of sensory receptors lead to altered afferent input impacting body schema is important for many fields, especially in occupations that require extensive motor precision and motor control. Many occupational and recreational settings require upper limb motor precision and motor skill acquisition in the presence of vibration or other mechanisms of altered afferent input. This includes awkward work postures or orienting the head away from the task at hand increasing the risk of fatigue, pain and joint dysfunction which research has demonstrated contribute to alterations in afferent input at the level of the neck. Professions under the construction, maintenance and medical umbrellas often require employees to work with power tools and equipment that vibrate at high frequencies while performing novel skills or precision-based tasks. This is very common in dentistry where medical professionals use vibrating tools to perform tasks requiring extreme precision and extensive motor control. If altered afferent input from the neck impacts upper limb proprioception and motor control, it has the potential to lead to errors that could impact the health, well-being and productivity of professionals and in some cases medical patients. The results from this thesis are important as they support the notion that even acute alterations in afferent input, in the absence of confounding factors presented in pain and fatigue models, can impact upper limb accuracy, and generate marked changes in the neurophysiological processes required to learn a novel motor skill or accurately control the upper limb. The basic science

knowledge gained from this thesis contributes to the current body of literature on body schema and mechanisms of altered afferent input and is the first study to demonstrate neurophysiological adaptations coupled with behavioural changes in response to vibration.

Future directions should investigate the effects of neck muscle vibration on precision vs gross motor tasks to determine the impact of transient alterations in muscle spindle input on different classes of motor control and motor learning paradigms. Future work should also assess retention at longer intervals to determine if the neurophysiological adaptations observed in the vibration group translate to more profound changes in motor performance and motor skill consolidation. Additionally, future work could examine the effects of vibration on upper limb kinematics with and without visual input to determine if transient alterations in afferent input can be corrected through visual feedback.

CHAPTER 5

APPENDICES

Appendix A – Edinburgh Handedness Inventory (EHI)

**Edinburgh Handedness Inventory**

Please indicate your preferences in the use of hands in the following activities *by putting a check in the appropriate column. Where the preference is so strong that you would never try to use the other hand, unless absolutely forced to, put 2 checks.* If in any case you are really indifferent, *put a check in both columns.*

Some of the activities listed below require the use of both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in parentheses.

Please try and answer all of the questions, and only leave a blank if you have no experience at all with the object or task.

	Left	Right
1. Writing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
2. Drawing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
3. Throwing	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
4. Scissors	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
5. Toothbrush	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
6. Knife (without fork)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
7. Spoon	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
8. Broom (upper hand)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
9. Striking Match (match)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
10. Opening box (lid)	<input type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input type="checkbox"/>
<b><u>TOTAL(count checks in both columns)</u></b>	<input type="text"/>	<input type="text"/>

Difference	Cumulative TOTAL	Result
<input type="text"/>	<input type="text"/>	<input type="text"/>

**Scoring:**

Add up the number of checks in the “Left” and “Right” columns and enter in the “TOTAL” row for each column. Add the left total and the right total and enter in the “Cumulative TOTAL” cell. Subtract the left total from the right total and enter in the “Difference” cell. Divide the “Difference” cell by the “Cumulative



Appendix B – Safety Checklist for Neurophysiological Techniques

**Safety checklist:**

The following questions are to ensure it is safe for you to complete this study. If you answer yes to any of the questions below, we may need to exclude you from participating.

QUESTION	ANSWER	
1. Do you suffer from epilepsy, or have you ever had an epileptic seizure?	Yes	No
2. Does anyone in your family suffer from epilepsy?	Yes	No
3. Do you have any metal implant(s) in any part of your body or head? (Excluding tooth fillings)	Yes	No
4. Do you have an implanted medication pump?	Yes	No
5. Do you wear a pacemaker?	Yes	No
6. Do you suffer any form of heart disease?	Yes	No
7. Do you suffer from reoccurring headaches**?	Yes	No
8. Have you ever had a skull fracture or serious head injury?	Yes	No
9. Have you ever had any head surgery?	Yes	No
10. Are you pregnant?	Yes	No
11. Do you take any medication or use recreational drugs (including marijuana)*?	Yes	No
12. Do you suffer from any known neurological or medical conditions?	Yes	No

Comments \_\_\_\_\_  
 \_\_\_\_\_

Name \_\_\_\_\_

Signature \_\_\_\_\_

Date \_\_\_\_\_

\*Note if taking medication or using recreational drugs please read through the medication list on the next page to see if you use contraindicated drugs or medications. You do not need to tell the researcher which medications or drugs you use, unless you wish to. However, all researchers have signed confidentiality agreements and this information will not be recorded in writing, if you do wish to discuss this issue.

\*\*Dr. Murphy will meet with participants who answer yes to this question to seek further information.

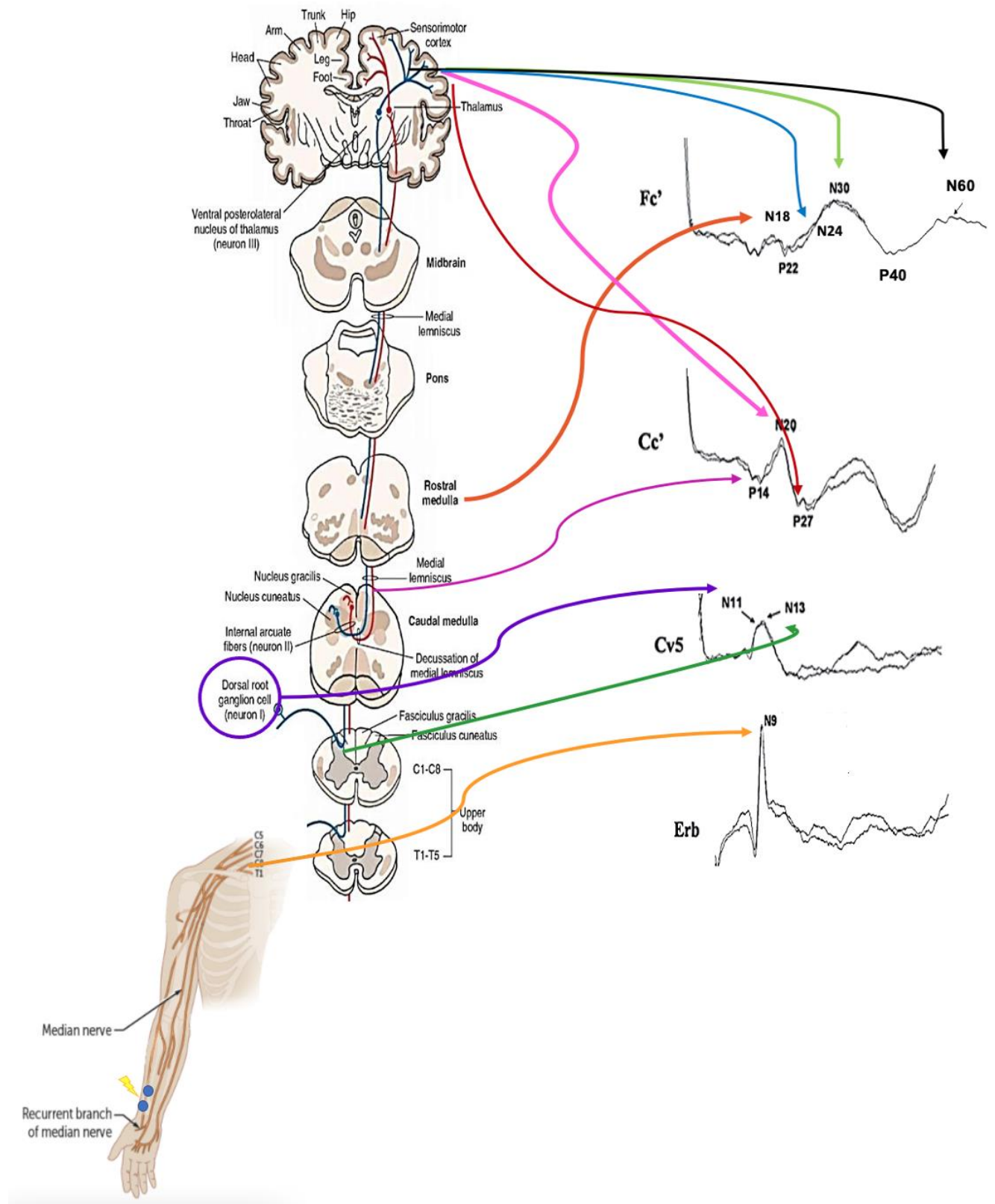
## Appendix C – Neck Disability Index (NDI)

This questionnaire has been designed to give your therapist information as to how your neck pain has affected your ability to manage in everyday life. Please answer every question by placing a mark in the **ONE** box that applies to you. We realize that 2 of the statements may describe your condition, but please mark only the **ONE** box that most closely describes your current condition.

<p><b>Neck Pain Intensity</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I have no pain at the moment.</li> <li><input type="radio"/> The pain is very mild at the moment.</li> <li><input type="radio"/> The pain is moderate at the moment.</li> <li><input type="radio"/> The pain is fairly severe at the moment.</li> <li><input type="radio"/> The pain is very severe at the moment.</li> <li><input type="radio"/> The pain is the worst imaginable at the moment.</li> </ul>	<p><b>Concentration</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can concentrate fully when I want to with no difficulty.</li> <li><input type="radio"/> I can concentrate fully when I want with slight difficulty.</li> <li><input type="radio"/> I have a fair degree of difficulty in concentrating when I want to.</li> <li><input type="radio"/> I have a lot of difficulty in concentrating when I want to.</li> <li><input type="radio"/> I have a great, great deal of difficulty in concentrating when I want to.</li> <li><input type="radio"/> I cannot concentrate at all.</li> </ul>
<p><b>Personal Care (eg washing, dressing)</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can look after myself normally without causing extra pain.</li> <li><input type="radio"/> I can look after myself normally but it causes extra pain.</li> <li><input type="radio"/> It is painful to look after myself, and I am slow and careful</li> <li><input type="radio"/> I need some help, but manage most of my personal care.</li> <li><input type="radio"/> I need help every day in most aspects of self-care.</li> <li><input type="radio"/> I do not get dressed, I wash with difficulty, and stay in bed</li> </ul>	<p><b>Work</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can do as much work as I want too.</li> <li><input type="radio"/> I can only do my usual work, but no more.</li> <li><input type="radio"/> I can do most of my usual work, but no more.</li> <li><input type="radio"/> I cannot do my usual work.</li> <li><input type="radio"/> I can hardly do any work at all.</li> <li><input type="radio"/> I cannot do any work at all.</li> </ul>
<p><b>Lifting</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can lift heavy weights without extra neck pain</li> <li><input type="radio"/> I can lift heavy weights, but it gives extra neck pain</li> <li><input type="radio"/> Neck pain prevents me from lifting heavy weights off the floor, but I can manage if they are conveniently positioned, for example on a table</li> <li><input type="radio"/> Neck pain prevents me from lifting heavy weights, but I can manage light to medium weights if they are conveniently positioned</li> <li><input type="radio"/> I can lift only very light weights</li> <li><input type="radio"/> I cannot lift or carry anything</li> </ul>	<p><b>Driving</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can drive my car without any neck pain at all.</li> <li><input type="radio"/> I can drive my car as long as I want, with slight pain in my neck.</li> <li><input type="radio"/> I can drive my car as long as I want, with moderate pain in my neck.</li> <li><input type="radio"/> I cannot drive my car as long as I want, because of moderate pain in my neck.</li> <li><input type="radio"/> I can hardly drive at all because of severe pain in my neck.</li> <li><input type="radio"/> I cannot drive my car at all because of the pain in my neck.</li> </ul>
<p><b>Reading</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I can read as much as I want, with no pain in my neck.</li> <li><input type="radio"/> I can read as much as I want, with slight pain in my neck.</li> <li><input type="radio"/> I can read as much as I want, with moderate pain in my neck.</li> <li><input type="radio"/> I cannot read as much as I want, because of moderate pain in my neck.</li> <li><input type="radio"/> I can hardly read at all because of severe pain in my neck.</li> <li><input type="radio"/> I cannot read at all because of pain in my neck.</li> </ul>	<p><b>Sleeping</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I have no trouble sleeping.</li> <li><input type="radio"/> My sleep is barely disturbed (sleepless less than 1 hr).</li> <li><input type="radio"/> My sleep is mildly disturbed (sleepless 1-2 hrs).</li> <li><input type="radio"/> My sleep is moderately disturbed (sleepless 2-3 hrs).</li> <li><input type="radio"/> My sleep is greatly disturbed (sleepless 3-5 hrs).</li> <li><input type="radio"/> My sleep is completely disturbed (sleepless 5-7 hrs).</li> </ul>
<p><b>Headaches</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I have no headaches at all.</li> <li><input type="radio"/> I have slight headaches that come infrequently.</li> <li><input type="radio"/> I have moderate headaches that come infrequently.</li> <li><input type="radio"/> I have moderate headaches that come frequently.</li> <li><input type="radio"/> I have severe headaches that come frequently.</li> <li><input type="radio"/> I have headaches almost all the time.</li> </ul>	<p><b>Recreation</b></p> <ul style="list-style-type: none"> <li><input type="radio"/> I am able to engage in all my recreational activities, with no neck pain at all.</li> <li><input type="radio"/> I am able to engage in all my recreational activities, with some pain in my neck.</li> <li><input type="radio"/> I am able to engage in most, but not all of my usual recreational activities, because of pain in my neck.</li> <li><input type="radio"/> I am able to engage in few of my usual recreational activities, because of pain in my neck.</li> <li><input type="radio"/> I can hardly engage in any recreational activities because of pain in my neck.</li> <li><input type="radio"/> I cannot engage in any recreational activities at all because of pain in my neck.</li> </ul>

Vernon, H. and S. Mior, *The Neck Disability Index: A Study of Reliability and Validity*. Journal of Manipulative and Physiological Therapeutics, 1991. **14**(7): p. 409-415.

# Appendix D – Somatosensory Evoked Potentials (SEPs)



### **SEPs Naming Conventions:**

The International Federation of Clinical Neurophysiologists (IFCN) uses two labelling conventions: polarity and latency (Cruccu, Aminoff et al. 2008). Each SEP peak and trough are named based on their deviation direction or polarity and their latency. Peaks, or upward deflections represent a negative polarity and are given the prefix “N” while troughs, or downward deflections represent a positive polarity and are given the prefix “P”. The number that follows represents the number of milliseconds it takes post-stimulus for the deflection to appear in a healthy population. Therefore, the N20 peak is an upward deflection occurring 20ms post stimulus while the P25 is a downward deflection occurring 25ms post stimulus. An average of 1000 stimulations leads to the extraction of predictable and reproducible waveforms based on the recording site.

### **SEPs Stimulation Parameters & Median Nerve Pathway:**

For the purposes of this thesis, bipolar transcutaneous electrical stimulation was done at two frequencies via surface electromyography (EMG) electrodes over the right median nerve using a continuous current stimulator (Cruccu, Aminoff et al. 2008). Because the median nerve is a mixed nerve, stimulus intensity must exceed the motor threshold without eliciting pain by depolarizing large diameter myelinated afferents (Ia) and not small diameter myelinated (A $\delta$ ) or unmyelinated (C) afferents, resulting in a visible 1-2cm thumb twitch. 100-300  $\mu$ s square waveform electrical pulses were sent at frequencies of 2.47 Hz and 4.98 Hz to enable optimal recordings of the N30 and N24 peaks respectively. Once the median nerve is stimulated, the afferent volley ascends to Erb’s point over the brachial plexus producing the N9 peak. It then

enters the cervical cord and collateral branches synapse with the mid-cervical cord giving rise to the N11 and N13 peaks recorded over the spinous process of the fifth cervical vertebrae. From here, the afferent volley passes through the cervicomedullary junction and enters the medial lemniscus producing the P14 (Nuwer, Aminoff et al. 1994, Mauguiere, Allison et al. 1999). The signal ascends through the inferior olive and lower medulla giving rise to the N18 peak before travelling through the thalamus to other regions of the cerebral cortex including the primary somatosensory cortex (N20 peak), Brodmann's area 1 (P25 peak), cerebellar-S1 pathways (N24), complex basal-motor networks (N30) and secondary somatosensory cortex (N60) giving rise to the respective SEP peaks at each area (Crucchi, Aminoff et al. 2008, Macerollo, Brown et al. 2018).

## References

- Abbruzzese, G. and A. Berardelli (2003). "Sensorimotor integration in movement disorders." Movement disorders **18**(3): 231-240.
- Akizuki, K. and Y. Ohashi (2015). "Measurement of functional task difficulty during motor learning: What level of difficulty corresponds to the optimal challenge point?" Human movement science **43**: 107-117.
- Alcaraz-Clariana, S., L. García-Luque, J. L. Garrido-Castro, C. Fernández-de-Las-Peñas, C. Carmona-Pérez, D. P. Rodrigues-de-Souza and F. Alburquerque-Sendín (2021). "Paravertebral muscle mechanical properties and spinal range of motion in patients with acute neck or low back pain: a case-control study." Diagnostics **11**(2): 352.
- Allison, T., G. McCarthy and C. C. Wood (1992). "The relationship between human long-latency somatosensory evoked potentials recorded from the cortical surface and from the scalp." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **84**(4): 301-314.
- Ambalavanar, U. (2021). Development and Validation of Tools to Examine Neural Correlates and Constructs Associated with Sensorimotor Integration. Masters, Ontario Tech University.
- Andrew, D., P. Yelder, H. Haavik and B. Murphy (2018). "The effects of subclinical neck pain on sensorimotor integration following a complex motor pursuit task." Experimental brain research **236**(1): 1-11.
- Baarbé, J., M. Holmes, H. Murphy, H. Haavik and B. Murphy (2015). "Neck pain participants show impaired ability to perform a mental rotation task in a four week longitudinal study as compared to healthy controls." Journal of Chiropractic Medicine **14**(2): 99-100.
- Baarbé, J. K., P. Yelder, H. Haavik, M. W. Holmes and B. A. Murphy (2018). "Subclinical recurrent neck pain and its treatment impacts motor training-induced plasticity of the cerebellum and motor cortex." PloS one **13**(2): e0193413.
- Barba, C., M. Valeriani, G. Colicchio and F. Mauguiere (2005). "Short and middle-latency Median Nerve (MN) SEPs recorded by depth electrodes in human pre-SMA and SMA-proper." Clinical neurophysiology **116**(11): 2664-2674.
- Blakemore, S.-J., C. D. Frith and D. M. Wolpert (2001). "The cerebellum is involved in predicting the sensory consequences of action." Neuroreport **12**(9): 1879-1884.
- Bloedel, J. R., V. Bracha, M. Milak and Y. Shimansky (1997). "Cerebellar contributions to the acquisition and execution of learned reflex and volitional movements." Progress in brain research **114**: 499-509.
- Britton, J. W., L. C. Frey, J. L. Hopp, P. Korb, M. Z. Koubeissi, W. E. Lievens, E. M. Pestana-Knight and E. St Louis (2016). "Electroencephalography (EEG): an introductory text and atlas of normal and abnormal findings in adults, children, and infants."
- Brown, G. G., M. Caligiuri, M. Meloy, S. C. Ebersson, S. S. Kindermann, L. R. Frank, L. T. Eyler Zorrilla and J. B. Lohr (2004). "Functional brain asymmetries during visuomotor tracking." Journal of clinical and experimental neuropsychology **26**(3): 356-368.
- Brown, M., I. Engberg and P. Matthews (1967). "The relative sensitivity to vibration of muscle receptors of the cat." The Journal of physiology **192**(3): 773-800.

Byl, N. N., M. M. Merzenich, S. Cheung, P. Bedenbaugh, S. S. Nagarajan and W. M. Jenkins (1997). "A primate model for studying focal dystonia and repetitive strain injury: effects on the primary somatosensory cortex." Physical therapy **77**(3): 269-284.

Childs, J. D., J. A. Cleland, J. M. Elliott, D. S. Teyhen, R. S. Wainner, J. M. Whitman, B. J. Sopky, J. J. Godges, T. W. Flynn and A. Delitto (2008). "Neck pain: clinical practice guidelines linked to the International Classification of Functioning, Disability, and Health from the Orthopaedic Section of the American Physical Therapy Association." Journal of Orthopaedic & Sports Physical Therapy **38**(9): A1-A34.

Cohen, J. (1995). "The earth is round ( $p < .05$ ): Rejoinder."

Consalez, G. G., D. Goldowitz, F. Casoni and R. Hawkes (2021). "Origins, development, and compartmentation of the granule cells of the cerebellum." Frontiers in Neural Circuits **14**: 88.

COOPER, S. and P. Daniel (1963). "Muscle spindles in man; their morphology in the lumbricals and the deep muscles of the neck." Brain **86**(3): 563-586.

Cordo, P., L. Bevan, V. Gurfinkel, L. Carlton, M. Carlton and G. Kerr (1995). "Proprioceptive coordination of discrete movement sequences: mechanism and generality." Canadian Journal of Physiology and Pharmacology **73**(2): 305-315.

Cruccu, G., M. Aminoff, G. Curio, J. Guerit, R. Kakigi, F. Mauguiere, P. Rossini, R.-D. Treede and L. Garcia-Larrea (2008). "Recommendations for the clinical use of somatosensory-evoked potentials." Clinical neurophysiology **119**(8): 1705-1719.

Dal Maso, F., B. Desormeau, M.-H. Boudrias and M. Roig (2018). "Acute cardiovascular exercise promotes functional changes in cortico-motor networks during the early stages of motor memory consolidation." Neuroimage **174**: 380-392.

Daligadu, J., H. Haavik, P. C. Yelder, J. Baarbe and B. Murphy (2013). "Alterations in cortical and cerebellar motor processing in subclinical neck pain patients following spinal manipulation." Journal of manipulative and physiological therapeutics **36**(8): 527-537.

de Vries, J., B. K. Ischebeck, L. P. Voogt, M. Janssen, M. A. Frens, G.-J. Kleinrensink and J. N. van der Geest (2016). "Cervico-ocular reflex is increased in people with nonspecific neck pain." Physical therapy **96**(8): 1190-1195.

Delhaye, B. P., K. H. Long and S. J. Bensmaia (2011). "Neural basis of touch and proprioception in primate cortex." Comprehensive Physiology **8**(4): 1575-1602.

Desmedt, J. E. and G. Cheron (1981). "Non-cephalic reference recording of early somatosensory potentials to finger stimulation in adult or aging normal: differentiation of widespread N18 and contralateral N20 from the prerolandic p22 and N30 components." Electroencephalography and clinical neurophysiology **52**(6): 553-570.

Desmedt, J. E. and I. Ozaki (1991). "SEPs to finger joint input lack the N20-P20 response that is evoked by tactile inputs: contrast between cortical generators in areas 3b and 2 in humans." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **80**(6): 513-521.

Doyon, J., A. M. Owen, M. Petrides, V. Sziklas and A. C. Evans (1996). "Functional anatomy of visuomotor skill learning in human subjects examined with positron emission tomography." European Journal of Neuroscience **8**(4): 637-648.

Doyon, J., V. Penhune and L. G. Ungerleider (2003). "Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning." Neuropsychologia **41**(3): 252-262.

Doyon, J., A. W. Song, A. Karni, F. Lalonde, M. M. Adams and L. G. Ungerleider (2002). "Experience-dependent changes in cerebellar contributions to motor sequence learning." Proceedings of the National Academy of Sciences **99**(2): 1017-1022.

Doyon, J. and L. G. Ungerleider (2002). "Functional anatomy of motor skill learning."

Eklund, G. (1972). "Position sense and state of contraction; the effects of vibration." Journal of Neurology, Neurosurgery & Psychiatry **35**(5): 606-611.

Elsig, S., H. Luomajoki, M. Sattelmayer, J. Taeymans, A. Tal-Akabi and R. Hilfiker (2014). "Sensorimotor tests, such as movement control and laterality judgment accuracy, in persons with recurrent neck pain and controls. A case-control study." Manual therapy **19**(6): 555-561.

Ernst, M. O. and M. S. Banks (2002). "Humans integrate visual and haptic information in a statistically optimal fashion." Nature **415**(6870): 429-433.

Ernst, M. O. and H. H. Bühlhoff (2004). "Merging the senses into a robust percept." Trends in cognitive sciences **8**(4): 162-169.

Falla, D. and D. Farina (2008). "Neuromuscular adaptation in experimental and clinical neck pain." Journal of Electromyography and Kinesiology **18**(2): 255-261.

Farid, B., P. Yelder, M. Holmes, H. Haavik and B. A. Murphy (2018). "Association of subclinical neck pain with altered multisensory integration at baseline and 4-week follow-up relative to asymptomatic controls." Journal of manipulative and physiological therapeutics **41**(2): 81-91.

Felten, D. L., M. K. O'Banion and M. E. Maida (2015). Netter's atlas of neuroscience, Elsevier Health Sciences.

Fitts, P. M. and M. I. Posner (1967). "Human performance."

Fookson, O., B. Smetanin, M. Berkinblit, S. Adamovich, G. Feldman and H. Poizner (1994). "Azimuth errors in pointing to remembered targets under extreme head rotations." Neuroreport: An International Journal for the Rapid Communication of Research in Neuroscience.

Freund, J. E. and F. J. Williams (1991). Dictionary/outline of basic statistics, Courier Corporation.

Frot, M. and F. Mauguière (1999). "Timing and spatial distribution of somatosensory responses recorded in the upper bank of the sylvian fissure (SII area) in humans." Cerebral Cortex **9**(8): 854-863.

Gilbert, P. and W. Thach (1977). "Purkinje cell activity during motor learning." Brain research **128**(2): 309-328.

Goodwin, G. M., D. I. McCloskey and P. B. Matthews (1972). "Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception?" Science **175**(4028): 1382-1384.

Graziano, M. S., G. S. Yap and C. G. Gross (1994). "Coding of visual space by premotor neurons." Science **266**(5187): 1054-1057.

Grigg, P. (1976). "Response of joint afferent neurons in cat medial articular nerve to active and passive movements of the knee." Brain Research **118**(3): 482-485.

GRIGG, P., G. A. FINERMAN and L. H. RILEY (1973). "Joint-Position Sense after Total Hip Replacement." JBJS **55**(5): 1016-1025.

Guadagnoli, M. A. and T. D. Lee (2004). "Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning." Journal of motor behavior **36**(2): 212-224.



Guerraz, M., J. Blouin and J.-L. Vercher (2003). "From head orientation to hand control: evidence of both neck and vestibular involvement in hand drawing." Experimental brain research **150**(1): 40-49.

Guerraz, M., S. Caudron, N. Thomassin and J. Blouin (2011). "Influence of head orientation on visually and memory-guided arm movements." Acta psychologica **136**(3): 390-398.

Haavik, H. and B. Murphy (2011). "An approach using fast rate stimulation to investigate changes in cerebellar processing." Clinical Chiropractic **14**(4): 174.

Haggard, P. and D. M. Wolpert (2005). Disorders of body scheme. In Freund, HJ, Jeannerod, M., Hallett, M., Leiguarda R.,(Eds.), Higher-Order Motor Disorders, Citeseer.

Head, H., W. H. R. Rivers, J. C. Sherren, G. C. Holmes, T. C. Thompson and G. C. Riddoch (1920). "Studies in neurology, in two volumes, Vol 1."

Holmes, N. P. and C. Spence (2004). "The body schema and multisensory representation (s) of peripersonal space." Cognitive processing **5**(2): 94-105.

Hoshiyama, M. and G. Sheean (1998). "Changes of somatosensory evoked potentials preceding rapid voluntary movement in Go/No-go choice reaction time task." Cognitive brain research **7**(2): 137-142.

Huysmans, M. A., M. J. Hoozemans, A. J. van der Beek, M. P. de Looze and J. H. van Dieën (2010). "Position sense acuity of the upper extremity and tracking performance in subjects with non-specific neck and upper extremity pain and healthy controls." Journal of rehabilitation medicine **42**(9): 876-883.

Janwantanakul, P., M. E. Magarey, M. A. Jones and B. R. Dansie (2001). "Variation in shoulder position sense at mid and extreme range of motion." Archives of physical medicine and rehabilitation **82**(6): 840-844.

Kandel, E. R., J. H. Schwartz, T. M. Jessell, S. Siegelbaum, A. J. Hudspeth and S. Mack (2000). Principles of neural science, McGraw-hill New York.

Karellas, A. M., P. Yelder, J. J. Burkitt, H. S. McCracken and B. A. Murphy (2019). "The Influence of Subclinical Neck Pain on Neurophysiological and Behavioral Measures of Multisensory Integration." Brain Sciences **9**(12): 362.

Knierim, J. (1997 - Present). Neuroscience Online, UT Health: 50.

Knox, J., P. Cordo, R. Skoss, S. Durrant and P. Hodges (2006). "Illusory changes in head position induced by neck muscle vibration can alter the perception of elbow position." Behavioral neuroscience **120**(6): 1211.

Knox, J. J. and P. W. Hodges (2005). "Changes in head and neck position affect elbow joint position sense." Experimental brain research **165**(1): 107-113.

Krajnak, K. (2018). "Health effects associated with occupational exposure to hand-arm or whole body vibration." Journal of Toxicology and Environmental Health, Part B **21**(5): 320-334.

Kulkarni, V., M. Chandy and K. Babu (2001). "Quantitative study of muscle spindles in suboccipital muscles of human fetuses." Neurology India **49**(4): 355.

Lackner, J. R. (1988). "Some proprioceptive influences on the perceptual representation of body shape and orientation." Brain **111**(2): 281-297.

Lee, H.-M., J.-J. Liau, C.-K. Cheng, C.-M. Tan and J.-T. Shih (2003). "Evaluation of shoulder proprioception following muscle fatigue." Clinical biomechanics **18**(9): 843-847.

Lundy-Ekman, L., C. Peterson, C. Siengsukon and D. Goodwin (2018). Neuroscience Fundamentals for Rehabilitation. Canada, Elsevier.

Lönn, J., A. G. Crenshaw, M. Djupsjöbacka, J. Pedersen and H. Johansson (2000). "Position sense testing: influence of starting position and type of displacement." Archives of physical medicine and rehabilitation **81**(5): 592-597.

Macefield, V. G. and T. P. Knellwolf (2018). "Functional properties of human muscle spindles." Journal of Neurophysiology **120**(2): 452-467.

Macerollo, A., M. J. Brown, J. M. Kilner and R. Chen (2018). "Neurophysiological changes measured using somatosensory evoked potentials." Trends in Neurosciences **41**(5): 294-310.

Manto, M., J. M. Bower, A. B. Conforto, J. M. Delgado-García, S. N. F. Da Guarda, M. Gerwig, C. Habas, N. Hagura, R. B. Ivry and P. Mariën (2012). "Consensus paper: roles of the cerebellum in motor control—the diversity of ideas on cerebellar involvement in movement." The Cerebellum **11**(2): 457-487.

Manzoni, D. (2005). "The cerebellum may implement the appropriate coupling of sensory inputs and motor responses: evidence from vestibular physiology." The Cerebellum **4**(3): 178-188.

Maravita, A., C. Spence and J. Driver (2003). "Multisensory integration and the body schema: close to hand and within reach." Current biology **13**(13): R531-R539.

Mauguiere, F., T. Allison, C. Babiloni, H. Buchner, A. Eisen, D. Goodin, S. Jones, R. Kakigi, S. Matsuoka and M. Nuwer (1999). "Somatosensory evoked potentials. The International Federation of Clinical Neurophysiology." Electroencephalography and clinical neurophysiology. Supplement **52**: 79-90.

Mauguiere, F., I. Merlet, N. Forss, S. Vanni, V. Jousmäki, P. Adeleine and R. Hari (1997). "Activation of a distributed somatosensory cortical network in the human brain. A dipole modelling study of magnetic fields evoked by median nerve stimulation. Part I: Location and activation timing of SEF sources." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **104**(4): 281-289.

Mauguière, F., J. Courjon and B. Schott (1983). "Dissociation of early SEP components in unilateral traumatic section of the lower medulla." Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society **13**(3): 309-313.

Mauguière, F., J. E. Desmedt and J. Courjon (1983). "Astereognosis and dissociated loss of frontal or parietal components of somatosensory evoked potentials in hemispheric lesions: detailed correlations with clinical signs and computerized tomographic scanning." Brain **106**(2): 271-311.

Mauk, M. D. (1997). "Roles of cerebellar cortex and nuclei in motor learning: contradictions or clues?" Neuron **18**(3): 343-346.

McDonald, J. H. (2009). Handbook of biological statistics, sparky house publishing Baltimore, MD.

Medina, J. and H. B. Coslett (2010). "From maps to form to space: Touch and the body schema." Neuropsychologia **48**(3): 645-654.

Mehrkanoon, S., T. W. Boonstra, M. Breakspear, M. Hinder and J. J. Summers (2016). "Upregulation of cortico-cerebellar functional connectivity after motor learning." Neuroimage **128**: 252-263.

Miall, R. C., H. Imamizu and S. Miyauchi (2000). "Activation of the cerebellum in co-ordinated eye and hand tracking movements: an fMRI study." Experimental Brain Research **135**(1): 22-33.

Miall, R. C., G. Reckess and H. Imamizu (2001). "The cerebellum coordinates eye and hand tracking movements." Nature neuroscience **4**(6): 638-644.

Miall, R. C. and D. M. Wolpert (1996). "Forward models for physiological motor control." Neural networks **9**(8): 1265-1279.

Mima, T., A. Ikeda, T. Nagamine, S. Yazawa, T. Kunieda, N. Mikuni, W. Taki, J. Kimura and H. Shibasaki (1997). "Human second somatosensory area: subdural and magnetoencephalographic recording of somatosensory evoked responses." Journal of Neurology, Neurosurgery & Psychiatry **63**(4): 501-505.

Murphy, B., H. H. Taylor, S. Wilson, G. Oliphant and K. Mathers (2003). "Rapid reversible changes to multiple levels of the human somatosensory system following the cessation of repetitive contractions: a somatosensory evoked potential study." Clinical neurophysiology **114**(8): 1531-1537.

Najarian, K. and R. Splinter (2012). Biomedical signal and image processing, Taylor & Francis.

Nixon, P. D. and R. E. Passingham (2001). "Predicting sensory events." Experimental brain research **138**(2): 251-257.

Noël, P., I. Ozaki and J. E. Desmedt (1996). "Origin of N18 and P14 far-fields of median nerve somatosensory evoked potentials studied in patients with a brain-stem lesion." Electroencephalography and clinical neurophysiology **98**(2): 167-170.

Nuwer, M. R., M. Aminoff, J. Desmedt, A. A. Eisen, D. Goodin, S. Matsuoka, F. Mauguière, H. Shibasaki, W. Sutherling and J.-F. Vibert (1994). "IFCN recommended standards for short latency somatosensory evoked potentials. Report of an IFCN committee." Electroencephalography and clinical Neurophysiology **91**(1): 6-11.

Nuwer, M. R., J. Daube, C. Fischer, J. Schramm and C. D. Yingling (1993). "Neuromonitoring during surgery. Report of an IFCN committee." Electroencephalography and clinical Neurophysiology **87**(5): 263-276.

O'Sullivan, S. B. and T. J. Schmitz (2007). Physical Rehabilitation, FA Davis Company.

O'Brien, S., D. Andrew, M. Zabihhosseinian, P. Yelder and B. Murphy (2020). "Proximal upper limb sensorimotor integration in response to novel motor skill acquisition." Brain Sciences **10**(9): 581.

Passmore, S. R., B. Murphy and T. D. Lee (2014). "The origin, and application of somatosensory evoked potentials as a neurophysiological technique to investigate neuroplasticity." The Journal of the Canadian Chiropractic Association **58**(2): 170.

Paulus, I. and S. Brumagne (2008). "Altered interpretation of neck proprioceptive signals in persons with subclinical recurrent neck pain." Journal of rehabilitation medicine **40**(6): 426-432.

Pearce, A. J. and D. J. Kidgell (2009). "Corticomotor excitability during precision motor tasks." Journal of Science and Medicine in Sport **12**(2): 280-283.

Pearce, A. J. and D. J. Kidgell (2010). "Comparison of corticomotor excitability during visuomotor dynamic and static tasks." Journal of science and medicine in sport **13**(1): 167-171.

Peng, B., L. Yang, Y. Li, T. Liu and Y. Liu (2021). "Cervical Proprioception Impairment in Neck Pain-Pathophysiology, Clinical Evaluation, and Management: A Narrative Review." Pain and Therapy: 1-22.

Pettorossi, V. E., R. Panichi, F. M. Botti, A. Biscarini, G. M. Filippi and M. Schieppati (2015). "Long-lasting effects of neck muscle vibration and contraction on self-motion perception of vestibular origin." Clinical Neurophysiology **126**(10): 1886-1900.

Picazio, S., M. Oliveri, G. Koch, C. Caltagirone and L. Petrosini (2013). "Cerebellar contribution to mental rotation: a cTBS study." The Cerebellum **12**(6): 856-861.

Pierantozzi, M., P. Mazzone, A. Bassi, P. Rossini, A. Peppe, M. Altibrandi, A. Stefani, G. Bernardi and P. Stanzione (1999). "The effect of deep brain stimulation on the frontal N30 component of somatosensory evoked potentials in advanced Parkinson's disease patients." Clinical neurophysiology **110**(10): 1700-1707.

Pierantozzi, M., A. Sabato, F. Leonardis, M. Marciari, C. Cicardi, P. Giacomini, G. Bernardi and P. Stanzione (2000). "Curariform peripheral block of muscular tone selectively increases precentral N30 somatosensory evoked potentials component. A pharmacological study carried out on healthy subjects and parkinsonian syndromes." Experimental brain research **133**(3): 368-376.

Popa, L. S., A. L. Hewitt and T. J. Ebner (2013). "Purkinje cell simple spike discharge encodes error signals consistent with a forward internal model." The Cerebellum **12**(3): 331-333.

Popov, K., B. Smetanin and V. Y. Shlykov (1989). "Changes in the direction of vestibulomotor response in the course of adaptation to protracted static head turning in man." Neurophysiology **21**(2): 159-164.

Proske, U. and S. C. Gandevia (2012). "The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force." Physiological Reviews **92**(4): 1651-1697.

Purves, D., G. J. Augustine, D. Fitzpatrick, L. C. Katz, A.-S. LaMantia, J. O. McNamara and S. M. Williams (2001). Projections from the Cerebellum. Neuroscience. 2nd edition, Sinauer Associates.

Restuccia, D., M. Valeriani, C. Barba, D. Le Pera, M. Capecchi, V. Filippini and M. Molinari (2001). "Functional changes of the primary somatosensory cortex in patients with unilateral cerebellar lesions." Brain **124**(4): 757-768.

Richmond, F. and V. Abrahams (1979). What are the proprioceptors of the neck? Progress in brain research, Elsevier. **50**: 245-254.

Riemann, B. L. and S. M. Lephart (2002). "The sensorimotor system, part I: the physiologic basis of functional joint stability." Journal of athletic training **37**(1): 71.

Rossini, P., F. Babiloni, G. Bernardi, L. Cecchi, P. Johnson, A. Malentacca, P. Stanzione and A. Urbano (1989). "Abnormalities of short-latency somatosensory evoked potentials in parkinsonian patients." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **74**(4): 277-289.

Salo, P. and W. Tatton (1993). "Age-related loss of knee joint afferents in mice." Journal of neuroscience research **35**(6): 664-677.

Schieppati, M., A. Nardone and M. Schmid (2003). "Neck muscle fatigue affects postural control in man." Neuroscience **121**(2): 277-285.

Schmidt, R. A. and T. Lee (1988). "Motor learning and control: A behavioral emphasis Champaign." IL: Human Kinetics.

Seki, K. and E. E. Fetz (2012). "Gating of sensory input at spinal and cortical levels during preparation and execution of voluntary movement." Journal of Neuroscience **32**(3): 890-902.

Shepherd, G. M. (2004). The synaptic organization of the brain, Oxford university press.

Sillitoe, R. V., Y. Fu and C. Watson (2012). Cerebellum. The mouse nervous system, Elsevier: 360-397.

Sonoo, M. (2000). "Anatomic origin and clinical application of the widespread N18 potential in median nerve somatosensory evoked potentials." Journal of Clinical Neurophysiology **17**(3): 258-268.

Sonoo, M., K. Genba, W. Zai, M. Iwata, T. Mannen and I. Kanazawa (1992). "Origin of the widespread N18 in median nerve SEP." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **84**(5): 418-425.

Stallings, W. M. and G. M. Gillmore (1971). "A note on "accuracy" and "precision"." Journal of Educational Measurement **8**(2): 127-129.

Stanton, T. R., H. B. Leake, K. J. Chalmers and G. L. Moseley (2016). "Evidence of impaired proprioception in chronic, idiopathic neck pain: systematic review and meta-analysis." Physical therapy **96**(6): 876-887.

Strimpakos, N., V. Sakellari, G. Gioftsos, E. Kapreli and J. Oldham (2006). "Cervical joint position sense: an intra-and inter-examiner reliability study." Gait & posture **23**(1): 22-31.

Synek, V. M. and J. C. Cowan (1982). "Somatosensory evoked potentials in patients with supraclavicular brachial plexus injuries." Neurology **32**(12): 1347-1347.

Taylor, H. H. and B. Murphy (2007). "Altered cortical integration of dual somatosensory input following the cessation of a 20 min period of repetitive muscle activity." Experimental brain research **178**(4): 488-498.

Treleven, J. (2017). "Dizziness, unsteadiness, visual disturbances, and sensorimotor control in traumatic neck pain." journal of orthopaedic & sports physical therapy **47**(7): 492-502.

Tuthill, J. C. and E. Azim (2018). "Proprioception." Current Biology **28**(5): R194-R203.

Urasaki, E., T. Tokimura, J.-i. Kumai, S.-i. Wada and A. Yokota (1992). "Preserved spinal dorsal horn potentials in a brain-dead patient with Lazarus' sign: Case report." Journal of neurosurgery **76**(4): 710-713.

Valeriani, M., D. Restuccia, V. Di Lazzaro, D. Le Pera, C. Barba and P. Tonali (1998). "The scalp to earlobe montage as standard in routine SEP recording. Comparison with the non-cephalic reference in patients with lesions of the upper cervical cord." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **108**(4): 414-422.

Vernon, H. (2008). "The Neck Disability Index: state-of-the-art, 1991-2008." Journal of manipulative and physiological therapeutics **31**(7): 491-502.

von Bernhardt, R., L. Eugénin-von Bernhardt and J. Eugénin (2017). "What is neural plasticity?" The plastic brain: 1-15.

Waberski, T. D., H. Buchner, M. Perkuhn, R. Gobbelé, M. Wagner, W. Kücker and J. Silny (1999). "N30 and the effect of explorative finger movements: a model of the contribution of the motor cortex to early somatosensory potentials." Clinical neurophysiology **110**(9): 1589-1600.

Wagner, W. (1991). "SEP testing in deeply comatose and brain dead patients: the role of nasopharyngeal, scalp and earlobe derivations in recording the P14 potential." Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section **80**(5): 352-363.

Wallwork, S. B., H. B. Leake, A. L. Peek, G. L. Moseley and T. R. Stanton (2020). "Implicit motor imagery performance is impaired in people with chronic, but not acute, neck pain." PeerJ **8**: e8553.

Wannaprom, N., J. Treleaven, G. Jull and S. Uthaikhup (2018). "Neck muscle vibration produces diverse responses in balance and gait speed between individuals with and without neck pain." Musculoskeletal Science and Practice **35**: 25-29.

Wasaka, T., T. Kida and R. Kakigi (2012). "Modulation of somatosensory evoked potentials during force generation and relaxation." Experimental brain research **219**(2): 227-233.

Wolpert, D. M., Z. Ghahramani and M. I. Jordan (1995). "An internal model for sensorimotor integration." Science **269**(5232): 1880-1882.

Zabihhosseinian, M., M. W. Holmes, B. Ferguson and B. Murphy (2015). "Neck muscle fatigue alters the cervical flexion relaxation ratio in sub-clinical neck pain patients." Clinical Biomechanics **30**(5): 397-404.

Zabihhosseinian, M., M. W. Holmes, S. Howarth, B. Ferguson and B. Murphy (2017). "Neck muscle fatigue differentially alters scapular and humeral kinematics during humeral elevation in subclinical neck pain participants versus healthy controls." Journal of Electromyography and Kinesiology **33**: 73-82.

Zabihhosseinian, M., M. W. Holmes and B. Murphy (2015). "Neck muscle fatigue alters upper limb proprioception." Experimental brain research **233**(5): 1663-1675.

Zabihhosseinian, M., P. Yelder, V. Berkers, U. Ambalavanar, M. Holmes and B. Murphy (2020). "Neck muscle fatigue impacts plasticity and sensorimotor integration in cerebellum and motor cortex in response to novel motor skill acquisition." Journal of Neurophysiology **124**(3): 844-855.

Zabihhosseinian, M., P. Yelder, M. W. Holmes and B. Murphy (2019). "Neck muscle fatigue affects performance of an eye-hand tracking task." Journal of Electromyography and Kinesiology **47**: 1-9.

Zabihhosseinian, M., P. Yelder, R. Wise, M. Holmes and B. Murphy (2021). "Effect of Neck Muscle Fatigue on Hand Muscle Motor Performance and Early Somatosensory Evoked Potentials." Brain Sciences **11**(11): 1481.